CRANFIELD UNIVERSITY

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APPLICATION OF INTEGRATED MODELS TO ASSESS THE IMPACTS OF FLOODPLAIN CONNECTIVITY ON ECOSYSTEM SERVICES: A CASE STUDY AT TEMPSFORD, UK

SCHOOL OF APPLIED SCIENCES
PhD THESIS

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This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

ABSTRACT

Floodplains in the United Kingdom have evolved from natural landscapes to artificially modified ecosystems through managing lateral and vertical floodplain connectivity leading to synergy or trade-offs in ecosystem service delivery. Research methods have been limited in understanding the processes by which ecosystem service values are formed and the data required to support ecosystem service assessment. Developing a methodology while complex and challenging is necessary in order to take the ecosystem approach forward to support decision making for policy makers, planners and stakeholders. The aim of this research was to develop a method to assess the delivery of ecosystem services in response to changes in floodplain connectivity and evaluate the performance. A case study floodplain was selected at Tempsford, downstream of the River Ivel in Bedfordshire, United Kingdom as an example for opportunities to deliver multiple ecosystem services. A sequential integrated modelling system was applied utilising a linked ISIS 1D-2D hydrodynamic model and WaSim, a 1D soil water balance model to simulate changes in floodplain connectivity and generate model data to improve estimates of ecosystem services indicators. A non-monetary multi-criteria analysis methodology was applied to further develop indicators for ecosystem services assessment and to assess the impacts of the model scenarios on ecosystem services delivery. The integration of the WaSim model was unsuccessful as the model performed poorly in the calibration and validation process and was not fit for its intended purpose. It was deduced that potential groundwater seepage in the regional aquifer occurs outside of the field study site, which cannot be modelled in WaSim. To demonstrate the impact of lateral connectivity controls on the water table position, an empirical method was developed using the mean observed water table position to represent a ‘no drainage system’ vertical connectivity scenario. The results showed that in low frequency/high magnitude flood events, increasing the lateral connectivity by lowering embankments provides synergy and benefits to flood alleviation, water supply and freshwater fish habitat and trade-offs and disbenefits to flood damage, agricultural productivity, terrestrial habitat and recreation. In high frequency/low magnitude flood events, decreasing the lateral connectivity by raising embankments still provides the same synergy and trade-offs yet lower benefits and disbenefits. Marginally decreasing the lateral connectivity creates a higher level of benefits and a lower level of disbenefits to promote multi-functional land use in the floodplain. Managing the control of floodplain connectivity needs to be carefully planned to enable multifunctional land use in a floodplain.

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“If I have seen further it is by standing on the shoulders of giants”.

- Sir Issac Newton

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LIST OF ABBREVIATIONS

ADI	Alternating Direction Implicit
AEP	Annual Exceedance Probability
AHP	Analytical Hierarchy Process
AWL	Actual Water table Level
BFIHOST	Base Flow Index Hydrology Of Soil Type
BGS	British Geological Society
BL	Baseflow recession constant (or Lag), (hours)
BR	Baseflow Recharge
BSi	British Standards Institute
CAP	Common Agricultural Policy
CBA	Cost-Benefits Analysis
CF	Correction Factor
CFMP	Catchment Flood Management Plan
CWL	barometrically Compensated Water table Level
Defra	Department of Environment and Rural Affairs
DCLG	Department of Communities and Local Government
DDF	Depth-Duration-Frequency
DEM	Digital Elevation Model
DTM	Digital Terrain Model
EA	Environment Agency
EAAP	Ecosystems Approach Action Plan
EEC	European Economic Community
EU	European Union
ESRI	Environmental Systems Research Institute
FAO	Food and Agriculture Organisation of the United Nations.
FEH	Flood Estimation Handbook
FGS	Flow Gauging Station
FSA	Flood Storage Area
FSR/FEH	Flood Studies Report/Flood Estimation Handbook/
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GS	Ground Surface
IDB	Internal Drainage Board
IPPC	Intergovernmental Panel on Climate Change
LiDAR	Light Detection and Ranging

LTA	Long Term Average
M	Manual measurement
MA	Millennium ecosystem Assessment
MAE	Mean Absolute Error
MAFF	Ministry of Agriculture, Fisheries and Food
mAGL	Metres Above Ground Level
mAOD	metres Above Ordnance Datum
MAUA	Multi Attribute Utility Analysis
mBGL	metres Below Ground Level
MCA	Multi-Criteria Analysis
MOSES	Met Office Surface Exchanges Scheme
NA	Not Applicable
NFCDD	National Flood and Coastal Defence Database
NGR	National Grid Reference
NSE	Nash-Sutcliffe Efficiency
OS	Ordnance Survey
PPS25	Planning and Policy Statement 25: Development and Flood Risk
ReFH	Revitalised Flood Hydrograph
RICS	Royal Institution of Chartered Surveyors
RMSE	Root Mean Square Error
SHE	Système Hydrologique Européen
SPA	Special Protection Areas
SSSI	Site of Specific Scientific Interest
SWE	Shallow Water Equation
TEV	Total Economic Value
TVD	Total Variation Diminishing
UK	United Kingdom
UKNEA	United Kingdom National Ecosystem Services Assessment
UK BAP	United Kingdom Biodiversity Action Plan
UNEP	United Nations Environment Programme
$URBEXT_{1990}$	FEH catchment descriptor defining URban EXTent in 1990
US SCS CN	United States Soil Conservation Society Curve Number
WFD	Water Framework Directive
WLMP	Water Level Management Plan
1D	1 - Dimensional
2D	2 - Dimensional
3D	3 - Dimensional

1 INTRODUCTION

1.1 Overview

A floodplain has been defined by Bridge (2003, p. 260) as ‘a strip of land that borders a stream channel, and that is normally inundated during seasonal floods’. Floodplains are ‘freshwater’ ecosystems that provide a wide range of ecosystem services inextricably linked to hydrology (UKNEA, 2011; Morris et al., 2009; Tockner and Stanford, 2002).

These services are wide ranging to include flood alleviation, flood defence, agricultural production, water supply, habitat conservation and recreation for example (De Groot et al., 2006). Historically, floodplains have evolved from natural landscapes to artificial and modified ecosystems resulting from anthropogenic activities mainly through floodplain connectivity management (Brown, 1996, Werrity, 2006). Their evolution of change is largely a function of their natural attributes e.g. flat terrain, fertile and workable land providing a valuable landscape to suit human needs to deliver a wide array of social, economic and environmental benefits (Penning-Rowsell et al., 2005; Fleming, 2002; Hey et al., 1997). A floodplain has competing demands from multiple stakeholders and ecosystem services with limited land availability leading it to become a highly valued finite natural resource causing synergies and trade-offs amongst ecosystem services (FLUFP, 2010; UKNEA, 2011).

As a result of these demands, the floodplain landscape and fluvial hydrosystem has undergone physical changes altering the floodplain connectivity in two hydrological dimensions (Hey et al., 2007). The first dimension is lateral connectivity, which is described by the episodic and permanent links between a river and a floodplain and the second is vertical connectivity, which is described by the exchange between the surface and groundwater via infiltration and percolation in a floodplain (Amoros and Bornette, 2002). Both these connectivity dimensions act as hydraulic controls in order to manage the hydrological regime of a floodplain (Morris et al., 2004).

Lateral connectivity between the river and floodplain has been subject to physical alterations at the riverbank through natural and structural measures in order to control the hydrological exchange between the river and floodplain (RPA, 2006). Flooding by natural hydrological processes has led to deposition on river banks raising embankments thereby disconnecting the river from the floodplain (Charlton, 2007). While the addition of earth embankments, flood defence walls and managing the crest levels have also led to disconnection of the river from the floodplain (Cook and

Williamson, 1999). Changes in the vertical connectivity of the floodplain have largely been a result of the installation of artificial drainage systems at the surface (e.g. field ditches and main drains), and sub-surface (e.g. pipe drains), in order to control the hydrological exchange between the floodplain surface and groundwater (Smedema et al., 2004 and Smout, 2000).

In the UK from the 13th century to the present day, changes to the floodplain connectivity were conducted in order to defend the land against flooding from rivers and manage water surface levels and water table levels for agricultural production, to prevent loss of life and to protect properties (RPA, 2006). In the last century, alterations in floodplain connectivity to alleviate flooding to reduce impacts upon downstream communities played an important role (RPA, 2006). These physical changes have also led to a reduction of ecological functioning of floodplains to maintain terrestrial habitats and as a habitat to freshwater fish species for spawning, feeding and refuge (Tockner et al., 2010 and Aarts et al., 2004). Water resources are also impacted by floodplain connectivity especially lateral connectivity, as embankments can inhibit overbank flows and flood inundation potentially reducing groundwater recharge to the aquifer from floodwaters (Kazama et al., 2007).

It is clear that floodplain connectivity plays an important role in the delivery of ecosystem services yet how the connectivity is managed, is critical to maximize delivery of ecosystem services and reduce the potential for trade-offs between multiple ecosystem services. Historically, synergy amongst multiple ecosystem services has occurred between flood defence, agricultural productivity and settlements (MAFF, 1999). Although, the trade-offs have affected space for flood alleviation, habitat and recreation ecosystem services. Morris et al. (2004) provided case study examples of synergies for flood alleviation, agricultural productivity and habitat conservation through the utilization of floodplains as ‘washlands’. While the trade-offs in this instance could potentially affect flood defence and recreation ecosystem service opportunities.

The floodplain is a complex and dynamic ecosystem with many dynamic and crucial transfer flows between the surface and sub-surface water regimes (Refsgaard et al., 1998). An integrated modelling system is required to simulate these hydrological processes and to model connectivity scenarios in order to thoroughly assess the impacts of floodplain connectivity (Refsgaard, 1998; Kazama et al., 2007).

Selection of models are critical with the application of well-proven model codes i.e. mathematical numerical solutions to enable the most accurate representation of the hydrological processes occurring in the floodplain and especially floodplain connectivity (Refsgaard and Henrikson, 2004; Refsgaard, 1998). An integrated modelling system is also essential in order to generate the necessary hydrological data e.g. river discharge, inundation area, volume, depth and velocity, and water table level to develop performance indicators to allow the assessment of ecosystem services (Scholes et al., 2010; Alkema and Middelkoop, 2005).

The ecosystems approach is consistent with multifunctional land use and the provision of benefits through the delivery of multiple goods and services in order to maintain a sustainable system (MA, 2003; Costanza et al., 1997; Daily, 1997). Managing the hydrological regime through controlling the floodplain connectivity is necessary to enable synergies rather than trade-offs in ecosystem services (Haase et al., 2012; UKNEA, 2011).The assessment of ecosystems services is essential to provide options for multifunctional land use enabling a sustainable floodplain ecosystem (Posthumus et al., 2010). The assessment of ecosystem services will also reveal the synergies and trade-offs under each floodplain connectivity scenario contributing to decision making. This will enable sustainable multifunctional land use to meet the needs of policy makers, planners and different interests of stakeholders (Defra, 2007; Posthumus et al., 2010). There is a wide range of monetary and non-monetary valuation techniques available to assess changes in ecosystem services (Defra, 2007). The key challenge is in the selection and application of an assessment method that utilizes appropriate indicators to measure the effects of modelling hydrological connectivity scenarios considering the whole ecosystem and considering the impacts of one ecosystem service upon another and how they interrelate (Scholes et al., 2010; Defra, 2007).

This research intends to establish the linkages between hydrological connectivity of floodplains and the impacts on ecosystem services, in order to improve understanding of ecosystem service delivery and support decision making for stakeholders, policy makers and planners. The research is formed of three sections as follows:

1. Identification of the dominant hydrological flows in a floodplain, floodplain connectivity controls and their impact on ecosystem service delivery.
2. Modelling the dominant hydrological flows of a case study floodplain and the floodplain connectivity controls.
3. Applying integrated models to generate hydrological data and design of an ecosystem services assessment method to assess the impacts of floodplain connectivity.

The combination of applying an integrated modelling system to simulate floodplain connectivity in floodplains and designing an ecosystem services assessment system to assess the modelled outputs will take the ecosystem approach forward. This challenge is necessary to enhance decision-making for policy makers and planners in order to choose floodplain connectivity options embracing the concept of a whole system to provide sustainable benefits to multiple stakeholders.

1.2 Research synthesis

1.2.1 **Introduction**

The following section describes the current state of research in terms of integrated modelling systems, floodplain connectivity and ecosystem services assessment techniques for floodplains to include reasoning for the research approach adopted.

1.2.2 **Integrated modelling of floodplain hydrology**

Floodplains are important ecosystems than can provide a host of services and benefits to multiple stakeholders (UKNEA, 2011). In hydrological terms, floodplains are dynamic and complex, as a number of hydrological flows take place, allowing the exchange of water between the river and floodplain surface and subsurface (Jolly and Rassam, 2009). There have been significant advances over the last 30 years to model these flows in order to enhance understanding of the effects of hydrological exchanges upon the delivery of ecosystem services (Jolly and Rassam, 2009). Refsgaard et al., (1998) discussed the importance of the application of integrated modelling systems in order to provide a quantitative assessment of the impacts of surface and groundwater in the floodplain ecosystem in regard to alternative options to enable delivery of ecosystem services. Several authors have discussed the importance of integrated modelling to simulate changes in the hydrological regime thus becoming a valuable tool to assess the impacts of hydrological exchanges on the delivery of ecosystem services (Refsgaard et al., 1998; Kazama et al., 2007; Dutta et al., (2006); Thompson et al., 2004).

An integrated modelling system can be described as made up of individual or coupled i.e. linked model codes that enable simulation of water exchange between three main components namely the atmosphere, surface and subsurface systems (Refsgaard et al., 1998). Each system is formed by the exchange of data i.e. transfer flows of water between the individual model components of which these components may represent a single or multiple flows. There are different degrees that can be applied for model integration as described by Refsgaard et al. (1998) as follows:

- Sequential runs: this is where the results from one model is applied as an input to the next model in an sequence and iterative mode involving model calculations.
- Full integration: coupling between models where the simulation between models takes place between computational time steps and shared memory allowing data transfer for the exchange of water based on transfer and feedback flows.

A number of pertinent research studies (Table 1.1) have employed floodplain modelling made up of either individual models or integrated modelling systems to assess the impacts of hydrological events and alternative floodplain connectivity option to assess the delivery of ecosystem services. Table 1.1 provides the following information:

- The title, author(s) and a brief description of the research study site in regard to the location, catchment or floodplain area and the length of river.
- The hydrological system provides a broad description of the prevailing water exchange components as modelled in the floodplain ecosystem. For example, the surface hydrological system refers to overbank flow, overland flow, surface runoff and channel discharge hydrological transfer flows and the sub-surface hydrological system referring to infiltration, seepage and groundwater recharge hydrological transfer flows.
- Hydrological connectivity provides a specific reference to lateral and/or vertical connectivity between the river-floodplain and floodplain-groundwater in regard to presence of embankments or drains.
- Hydrological events refer either to observed hydrological events at the site e.g. rainfall, river flows or water table depths applied or probability design events e.g. flood return periods as applied in the studies.
- The model type refers to the modelling system applied in terms of the type of model integration i.e. sequential or fully integrated system and/or individual modelling components.
- The model method and application describes the dimensionality approach and model codes.
- The model software applied in the research where applicable is described along with the model outputs.

- Assessment methods provide a brief description of the methods applied to assess the impacts of hydrological events and/or floodplain connectivity.
- The ecosystem services assessed for each research study are also described.

Table 1.1 Floodplain modelling techniques research synthesis

Research			**Hydrological**			**Model**				**Assessment methods**	**Ecosystem Services**
Title	**Author(s)**	**Study area description**	**System(s)**	**Connectivity**	**Event**	**Type(s)**	**Method/ Application**	**Software**	**Outputs**		
The Influence of Floodplain Compartmentalization on Flood Risk within the Rhine–Meuse Delta	Alkema and Middelkoop (2005)	Rhine-Meuse delta	Surface	Lateral e.g. embankments	Design flood (0.08 %AEP)	Individual	2D flood propagation model	Delft-FLS	1. Inundation depth 2. Inundation velocity 3. Inundation duration 4. Attenuation (time)	▪ Flood Hazard Assessment/ ▪ estimation (stage – discharge) ▪ Multi Criteria Analysis – Decision Support Systems	▪ Agriculture productivity ▪ Recreation
Flood detention, nature development and water quality along the lowland river Sava, Croatia	Baptist et al. (2006)	Central Sava Basin, River Sava	Surface and Subsurface (unsaturated zone and saturated zone)	Lateral e.g. embankments	Design flood magnitude events based on the average hydrological year and 1% AEP	Integrated (Sequential)	1. 1D/2D hydrodynamic model 2. Water Balance – field values	1. SOBEK	1. Hydrograph discharge peak 2. Inundation duration 3. Inundation depth 4. Inundation velocity 5. Inundation volume	Hydrological analysis	▪ Flood alleviation ▪ Terrestrial habitat
An application of a flood risk analysis system for impact analysis of a flood control plan in a river basin	Dutta et al. (2006)	Ichinomiya river basin (220 km^2)	Surface and Subsurface	Lateral e.g. dikes (increase embankment height	Observed flood magnitude event (1996) e.g. similar to 2% AEP 1% AEP	Individual	Physical based distributed hydrological model (finite difference schemes) a. Interception (BATS concepts), evapotranspiration (Kristensen and Jensen equations) b. River flow (1D St. Venant equations) c. Overland flow (2D St. Venant equations) d. Unsaturated zone (3-D Richards equation) e. Saturated zone (2D Boussinesq equation)	NA	1. Inundation duration 2. Inundation depth 3. Inundation velocity	Flood estimation model	Urban damage ▪ Flood damage ▪ Agriculture productivity
A mathematical model for flood loss estimation	Data et al. (2003)	Ichinomiya river basin (220 km^2)	Surface and Subsurface	Existing	Observed flood magnitude event (1996)	Individual	Physical based distributed hydrological model (finite difference schemes)	NA	1. Inundation duration 2. Inundation depth 3. Inundation velocity	Flood estimation loss model (grid-based)	Urban damage ▪ Flood damage ▪ Water Supply ▪ Agriculture productivity
Hydrodynamic simulation of the operational management of a proposed flood emergency storage area at the middle Elbe River	Förster et al. (2008)	Middle Elbe 20 km river reach in Germany, 17 km^2 floodplain area	Surface	Lateral e.g. Dikes	1% and 0.5% AEP	Individual	1D+ overland flow and storage	MIKE 11	1. Hydrograph discharge peak	Hydrological analysis	Flood alleviation

Research			Hydrological			Model				Assessment methods	Ecosystem Services
Title	Author(s)	Study area description	System(s)	Connectivity	Event	Type(s)	Method/ Application	Software	Outputs		
Modelling wetland connectivity during overbank flooding in a tropical floodplain in north Queensland, Australia	Karim et al. (2011)	Tully–Murray catchment 2072 km^2, of which 832 km^2 is floodplain	Surface	Existing/Lateral e.g. levees	Design flood events ▪ 100% AEP ▪ 20% AEP ▪ 2% AEP	Integrated (Sequential)	1. 1D hydrodynamic model 2. 2D hydrodynamic model 3. Physical based lumped hydrological model (linked mathematical equations to represent main components of rainfall-runoff process)	MIKE 11 MIKE 21 NAM – MIKE 11	1. Inundation area 2. Inundation duration 3. Inundation seasonality 4. Inundation connectivity 5. Runoff peaks and low flows 6. Timing of peaks and low flow 7. Total volume of runoff	Hydrological analysis	Habitat suitability ▪ Fish habitat
Evaluation of flood control and inundation conservation in Cambodia using flood and economic growth models	Kazama et al. (2009)	Lower Mekong Basin (15,400 km^2) and Mekong river (140 km)	Surface	Lateral e.g. Levees	Observed flood magnitude events in 1993, 1997 and 1998	Integrated (Coupling)	Numerical modelling (finite difference techniques) 1. Surface a. 1D dynamic wave model b. 2D non uniform flow model c. Overflow: weir equation	NA	1. Hydrograph discharge peak 2. Inundation area 3. Inundation depth	Economic model (utility level) 1. Ramsey Diamond overlapping generations model	Agricultural productivity
Evaluation of groundwater resources in wide inundation areas of the Mekong River basin	Kazama et al. (2007)	Lower Mekong Basin (15400 km^2) and Mekong river (140 km)	Surface and Subsurface	Lateral e.g. Levees	Observed flood magnitude events in 1993, 1997 and 1998	Integrated (Sequential)	Numerical modelling (finite difference techniques) 1. Surface a. 1D dynamic wave model b. 2D non uniform flow model c. Overflow: weir equation 2. Groundwater a. Conservation equation b. Darcy's law	LISFLOOD-FP, dynamic flood inundation model to operate with high-resolution raster Digital Elevation Model	1. Hydrograph discharge peak 2. Inundation duration 3. Inundation depth 4. Inundation velocity 5. Groundwater levels	Hydrological analysis	Water supply
An Integrated Model for the Daubing Lowland – Methodology and Applications	Refsgaard et al. (1998)	Danubian lowland (20 km reach) 3000 km^2	Surface and Sub-surface	NA	Observed flows	Integrated (Coupling and Sequential)	1. 1D River modelling 2. 2D overland flow and 2D groundwater flow 3. Reservoir modelling 4. 1D root zone model	1. MIKE SHE 2. MIKE 11 3. MIKE 21 4. DAISY	1. Groundwater table levels 2. Flood frequency, magnitude and duration	Hydrological analysis	Habitat (ecological impact) ▪ Terrestrial habitat
Application of the coupled MIKE SHE/MIKE 11 modelling system to a lowland wet grassland in southeast England	Thompson et al. (2004)	Elmley Marshes (8.7 km^2) Main ditch network (16.6 km)	Surface and Subsurface	Existing/lateral	Observed hydrological data (1997-2000)	Integrated (Coupling)	1. 2D St. Venant equation) 2. Unsaturated (1D - Richards' equation) 3. Saturated (3D-Boussinesq equation) 4. Analytical solutions: interception and evaporation	MIKE SHE/MIKE 11	1. Groundwater table level 2. Ditch water levels 3. Flood surface inundation extent and depth	Hydrological analysis	Habitat (lowland wet grassland management)
Estimating spawning habitat availability in flooded areas of the River Waal, the Netherlands	Van de Wolfshaar et al. (2010)	River Waal, Lobith	Surface	Existing/Lateral	Observed range of river discharges	Individual	2D hydrodynamic model	WAQUA	1. Hydrograph discharge peak 2. Inundation depth 3. Inundation velocity	Habitat suitability model based on model outputs	Habitat suitability ▪ Fish habitat

The majority of pertinent studies (Table 1.1) applied individual model components, while sequential and coupled integrated modelling systems featured less prominent (Table 1.1). Only Kazama et al. (2007); Dutta et al. (2006); Thompson et al. (2004) and Dutta et al. (2003) considered the three main components of floodplain hydrological exchange systems i.e. atmosphere, surface and subsurface (unsaturated and saturated zones) hydrological systems. Many of the studies investigated the impacts of hydrological events and only lateral connectivity options upon the hydrological regime. The predominant ecosystem services assessed in these studies were agricultural productivity, flood damage and flood alleviation, water supply and terrestrial habitat. Van de Wolfshaar et al. (2010), Alkema and Middelkoop (2005) discussed the impacts for fish species and recreation in floodplains respectively. In terms of hydrological events and floodplain connectivity, focus was mainly placed on frequent or extreme observed or design flood events and either presence or absence of embankments controlling lateral connectivity in floodplains. While past studies have provided an improved understanding of the impacts of hydrological events affecting ecosystem service delivery, they were limited to studying the extremities.

The impacts of vertical connectivity e.g. surface drains on ecosystem service delivery are less known except for Thompson et al. (2004) which applied an integrated model to include a drainage network encompassing main and secondary ditches and modelling seasonal rainfall and water table events. This study assessed the application of integrated models to simulate the impacts of seasonal hydrological impacts on managing the hydrological regime and the potential to apply water level management scenarios to support lowland wetland grassland communities. Research has benefited from the adoption of integrated modelling systems to understand the impacts of hydrological events and alternative floodplain connectivity management to deliver ecosystem services. However, research has been sporadic in terms of understanding the impacts of hydrological events and alternative floodplain connectivity management options across the atmosphere, surface and subsurface hydrological exchange systems on multiple ecosystem service delivery.

Further research would benefit from a more complete understanding of the impacts of managing the hydrological regime to enable multiple ecosystem service delivery. This can be achieved through assessing a wider range of hydrological events considering a combination of the following:

- Design flood events to encapsulate frequent, mid-range and extreme events to study the impact of flow discharge from the river and potential inundation to the floodplain.
- Seasonal year events based on rainfall for a year or series of years encompassing the hydrological summer and winter periods representing low and high water tables respectively.

The combination of both hydrological events will enable for example the study of the impacts of the design flood events upon the seasonal water table position and thus the impact to ecosystem services delivery.

The application of multiple alternative floodplain connectivity scenarios to lower and raise embankments integrated with drain spacing configurations will improve understanding of the impacts of hydraulic controls on manipulating the hydrological regime to control the delivery of ecosystem services.

The combination of:

- an integrated modelling system considering the complete floodplain hydrological exchange systems and dominant hydrological flows,
- a wide range of hydrological events, and
- alternative floodplain connectivity configurations

will enable a greater understanding of the impacts of the hydrological regime on ecosystem services, synergies and trade-offs and the floodplain connectivity configuration required to enable multifunctional use of floodplains to enhance ecosystem sustainability.

1.2.3 **Ecosystem services and assessment**

Ecosystem services are defined as the benefits that people obtain from an ecosystem (MA, 2001; Costanza et al., 1997). The concept of ecosystem services has largely evolved in the late 1970s with increased interest and mainstreaming in research taking place from the 1990s onwards (Gómez-Baggethun et al., 2010).

Posthumus et al. (2010) and Defra (2007a) discussed that the valuation of ecosystem services will contribute towards better decision-making to meet the needs of policy makers and stakeholder interests. Table 1.2 provides a synthesis of ecosystem services assessment techniques in the context of the valuation of hydrological based ecosystem services in floodplains utilized as a basis to conduct this research.

Table 1.2 provides the following information:

- The title, author(s) and a brief description of the research study site in regard to the location, catchment or floodplain area and the length of river.
- The hydrological events i.e. design flood events, observed flood events, seasonal year events for each research paper and hydrological outputs applied as indicators to assess ecosystem services.
- The ecosystem services assessment describes the category, sub category, technique, element of Total Economic Value (TEV) captured. This refers to the use value as direct i.e. were individuals derive a benefit from actual and/or planned use for an ecosystem service e.g. food and/or indirect i.e. where individuals derive benefit from ecosystem services supported by the resource (Defra, 2007b). The description refers to a brief context of the ecosystem service assessment method applied for each respective research paper.
- The ecosystem services that were assessed for each respective research paper.

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Table 1.2 Hydrological based floodplain ecosystem services assessment techniques research synthesis

Research			**Hydrological**			**Ecosystem service assessment**				
Title	**Author(s)**	**Study area description**	**Events**	**Outputs**	**Category**	**Method Type**	**Method name**	**Element of TEV captured**	**Description**	**Ecosystem services**
Approaches to valuing the hidden hydrological services of wetland ecosystems	Acharya (2000)	Hadejia-Nguru floodplain wetland	Observed flood events (1994, 1995)	▪ Inundation area ▪ Water table elevations	Monetary value	Revealed preference	Household/ Production function	Indirect use	Economic analysis of groundwater recharge	Agricultural productivity
				▪ Water volume		Stated Preference	Contingent valuation	Direct and Indirect use		Water supply
The Influence of Floodplain Compartmentalization on Flood Risk within the Rhine–Meuse Delta	Alkema and Middelkoop (2005)	Rhine-Meuse delta	Design flood (0.08 %AEP i.e. 1 in 1250 year	▪ Inundation depth ▪ Inundation velocity ▪ Inundation duration ▪ Attenuation (time)					Flood Hazard Assessment/estimation (stage –discharge) and Multi Criteria Analysis – Decision Support Systems	▪ Flood alleviation ▪ Agriculture productivity ▪ Recreation
Integrated ecological, economic and social impact assessment of alternative flood control policies in the Netherlands	Brouwer and van Ek (2004)	Rhine-Meuse Delta, rivers Lek, Merwede, Meuse and Waal, Netherlands	1% and 0.5% AEP	▪ Annual average seepage flux ▪ Watercourse levels ▪ Water table level	Monetary and non-monetary	Decision Support Systems ▪ Multi Criteria Analysis	▪ Bespoke Cost Benefit Analysis ▪ Bespoke Weighted Summation ▪ Evaluation by graphics	Direct and indirect use	Economic and ecological assessment of multiple ecosystem services of alternative flood control options	▪ Flood defence ▪ Agricultural production ▪ Habitat − Terrestrial − Wildlife ▪ Transport ▪ Recreation
The Benefit: Cost Analysis of River Maintenance	Dunderdale and Morris (1997)	Multiple sites in England and Wales ranging with areas from 46 ha–1362 ha and river reach lengths at 3-8.5 km	Four seasons of year classified into dry, average or wet weather conditions	▪ River levels ▪ Water table depth ▪ River stage	Monetary value	Decision support systems	Bespoke Cost Benefit Analysis	Direct and Indirect use	Compares benefits and costs or alternative options e.g. river maintenance	▪ Flood defence ▪ Agricultural productivity
The economic dimensions of integrating flood management and agri-environment through washland creation: A case from Somerset, England	Morris et al. (2008)	Parrett catchment, UK	Dry, average or wet weather conditions	▪ Inundation depth ▪ Inundation duration ▪ Water table levels	Monetary value	Decision support systems	Bespoke Cost Benefit Analysis	Direct and Indirect use	Cost benefit analysis of integrated flood alleviation and agri-environment services	▪ Flood alleviation ▪ Agricultural productivity ▪ Terrestrial Habitat ▪ Terrestrial species
A framework for the assessment of ecosystem goods and services; a case study on lowland floodplains in England	Posthumus et al. (2010)	Beckingham marshes, 900 ha, River Trent, UK	Hydrological regimes based on land use options	▪ Inundation duration ▪ Inundation volume ▪ Mean water table depth and flood probability (%)	Monetary and non-monetary	Decision Support Systems ▪ Multi Criteria Analysis	▪ Bespoke Cost Benefit Analysis ▪ Bespoke Weighted Summation ▪ Evaluation by graphics	Direct and indirect use	Assessment and comparison of multiple ecosystem services under different management scenarios	▪ Agricultural productivity ▪ Financial return ▪ Employment ▪ Soil quality ▪ Floodwater alleviation ▪ Water quality ▪ Greenhouse gas balance ▪ Habitat provision - Wildlife ▪ Transport ▪ Settlement ▪ Space for water ▪ Recreation ▪ Landscape

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Hydrological outputs were also utilized as key indicators in order to assess these ecosystem services. The majority of ecosystem assessment methods applied were monetary based decision support systems i.e. a cost benefit analysis method considering the impacts of land management options and hydrological events on ecosystem service delivery. Turner et al., (2003) and Hardin (1968) discussed that when services have no price; their value is rarely considered in decision-making. Dunderdale and Morris (1997) devised and developed an elegant and complex bespoke cost benefit method for assessing agricultural productivity based on market prices, expropriation and compensation payments and considering floodplain hydrology. Attaching monetary values to ecosystem services can be quite complex with uncertainties in ecosystem services values largely generated through manipulation of markets as a function of an institution or individuals notion of property, ownership and rationality (Gómez-Baggethun et al., 2010). In many instances, markets do not exist especially in terms of habitat and flood alleviation ecosystem services. Several studies have applied multi-criteria analysis methods to assess flood alleviation, flood hazard i.e. damage and habitat considering sets of hydrological indicators and applying a performance score to value land use options which are related to managing the hydrological regime with consideration of floodplain connectivity (Posthumus et al., 2010; Alkema and Middelkoop, 2005; Brouwer and van Ek, 2004). This type of ecosystem assessment method allows for a relative assessment in order to support decision making to highlight preferences for one floodplain connectivity management over another.

Posthumus et al. (2010) discussed that valuing ecosystem services remains quite challenging with some indicators having a basis in well-established methods and data sets e.g. agricultural production and flood defence. Alkema and Middelkoop (2005) reiterated that understanding the hydrological processes is essential and should consider the application of multiple set of indicators to assess ecosystem services in order to improve reliability and allow a wider interpretation of the value under floodplain management i.e. connectivity options.

Table 1.2 indicates that decision support systems are the most appropriate and commonly utilized to assess ecosystem services in regard to floodplain connectivity options. Several authors have defined and developed comprehensive, reliable and robust hydrological based set of indicators considering the main hydrological process in order assess flood damage, water supply, agricultural productivity and flood alleviation ecosystem services for example (Posthumus et al., 2010; Morris et al., 2008; Alkema and Middelkoop, 2005; Archarya, 2000; Dunderdale and Morris, 1997). Brouwer and van Ek (2004) applied a set of hydrological based indicators to assess terrestrial habitat ecosystem services. While some estimates of indicators for ecosystem services have been established, there is considerable scope to improve upon these estimates to allow an improved understanding of the hydrological processes and types of floodplain connectivity that can impact on ecosystem service delivery. The application of multiple indicators is also an important consideration as Alkema and Middelkoop (2005) for example assessed the recreation ecosystem service applying a single hydrological indicator e.g. inundation level, which was found to be unreliable as it neglected other relevant hydrological indicators that impact on ecosystem service delivery as a function of floodplain connectivity. Posthumus et al., (2010) also discussed that the estimates of indicators can be considerably improved through the use of hydrological models.

Hydrological indicators have been proven as effective instruments to allow comparison of ecosystem services delivery in a floodplain under alternate land or hydrological based scenarios (Table 1.2). However, research that has utilized hydrological indicators to assess multiple ecosystem services under options have heavily focused on regulation and production ecosystem functions and their services.

1.3 Aim

The aim of this research is to develop a method to assess the delivery of ecosystem services in response to changes in floodplain connectivity and evaluate the performance.

The outcome of this research will improve understanding on the impact of floodplain connectivity and their hydrological controls to manage the hydrological regime for ecosystem service delivery. The further development of a method to estimate hydrological indicators will improve understanding of the implications of controlling floodplain connectivity and will take the ecosystems approach forward. The product of the research will enhance decision making for policy makers and planners embracing the complete hydrological system to provide sustainable benefits to multiple stakeholders.

1.4 Objectives

The objectives to deliver the aim of this research are to:

- Select and characterize a suitable case study site floodplain.
- Define a range of hydrological event and floodplain connectivity scenarios.
- Select and apply a suitable integrated modelling system to simulate the impacts of the hydrological regime under hydrological event and floodplain connectivity scenarios.
- Design a floodplain ecosystem services assessment method to assess the impacts of hydrological events and floodplain connectivity.
- Assess the impacts of hydrological events and floodplain connectivity on ecosystem services delivery, synergies and trade-offs.

1.5 Thesis structure

This thesis is composed of eight chapters comprising the following information.

Chapter 2 describes floodplain characteristics in terms of their evolution from a natural to a modified landscape including the hydrological and fluvial geomorphological processes, features and controls and their impacts on ecosystem services delivery. Past and present floodplain management is described and finally, the policies, strategy and legislation applied to floodplains are also described.

Chapter 3 provides background information on modelling floodplain processes to include individual and integrated modelling systems describing model types, methods and applications. The choice of the integrated modelling system is described and justified. The research integrated modelling system and approach is defined and described with justification for its application in this research. A brief description is provided of the model outputs generated from the integrated modelling system and their application to develop an ecosystem services assessment method.

Chapter 4 introduces the concept of ecosystem services and their classification in floodplains e.g. functions/services, which are hydrological based. The multifunctional land use approach in floodplains is described in regard to ecosystem services. The drivers of changes in ecosystem service delivery are described. Assessment methods applied to ecosystem services in floodplains are described. Finally, the selection of an ecosystem services method for application in this research is described and justified.

Chapter 5 provides information on the selection and characterization of the case study site to include the methodology and discussion of site selection and characteristics in terms of hydrology/morphology, hydrogeology and ecosystem services.

Chapter 6 describes the methods applied and data sources utilized to further describe the floodplain hydrology of the case study site. The methodology for hydrological events, floodplain connectivity and the integrated model components design, simulation, sensitivity tests, parameterization or calibration and validation are described. Finally, the results and discussion are provided for all of the above.

Chapter 7 provides a description of the methodology for the ecosystem services assessment method for the floodplain hydrological based ecosystem services. The results of the hydrological events and floodplain connectivity model scenarios are displayed to include a discussion of the impacts for each ecosystem service and assessing synergies and trade-offs for multiple ecosystem services under the scenarios.

Chapter 8 provides the conclusion revisiting each objective, the limitations as a result of the research are discussed and finally recommendations for further work.

2 FLOODPLAIN CHARACTERISTICS AND MANAGEMENT

2.1 Fluvial geomorphological characteristics

Floodplains can develop and occur on all alluvial valleys, alluvial fans and deltas. Their geometry is varied and includes a host of geomorphic features as a direct result of long-term cumulative action of flow, erosion and depositional processes (Howard, 1996 and Figure 2.1 a,b). Floodplain morphology is closely linked with the behaviour of the river channel that may shape them with a number of deposition and erosion processes involved in the development and formation of floodplains and features (Charlton, 2008).

Figure 2.1(a,b) illustrates floodplain features created by erosional and deposition fluvial geomorphological processes. The floodplain features are illustrated in two diagrams to distinguish between each feature and fluvial geomorphological processes forming them. Further description of the fluvial geomorphological features and processes that create them to include their impact on ecosystem service delivery are outlined in this section.

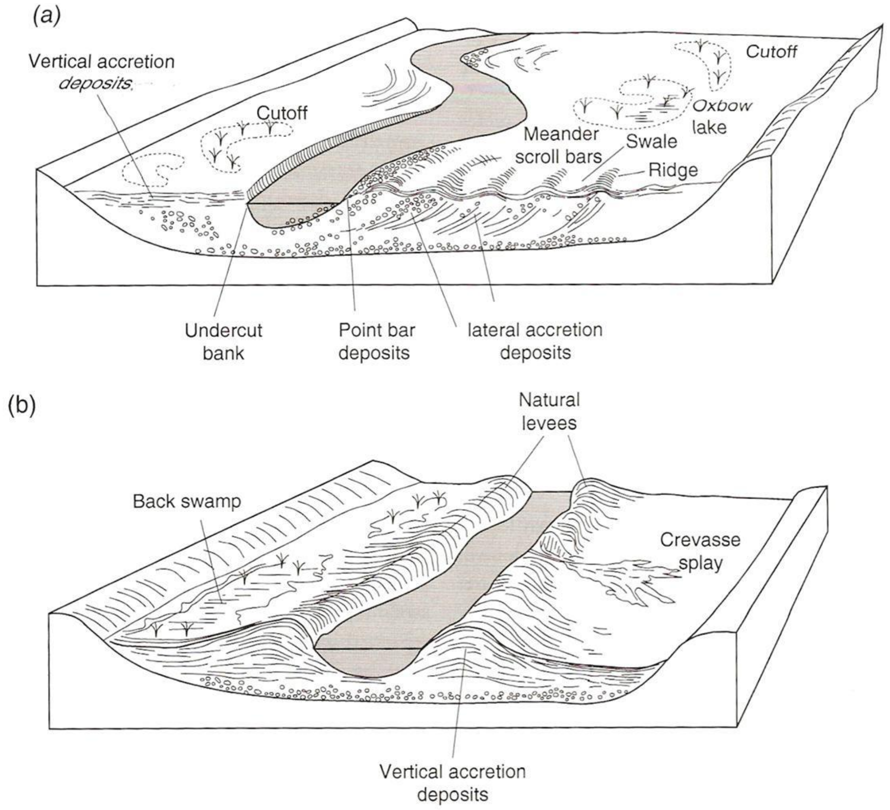

Figure 2.1(a,b) Floodplain fluvial geomorphological features

Source: Charlton (2008, p. 135)

1. River channel (Figure 2.1 a,b): Rivers are formed through erosion of the river bed and deposition and reworking of sediments continuously to shape and reform the channels as described by Charlton (2008). Channels can be eroded in the underlying bedrock and alluvium. Where the valley floor is wide enough, material e.g. alluvium ranging in unconsolidated particles of boulders, gravels, sands, silts and clay laid down in the channel to include the deposition of silt by floods will form a floodplain adjacent to the river channel. Rivers can drain over a large catchment area formed of a branching network of channels i.e. eventually forming a main channel fed by a number of tributaries. The size of the river channel at a given point is determined by the upstream discharge. The upper reaches in a river represent relatively smaller discharge and channel size while the downstream reaches will display an increase in channel size and discharge as a result of the upstream drainage area. The continuous reworking of the river shape from erosion and deposition of sediments can cause the river channel to deviate from a straight line and form meanders, braided channels and anabranching channels. In addition, erosional processes can cause the channel to become widened and deeper thus increasing the discharge flow and volume. The erosion of the channel can change the slope of the watercourse thus affecting the timing in response to peak discharge with steeper slopes producing greater peak discharges from flooding (Gordon et al., 2004). While depositional processes can decrease the channel depth reducing flow discharge and volume. The fluctuation of flow and sediment supply in a river channel at a particular point e.g. downstream reach is an important aspect of the rivers capacity to contain flow discharge and volume and remain confined within the channel. This is an important control factor regarding the potential for flooding at a given point on a river reach which can provide contrasting benefits and disbenefits in regard to ecosystem service delivery. For example:
    - Kazama et al. (2007) discussed that flooding provides water for groundwater recharge hence beneficial for water supply.
    - Penning-Rowsell et al. (2005) described the maximum flood probability tolerance for different agricultural land uses and crops with high frequency/low magnitude flood events preferential for intensive and extensive grassland for pasture farming and intensive and extensive arable farming e.g. potatoes and cereals.
    - Smedema et al. (2004) and Dunderdale and Morris (1997) discussed that flooding can induce waterlogging hence reduce agricultural productivity.

  - Penning-Rowsell et al. (2005) discussed that flooding can cause flood damage to properties in terms of building structural integrity and inventory items.

2. Natural levees (Figure 2.1b): Levees also known as embankments are raised berms and crests above the floodplain surface adjacent to the river channel, usually containing coarser materials deposited as a result of floodwaters overtopping the channel banks (Leopold et al, 1964). Embankments are formed through deposition of fine sediment materials from the river as a result of overbank flows inundating the floodplain. The cumulative effect of overbank flows causes vertical accretion i.e. development of thin layers which raise the elevation of the embankment with the cumulative effect of each overbank flow (Charlton, 2008). The sudden loss of momentum from overbank flows moving across the floodplain can lead to the preferential deposition of sediments at the channel/floodplain boundary known as embankments.

   Lateral connectivity controls the frequency, extent and duration of overbank flows from flood events (Charlton, 2004). The presence and absence of embankments can have contrasting impacts to ecosystem service delivery. For example:

   - Morris et al. (2004) described that deposition of silt from floodwaters laden with sediment can enrich the soil hence improve the agricultural productivity in a floodplain post flood event inundation. Smedema et al. (2004) discussed that inundation of floodwaters can lead to waterlogging which can potentially reduce crop productivity due to raising the water table level and the ponding duration.
   - Penning-Rowsell et al. (2005) and MAFF (1999) discussed that decreasing connectivity by raising embankments reduces the impact of overbank flows and flood inundation to limit flood damage to properties especially in urban areas
   - Kazama et al. (2007) discussed that increasing connectivity by lowering embankments allows for more preferential flood inundation for groundwater recharge to increase water supply.
   - Caruso and Downs (2007) and Morris et al. (2004) discussed that increasing the lateral connectivity by lowering embankments enables improved access to the river corridor and can provide recreation benefits e.g. nature reserves and visitor centres through the biodiversity of the landscape as a product of overbank flows and flood inundation e.g. wet grasslands. However, increasing the lateral connectivity by lowering embankments will incur greater flood inundation and may inhibit land access to avail of recreation opportunities. Although, decreasing lateral connectivity by raising embankments will reduce

flood inundation making the land more accessible to dryland based activities e.g. walking, running, cycling, picnicking and camping (Woolsey et al., 2007).

- Aarts et al. (2003) and Amoros and Bornette (2002) discussed that decreasing connectivity by the presence of embankments can inhibit the use of the floodplain by freshwater fish for spawning, feeding and refuge as part of lifecycle requirements affect fish diversity and populations.
- Tockner and Stanford (2002) discussed that lateral disconnection through raised embankments between the river and floodplain reduce floodwater inundation which causes degradation and destruction of floodplain grasslands and alter the plant community composition in response to the hydrological regime.

Overbank flows where the flow is relatively high and exceeds the capacity of the channel overtopping into the floodplain can create further floodplain features e.g. meander scrolls, cut-offs and oxbow lakes, crevasse splays, back swamps and discontinuous channels.

3. Meander scrolls (Figure 2.1a): These are depressions and rises on the convex side of bends, which are formed through lateral accretion and lateral channel migration (Leopold et al., 1964). The lateral accretion process occurs through migrating rivers, where deposits are laid down after erosion into the floodplain forming point bars. Meander scroll bars are a series of concentric undulating ridges and swales formed across the floodplain representing former location of point bars (Charlton, 2008).
4. Cut-offs/oxbow lakes (Figure 2.1a) refer to the cut-off portion of meander bends from rivers. Oxbow lakes are formed by erosion of the river bank at the meander bend as a result of high river discharge causing the meander to be cut off (Charlton, 2008). This forms a U-shaped free standing body of water. Over time cut-offs become infilled with sediment from deposition as a result of overland flow or flood inundation.
5. Crevasse splays (Figure 2.1b): are deposits of flood debris with usually coarser particles in the form of splays and scatter debris (Leopold et al., 1964) The breaching of embankments by floodwaters leads to the formation of crevasse splays, which appear as fan shape lobes of sediment as a result of flows containing sediment escaping down an embankment (Charlton, 2008).
6. Backswamp (Figure 2.1b): are overbank deposits made up of finer sediments deposited in ponded areas between the natural embankment and valley wall (Leopold et al, 1964). Back swamps are formed as a result of sediment build up in

the channel becoming higher than the floodplain and floodwater from overbank flows occupies a low-lying areas or depressions on the other side of the levee.

7. Discontinuous channels (not featured in Figure 2.1a,b): are formed from erosional process of avulsion from flood flows being sufficient enough to remove entire sections of the floodplain surface (Charlton, 2008).

These floodplain features in points 3-7 have contrasting impacts on ecosystem services with examples described as follows:

- Hey (1997) described floodplains as a valuable resource for either urban and industrial development and also for agriculture due to its flat terrain. Floodplain features such as a backswamp and oxbow lakes can reduce the spatial extent and accessibility of the land for farm machinery and also for intensive and extensive arable and pasture farming due to the ponded surface waters (Smedema et al., 2004). Crevasse splays and meander scrolls alter the floodplain topography which essential can become filled with ponded water from overland flows and flood inundation reducing the productivity of the land for agricultural use. Ponded waters may reduce crop productivity e.g. intensive and extensive arable crops and reduce land access for livestock grazing and also machinery access (Smedema et al., 2004).
- Aarts et al. (2004) described that the erosional and deposition processes from floods can provide a mosaic of different aquatic habitats on floodplains for fish species to utilise for spawning, feeding and refuge during flood events as part of their lifecycle.
- Wheeler et al. (2004) described that the topography of the floodplain landscape can affect the distribution of the floristic composition with regard to creating a subtle difference in the hydrological regime. Floodplain features e.g. meander scrolls, cut-offs and oxbow lakes, crevasse splays, backswamps and discontinuous channels can act to pond water from overbank flows and surface runoff and raise the water table level and/or reduce ponding and increase the ground surface elevation further away from the water table. These flows will enable the necessary hydrological regime to maintain or change the floristic composition of a grassland habitat community within a floodplain.

2.2 Hydrological characteristics

The hydrological regime of a floodplain and river with its crucial hydrological flows occur with the exchange within and between the atmosphere, surface and subsurface hydrological systems (Refsgaard et al., 1998). These systems and flows are basic components of the hydrological cycle (Ward and Robinson, 2000). The atmosphere system is explicit, while the surface system describes the floodplain ground surface and open water channels and the subsurface system is described by the floodplain subsurface i.e. unsaturated and saturated zones.

The hydrological flows occurring in the floodplain/river hydrological system are described as transfer ‘flows’ occurring through the exchange within and between the hydrological systems (Figure 2.2). A further description of each hydrological flow and hydrological system exchange is provided throughout the section.

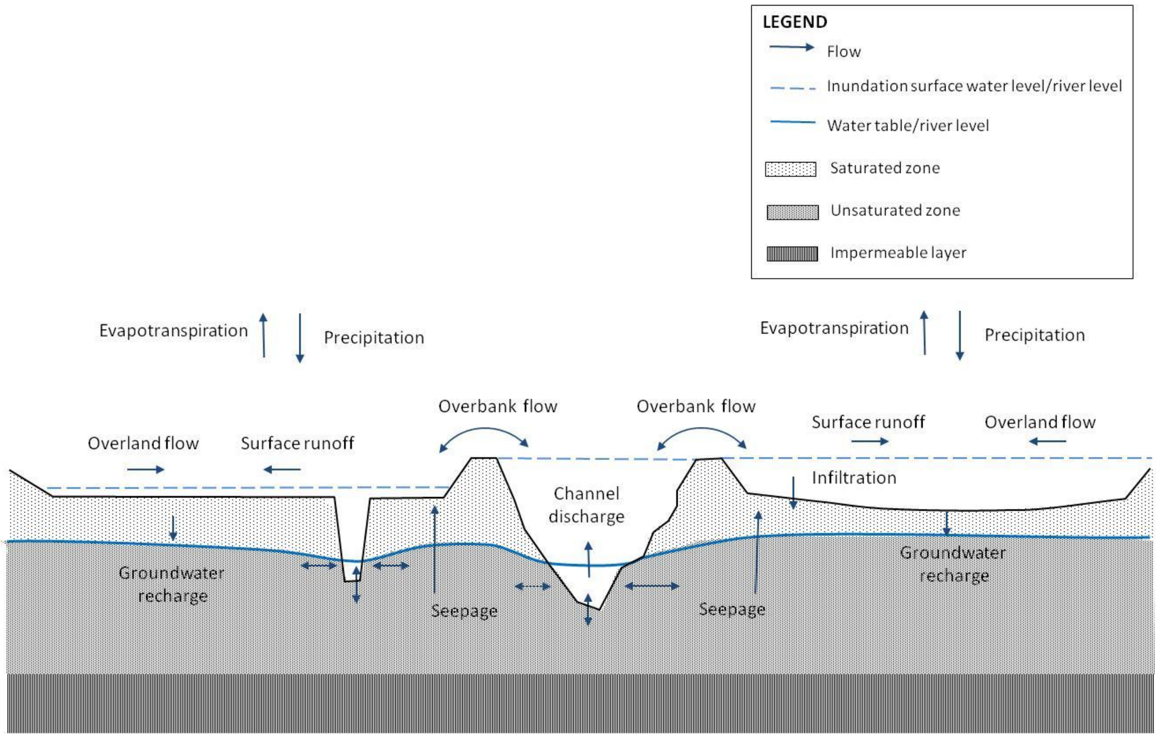

Figure 2.2 Schematic of floodplain and river hydrological processes

Source: after Ward and Robinson (2000, p. 7, 9 and 10)

The atmosphere-surface systems are comprised of precipitation, evapotranspiration, channel discharge and overland flow. These flows occur between the atmosphere and the floodplain surface and described as follows:

- Ward and Robinson (2000) describe precipitation as a major controlling factor of hydrology in a region and the main input of water to the earth’s surface. It is a key flow that influences other rates of other processes i.e. channel discharge, surface runoff and overland flow, infiltration, seepage and groundwater recharge. Precipitation can occur in a number of forms e.g. rainfall, hail and snowfall with variable distribution and concentration where it falls to the ground surface (Ward and

Robinson, 2000). In this research, precipitation shall be defined in terms of ‘rainfall’ occurrence and distribution, as other forms of precipitation are less common in Eastern England. Precipitation is also an important transfer flow in terms of causing floods as heavy and/or prolonged rainfall onto the ground surface can lead to saturation and infiltration excess overland flow (Ward and Robinson, 2000). Rainfall can induce flooding directly onto the floodplain and increasing river discharge causing overbank flow and surface runoff to the floodplain. For example, both forms can impact on increasing the area of inundation and the surface water flooded depth, which may cause flood damage to properties, reduce agricultural productivity and inhibit recreation land access (Alkema and Middelkoop, 2005; Penning-Rowsell et al., 2005; Smedena et al., 2004). However, rainfall as a source of flooding can also provide benefits for groundwater recharge for water supply and as a freshwater fish habitat in the floodplain (Van de Wolfshaar et al., 2010; Kazama et al., 2007).

- Evapotranspiration describes the combined processes of evaporation from a bare soil, open water and including transpiration from vegetation surfaces (Ward and Robinson, 2000).
    - The rate of evaporation from bare soils is often less than an open water surface due to the limitation of available water in soil and the ability of soil to transmit water to the ground surface although evapotranspiration from vegetated surfaces provides most of the evaporation (Ward and Robinson, 2000). Evapotranspiration is an important hydrological transfer flow to limit the input of rainfall. In addition, where flooding has occurred as a result of a rainfall event, evapotranspiration can reduce the effect of the flood inundation depth and ponding duration with the transfer of water into the atmosphere from the ponded surface waters. For example, this flow contributes to reducing damage to agricultural productivity from ponding duration and contributes towards the removal of water from the ponded water surface for recreation access (Smedena et al., 2004).
- Channel discharge occurs in the river and surface drains and may lead to overbank flows thus contributing to surface runoff in the floodplain and groundwater recharge (Hugget, 2003). This process is a quite important transfer flow linked to overbank inflow as when the channel discharge exceeds the channel capacity i.e. bankfull stage, this is general is defined as a ‘flood’ (Charlton, 2008). The channel discharge is a direct product of rainfall and overland flow into the channel, which can lead to an increase in discharge and potentially overbank flow to cause flood inundation. The impacts on channel discharge are the same as described for precipitation above.

- Overland flow is described by Ward and Robinson (2000) as water that flows over a ground surface to a river channel due to the inability of water to infiltrate the surface as result of high intensity rainfall and/or low infiltration capacity. It may occur as sheet flow or in small rivulets or trickles with the surface water originating from either precipitation or floodwaters.

The surface hydrological system is comprised of overbank flow and surface runoff. Theses flows occur in various parts between the river and floodplain as follows:

- Overbank flow is described in two ways as follows:
  - Inflow: is a transfer process that occurs through the interaction of the river and floodplain in the surface system (Huggett, 2003). It is closely linked with channel discharge as it occurs during relatively high flows when the capacity of the river channel i.e. bankfull stage/discharge is exceeded (Charlton, 2008). This process is also linked to surface runoff in the floodplain causing floodwater inundation.
  - Outflow: is a transfer process that occurs as the result of the interaction between the floodplain and river in the surface system. This process is described by the return of surface runoff in the floodplain to the river channel as the river stage falls with any water remaining in the floodplain being retained by the embankments (Morris et al., 2004; Ward and Robinson, 2000). This process is an important flow in regard to the full or partial removal of the floodwaters after the flood event has passed. Full and partial removal of floodwater will depend on the lateral connectivity, with raised embankments retaining some floodwaters and vice versa. For example, the removal of floodwaters can alleviate disbenefit impacts for agricultural productivity and improve land access for recreation.
- Surface runoff in this research is defined as a transfer flow occurring between the river and floodplain. It is described by the flow of water over the ground surface as a result of high river discharge and overbank inflows from the river to the floodplain. This flow is critical in regard to the lifecycle water depth and velocity requirements of freshwater fish to utilise the floodplain for feeding, spawning, refuge and shelter from predators (Cowx et al., 2004).

The subsurface system is comprised of infiltration, seepage and groundwater recharge. These flows occur between the river/floodplain and in the floodplain (i.e. unsaturated zone-saturated zone) as follows:

- Infiltration is a process described by the entry of water originating from the atmosphere e.g. precipitation or from overland flow or surface runoff from the ground surface into the soil through the soil surface i.e. unsaturated zone (Ward and Robinson, 2000). This flow is a pivotal process in the surface hydrology as it can influence the potential surface water depth, duration of ponding and the water table position (Smedema et al., 2004). Once the water is in the soil, it will either move laterally as throughflow or can be temporarily retained before either moving upwards e.g. evaporation or downwards e.g. percolation. Infiltration is affected by the infiltration capacity describing the amount of water that can be absorbed by soil and/or the infiltration rate describing the supply rate of water e.g. rainfall (Brady and Weil, 2008). Infiltration of water will occur at the soil surface until the soil reaches infiltration capacity were excess water will either become ponded or waterlogged at the soil surface and/or lead to overland flows to channels on the floodplain surface (Ward and Robinson, 2000). The influence of this flow can impact on agricultural productivity, land access for recreation and terrestrial habitat e.g. tolerance to grass kill or floristic community change (Smedema et al., 2004 and Wheeler et al., 2004).
- Seepage is a process that occurs naturally via two distinct ways described by Ward and Robinson (2000) as follows:
    - Upward movement of groundwater from an aquifer to the ground surface.
    - Upward and lateral movement of groundwater as seepage into surface drains and rivers.
    - Downward and lateral movement of channel discharge as seepage from the river and surface drains into the groundwater.

  This transfer flow can contribute to raising water levels in channels i.e. surface water drains in the floodplain and the river channel. It can also impact on increasing channel discharge and raising water table levels hence potential for flooding causing flood damage to properties, agricultural productivity, terrestrial habitat loss or habitat community change and reduced access to land for recreation.
- Groundwater recharge is a process that occurs naturally via two distinct ways described by Ward and Robinson (2000); Brady and Weil (2008) as follows:
    - Infiltration of rainfall at the floodplain ground surface into the unsaturated zone.
    - Percolation involves the movement of the infiltrating rainfall from infiltration down through the unsaturated zone to the saturated zone.
    - Seepage from the bed and banks of channels i.e. surface drains in the floodplain and a river channel.

The hydrological process described above cause the water table to rise. Recharge rates in regard to unconfined aquifers are a function of rainfall and seasonal conditions. For example in winter, recharge rates are higher due to soil in the unsaturated zone is wetter and evapotranspiration losses are smaller (Shaw et al., 2011). Groundwater recharge has an impact on providing water supply, yet the water table position can be critical in terms of acceptable levels for agricultural productivity and water regime tolerance for terrestrial grassland habitats (Smedema et al., 2004 and Wheeler et al., 2004).

2.3 Floodplain connectivity and hydraulic controls

Floodplain connectivity in floodplains can be described in four hydrological dimensions (Amoros and Bornette, 2002; Zsuffa and Bogardi, 1995) as follows:

1. Longitudinal (Upstream-downstream gradient)
2. Lateral (permanent and episodic links between the river and floodplain)
3. Vertical (exchange between surface and groundwater i.e. infiltration into the aquifer and groundwater interflow/seepage from a channel and floodplain).
4. Flow control
    a. Passive (appropriate sizing and linking of lateral spillways between the river and floodplain for unregulated flow)
    b. Active (operation and management of control structures at lateral spillways to regulate flow)

This research focuses on lateral and vertical connectivity for the following reasons:

1. These types of hydrological connectivity are the main dimensions of water flow and exchange pathways between the river and floodplains (Tockner and Stanford, 2002)
2. In the UK, these types of connectivity are the most widely applied modifications of floodplains to manage the hydrological regime to enable the delivery of ecosystem services (Werrity, 2006)

Figure 2.3 illustrates floodplain connectivity conditions and their hydraulic control examples. Lateral connectivity is described by the bankfull stage, natural and artificial embankments located at the boundary between the floodplain and river banks. Vertical connectivity is described by the connection between the floodplain surface and subsurface as no drain, natural and artificial drains which control the water table level between the floodplain surface and subsurface.

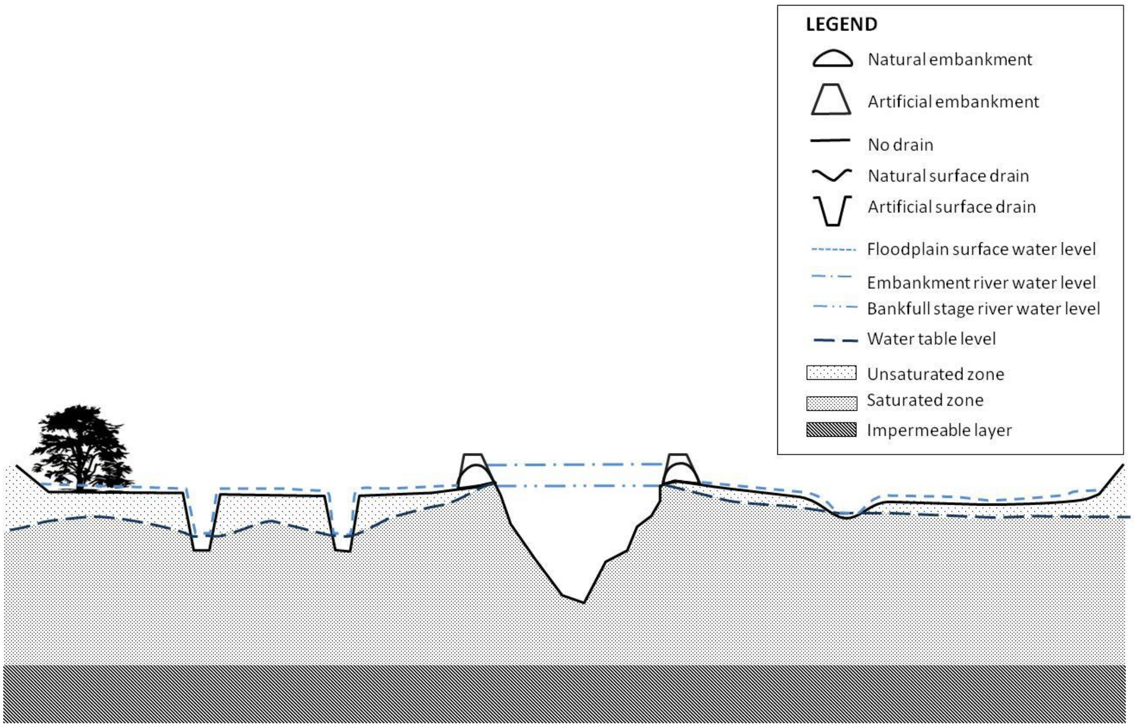

Figure 2.3 Lateral and vertical connectivity schematic diagram

2.3.1 **Lateral connectivity**

Lateral connectivity is the exchange of water between the river and floodplain with natural or artificial embankments acting as hydraulic controls to permit the transfer of overbank inflows from flood events into the floodplain and the transfer of overbank outflow returning to the river (Charlton, 2008). Figure 2.3 illustrates lateral connectivity conditions and the position of the surface water level in the river and floodplain as a result of lateral connectivity between the river and floodplain.

Table 2.1 provides a list and description of lateral connectivity examples between rivers and floodplains including their condition, level of connectivity and hydraulic control.

Table 2.1 Examples of lateral connectivity in floodplains

Lateral connectivity condition	**Connectivity level**	**Hydraulic control level**
Bankfull stage	Full connection	No control
Natural embankment	Partial connection	Partial control
Artificial embankment	Disconnection	Full control

Source: after Charlton (2008); Leopold et al. (1964).

Charlton (2008) describes the bankfull stage as the incipient water elevation occurring at the top of channel banks and where water begins to flow over the banks into the floodplain. Leopold et al., (1964) mentioned that the recurrence interval of the bankfull stage and discharge appears in the range of 100% - 50% AEP in general yet can vary and diverge due to physiographic settings of a floodplain. The inflow from the river will vary along the channel length due to variation in bank heights (Charlton, 2008). This type of connection allows natural unimpeded flow exchange between the river and floodplain with inundation starting to occur in areas of low bank topography.

Natural embankments (Figure 2.3) and their crest levels can vary along the river channel with overbank flows from flood events impeding flows into the floodplain based on the height of the natural embankment (Charlton, 2008). This type of connection will impede high flows from the river based on the embankment crest elevation potentially allowing for partial connection between the river and floodplain.

Artificial embankments (Figure 2.3) are built alongside river channel margins in lowland rivers with their purpose to increase channel capacity during high flows in the river and also to protect the surrounding floodplain from inundation. Traditionally, these embankments are constructed from earth and in some cases are made from concrete i.e. flood walls (Charlton, 2008). In economic and practical terms, it is not feasible to construct embankments that would contain all floods that may possibly occur (Charlton, 2008). Therefore, embankments are suitably built to withstand a certain design flood event and expressed as a ‘Standard of Protection’ (SoP). Table 2.2 describes the indicative standards of protection as per land use i.e. agriculture, urban and rural areas and environmental assets in England and Wales (MAFF, 1999).

Table 2.2 Land use band indicative standards of protection for %AEP flood events

Land use band	Description	Indicative standards of protection (% AEP flood events)
		Fluvial
A	Typically intensively developed urban areas at risk from flooding.	2 – 0.5
B	Typically less intensive urban areas with some high-grade agricultural land and/or environmental assets of international importance requiring protection.	4-1
C	Typically large areas of high-grade agricultural and and/or environmental assets of national significance requiring protection with some properties also at risk, including caravans and temporary structures	20-2
D	Typically mixed agricultural land with occasional, often agriculturally related properties at risk. Agricultural land may be prone to flooding and waterlogging. May also apply to environmental assets of local significance.	80-10
E	Typically low-grade agricultural land, often grass, at risk from flooding, impeded land drainage with isolated agricultural or seasonally occupied properties at risk, environmental assets at little risk from frequent inundation.	>40

Source: after MAFF (1999, p. 62)

Where the flow of a design flood event is exceeded, the embankments will be overtopped. Charlton (2008) described that the depth of flow contained within the embankments is greater than it would be if no embankments were present and the water was able to inundate the floodplain. This type of connection acts to impeded overbank flows and reduces frequency, extent and duration of inundation from a flood event to reduce the connectivity between the river and floodplain.

2.3.2 **Vertical connectivity**

Vertical connectivity is the exchange of water between the floodplain surface and subsurface. Natural and artificial drains act as hydraulic controls to permit the transfer of water via infiltration, percolation from precipitation and/or flood inundation and feedback of seepage and groundwater recharge within the floodplain or from a surface drain (Charlton, 2008: Werrity, 2006). Figure 2.4 (A,B) illustrates examples of vertical connectivity conditions and the water table position as a result of no drains and surface drains in the floodplain.

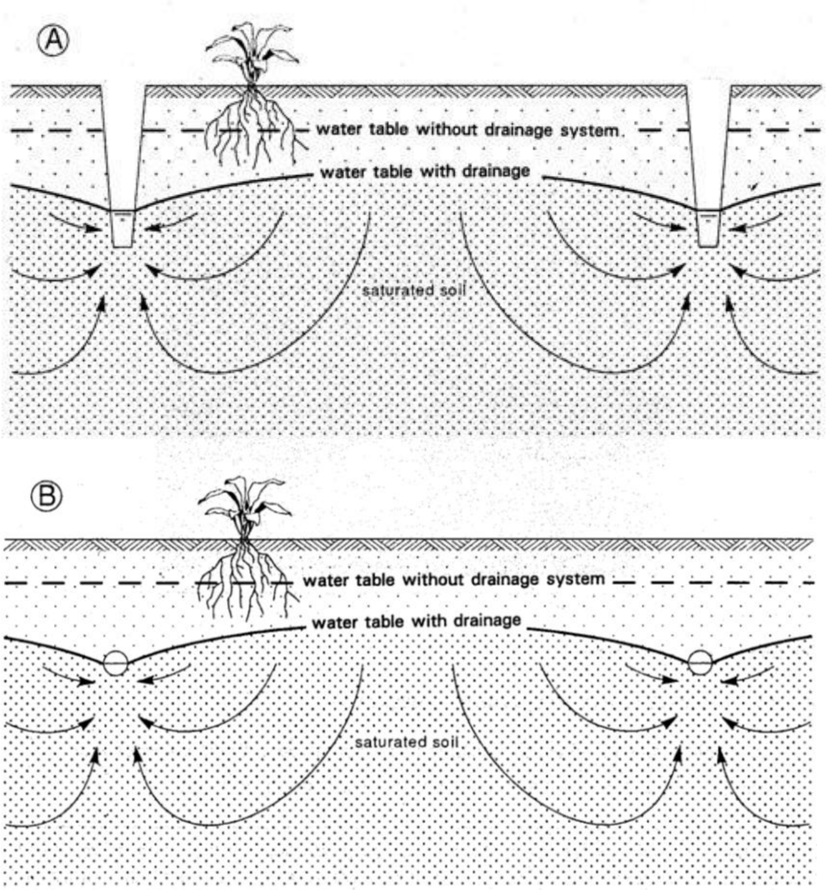

Figure 2.4 Vertical connectivity schematic diagram (A) Surface drains, (B) subsurface drains

Source: FAO (1996, p. 16)

Table 2.3 provides a list and description of vertical connectivity conditions, their connectivity level and hydraulic control description.

Table 2.3 Examples of vertical connectivity in floodplains

Vertical connectivity conditions	Connectivity level	Hydraulic Control
No drain	Full connection	No control
Surface drain	Full connection	Full control
Subsurface drain		

Source: after Smedema et al. (2004); FAO (1996)

No drain (Figure 2.4 A,B) refers to the natural connectivity between the floodplain surface and subsurface where excess water from precipitation and/or flood inundation are ponded on the floodplain surface and eventually infiltrate the soil surface and percolate through the unsaturated zone to the saturated zone i.e. water table. This system offers no hydraulic control of the water table and is a function of the soil structure and permeability, and the water inputs (precipitation, flood inundation) directly affecting the position of the existing water table level (Castle et al., 1984).

Surface drains (Figure 2.4 A) allow full connectivity between the soil surface and the water table in the floodplain applying full control of the water table. This type of drainage can be either natural and formed as a result of floodplain stripping or artificial (man-made constructed) shallow drain with the main hydraulic control to remove excess water from the floodplain surface as a result of ponding and waterlogging from the soil root zone (Charlton, 2008; FAO, 1996). These types of drainage systems allow for full connectivity and hydraulic control between the soil surface and the water table providing increased bearing strength for farm operations and soil workability (Brady and Weil, 2008).

Subsurface drains (Figure 2.4 B) allow full connectivity and hydraulic control of the water table in the unsaturated zone to remove excess water from the soils via groundwater flow to the drains (FAO, 1996). This type of drainage system either can be a deep open-ditch drain or buried perforated pipes known as tile drains (Brady and Weil, 2008). The deep open-ditch drain (Figure 2.5 A) for example may be excavated to a depth below the water table where water will seep into the unsaturated soil. However, this type of drainage can be impractical as they are normally 1 m or greater in depth and present barriers to farm machinery access and only applied in sandy soils with greater spacing between drains (Brady and Weil, 2008). Buried perforated drains consist of a network of pipes laid underground with water in the soils moving into the pipe through the perforations (Smedema et al., 2004). The drain spacing of these drainage systems act also act as critical hydraulic controls in the unsaturated zone of a floodplain to either lower or raise the water table position through decreasing or increasing drain spacing respectively (Young's, 1992).

The other components of a complete land drainage system include the 'main drainage system', which receives water from the surface and subsurface drainage systems. For example, these include the ditches, canals or collection drains conveying water away from the land and the 'outlet', which is the terminal point of the complete, land drainage system, where the drainage water is then discharged into the river (Smedema et al., 2004; FAO, 1996). The main function of these drainage system components is to receive and discharge excess water and groundwater to flow out of the land area rather than hydraulic control of the water table position.

2.3.3 **Impacts of hydrological controls on ecosystem services**

Tockner and Stanford (2002, p. 312) described that 'hydrology is by far the single most important driving variable in floodplains' with floodplain connectivity acting as a key control process for the transfer and exchange of water flows affecting delivery of major ecosystem services e.g. terrestrial and fish habitat conservation, water supply and flood regulation services. The same study discussed that the key controls involve management of water flow and exchange from lateral connectivity for overbank inflow and outflow and vertical connectivity in regard to water table control from precipitation, overland flows, surface flows and the groundwater. Table 2.4 describes lateral connectivity types and their connectivity and hydraulic control level including associated ecosystem services in terms of benefits and disbenefits in floodplains.

Table 2.4 Lateral connectivity, hydraulic controls with associated ecosystem services, benefits and disbenefits in floodplains

Lateral connectivity type	**Connectivity level**	**Hydraulic control level**	**Ecosystem Services**	
			Benefits	**Disbenefits**
Bankfull stage	Full connection	Full control	▪ Flood alleviation ▪ Water supply Terrestrial Habitat ▪ Fish habitat	▪ Flood damage ▪ Agricultural productivity
Natural embankment	Partial disconnection	Partial control		
Artificial embankment	Disconnection	No control	▪ Flood alleviation ▪ Flood defence ▪ Agricultural productivity ▪ Recreation	▪ Water Supply ▪ Fish habitat ▪ Terrestrial habitat

Source: after Kazama et al. (2007); Gren et al. (1995)

Tockner and Stanford (2002, p. 325), stated that ‘Floodplains are natural flood control structures and they should be used that way’.

The bank full stage and natural embankments increase lateral connectivity between the river and floodplain along with minimal control to reinstate the natural hydrological regime to maintain and enhance

- plant community composition in floodplain grasslands (Duranel et al., 2007; Tockner and Stanford, 2002)
- diversity and abundance of fish (Funk et al., 2009; Henning et al., 2007; Lasne et al., 2007)

Artificial embankments (Table 2.4) can provide flood alleviation through the ‘storage of floodwaters’ and subsequent release and/or regulation of returning floodwaters (Hey et al. 1997). The storage of floodwaters can be achieved in mainly two ways as follows:

- Storage of floodwater in the floodplain e.g. washlands and flood storage areas
- Storage of floodwater in the river by increasing the flood capacity of the channel through increasing embankment crest elevation, channel widening and dredging.

There are two distinct ways to deliver flood alleviation known as ‘on-line’ and ‘off-line’ flood storage as described by Morris et al. (2004). On-line flood storage describes the floodplain as contiguous with the river system and off-line flood storage describes the diversion of floodwater from a river into a storage area. In a natural floodplain system, uncontrolled inflow and gravity return flow between the river and floodplain are apparent. The river stage rises, overtops the riverbank unimpeded, and inundates the floodplain allowing temporary storage with subsequent return of floodwaters to the river at low points in riverbank elevations further downstream in the system. An artificial system applies fixed control or variable control inflow and outflows. The inflow could be based on a threshold stage for overbank flow based on an engineered embankment crest level or via a sluice gate. After the river stage has fallen, floodwater retained behind the embankment returns to the river via drain network and flapped outfall or controlled via a sluice/pumping. Artificial embankments that are constructed to a standard of protection alongside river channel margins in lowland rivers act as flood defences to withstand a certain design flood event (Shaw et al., 2011). This type of connectivity applies full control to the channel river discharge based on a design flood event, which inhibits overbank flows and flood inundation thus providing protection to assets within the floodplain. Flood defences are a critical component to protect against flood events to deliver agriculture productivity and the protection of infrastructure, commercial and residential properties in the floodplain (Penning-Rowsell et al., 2005; MAFF, 1999).

Artificial embankments can reduce the opportunity for flood inundation and vertical transfer of floodwaters to recharge the underlying aquifer thus affecting water supply ecosystem service (Charlton, 2008). Kazama et al. (2008) discussed that flood control from artificial embankments can contribute to a reduction in floodwater inundation resulting in a reduction in groundwater recharge and storage for the water supply.

Toogood et al. (2008) and Tockner and Stanford (2002) described that flood control from artificial embankments is one of the key factors to the degradation and destruction of floodplain grasslands in the UK. Disconnecting the river from the floodplain alters the natural hydrological regime required for the maintenance and conservation of the plant community composition e.g. inundation grasslands (flood meadows). The lack of hydrological connection inhibits flood inundation from overbank flows, which reduce the vertical transfer of water to recharge of the alluvial aquifer, which may lead to a drop in water table levels thus impacting on terrestrial habitats (Charlton, 2008; Wheeler et al., 2000).

An artificial embankment can act as a hydraulic control to disconnect the river from the floodplain thereby affecting the maintenance of fisheries habitat ecosystem service where increasing connectivity, reducing control on lateral connections i.e. the bankfull stage and natural embankments are preferential to excise benefits for fisheries habitat ecosystem service. The floodplain provides a crucial habitat for fish species during their life cycle for changing requirements for flow velocity, water depth, water temperature, substrates and food and also for nursery, spawning, recruitment and refuge to sustain fish populations (Amoros and Bornette, 2002; Bunn and Arthington, 2002). Several authors discussed that overall fish species richness, diversity and of ecological guilds decrease with decreasing lateral connectivity in floodplain water bodies in the major river systems in Europe (Bolland et al., 2012; Henning et al., 2007; Aarts et al., 2004; Amoros and Bornette, 2002). Aarts et al. (2004) found that that migratory riverine fish species e.g. Flounder (Platichthys flesus), Twaite Shad (Alosa fallax), Allis Shad (A. alosa) and Sturgeon (Acipenser sturio), have become rare in most large European rivers as a result of decreasing lateral connectivity. Copp, (1990) stated that river regulation i.e. weirs, dredging and embankments, have led to the absence of localized salmonids and pelagic spawning fishes (e.g. Burbot), and also a reduction in the abundance of rheophilic and limnophilic cyprinids with the dominance of generalist fish species (Roach and Minnows) in most of the system. This study is of particular importance in the context of this research as the study by Copp (1990) was based on the 160 km of the Bedford Ouse catchment, which encompasses the River Great Ouse and is also located in the case study catchment of this research.

Gren et al. (1995) described that floodplains have merit as areas to deliver recreation opportunities and offering a unique outdoor experience. Hydraulic controls of lateral connectivity between the river and floodplain can offer recreational value serving as benefits or disbenefits depending on the level of connectivity. Where lateral connectivity is disconnected through artificial embankments limiting the effects of flooding, access to the floodplain as a recreational space is available for hunting, walking, running, cycling, wildlife observation, picnicking and camping activities thus providing benefits (Woolsey et al., 2007; Brouwer and van Eck, 2004; De Groot et al., 2002). Bolund and Hunhammar (1999) described that especially in urban areas the possibilities to avail of recreation through access to play and rest and/or view the appearance of flora and fauna is the most highly valued ecosystem service. Caruso and Downs (2007) discussed that recreational use in floodplains is improved by access to the river corridor where there is lowered embankments/ levees. In this instance, the bankfull stage and natural embankments favour improved access for recreational opportunities and aesthetic enjoyment of flora and fauna.

Table 2.5 describes vertical connectivity types and their connectivity and hydraulic control level including associated ecosystem services in terms of benefits and disbenefits.

Table 2.5 Vertical connectivity, hydraulic controls with associated ecosystem services benefits and disbenefits in floodplains

Vertical connectivity type	**Connectivity level**	**Hydraulic control level**	**Ecosystem Services**	
			Benefits	**Disbenefits**
No drain	Full connection	No control	▪ Terrestrial habitat	▪ Flood alleviation ▪ Flood defence ▪ Agricultural productivity ▪ Recreation
Natural drain e.g. surface drain	Full connection	Full control	▪ Flood defence ▪ Flood alleviation Terrestrial Habitat ▪ Agricultural productivity ▪ Recreation	▪ Habitat terrestrial ▪ Agricultural productivity
Artificial drain e.g. surface and subsurface drains	Full connection	Full control		

Source: after Adams et al. (2004); Gren (1995)

Floodplains with no drainage system between the floodplain surface and the alluvial aquifer provide no control of the water table. This type of connectivity is beneficial for terrestrial habitats e.g. wetlands maintaining the hydrological conditions influenced by flood inundation and groundwater sources to maintain wetland plant community drainage composition and features (Tockner and Stanford, 2002). Drainage systems i.e. natural or artificial are key components of controlling the plant community composition of floodplains grasslands (Härdtle et al., 2005 and Wheeler et al., 2004). Prolonged duration of waterlogging will alter the grassland towards a mire or swamp and water table drawdown will result in the gradual loss of the grasslands plant community composition (Wheeler et al, 2004)

Drainage in floodplains with the use of surface drains for example is an essential component of flood alleviation and defence to control ponding and waterlogging as a result of precipitation and flood inundation to protect commercial and residential properties (Werrity, 2006). It allows the full control and connectivity between the floodplain surface and subsurface for the removal of water from the floodplain as a result of overland flow and surface runoff.

The drainage in floodplains is also a critical component for the maintenance and enhancement of agricultural productivity (Castle et al., 1984). Surface drains are applied extensively to agricultural land to reduce the adverse impacts e.g. impaired crop growth and farm operations as a result of waterlogging and ponding from precipitation and flood inundation (Smedema et al., 2004). Both surface drains and subsurface drains allow full connectivity and control of the water table to enable agricultural productivity for horticulture, intensive and extensive arable use, intensive and extensive grass for cattle and sheep and farm operation conditions (Smedema et al., 2004; Dunderdale and Morris, 1997). An example of field water table depths, drainage conditions and freeboard levels are provided in Table 2.6.

The field water table conditions for agricultural productivity indicate that limitations on crop and grass yields, field operations and turning out livestock can be reduced and delayed as the water table reaches the ground surface (Table 2.6). The control and connectivity of artificial drains are critical to enhance agricultural productivity.

Table 2.6 Field water table levels, drainage conditions and freeboard*

Agricultural drainage condition	Agricultural productivity class	Depth to water table from surface	Spring time freeboards in watercourses (natural drainage)	Spring time freeboards in water course (field drains)
Good: 'rarely wet'	Normal, no impediment imposed by drainage	0.5 mbgl or more	1 mbgl (sands), 1.3 mbgl (peats) 2.1 mbgl (clays)	1.2 mbgl (clays) to 1.6 mbgl sands (0.2 mbgl below pipe outfall)
Bad: 'occasionally wet'	Low, reduced yields, reduced field access and grazing season 0.3 m to 0.49 m	0.3 to 0.49 mbgl	0.7 mbgl (sands) 1 mbgl (peats) 1.9 mbgl (clays)	Temporarily submerged pipe outfalls
Very Bad: 'commonly or permanently wet'	Very low, severe constraints on land use, much reduced yields, reduced field access and grazing season: mainly wet grassland	Less than 0.3 mbgl	0.4 mbgl (sands) 0.6 mbgl (peats) 1 mbgl (clays)	Permanently submerged pipe outfalls

*Freeboard level here is the height difference between water in the ditch and adjacent field surface level.

Source: Penning-Rowsell et al. (2005, p. 63),

2.4 Floodplain management

The floodplain represents a valuable landscape and resource for either urban and industrial development and preferential for settlement due to its flat terrain or for agriculture due land fertility and workability (Hey, 1997). This resource provides a variety of social and economic activities yet these pursuits along with demographic change have led to mass changes in floodplain land use (Penning-Rowsell et al., 2005; Fleming, 2002)

In the UK, from around 12th and 13th century, river embankments and land drainage in floodplains were common to protect and enhance arable and pasture farming practices (Cook and Williamson, 1999). From the 1930s, further intensification of agriculture and installation of drainage systems were applied by farmers for self sufficiency in food production and also due to agricultural subsidies delivered via Common Agricultural Policy (CAP) since the UK joined the EEC in 1973. This involved increasing the addition of drainage systems and embankments in floodplains to control the water table to maximise agricultural production and for protection from flooding (Lowe, 2009 ; Werrity, 2006). Between 1945 and 1985, publicly funded investments to enable land drainage and flood defence schemes to protect the farmland from flooding were made to enhance agricultural productivity in order to provide reliable economical food supply and to support the rural economy (Posthumus et al., 2010). The concerns regarding overproduction and environmental damage from intensive farming led to changes by 2000 with the decoupling under the McSharry and Agenda reforms of the European

Union CAP (Morris et al., 2008). The current policy works with cross compliance with the Department for Environment, Food and Rural Affairs (Defra) under agri-environment schemes for environmental enhancement while maintaining a diversity of economic activity (Morris et al., 2008).

Land drainage and flood defence for England and Wales is the responsibility of Defra and implementation is undertaken by the Environment Agency (EA), Internal Drainage Boards (IDBs) and local authorities (Werrity, 2006; Downs and Thorne, 2000). The EA has supervisory duty in regard to flood defence on main rivers to construct artificial embankments of a design standard for flood risk protection. IDBs and local authorities undertake schemes on ordinary watercourses and both manage drainage along with private owners on lowlands (Werrity, 2006).

While managing floodplain connectivity has provided several benefits and been highly successful, the increase in flooding over the recent decades and the impacts of lateral connectivity e.g. disconnection of rivers from floodplains has led to loss and degradation of ecosystem services (Werrity, 2006; Tockner and Stanford, 2002). In the UK, examples of extreme floods from 1947 to the present day have posed as one of the most threatening natural hazards to human society exacting flood damage to properties and infrastructure, serious injury and agricultural productivity losses (Met Office, 2014; EA, 2013; EA, 2007; Knight, 2006 and NCDC, 2004). In Easter 1998, mainly in the midlands stretching towards East Anglia, extreme flooding let to the death of five people died and caused £350 million in flood damage to properties and infrastructure. In summer 2007 (June –July), large areas of the UK were subjected to a 0.5% AEP flood event causing flood defences (decreasing lateral connectivity by raising embankments) to become overwhelmed causing £3 billion in damages to properties and building infrastructure (EA, 2007). Agricultural productivity is often a casualty of fluvial flooding. For example, Posthumus et al. (2009) investigated the impacts of the summer 2007 floods as a result of heavy surface flows, overloading and surcharging of the surface and subsurface drainage systems to include overtopping of river flood embankments highlighted the following:

- Rainfall, hail and snowmelt.
- High ground water levels (hence quicker runoff in catchments and/or saturated ground)
- Climate change (affecting precipitation).

ADAS (2008) estimated that 42,000 ha of English farmland in total had been flooded by rivers in the summer 2007 floods. At national level, extrapolating the average flood damage costs, a total of £50 million of damage was caused to the agricultural sector (Posthumus et al., 2009). Reports by both EA (2009) and IPPC (2007) both described that climate change i.e. leading to unpredictable weather patterns, increased rainfall and river flows, will increase flood risk and resulting impacts in the future. Several authors discussed that the reduction of floodplain connectivity as a result of flood defences has led to fragmentation and loss of floodplains as a valuable habitat of terrestrial grassland and also for freshwater fish leading to a loss of biodiversity (Ward et al., 1999; Ward, 1998; Junk et al., 1989. Several authors discussed that floodplains are becoming a rare, threatened and vulnerable ecosystem in the world (Tockner et al., 2010; Tockner and Stanford, 2002; Ward et al., 1999; van Diggelen et al., 2006). In the UK, the UKNEA (2011) estimated that extensive areas of semi-natural vegetation grasslands e.g. 97% were either converted or modified or lost between 1930-1984 through intensification or arable land conversion. Land change, combined with flow and flood control as a result of meeting demographic needs has contributed to the natural floodplain to become functionally extinct and rapidly disappearing (Tockner and Stanford, 2002).

2.5 Policy, strategy and legislation

There is a wealth of policy and legislation that can affect the management of lowland floodplains in the UK. A comprehensive overview was presented in Morris et al. (2009) which encompasses International treaties, EU policies, National Legislation, National Policies, regulatory; economic and voluntary instruments. This section will highlight some of the more important strategies, policies and legislation that have an impact on lowland floodplain management in the UK.

2.5.1 **Government strategies**

One of the most important policies to be initialized since 2005 is Defra’s ‘Making Space for Water’ strategy (Defra, 2005). The aim is to provide a more holistic approach to manage flood risks by employing an integrated portfolio of approaches to deliver economic, environmental and social benefits. This policy adopts an integrated approach involving multiple stakeholders to engage in the provision of flood risk management strategies to deliver multiple benefits. In terms of floodplain connectivity, the source of flood risk considers river-floodplain and floodplain-water table in order to manage flood risk to enable delivery of multiple benefits to stakeholders. This policy also advocates the creation of wetlands and/or washlands in order to enable the delivery of multiple benefits (UKNEA, 2011). Washlands are defined in Morris et al. (2004, p. 18) as ‘an area of the floodplain that is allowed to flood or is deliberately flooded by a river or stream for flood management purposes, with potential to form a wetland habitat”. This definition is inclusive of the existing lateral connectivity e.g. no embankment/natural riverbanks and the existing agricultural defences providing a relatively high standard of flood protection (EA, 2009b; Morris et al., 2004). There are several examples of floodplains in the UK (Morris et al., 2004) which are utilized as ‘washlands’ in rural land areas which work with natural processes. Morris et al. (2004) described the benefits of managing a floodplain as a washland, as follows:

- Flood alleviation: regulate flood risk by the attenuation and storage of floodwaters in reducing flood damage to properties.
- Terrestrial habitat: Inundation of floodwaters to provide the necessary hydrological regime to conserve or enhance washland habitat types.
- Agricultural productivity: dairy/beef farming, grassland and cereal production where flooding is relatively infrequent but this will depend on the priorities given to flood risk management and biodiversity objectives.
- The productivity of land for agricultural land use will depend on the impact or absence of flood inundation.
- Recreation: the association of the landscape as an amenity for recreation and tourist activities e.g. nature reserve and visitor centres. Land access and benefit impacts will depend on the impact or absence of flood inundation.

UK Government strategy has continued to broaden and evolve to encompass the following:

Future Water of 2008 sets out a strategy for water e.g. demand, supply, quality, surface water drainage, river flooding, greenhouse gas emissions and charging with the reaffirmation of Making Space for Water strategy as a basis to manage river flooding (Defra, 2008b). It sets out a vision for better management of surface waters for improvement and sustainability in regard to dual pressures of housing development and climate change (EA, 2009a)

The Pitt Review of 2008 and the Foresight Future Flooding of 2004 have advocated, the need for a more sustainable and holistic approach to land use involving multiple stakeholders as a direct result of past serious flooding events (Pitt, 2008 and King, 2007). In particular, the Pitt Review (Pitt, 2008, p. 130) provided a recommendation as follows:

“Recommendation 27: Defra, the Environment Agency and Natural England should work with partners to establish a programme through Catchment Flood Management Plans to achieve greater working with natural processes”

These documents reinforced the need for integrating structural and non-structural measures and working with natural processes to achieve economic, social and environmental benefits to manage flood risk.

The UK National Ecosystem Assessment (UKNEA, 2011) provided a comprehensive overview of the state of floodplains in the UK and the ability of this natural environment to deliver future benefits. Floodplains according to the UKNEA come under freshwater habitats, yet the status of ecosystem service delivery indicates some decline and deterioration. This is as a direct result of conversion and management of floodplains to provide mainly single ecosystem services e.g. agriculture. There is a great need to apply more sustainable management of floodplains to deliver multiple rather than single ecosystem service benefits to multiple stakeholders. The UKNEA serves as a basis to inform the delivery of long-term sustainable ecosystem services in combination with Defra’s ‘Action Plan for Embedding an Ecosystems Approach which will assist in the integration and promotion of the ecosystems approach in future policies (Defra, 2007b).

2.5.2 **European Policy**

The European Union Water Framework Directive (European Parliament. Council of the European Union, 2000) is an important directive to progress an integrated approach towards river basin management for the balance of social, economic and environmental demands (Meyerhoff and Dehnhardt, 2007). Interestingly, in the European Union (EU) Water Framework Directive (WFD), floodplains are not mentioned except for wetlands, which may incorporate a riparian floodplain. Reference is made to the protection and enhancement of water bodies and aquatic systems through water needs and terrestrial ecosystems (Brunke, 2002). The functioning of a wetland is recognized in the EU WFD through processes such as hydrological e.g. groundwater recharge, floodwater detention and ecological e.g. habitat maintenance and biogeochemical e.g. nutrient and carbon retention (Meyerhoff and Dehnhardt, 2007). The directive also discusses the mitigation of flood effects. The integrated approach to river basin management aims at the achievement of good water status for ground and surface waters (Meyerhoff and Dehnhardt, 2007).

The Habitats Directive (European Parliament. Council of the European Union, 1992) is an important driver for floodplain habitat and biodiversity maintenance, conservation and restoration (Adams et al., 2005). UK Biodiversity Action Plans (UKBAP) identify floodplains as having six priority habitats as emphasized in the United Kingdom Biodiversity Action Plan (UK BAP) namely rivers, lowland meadows, grazing marsh, fens, reedbed and lowland raised bogs (Matlby et al., 2011). The UK BAPs provide targets and plans for the recovery of species and habitats and promote their conservation.

The Floods Directive (European Parliament. Council of the European Union, 2007) focuses on the prevention, protection and preparation to manage flood risks recognising the impacts of climate change while advocating more space for rivers. Application of sustainable floodplain land use will balance the delivery of benefits to multiple stakeholders encompassing social, economic and environment activities (Wharton et al., 2007; Corbelli, 2004). Chapter 2, Article 4(d) of the Floods Directive (European Parliament. Council of the European Union, 2007) advocates the consideration of catchment characteristics in terms of location and utilisation of a floodplain as a natural retention area as a sustainable solution for the provision of benefits to multiple stakeholders.

2.5.3 **National Legislation**

The Floods and Water Management Act (2010) builds on recommendations from the Pitt review of 2008 placing responsibilities on the Environment Agency, local authorities and also developers to manage flood risk as follows:

- Develop, maintain, apply and also monitor strategies for flood risk management to control risk of flooding from surface water, watercourses and groundwater
- Improved flood resistance of existing buildings
- Surface water management
- Water supply protection

The Water Act (2014) provided major reforms in the water industry making it more responsive to the public sector customers, business and charities and also to increase the resilience of water supply in the event of natural hazards i.e. floods and drought. Some of the key features of this Act in regard to floodplains are outlined as follows:

- Continual development of the national water supply and enabling water companies to buy and sell water from one another
- Owners with small-scale storage may sell excess water for public supply
- Improve water resource management with additional measures in place to restore the sustainable abstraction of water
- Ministers can set the level to which a water company can utilise for plans to cope in the event of droughts

The Conservation of Habitats and Species Regulations (2010) provides regulations on the conservation through designation and protection of natural habitats i.e. wild flora and fauna species. Both legislations have been transposed into national legislation as of the EU Flood Directive (European Parliament. Council of the European Union, 2007) and the Habitats Directive (European Parliament. Council of the European Union, 1992). They both seek to protect and enhance the floodplain as a natural resource and biodiversity.

The Climate Change Act (2008) requires a risk assessment of UK wide climate change every five years along with a national adaption programme, which is reviewed every five years (EA, 2009a). This Act also gives the government power to direct public bodies and statutory organizations e.g. water companies, to report on their climate risks and also their adaption plans (EA, 2010). In terms of flooding alongside the Flood and Water Management Act (2010), it is expected that climate change will continue to influence rainfall patterns creating more rain in winter and falling in heavy intense bursts, management to reduce the probability of flooding and consequences are priorities of adaption programmes as implemented by the Environment Agency (EA, 2010).

2.5.4 **Development control strategy**

The Planning and Policy Statement 25: Development and Flood Risk (PPS25) by the Department of Communities and Local Government (DCLG) provides guidance on development and flood risk to ensure sustainable development in floodplains thus limiting or reducing flood risk (DCLG, 2009). PPS25 is mainly concerned with the protection of flood risk and delivery of residential and non-residential properties which are represented by employment; habitation and transportation ecosystem services in the floodplain.

2.5.5 **Local flood management strategy**

The concept of multi-purpose management of floodplains in the UK was first enunciated in 1871 by Lord Montague who in turn argued that various interests in floodplains i.e. navigation, mills, drainage and water supply, fishing and manufacturers can be adjusted and developed but only by one management system over the whole river (Bailey, 1991). A new paradigm is being proposed to manage floodplain connectivity especially lateral connectivity in terms of reconnecting the river and floodplain to restore and enhance ecosystem services (Werrity, 2006). A number of management practices are being implemented to manage floodplain connectivity in order to deliver multiple ecosystem services.

There is a variety of floodplain management practices in place to manage a floodplain land use. The Environment Agency implement Catchment Flood Management Plans (CFMP) as part of strategic planning for policies to achieve sustainable flood risk management for every catchment (Fleming, 2000). These plans are based on managing flood risk to allow for multiple land use encompassing social, economic and environmental activities through spatial planning, water level management plans, land management and habitat creation and surface water management plans (EA, 2010b)

Drainage boards e.g. Internal Drainage Board (IDB) operate Water level Management Plans (WLMP) as a means to provide integrated water management for a variety of land use activities e.g. flood risk management, agriculture, biodiversity and recreation in a specified area (WMA, 2010). Priority is given to areas of conservation interest e.g. Site of Specific Scientific Interest (SSSI), Special Protection Area (SPA) and Ramsar Wetlands (SDBC, 2010).

Agri-environment schemes have provided a range of management plans for sustainable land use to enable the following:

- Protection and enhancement of biodiversity habitat and species, landscape character, historic environment, soils and natural resources.
- Contribution to climate change and flood risk mitigation and conservation of genetic resources.
- Tourism and recreation opportunities.

(Natural England, 2009)

Floodplains are currently managed to deliver a limited range of ecosystem services with primary single uses e.g. habitation, agricultural productivity and terrestrial habitats. In some instances, multiple ecosystem services have been offered by floodplains through agri-environment schemes operating agriculture and habitat based ecosystem services (Natural England, 2009). Floodplains are also managed as ‘washland’ as described in Morris et al. (2004) which can provide flood alleviation and habitat ecosystem services. The Environment Agency also create and manage ‘Flood Storage Areas’ (FSA) to primarily deliver flood alleviation for the protection of downstream communities yet can be managed for habitats creation, conservation and maintenance (EA, 2009b).

All of these management plans are inextricably linked to the hydrological management of the land. While current floodplain management practices are starting to address the delivery of multiple ecosystem services, the range of benefits they can provide is limited. The challenge remains to enable a solution to manage floodplains to deliver a wider range of ecosystem services to meet the needs of policies and directives while serving the needs of the stakeholder (Lowe et al., 2009).

3 MODELLING FLOODPLAIN PROCESSES

3.1 Introduction

A ‘model’ is described as a representation of designed or natural processes and natural systems, especially a mathematical one to assist in calculations and predictions (Refsgaard and Henrikson, 2004). This representation is an abstraction of reality, and represents the simplification of a complex real system that is adequate for the modelling purpose (Wainright and Mulligan, 2004a). Since the 1950s, the application of models have grown significantly, becoming valuable and powerful tools to conceptualize and explore the behaviour of processes, their interaction as a means for better understanding of hydrological systems and ecosystems (Wainright and Mulligan, 2004b). The improvement of understanding these systems through research is necessary to enable sustainability for human dependency. There have been significant advances in modelling components and systems to simulate dynamic and complex hydrological flows in the floodplain over the last 30 years (Jolly and Rassam, 2009).

There is an exhaustive choice and range of models available to describe the hydrological processes within a river and floodplain with the selection of a model and/or models being a crucial component to adequately capture these processes in order to facilitate the assessment of ecosystem services (O’Connell et al., 2007; Horritt and Bates, 2001). Knight and Shamseldin (2006) mention that no universal model exists that can be applied in all circumstances and purposes and the selection of models and methods applied will depend on the purpose of the research and desired outcomes.

Modelling systems in rivers and floodplains are most commonly limited to the independent modelling of surface hydrological systems i.e. river systems and the floodplain surface and/or subsurface hydrological systems i.e. groundwater systems, modelling each system separately (Refsgaard et al., 1998). The complexity of the hydrological processes in the river and floodplain has led to a reductionists approach concentrating on individual elements sometimes ignoring important process and interactions between the surface and subsurface hydrological systems, modelling them separately and in isolation from each other (Michaelides and Wainwright, 2004).

Integrated modelling systems have been developed and applied since the early 1970s (Hunter et al., 2007). Several authors have discussed the importance of applying integrated modelling systems to adequately represent the complex interactions between the surface and subsurface hydrological systems in floodplains (Refsgaard et al., 1998; Kazama et al., 2007; Dutta et al., 2006; Thompson et al., 2004). Refsgaard et al. (1998) in particular described that an integrated modelling system is a valuable tool to simulate the changes in the hydrological regime as a result of alternative water management scenarios to enable decision making to manage floodplains.

The following sections will describe the types of models and methods available to simulate the dynamic and complex hydrological process occurring in surface and subsurface hydrological systems of a river and floodplain. The concept of integrated modelling systems with methods and examples in regard to floodplains are explored and discussed. The model choice to make up an integrated modelling system is discussed with justification for the choice of the integrated modelling system and approach applied. Finally, a brief summary of the application of the integrated modelling system outputs for this research in regard to assessing the impacts of floodplain connectivity will be discussed.

3.2 Lateral connectivity modelling

3.2.1 **Introduction**

For the purpose of this research, lateral connectivity modelling shall be defined as models that are applied to represent the hydrological processes and dominant water transfer flows of the river and floodplain surface. This type of modelling is also applied to simulate the impacts of lateral connectivity configurations. This definition also refers to grouping of models also known as ‘hydrodynamic models’ that simulate these processes and flows between the river and floodplain surface. Hydrodynamic modelling is an ever-increasing requirement to deal with the problems associated with flooding (Horritt and Bates, 2002). Growth in the utilisation of hydrodynamic models is in response to greater availability of data, low cost computation power and meeting the requirements of the European Floods Directive (European Parliament. Council of the European Union 2007) i.e. requiring prediction of flood hazards (Néelz and Pender, 2009).

Hydrodynamic modelling of the river and floodplain are quite commonplace in order to model the hydrological processes of river discharge and flood inundation (Knight and Shamseldin, 2006). One and two-dimensional hydrodynamic models for example have proven ability to capture hydraulic processes in the river channel and floodplain for predicting flood risk as a function of different flood frequencies and magnitudes and also lateral connectivity configurations (Hunter et al., 2007).

3.2.2 **Classification**

The classifications of hydrodynamic models are based on dimensionality or through combination of different dimensionality approaches representing the spatial domain and flow processes i.e. Table 3.1 (Néelz and Pender, 2009; Chatterjee et al., 2008). Table 3.1 provides a classification of hydrodynamic models providing a description of methods and application with model data outputs and including examples of commercial models available.

Table 3.1 Classification of lateral connectivity modelling methods and applications

Method	**Description**	**Application**	**Typical computation times**	**Outputs**	**Model software examples**
1D	Solution of the one-dimensional St-Venant equations.	Design scale modelling which can be of the order of 10 s to 100 s of km depending on catchment size.	Minutes	Water depth, cross-section averaged velocity and discharge at each cross section. Inundation extent of floodplains are part of the 1D model, or through horizontal projection of the water level.	▪ Mike 11 ▪ HEC-RAS ▪ ISIS 1D ▪ InfoWorks RS ▪ SOBEK
1D+	1D plus a storage cell approach to the simulation of floodplain flow.	Design scale modelling which can be of the order of 10 s to 100 s of km depending on catchment size, also has the potential for broad scale application if used with sparse cross-section data.	Minutes	As for 1D models, plus water levels and inundation extent in floodplain storage cells	▪ Mike 11 ▪ HEC-RAS ▪ ISIS 1D ▪ InfoWorks RS
2D-	2D minus the law of conservation of momentum for the floodplain flow.	Broad scale modelling and applications where inertial effects are not important.	Hours	▪ Inundation extent ▪ Water depths	▪ LISFLOOD-FP ▪ JFLOW ▪ ISIS FAST
2D	Solution of the two-dimensional Shallow water equations.	Design scale modelling of the order of 10 s of km. May have the potential for use in broad scale modelling if applied with very coarse grids.	Hours or days	▪ Inundation extent ▪ Water depths ▪ Depth-averaged velocities	▪ TUFLOW ▪ Mike 21 ▪ TELEMAC ▪ SOBEK ▪ InfoWorks2D ▪ ISIS 2D
2D+	2D plus a solution for vertical velocities using continuity only.	Predominantly coastal modelling applications where 3D velocity profiles are important. Has also been applied to reach scale river modelling problems in research projects.	Days	▪ Inundation extent ▪ Water depths ▪ 3D velocities	▪ TELEMAC ▪ 3D
3D	Local predictions of three-dimensional velocity fields in main channels and floodplains.	Local predictions of three-dimensional velocity fields in main channels and floodplains.	Days	▪ Inundation extent ▪ Water depths ▪ 3D velocities	CFX

Source: after Néelz and Pender (2009, p. 5)

Figure 3.1 provides an example schematic of 1D and 2D, linked 1D-2D hydrodynamic model methods and approach.

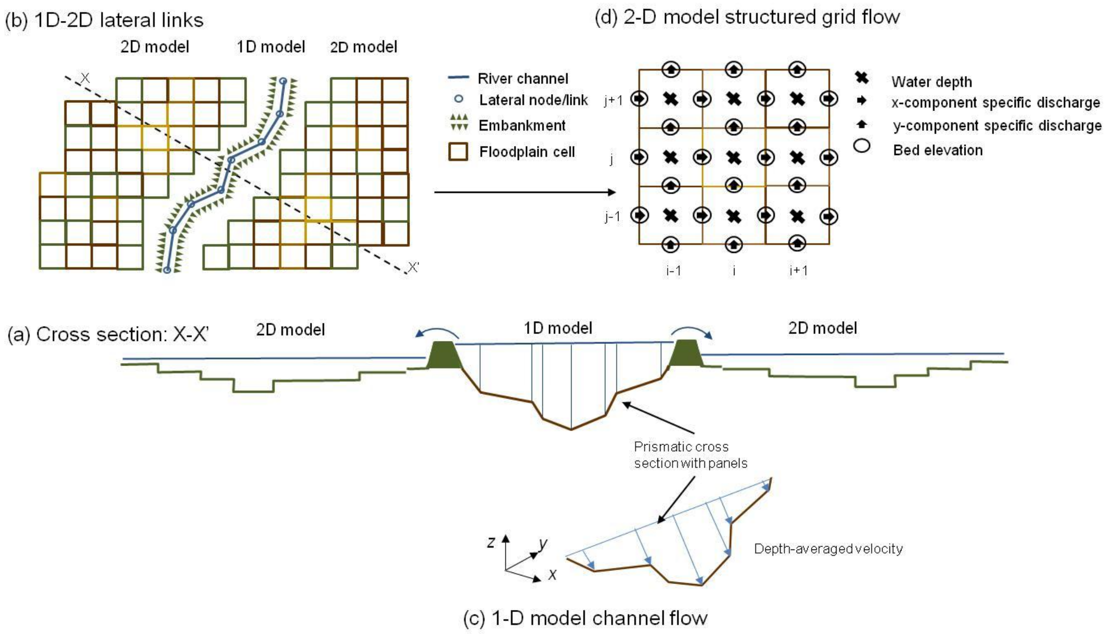

Figure 3.1 1D and 2D, linked 1D and 2D hydrodynamic model method approach diagram

One-dimensional hydrodynamic models apply a form of one-dimensional St. Venant equations or shallow water equations (Barré de St-Venant, 1871) and can be derived by the integration of the Reynolds-averaged Navier-Stokes equations (Navier, 1822; Hinze, 1975) over the cross-sectional surface flow. The St. Venant equations can be expressed as conservation of mass (continuity) and conservation of momentum equations describing the calculations of flow discharge based on cross sectional averaged velocity and surface area (Figure 3.1c). Flow can be classified as steady i.e. depth and velocity are not variable with time and unsteady i.e. depth and velocity are variable with time. The discharge and stage are calculated based on a single direction of water movement aligned to the river cross-section centre lines (Knight and Shamseldin, 2006). The floodplain is an extension of the river cross sections representing two channels e.g. one channel for each side of the floodplain. Modelling the floodplain flows with this technique has two main disadvantages (Néelz and Pender, 2009). Firstly, the floodplain flow is assumed to be flowing in one direction parallel to the river channel, which is not always the case. Secondly, the predicted cross-sectional averaged velocity as per St-Venant equation has a less tangible physical meaning in cases where large variations in velocity magnitudes occur across the floodplain.

A 1D+ method applies a storage cell as the floodplain defined by a water level/volume relationship with the river channel modelling the flow only (Néelz and Pender, 2009). Lateral links i.e. weirs, are applied for transfer of flow from the river to the floodplain.

The benefit of this approach is the ability to model larger floodplains whilst not assuming parallel flow to the main river channel. The disadvantages of this method are:

- conservation of momentum is not included on the floodplain as the water is transferred instantly from one storage cell to another
- inter-cell flow calculations can create significant errors due to lateral link discharge equations
- Were cell storage cells are created too large, errors in predicted water levels locally occur.

While 1D, 1D+ methods are computationally efficient; they suffer from disadvantages in application to floodplain flows (Hunter et al., 2007). They have an inability in simulating lateral diffusion of the flood wave and discretisation of topography in the form of cross sections rather than a dynamic surface (Samuels, 1990).

The constraints of 1D model methods can be overcome by 2D model approaches (Figure 3.1a,b) as described by Néelz and Pender (2009). Two-dimensional hydrodynamic models apply 2D shallow water equations i.e. 2D St. Venant equations derived by the integration of Reynolds-Average Navier-Stokes equations over the flow depth. 2D shallow water equations are expressed in vector form describing the depth averaged velocity in x and y directions (Figure 3.1d). The solution of these equations can then be obtained from numerical methods i.e. finite difference, finite element or finite volume by using numerical grids i.e. Cartesian or boundary fitted, structured or unstructured grid cells (Hervouet, 2007).

The 2D- method applies simplified versions of 2D shallow water equation only representing kinematic and diffusive wave and no conservation of momentum relying on square grid DEM and a simplified version of the 1D approach to calculate the flow between the DEM grid cells (Néelz and Pender, 2009). These models tend to be applied to broad scale modelling with coarser grid detail with shorter computational times to study the effects of flooding over larger areas e.g. catchments.

The 2D+ method applies a similar approach as the 2D+ modelling provides a solution for vertical velocities utilising continuity equations only. This method is more commonly applied to coastal modelling. The 3D approach applies 3D Reynolds-averaged Navier-Stokes equations to predict 3D velocity field and water levels in river channels and floodplains. Both 2D+ and the 3D methods can be applied in local predictions and reach scale river modelling problems and in research yet typical computational times are in days and therefore not practical at the necessary scale for flood risk management applications (Néelz and Pender, 2009).

All of the above model methods may also be described as unsteady state event based models which can simulate a individual hydrological event by varying the water depth and velocity or river discharge with time. The hydrological events can be elicited from observed river depth or velocity or river discharge in the river and floodplain. They can also be elicited as products of hypothetical rainfall events e.g. design storms through flood frequency analysis or rainfall-runoff modelling. The duration of these events could range from hours to several days. These hydrological events may be applied to study the impact of storms for example on the depth, velocity and/or discharge in a river channel and/or inundation extent, volume, depth and velocity in the floodplain from overbank flows.

3.2.3 **Modelling approach**

The selection of model type and approach depends on the required river flooding application of the surface flows. 1D models have limitations to representing floodplain flows as flow is assumed to be unidirectional i.e. parallel to the main channel with conveyance predications sometimes overestimated. 1D+ model approaches are generally applied in disconnected floodplains and provide an improved representation of floodplain conveyance but are limited to floodplain storage functions with large errors related to the predictions of lateral flow exchange by use of weir equations (Néelz and Pender, 2009; Evans et al., 2007).

Another approach to modelling river and floodplains involves linking i.e. integrating a 1D river model to 2D floodplain grids (Néelz and Pender, 2009). There are several existing methods to link 1D and 2D models. This research describes three of the more commonly applied linking methods as displayed in Figure 3.2 and labelled as follows:

(a) Longitudinal link
(b) Vertical link
(c) Lateral link

A longitudinal link is characterised by modelling a river (1D) partly upstream and a floodplain partly downstream (2D) or to connect the downstream part of a river (1D) to the floodplain (2D), see Figure 3.2(a), (Evans et al., 2007; Liang et al., 2007). This approach involves the flow from the 1D entering the 2D model as a source with the water level in the 2D model used as a downstream boundary condition on the 1D model.

A vertical link represents the floodplain utilising an uninterrupted (2D) grid overlaying a (1D) river model, see Figure 3.2(b), (Stelling and Verway, 2005). The (1D) river model functions on its own until the bankfull level is reached in the river where at this point the water above the bankfull level is then transferred to the (2D) floodplain model.

A lateral link is the most widely applied method to model the exchange of flows between the (1D) river model and the (2D) floodplain model, see Figure 3.2(c), (Evans et al., 2007). The exchange of flows is typically modelled via water level, flow and weir linking (Néelz and Pender, 2009).

Néelz and Pender (2009) also discussed that the application of a single 2D model to represent the river and floodplain is not a common practice due to the long established tradition of 1D model application in the UK. This has arisen through highly available surveyed river cross-sections, well known Manning's 'n' values for river types and fine resolution DEM grids available for floodplains.

Figure 3.2 displays a schematic of a 1D and 2D model linking approach to numerical approaches for calculation of river discharge and flood inundation.

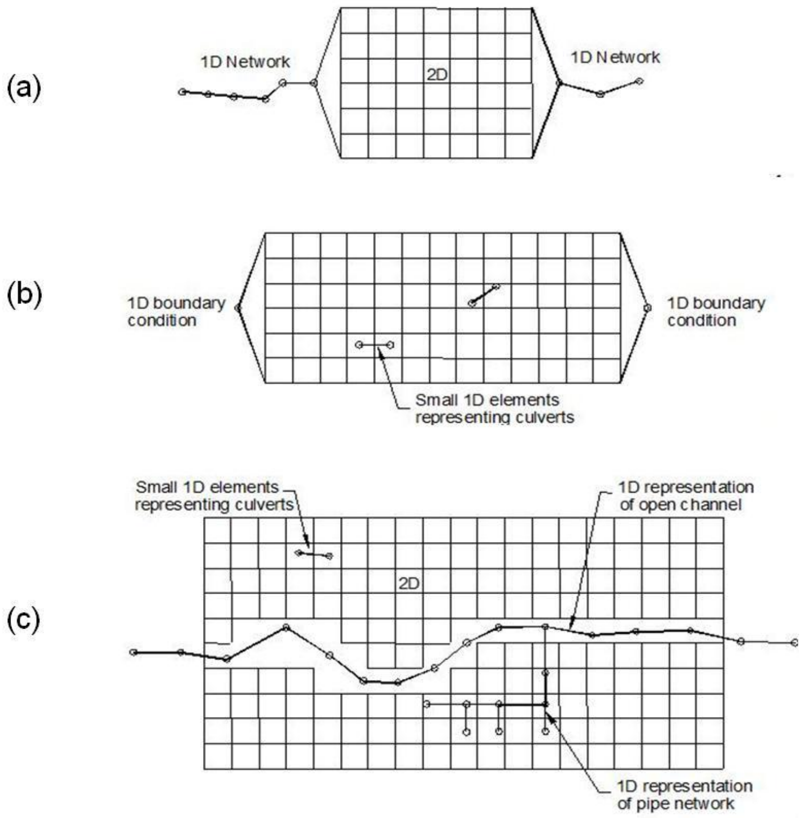

Figure 3.2 (a,b,c) 1D and 2D model linking approach to numerical approaches schematic

Source: BMT WBM, (2014b, p. 3-4)

3.3 Vertical connectivity modelling

3.3.1 **Introduction**

For the purpose of this research, vertical connectivity modelling shall be defined as models that are applied to represent the hydrological processes and dominant water transfer flows of the floodplain surface and subsurface. This type of modelling is also applied to simulate the impacts of vertical connectivity. This definition refers to grouping of models that simulate the processes and flows between the floodplain surface, unsaturated zone and saturated zone (Smedema et al., 2004; Jolly and Rassam, 2009).

3.3.2 **Classification**

Smedema et al. (2004) described the classification of widely used vertical connectivity models applied in the drainage sector grouped in five categories relating to drainage based applications i.e. field, canal, rainfall-runoff, groundwater and agrohydrological models. An example of each model type, methods, applications, outputs and software is displayed in Table 3.4.

Field models refer to single purpose models for the planning and design of drainage, applying steady state and non-steady state methods for the design of surface and subsurface drainage systems i.e. drain pipe dimensions (Smedema et al., 2004). An example of a field model is DRAINCAD, which is a design package, that applies drain spacing formulas of Hooghoudt and Glover-Dumm handling fields of irregular shapes and sizes providing layout maps for the field, longitudinal profiles of the lateral and collector pipes and cross-sectional and longitudinal profiles of the ditches (Liu and Feyen, 1992). Further information on the material list of pipes and also earth movement requirements are also provided after the design of the drainage system. The advantage of this model and its application is that it’s mainly used for the purpose of planning and design of a drainage system and evaluating the theoretical performance of the drainage design (Liu and Feyen, 1992). A disadvantage of this model is that its application is specific to design of drainage systems to manage agricultural production and nowadays focus of drainage now involves drainage design for plant growth e.g. habitat and evacuation of floodwaters and also only considers some aspects of the hydraulic design (Smedema et al., 2004).

Canal models apply methods of hydraulic design of the drainage canal systems and structures using steady and non-steady flow equations (Smedema et al., 2004). These systems can evaluate the performance of steady or unsteady discharge in the canals to include maintenance performance, effects of hydraulic structures on flows as a result of operational strategies etc. DUFLOW developed by STOWA (2000) and HEC-RAS developed by HEC (2010a) are examples of software that apply numerical solutions of the St. Venant equations for steady and/or non-steady state 1D canal flow (HEC, 2010a; STOWA, 2000). The advantage of these models are that they can be applied to evaluate the performance of single or multiple canals and networks for a range of discharge events to study the effects of maintenance of hydraulic control structure and their operation on hydraulics e.g. velocity and stage, within the canal. The disadvantage of these models are that they only consider the impact of hydraulic design specific to the drainage canal and structures contained within and not of the canal system on the water table level.

Rainfall-runoff models simulate the generation of discharge of water and their processes in drainage basins as a function of weather events and the soil hydrological regime (Smedema et al., 2004). They have a number of applications to include flood forecasting, the design of flood defences for flood risk management and urban drainage systems, assessment for water resources, prediction of hydrological response in ungauged catchments and water management for the conservation of terrestrial habitats and species (Shaw et al., 2011; Hess et al., 2010; Thompson et al., 2004).

At present, there is a wide choice of models available and being applied worldwide in excess of 100 rainfall runoff models to represent the fundamental water transfer flows that impact on runoff generation (O’Connell et al., 2007). Table 3.2 provides a brief example and description of widely tested rainfall-runoff models that are well documented and readily available for public use (Smedema et al., 2004). These modelling systems can be described as mainly physically based models, which simulate runoff as a function of continuous rainfall events e.g. a series of years/seasons or design rainfall events and single events. These models simulate water transfer by applying a variety of methods/techniques for each hydrological component based on water transfer flows in the surface and subsurface system (Smedema et al., 2004; Beven, 2001). These models can account for spatial variations in hydrological inputs and drainage area responses treating the catchment in sub-basins and/or reach and gridded elements (Shaw et al., 2011). Advantages of applying rainfall-runoff methods are related to their wide range of application e.g. flood risk and urban drainage management, water resource assessment and wetland conservation

(Shaw et al., 2011; Thompson et al., 2004). Other advantages relate to the nature of the system allowing for analysis of the water transfer flows to understand the influence of hydrology in a drainage basin by applying multi component systems between the surface and subsurface system in a floodplain. Disadvantages of these systems can be described in the form of model limitations. There are many rainfall-runoff models in existence and this research will highlight the limitations of rainfall-runoff models highlighted in Table 3.2 to serve as an example.

In general, procedures in WinTR-55 are simplified by assumptions for some of the parameters with the provision of results that are less accurate than more detailed methods (NRCS, 2009). Other main limitations involve flow calculation, which is based on open and unconfined overland flow and/or in channels; reach routing applies Muskingum-Cunge method, which is a simple approximation of attenuation and cannot model backwater affects or rapidly rising flows (Beven, 2001). The WinTR-55 model is ideally suited to applying hydrologically homogenous drainage basins with one main stream and tributaries of equal time of concentration (NRCS, 2009).

Limitations of HEC-HMS arise from the model design involving specific aspects of the model design i.e. simplified model formulation allowing quick simulations to produce accurate and precise results and the simplification of flow representation, which maintains efficient computational process (HEC, 2010b). The mathematical models utilised in HEC-HMS use constant parameter values and are assumed to be time stationary which may reduce model accuracy as parameters can change over time due to processes in drainage basin or through human interference over a long period of time (HEC, 2010b). All mathematical models in HEC-HMS simulate individual components of the surface and subsurface systems and therefore not numerically linked and uncoupled with computations occurring in sequence which can give rise to errors (HEC, 2010b). The error is minimized in this instance through the application of a small time interval for each calculation. The representation of flow only allows for dendritic stream/river networks with each hydrological element to have only one downstream connection so as not to split the outflow, and therefore branching and looping stream networks cannot be simulated. Backwater effects in the stream/river network cannot be computed with no iteration or looping between elements e.g. reach and sub-basin.

Groundwater flow models apply essentially finite difference/element solutions of the Laplace equation in non-steady two-dimensional and three-dimensional flow (Shaw et al., 2011). These models can handle the analysis of complicated groundwater flow situations and patterns (Smedema et al., 2004). Nowadays, there is a large number of groundwater modelling packages available from either commercial or public domain sources (USGS, 2010). These models have been applied to allow the complex analysis of groundwater flow for water resource assessment, transport and fate of pollutants and effects of groundwater on vegetation change for example (Zhao et al., 2005, Smedema et al., 2004; Bradley, 1996). These models simulate water transfer flows in the subsurface system to include the simulation of abstractions, infiltration, groundwater recharge, evapotranspiration, channel flow e.g. rivers/drains and aquifer interactions (Smedema et al., 2004). Shaw et al. (2005) discussed that MODFLOW as packaged by several companies and FEFLOW are widely applied groundwater models based on their modelling capabilities to simulate groundwater flow and user-friendly graphic interface. The main advantages for the application of groundwater models are that they provide a sophisticated platform to model the water transfer flows in subsurface systems. There are many disadvantages of applying groundwater models largely in reference to the correct selection and application of the many options available. These include the discretizing of the flow domain, set up of initial and boundary conditions and time stepping and the specification and optimisation of model parameters and poor choices of a time step may lead to model instability problems and mass balance errors (Shaw et al., 2011). Groundwater models like MODFLOW are restricted to the simulation of flows in the saturated groundwater zone only although it is possible to apply a recharge value after accounting for evapotranspiration, surface runoff and the change in storage of the unsaturated zone (DHI, 2007). These processes must be accounted for through the application of a constant rule of thumb fraction to the precipitation data, which is contradictory as precipitation is neither constant in space nor time.

Agrohydrological models apply water balance concept to simulate soil moisture and water table regimes under climatic, land use and drainage conditions at field scale (Smedema et al., 2004). These models can apply continuous design and historic data to a wide range of prediction, evaluation and scenario-based assessments and especially for the design of drainage requirements for water table control for crops, waterlogging to establish optimal drainage criteria (Smedema et al., 2004). There are three widely applied models in research namely DRAINMOD, SWAP and WaSim (Smedema et al., 2004; Depeweg and Otero, 2004; Hirekhan et al., 2007). The main application of these models is to assess the response of water movement for crop yields (Smedema et al., 2004). WaSim for example has also been demonstrated for application to hydrological studies e.g. effects of climate change on water resources (Hess et al., 2010; Holman et al., 2009). These models simulate the soil water regime, crop yields and drainage based on water balance concepts and well-established empirical relationships for water transfer flows between the surface and subsurface systems (Smedema et al., 2004). Advantages of applying these models are that have been widely field tested and valued as research and practical management tools, quite user friendly in regard to model setup and parameterisation, provide clear results visualisation and flexible in the application of the water management studies (Hess et al., 2010; Hirekhan et al., 2007; Smedema et al., 2004). Disadvantages of agrohydrological models include the simple parameterisation, which provides less accurate predictions and limitations on boundary and initial conditions in terms of inputs applied (Hess and Counsell, 2010; Kroes et al., 1999). The concept of field capacity is not physically meaningful when the water tables are shallow (Skaggs et al., 2012). In particular, for the SWAP model, the functioning of the Leaf Area Index is critical for soil evaporation and crop transpiration with partial dependence for determination of low groundwater levels (Kroes et al., 1999).

Canal and rainfall-runoff models can apply event based scenarios based on individual hydrological events to simulate observed or hypothetical design rainfall events to study the impact of storms for example on the depth, velocity and/or discharge in a river channel and/or surface runoff in the floodplain from overbank flows. Rainfall–runoff, groundwater and agrohydrological models can apply continuous events to simulate water flow transfers in the river and/or the floodplain and between the surface and subsurface hydrological systems. The duration of continuous events are generally longer than that of an individual event and may range from a year or series of years. In contrast to applying event based scenarios, there are many advantages of applying a continuous based events as follows:

- Study the effects of a number of rainfall events and also their cumulative effects on both the hydrological surface and subsurface systems.
- The longer event duration of a year or series of years can encompass seasonal responses in dry, wet or average hydrological regimes e.g. water table responses and fluctuation.

Table 3.2 Classification of vertical connectivity modelling methods and applications

Model	Method	Description	Application	Example model outputs	Example model software
Field	1D	Solution to Hooghoudt and Glover-Dumm equations	Hydraulic design and drainage of drainage canals in AutoCAD and calculation of drainage spacing applying spreadsheets.	Water table position	DrainCAD
Canal	1D	Solution of St-Venant equations	Surface-water model designing canal networks incorporating hydraulic structures.	▪ Discharge, ▪ Stage ▪ Mean velocity	▪ DUFLOW ▪ HEC-RAS
Rainfall-runoff	1D	USDA - SCS methods	▪ Physically based small watershed scale runoff event ▪ Simplified procedures ▪ Single event based ▪ Urban hydrology and small watersheds ▪ Multiple sub areas and reaches	▪ Storm Runoff Volume ▪ Peak rate of discharge ▪ Hydrographs, ▪ Storage volumes required for floodwater reservoirs	WinTR-55
	1D	▪ Runoff-volume models e.g. SCS curve number, Green Ampt ▪ Direct-runoff models e.g. Unit hydrograph, SCS UH ▪ Baseflow models e.g. Constant monthly, linear reservoir ▪ Routing model e.g. Kinematic wave, Muskingham-Cunge	▪ Analyse urban floodplains, flood frequency and forecasting, reservoir design and stream restoration. ▪ Rainfall-runoff routing ▪ Subsurface drainage discharge on land types and can incorporate hydraulic structures. ▪ Single event based or continuous events ▪ Catchment based ▪ Complex distributed and mechanistic components	Hydrological element i.e. reach or sub-basin ▪ Drainage area ▪ Peak discharge, time of peak ▪ Volume ▪ Depth ▪ Baseflow	HEC-HMS
	1D	▪ Solution of St-Venant equations	▪ Physically based watershed scale runoff event ▪ Single event based	▪ Discharge and baseflow	DUFLOW/RAM
Groundwater flow	3D	▪ Finite difference solutions of the Laplace equation ▪ Finite element methods	▪ Complex analysis of groundwater flow situations. and patterns in surface water/groundwater systems. ▪ Water resource assessment. ▪ Transport and fate of pollutants. ▪ Effects of Groundwater level on vegetation change	Subsurface ▪ drainage flow ▪ abstraction ▪ infiltrations ▪ area recharge ▪ stream discharge	▪ MODFLOW ▪ FEFLOW

Model	Method	Description	Application	Example model outputs	Example model software
Agrohydrological	1D	▪ Water balance equation for movement of water from soil surface to unsaturated zone ▪ Infiltration: Green-Ampt equation ▪ Subsurface drainage: steady-state Hooghoudt equation	▪ Predict the effects of drainage and water management practices on water table depths, the soil water regime and crop yields. ▪ Simulates the performance of drainage, controlled, drainage and sub-irrigation systems. ▪ Developed for soils with a shallow water table and parallel drains on mostly level landscapes.	▪ Infiltration ▪ Soil moisture conditions ▪ Evapotranspiration, ▪ Water table regime ▪ Drainage rates.	DRAINMOD
	1D	▪ Vertical water movement (unsaturated zone) – Richard's equation ▪ Field drainage: Ernst and Hooghoudt equations	Simulation of water flow in saturated top soil (vadose zone) including drainage for plant growth and for environmental protection in agricultural and environmental systems.	Water balance components: ▪ Runoff ▪ Net drainage ▪ Water table level ▪ Evapotranspiration ▪ Water storage profile changes	SWAP
	1D	▪ SCS Curve number method ▪ Drainage rate: (Raes and van Aelst, 1985) ▪ Field drainage: mid-drain water table height (after Youngs et al, 1989)	▪ Simulation of soil water storage and water inflow and outflow in response to different water management strategies and environmental scenarios i.e. drainage design and weather data, soil type and cropping patterns respectively. ▪ Simulate water table regimes in response to climate and inundation. ▪ Water resources under climate change scenarios.	▪ Surface runoff ▪ Evapotranspiration for crop cover and also soil water status ▪ Mid-span water table level ▪ Drain flow ▪ Soil water content	WaSim

Source: after NCSU (2013); USGS (2010); Shaw et al. (2011); Christiaens and Feyen (2001); Smedema et al. (2004); STOWA (2000); Lui et al. (1990); Counsell and Hes, (2000); Kroes et al. (1999); Skaggs, (1999); Liu and Feyen (1992); Raes and Aelst (1985)

3.4 Integrated modelling systems

In the last three decades, there have been significant advances to model the dominant transfer water flows occurring in surface and subsurface hydrological systems of the floodplain (Jolly and Rassam, 2009). A floodplain is a complex and dynamic ecosystem with many dynamic and crucial hydrological processes occurring i.e. links and feedback flows between the surface and sub-surface water regimes (Refsgaard et al., 1998). Several authors have discussed the importance of integrated modelling to simulate changes in the hydrological regime thus becoming a valuable tool to assess the impacts of hydrological exchanges on the delivery of ecosystem service (Kazama et al., 2007; Dutta et al., 2006; Thompson et al., 2004; Refsgaard et al., 1998).

An integrated modelling system is formed by the exchange of data and feedback between the chosen individual model components and therefore crucial to describe the dynamic interaction of water transfer flows in surface and subsurface systems (Refsgaard et al., 1998).

There are different degrees that can be applied for model integration as described by Regsgaard et al. (1998) as follows:

- Sequential runs: this is where the results from one model are applied as an input to the next model in a sequence and iterative mode involving model calculations.
- Full integration: coupling e.g. linking between models where the simulation between models takes place between computational time steps and shared memory allowing data transfer for the exchange of water based on transfer and feedback flows.

Table 3.3 provides examples of integrated modelling systems applied in industry and research. The degree of model integration, methods and a brief description is provided. The hydrological system i.e. surface and/or subsurface and dominant transfer/feedback flows for each integrated modelling system are described. The software components/packages, typical applications and model outputs along with examples of application in industry and research for each integrated modelling system is further described.

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Table 3.3 Examples of integrated modelling systems in industry and research

Model Integration				**Hydrological**		**Software**				
Example	**Type**	**Method**	**Description**	**System**	**Transfer flows**	**Components/package(s)**	**Typical Application(s)**	**Typical Outputs**	**Industry**	**Research**
1	Full integration (Coupled)	1D hydrodynamic model	One dimensional St. Venant equation	Surface	Overland inflow and gravity return flow	▪ SOBEK D-FLOW 1D Open Water and ▪ D-FLOW 2D Overland by Deltares systems	Studying the effects of dam breaks, surface water and urban flooding, dike/embankment breaches, flood warning , flood forecasting, flood alleviation scheme design, flood risk assessments	▪ Peak discharge ▪ Flood peak attenuation (derived) ▪ Flood peak translation (derived) ▪ Flood inundation – Depth – Velocity – Area – Volume	Applied by water authorities, consultancy firms, research institutes and universities worldwide	Baptist et al. (2006)
		2D hydrodynamic model	Two dimensional St. Venant equation (Finite difference schemes)		▪ Overland gravity return flow ▪ Surface runoff	▪ ISIS 1D and ISIS 2D by CH2MHILL ▪ ISIS 1D-TUFLOW by CH2MHILL and BMT WBM ▪ ESTRY-TUFLOW ▪ by BMT WBM				NA
2	Full integration (Coupled)	1D hydrodynamic model and	One-dimensional Saint-Venant equation	Surface	Overland inflow and gravity return flow	MIKE 11 by DHI	▪ Integrated catchment hydrology ▪ Conjunctive use of surface water and groundwater ▪ Irrigation and drought management ▪ Wetland management and restoration ▪ Environmental river flows ▪ Floodplain management ▪ Groundwater induced flooding ▪ Land use and climate change ▪ Groundwater remediation	▪ Peak discharge ▪ Flood peak attenuation (derived) ▪ Flood peak translation (derived) ▪ Flood inundation – Depth – Velocity – Area – Volume	MIKE software by DHI is extensively applied in worldwide in over 14 countries for water professionals benefiting from over 50 years of dedicated research and development.	Thompson et al. (2004) and Refsgaard et al. (1998)*
		Deterministic, fully distributed and physically based model.	Two-dimensional Saint-Venant equation)		Overland surface runoff	MIKE SHE by DHI				
			▪ Unsaturated (1D-Richards equation) ▪ Saturated subsurface flows (3D- Boussinesq equation) ▪ Analytical solutions for interception and evapotranspiration	Subsurface	▪ Infiltration ▪ Percolation ▪ Groundwater recharge			▪ Precipitation rate ▪ Actual evapotranspiration ▪ Water content in root zone ▪ Unsaturated zone flows ▪ Water table depth ▪ Groundwater discharge/recharge		
3	Sequential	2D hydrodynamic model	▪ Numerical modelling (finite difference techniques) ▪ 1D dynamic wave model ▪ 2D non uniform flow model ▪ Overflow: weir equation	Surface	▪ Overland inflow and gravity return flow ▪ Overland and surface runoff	LISFLOOD-FP	Dynamic flood inundation model operating with a simple raster based Digital Elevation Model for lowland floodplains and rivers.	▪ Flood inundation ▪ Depth ▪ Area/Extent	NA	Kazama et al. (2007)
		Numerical solutions	▪ Conservation equation ▪ Darcy's law	Subsurface	▪ Infiltration ▪ Percolation ▪ Groundwater recharge	NA	Bespoke application as applied by Kazama et al, 2007	▪ Groundwater storage ▪ Groundwater table level		
4	Sequential integration	Coupled 1D-2D model	1D St. Venant	Surface	▪ Peak discharge ▪ Overland inflow and gravity return flow ▪ Surface runoff	MIKE11 by DHI	▪ Flood inundation ▪ Wetland connectivity ▪ Catchment runoff	▪ Peak discharge ▪ Flood peak attenuation (derived) ▪ Flood peak translation (derived)	MIKE software by DHI is extensively applied in worldwide in over 14 countries for water professionals benefiting from over 50 years of dedicated research and development.	Karim et al. (2012)
			2D St. Venant (finite difference scheme)			MIKE 21 by DHI	▪ 2D hydrodynamics (floodplains, coast and sea ▪ Waves ▪ 2D ecosystems	▪ Flood inundation ▪ Depth ▪ Velocity ▪ Area ▪ Volume		
		Lumped conceptual rainfall-runoff module with in 1D model	Simple empirical rainfall-runoff methods for each water transfer exchange flow			MIKE 11 NAM module by DHI	▪ Catchment storage capacity ▪ Simulation of manmade interventions in hydrological cycle i.e. irrigation and groundwater pumping	▪ Runoff peaks and low flows, ▪ timing of peaks and low flows ▪ Total volume of runoff		

*Note that while the study by Refsgaard et al, 1998 utilised a full model integration system using MIKE 11/MIKE SHE, and sequential integration of the DAISY model .

Source: after BMT WBM (2014a,b); CH2M HILL (2014a,b,c,d); DHI (2013a,b,c); Deltares (2013a), Karim et al. (2011); Kazama et al. (2007); Baptist et al. (2006); Thompson et al. (2004); Bates and De Roo (2000); Refsgaard et al. (1998)

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Full integrated modelling systems i.e. coupled 1D-2D hydrodynamic models have been developed and applied since 1975-1976 (Hunter et al., 2007). Internationally, these modelling systems for example MIKE 11/MIKE 21, ISIS 1D/TUFLOW and ESTRY/TUFLOW are applied by consultants, developers, individuals and/or local planning authorities for flood risk assessments. The same systems are commonly employed by the Environment Agency, the principal environment regulator of England & Wales for flood risk assessment, management and mapping (EA, 2006). Néelz and Pender (2009) discussed that this type of integrated model system has become quite popular in recent years as it allows the modeller to take advantage of the respective benefits offered by both the 1D river model and 2D floodplain model providing a better representation of channel and floodplain flows. Chatterjee et al. (2008) described that 1D-2D integrated modelling systems can provide more detailed information in terms of floodplain processes i.e. inundation depths, velocities and area extents in a floodplain. Although the same study discussed that computation, storage space requirements and modelling effort are generally higher for a coupled 1D-2D hydrodynamic model. The research synthesis found that limited research is available which apply 1D-2D integrated model systems. Chatterjee et al. (2008) and Baptist et al. (2006) discussed that these systems are particularly useful for studying hydrological processes in the floodplain. Baptist et al. (2006) discussed that this type of integrated modelling system can help to quantify parameters needed to evaluated different scenarios and also necessary to apply to a multi criteria analysis method for flood safety and ecology for example.

The other full integrated systems derived from the research synthesis were from Thompson et al. (2004) and Refsgaard et al. (1998) which applied a coupled 1D hydrodynamic model (MIKE 11) with a deterministic, fully distributed and physically based model (MIKE SHE). The Système Hydrologique Européen (SHE) model is the most widely recognized model of its type providing a grid based model dividing the catchment into a number of rectangular grid elements linked to channel reaches along the grid boundary and can account for spatial variations in hydrological inputs and also catchment responses (Shaw et al., 2011; Beven, 2001). This particular integrated model system is ‘coupled’ utilising the optimum numerical solutions i.e. 1D river model: St Venant equation; 2D floodplain: 2D St Venant equation; unsaturated: 1D-Richards’ equation and saturated subsurface flows: 3D- Boussinesq equation and analytical solutions for interception and evapotranspiration to represent the water transfer, exchange and feedback flows of a river and floodplain. The Système Hydrologique

Européen (SHE) model has benefitted from extensive development in research since 1977 and more so by the Danish Hydraulic Institute with the commercial version as MIKE SHE (Shaw et al., 2011). In the last two decades, Refsgaard et al. (1998) and Thompson et al. (2004) have discussed the importance of coupling MIKE 11 and MIKE SHE models for the improvement of the channel flow component especially considering complex channel networks and hydraulic structures. The application of this integrated modelling system as described is advantageous by effectively providing a single interface to model a wide array of crucial hydrological water transfer, exchange and feedback flows in the surface and subsurface hydrological systems yet it is not without limitations. There are a few limitations with the application of the MIKE 11/MIKE SHE integrated modelling system. Extensive model data to include a large number of individual physical parameters is required in regard to the grid cells especially considering the initial model setup (Shaw et al., 2011). In addition, it is still not clear that the description of flow in the unsaturated and saturated zones in this model is adequate to describe the complex flow pathways based on reality (Shaw et al., 2011).

Sequential integrated modelling systems used in Karim et al. (2011) and Kazama et al. (2007) have utilised a 1D-2D linked hydrodynamic based models with a sequential link to rainfall-runoff based models and numerical approaches. Refsgaard et al. (1998) had applied a full integrated model system e.g. MIKE11/MIKE SHE model and incorporating sequential form also e.g. DAISY model noted that application of individual model components of the integrated modelling system represent state of the art techniques within their respective disciplines providing the required levels to describe hydrological processes and characteristics. The choice of applying a sequential integrated modelling system is based on the purpose of the study and the choice of hydrological processes of particular interest to be modelled.

Limitations of applying a sequential form of an integrated modelling system as discussed in Refsgaard et al. (1998) are as follows:

- This system will involve different degrees of integration ranging from sequential runs i.e. one model data output is used as an input for another model to full integration, such as coupled systems.
- Some hydrological feedback flows may be considered of minor importance and do not essentially account for nor are modelled for practical purposes.

3.5 Model choice

The previous sections have classified and defined a range of models, methods and software packages along with their applications through research and the real world that are available to model floodplain processes especially in terms of river-floodplain-aquifer interactions and water transfer, exchange and feedback flows. Advantages and limitations of their use have also been discussed as derived from literature. To enable the choice and selection of the appropriate models to apply to an integrated modelling system to study the impact of floodplain connectivity, this research adopted model evaluation procedures as described by Beven (2001) as follows:

1. Preparation of a list of models under consideration to include models that are readily available.
2. Preparation of a list of model outputs i.e. variables for each model and those required to meet the aims of the research.
3. Preparation of a list of methods applied for each model to understand the assumptions and limitations of each model in terms of the hydrological flows occurring in the river-floodplain-aquifer.
4. Highlight model use application and by whom e.g. industry and research examples.
5. In general, EA (2006) discussed that it is appropriate to choose commercial modelling software in widespread use. In specific situations, the applicability of the model chosen must either have independent benchmarking tests carried out in order to demonstrate the model performance.
6. Highlight the water transfer, exchange and feedback flows represented for each model.
7. Consideration of the range of inputs required for each model e.g. specification of the model boundary, initial conditions and parameter values.
8. Determination and selection of the most appropriate model choice to apply to an integrated modelling system. If no suitable integrated modelling systems are determined, review the previous steps and relax the criteria used.

It is clear from Tables 1.1. and 3.3 that integrated modelling systems enable a quite detailed level of modelling, to include quantitative predictions of the surface and subsurface water regimes in a floodplain (Refsgaard et al., 1998). A full integrated system allows for the complete exchange and feedback water transfer flows through ‘coupling’ of model components in surface and subsurface hydrological systems (Refsgaard et al., 1998). Although a sequential integrated modelling system can provide similar detail, yet its application is highly dependent in the context of research and particular process of required interest.

Beven (2001, p. 304) aptly discussed that ‘the single ‘true’ model is an ideal, it has been suggested that it is an ‘unreachable ideal’. This is because there is neither the model structure, or the necessary data required to identify the complex and unique single realisation that can represent a real catchment or in this case the floodplain. Although, as discussed in the preceding sections, there are many models that are acceptable simulators and that their selection is critical in order to best represent a floodplain and its hydrological processes. Shaw et al. (2011) also discussed that there are an enormous variety of models available, which can range from very simple to complex models to allow predictions in space and time. Even the application of a complex model will still only be an approximate representation and involve some degree of uncertainty and assumptions (Shaw et al., 2011). The importance of model choice and selection is based on whether the models can adequately represent floodplain processes and adequately mimic flood characteristics yet this is still subject to on-going research and debate (Horritt and Bates, 2001). The concept of ‘parsimony’ bears consideration, as a model or modelling system should be no more complex that necessary to make predictions, which are sufficiently accurate to be useful (Beven, 2001).

For this research, a sequential integrated modelling system was applied using a full integrated ISIS 1D and ISIS 2D hydrodynamic models developed by CH2M HILL and WaSim, a one dimensional, daily, soil water balance model developed by HR Wallingford and Cranfield University (CH2M HILL, 2013a; Hess and Counsell, 2000). The main reasons for the choice of applying the ISIS software package were as follows:

The ISIS software package was chosen as it benefited from robust and proven technology with industry leading solvers i.e. model code having been developed over the last 30 years and widely applied worldwide (CH2M HILL, 2013a). Other significant benefits of this model package are that it is an effectively complimentary tool to balance detail and model efficiency providing close to real life behaviour of the river and floodplain flows and levels. There are a comprehensive set of numerical solvers/methods available for greater accuracy in the predication and representation of especially floodplain flows (CH2M HILL, 2013b). The ISIS software package has had an independent benchmark test for model performance and is widely utilised by the research sponsor i.e. the Environment Agency and its consultants for flood risk management purposes with proven capabilities in the prediction of variables required for flood risk management to form the basis for decisions (Néelz and Pender, 2010). While ISIS 2D is not widely utilised on Environment Agency projects at present, it may become popular in the future, as it is included with ISIS 1D, which is in widespread use (Néelz and Pender, 2009).

The main reason for the choice of applying WaSim software is that since its development, WaSim has been widely demonstrated as a valuable research tool for hydrological studies (Holman et al., 2011; Hess et al., 2010; Holman et al., 2009; Fasinmirin et al., 2008) and also water management studies (Hirekhan et al., 2007; Depeweg and Otero, 2004).

3.5.1 **ISIS hydrodynamic models**

ISIS software has been developed by Sir William Halcrow and Partners and HR Wallingford to model open channel flows and floodplain flows and has been considered an industry standard (Crowder et al., 1997; Halcrow and HR Wallingford., 1996).

ISIS software is commercially owned and continually developed, maintained and supported by CH2M HILL and benefited from over 30 years of continual development with extensive application and independent benchmarking tested making it a proven and robust model suite to simulate a range of simple to complex water flow, hydrology water quality, sediment transport in rivers and floodplains (CH2M HILL, 2013a).

The ISIS suite contains a range of modular software packages of which this research shall apply ISIS 1D and ISIS 2D model component software. Typical applications of the software models as mentioned are as follows:

- Flood risk mapping
- Developing catchment management plans
- Flood alleviation scheme design
- River engineering and irrigation schemes
- Environmental impact assessments
- Flood risk assessment and hazard analysis
- Integrated modelling
- Surface water management plans
- Catchment and floodplain development

ISIS 1D is a full, one-dimensional (1D) hydrodynamic model used to simulate water flows and levels in open channels (CH2M HILL, 2013b). The channel flow is described by Shallow Water Equations (SWEs) or St. Venant equations which express the conservation of mass (continuity equation) and momentum (conservation of momentum equation) as a pair of one-dimensional non-linear hyperbolic partial differential equations to calculate flows and levels between cross sections (Halcrow, 2010). Key applications of ISIS 1D as described by CH2M HILL (2014a) are as follows:

- Water-Resource Management
- Flood Risk Mapping
- Flood Risk Assessments
- Catchment Management Planning Projects
- Flood Alleviation Scheme Designs

ISIS 2D is a full, two-dimensional (2D) hydrodynamic model used to simulate water flows and levels in a floodplain (CH2M HILL, 2013c). The water flow is described by 2D shallow water equations e.g. 2D St. Venant Equations, which are derived from depth averaging the Navier-Stokes equations of three-dimensional (3D) incompressible fluid (Halcrow, 2010). The core computational engine is derived from the Depth Integrated Velocities and Solute Transport (DIVAST) model developed in the 1980s by Cardiff University and then further developed by CH2M HILL. The DIVAST model is widely known and applied in research with well over 30 journal articles and conference proceedings published and also utilises widely applied and recognized shallow water solvers for research work (Halcrow, 2010). ISIS 2D can be operated independently or with ISIS 1D thus enabling a dynamic interaction between the ISIS 1D and ISIS 2D models, which are coupled by water level or flow or weir linking methods describing the exchange of water between the models. These forms of coupling enable ISIS 1D and ISIS 2D to represent lateral floodplains, spill over defences e.g. embankments and other representations of river and floodplain systems (CH2M HILL, 2014e).

Also as part of ISIS 2D, there are two main integrated solvers to tackle different types of hydraulic conditions within rivers and floodplains for environment studies or hydraulic studies (CH2M HILL, 2014f,g) These solvers are namely Alternating Direction Implicit (ADI) and Total Variation Diminishing (TVD) ,(Halcrow, 2010). Both these solvers apply finite difference schemes, which divide the floodplain into structured mesh grids to solve the shallow water equations. The ADI scheme discretizes the SWEs over a structured grid of square cells and calculates the water depths at the cell centres with the discharges calculated at the cell edges in x- and y-directions (Halcrow, 2010). The ADI solver is applied to fluvial and overland modelling problems where flow is not rapidly changing and TVD is applied to dam breaks, breaches in defences or rapid flow around buildings to accurately represent shock's where water flow is rapidly changing in the surface profile (CH2M HILL, 2013f,g)

Key applications of ISIS 2D as described by CH2M HILL (2014c) are as follows:

- Surface water and urban flooding
- Rapidly varying flow around structures
- Local and Catchment scale assessments

A linked ISIS 1D-2D model can simulate the following water transfer flows between the river and floodplain:

1. River (discharge, velocity and water levels) – ISIS 1D
2. Overbank flows (discharge or water level exchange between the river and floodplain) – Coupled ISIS 1D and ISIS 2D
3. Surface runoff in the floodplain – ISIS 2D

An example of ISIS 1D and ISIS 2D model components and their modelled outputs are described in Table 3.4.

Table 3.4 ISIS 1D and ISIS 2D model components and modelled outputs

	Model component	**Modelled outputs**
1	ISIS 1D	River channel discharge, velocity and depth; hydrograph discharge peak translation and attenuation (derived)
2	ISIS 2D	Inundation velocity, depth, area and volume

Source: after Halcrow (2010)

3.5.2 **WaSim: agrohydrological model**

WaSim is a one-dimensional, daily, soil water balance model that simulates the soil water and salinity relationship in response to a variety of management strategies e.g. drainage and irrigation design and environmental scenarios e.g. weather data, soil types and cropping patterns (Counsell and Hess, 2000).

The model divides the ground profile into five compartments to describe the distribution of soil water (Hess et al, 2000). The upper boundary makes up the soil surface while the lower boundary makes up the impermeable layer with water being stored between these two boundaries (Figure 3.3).

- Compartment 0: The surface (0–0.15 m) layer
- Compartment 1: The active root zone (0.15 m–root depth)
- Compartment 2: The unsaturated compartment below the root zone (root depth–water table)
- Compartment 3: The saturated compartment above drain depth (water table–drain depth)
- Compartment 4: The saturated compartment below drain depth (drain depth–impermeable layer)

As the roots grow, the boundary will change between compartments 1 and 2, before the plant roots reach 0.15 m in depth, compartment 1 will have zero thickness and the boundary between compartments 2 and 3 will fluctuate as a function of the water table (Hess et al, 2000). Figure 3.3 describes the hydrological process applied in the WaSim model.

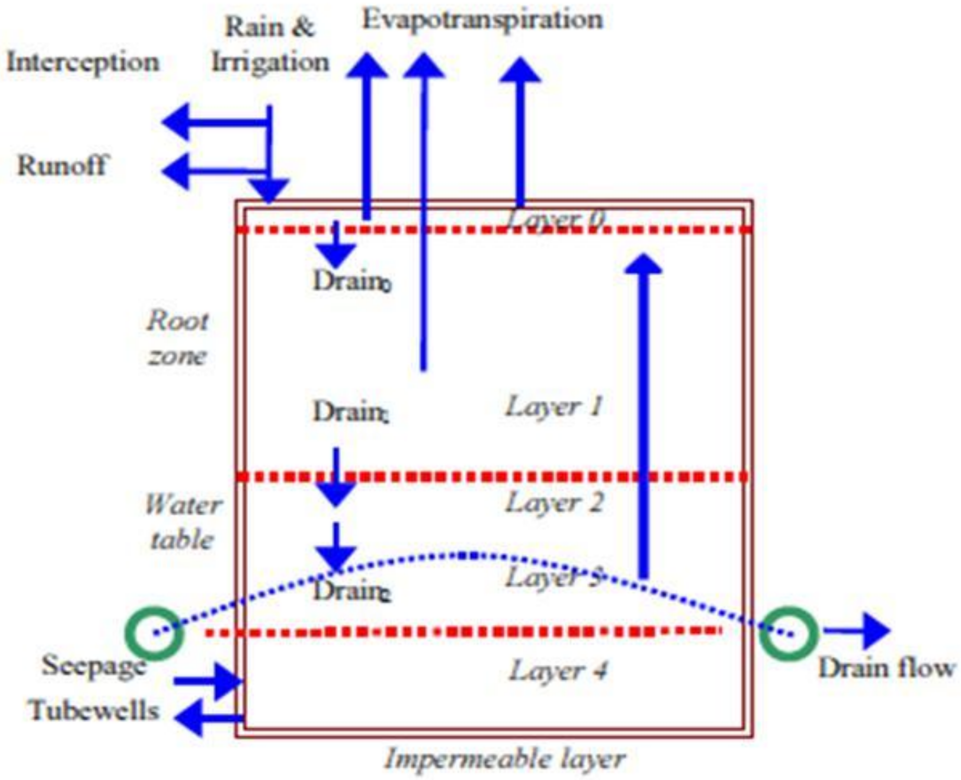

Figure 3.3 WaSim model conceptual diagram

Source: Hess et al. (2000, p. 3)

The water inputs where relevant are from net rainfall, net irrigation and lateral seepage. Net rainfall and irrigation have been defined as the gross amounts, which are less interception losses and surface runoff. The water outputs in the compartments are described as follows:

1. Open water evaporation only occurs where there is ponding at the soil surface. In this instance there is no transpiration
2. Soil evaporation will occur in Compartment 0 only.
3. Plant transpiration will occur from compartments 0 and 1
4. Capillary rise from groundwater is simulated by a direct shortcut from the groundwater to evaporation and transpiration between compartments 2 and 3. This process is a function of conditions in the compartments made up of a series of empirical formulae (Hess et al., 2000)
5. Drain flow occurs in lower compartments where the water table is above the drain depth with the drain flow rate a function of height of the water table above the drain between compartments 3 and 4. The drain flow is a function of mid-drain water table height (Youngs et al., 1989)

When the soil layer exceeds field capacity, the soil water moves from the upper to lower compartments with the drainage rate a function of the amount of excess water based on calculations from Raes and van Aelst (1985). Surface runoff is formed of two components i.e. runoff due to intense rainfall e.g. infiltration excess and runoff due to the saturated soil (Hess et al., 2000). The first component i.e. infiltration-excess runoff is estimated utilising the widely recognised US SCS Curve Number Method (CED, 1986). In saturated soils, where precipitation has not infiltrated the soil, runoff is assumed to occur and is a function of precipitation and ponding conditions (Hess et al, 2000).

The actual evapotranspiration is estimated using a method by Richie (1972) involving a two stage process based on soil conditions being dry or wet and also plant transpiration. Where the water table reaches the soil surface, ponding occurs and is treated as open water with no transpiration or soil evaporation loss but open water evaporation loss, which is proportional to the reference evapotranspiration (Hess et al, 2000). Seepage from irrigation canal/river assumes a constant addition rate to the water table.

The WaSim model simulates the following hydrological flows in the floodplain:

1. Rainfall (from the atmosphere to the soil surface)
2. Evapotranspiration (from the soil surface to the atmosphere)
3. Infiltration (from the soil surface to the soil root zone)
4. Percolation (from the unsaturated zone to the saturated zone)
5. Groundwater table flow i.e. rise and fall in the water table (unsaturated zone)
6. Seepage (from the river to the groundwater in the unsaturated zone)

An example of the modelled outputs for WaSim is as follows:

- Open water evaporation
- Soil evaporation
- Crop transpiration
- Drain flow
- Water table depth
- Runoff

These results are generally supplied in daily format but can be summarised in seasonal (crop season), monthly or annual formats with only information on total rainfall, irrigation, runoff, deep percolation and relative transpiration (Hess, 2000)

3.6 Research integrated modelling system

3.6.1 **Individual model components**

A sequential integrated modelling system (Figure 3.4) has been establishing by applying the following existing model components made up of extensively tested model codes:

- ISIS 1D (CH2M HILL, 2013b)
- ISIS 2D (CH2M HILL, 2013c)
- WaSim (Hess and Counsell, 2000)

Figure 3.4 illustrates the basic structure of the integrated modelling system displaying the individual model components and the data transfer and/or exchange and feedback flows.

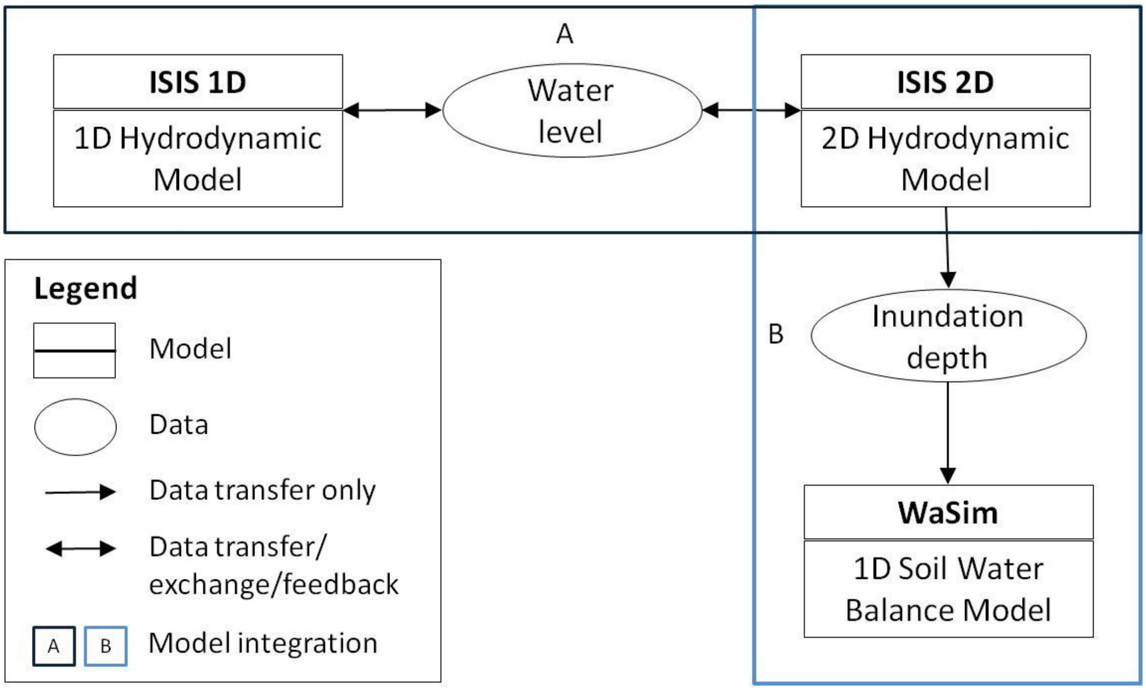

Figure 3.4 Integrated model system structure and individual model components and interactions.

3.6.2 **Integration of model components**

The integrated model system was formed by the transfer/exchange of data and feedbacks between the individual model components. The general structure and the exchange of data and interfaces between the individual model components is illustrated in Figure 3.4 and steps of the integrated modelling system are described further in Section 3.6.3 and illustrated in Figure 3.5 for river and floodplain modelling.

The following points summarise a description of the integration system considering each model component.

A. ISIS 1D and ISIS 2D are linked as part of the full dynamic coupling for the exchange, transfer of data in the surface system between the river and floodplain. The ISIS 1D model calculates the water level, velocity and discharge in the river where the water level is transferred and to ISIS 2D model, where the inundation flood depth, velocity and areal extent is mapped by the comparison of calculated flood depth with the surface topography within the model grid in ISIS 2D. Exchange and feedbacks occur between ISIS 2D (floodplain) from the inundation depth to the ISIS 1D (river) water level during the course of the design flood event based on low topographic points in the linked ISIS 1D-2D model boundary at the embankment permitting overbank flows. The linked ISIS 1D and 2D model is crucial for the accurate representation of river-floodplain surface system interaction.

B. The linked ISIS 1D-2D model is sequentially integrated with WaSim through the provision of the linked ISIS 1D-2D model outputs to the WaSim model initial boundary conditions inputs.

C. The linked ISIS 1D and ISIS 2D simulations provide the inundation depth as a result of overbank flows from a design flood event. This inundation depth is then applied as a ponded depth as part of the initial boundary conditions in WaSim that will infiltrate at the soil surface and percolate from the unsaturated zone to the saturated thus affecting the water table position.

3.6.3 Modelling Approach

The application of an integrated modelling system approach will provide a comprehensive analysis to understanding the hydrological regimes that may impact on ecosystem services delivery in floodplains. The models in this research will be applied in a scenario approach in order to simulate the alternative hydrological regime conditions resulting from alternative floodplain connectivity i.e. lateral and vertical connectivity and also hydrological events i.e. design flood events and seasonal year events. The design flood events refer to a range of high to low frequency/magnitude %AEP flood events. The seasonal year events refer to wet, average and dry year rainfall which impact on the water table position. The integrated modelling system for this research incurs a sequential process involving a number of iterations for each modelling sequence to simulate the hydrological regime conditions as illustrated in Figure 3.5 and involves the following steps:

Step 1a & b. River and Floodplain (surface) modelling: ISIS 1D-2D

Model simulation: The linked ISIS 1D-2D model simulates the river discharge, velocity and water levels in the ISIS 1D model and the inundation depth, velocity, area and volume in the ISIS 2D model. This linked model represents the overbank flows between the river and floodplain and inundation in the floodplain in the hydrological surface system. Each design flood event is simulated under each lateral connectivity scenario in order to further assess the alternative hydrological regime condition results in the hydrological surface system and impacts to ecosystem services delivery.

Model integration (coupling): There are three methods namely water level (H), flow (Q) and weir (W) linking to represent the exchange of water between the river and floodplain (Halcrow, 2010). The choice of linking method is dependent on the hydraulics to be represented e.g. where the floodplain has no defence, level linking should be applied and where defences are present, flow or weir linking may give better results. The water level linking method was applied for simplicity and consistency for each hydrological connectivity scenario. This method works through taking water levels from the ISIS 1D model nodes, which are then imposed as a boundary condition on the ISIS 2D model. The 2D flow is calculated at these linked boundaries and then transferred back to the ISIS 1D model with flow added or removed from the ISIS 1D model (Halcrow, 2010).

Step 2. Floodplain (surface and subsurface) modelling: Linked ISIS 1D-2D/ WaSim

Model simulation: The WaSim model is applied to simulate the water table level as a result of infiltration and percolation of the inundated floodwaters and seasonal year events from the hydrological surface into the subsurface system. Each seasonal year event is simulated under each vertical connectivity scenario in order to further assess the results of alternative hydrological scenarios in the hydrological subsurface system and the impacts to ecosystem services delivery.

Model integration (sequential): The inundation depth results from the linked ISIS 1D-2D model are applied as the ponding depth in WaSim as an initial boundary condition. In the WaSim model, the hydrological processes of precipitation, evapotranspiration and infiltration into the soil surface along with percolation through the unsaturated zone to the saturated zone are modelled to simulate the impact of flood inundation on the water table level.

Figure 3.5 illustrates the integrated modelling system applied in this research, along with the hydrological events, floodplain connectivity scenarios and data transfer between each individual model component as applied.

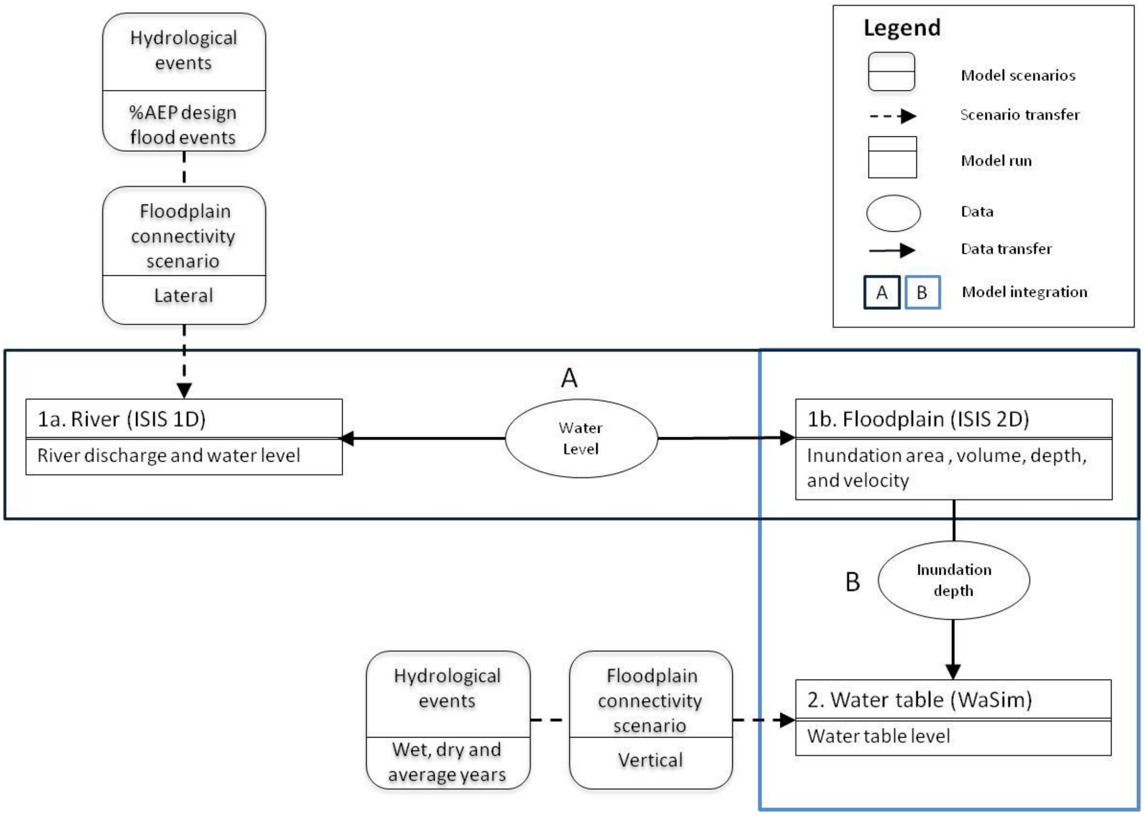

Figure 3.5 Integrated modelling system, individual model components, hydrological event and connectivity scenario and data transfer

3.7 Model outputs

The model outputs of the integrated modelling system for the hydrological events and floodplain connectivity describe the resulting hydrological regime conditions of the interacting scenarios. These outputs are also utilised as a hydrological indicators in order to develop an ecosystem services assessment methodology to evaluate the impacts of the interacting hydrological events with floodplain connectivity scenarios to understand the impacts to ecosystem service delivery. The model output results for each model scenario will then be assessed under the developed ecosystem services assessment methodology.

4 ECOSYSTEM SERVICES

4.1 Introduction

Ecosystems are essential for the provision of goods and services for the sustenance and well-being of the human race. The symbiosis within the biosphere between humanity and ecosystems is vital to ensure the life cycle of both and also a sustainable synergy (MA, 2003). The Millennium Ecosystem Assessment (MA) simply defines ecosystem services as ‘the benefits people obtain from ecosystems’ (MA, 2001). The term implies that benefits are considered as ‘goods’ and ‘services’, which may be obtained from ecosystems (Costanza et al., 1997; Daily, 1997). The concept of ecosystem services was initially conceived by King (1966) with research gathering more prominence in the last three decades (Gómez-Baggethun et al., 2010). The catalyst in the progression of the Ecosystems approach was largely led by the United Nations Environment Programme (UNEP) which initiated the Millennium Ecosystems Assessment (MA) in 2001 as the result of the April 2000 Millennium Report address by Kofi Annan to the United Nations General Assembly (MA, 2003). The MA recognised the progressive burden that a degraded ecosystem can place on economic development and human well-being (MA, 2003). The project involved international and multi-sectoral partnership and participation in order to improve the management of ecosystems thus enhancing conservation while concomitantly contributing to humanities needs with the opportunity for sustainable development. This assessment provided for the first time a global assessment of the Earth’s ecosystems and their related services. In the UK, a National Ecosystem Assessment (UKNEA) also applied a comprehensive assessment of the state of the UK natural environment and concluded while some services are being delivered well, some are in decline and also that natural resources are undervalued (UKNEA, 2011). The MA (2001) discussed that climate change and demographic changes will increase pressures on how ecosystem services can be delivered, yet actions taken now to move towards sustainable development require integration of the ecosystems approach into a number of actors e.g. government, private sector and the individual (UKNEA, 2011; MA, 2005a).

In the UK, Defra recognized the importance of ecosystem services in 2007 by setting up the “Securing a healthy natural environment: An action plan for embedding an ecosystems approach” also known as “Ecosystems Approach Action Plan” EAAP (Defra, 2007c). This plan seeks to integrate ‘ecosystem services’ into national policy to provide a more sustainable system for addressing the benefits a natural environment as an ecosystem and functional unit to provide health and prosperity (Defra, 2007c).

The following section will describe specifically the ecosystem functions and services within a floodplain ecosystem that are controlled by floodplain connectivity. Drivers of change in delivery of floodplain ecosystem services will be discussed. Methods to assess the impacts of ecosystem services change in floodplains are identified and described. Finally, the assessment method chosen in the context of this research is described and its selection justified.

4.2 Ecosystem functions and services

The MA (2003) states that there are a number of ways that ecosystem services may be categorized; namely organizational, descriptive and functional. For the purpose of this research, ecosystem services shall be categorized in functional groupings based on De Groot et al. (2006; 2002). They are described as the capacity of natural processes and their components to provide goods and services to satisfy human needs, either directly or indirectly. The five groups described are namely Regulation, Habitat, Production and Information functions.

4.2.1 **Function and services**

The following section describes floodplain ecosystem functions and services, their processes and components and examples of benefits. The floodplain connectivity controls are also described for each ecosystem function and service.

4.2.1.1 **Regulation function**

Floodplains play an important role in the regulation and maintenance of flows and storage and controlled by floodplain connectivity in order to manage the hydrological regime to enable a number of ecosystem services delivery (Posthumus et al., 2010; Brauman et al., 2007; De Groot et al., 2002). Regulation functions are not often recognized as they provide indirect benefits e.g. flood alleviation, yet their existence is necessary for human well being (De Groot, 2002). Table 4.1 provides a list of floodplain ecosystem regulation functions/services, ecosystem processes and components with examples of their benefits.

Table 4.1 Regulation function/services, process and components and their benefits

	Functions and Services	Ecosystem processes and components	Benefits (examples)
1	***Regulation***	Regulation of water flow from the river and in the floodplain as a result of hydrological events e.g. floods and seasonal weather events.	Maintenance of water flow and storage for protection from flood hazards and water storage.
1.1	Flood alleviation	Influence of lateral connectivity on damping flood events through storage in the floodplain and translation and attenuation of river discharge.	a. Flood prevention through storage in washlands and flood storage areas.
1.2	Flood damage	Influence of lateral and vertical connectivity in the floodplain to regulate runoff and river discharge to defend against flood hazards and reduce damages from flooding.	a. Flood damage to settlements and industrial developments. b. Buffering of river discharge extremes c. Regulation of channel flow and floodplain drainage.
1.3	Water storage	Influence of lateral connectivity on storage of floodwaters and infiltration to the alluvial aquifer to recharge groundwater levels.	Provision of water for consumptive use (e.g. drinking, irrigation and industrial use)

Source: after De Groot (2006, p. 396); Posthumus et al. (2010); MA, (2005); Brauman et al. (2007); Matlby et al. (2011)

The control of floodplain connectivity is essential to limit damages to properties as a result of flood inundation e.g. disturbance prevention. Throughout history, floodplains have essentially been suitable as a prime location for settlement and industrial development delivering social and economic benefits with the rapid expansion of towns and cities now encroaching upon floodplains due to their flat terrain (Fleming, 2000).

In this research, flood defence is defined as a ‘flood damage’ ecosystem service as it refers to the damage incurred by settlements, industrial developments property contents as the result of a flood event. Flood defence has featured in the UK throughout history in the form of artificial embankments and drainage systems to protect fertile land and settlements within floodplains as a result of flood events from fluvial and pluvial events (Werrity, 2006). While decreasing lateral connectivity can act to control the flood frequency and magnitude from the river at a specific location it can also exacerbate peak flows further downstream by up to 150% as study by Acreman et al. (2003) has shown. Flood defence can also be ambiguous in terms of also being a carrier function e.g. habitation, as a floodplain provides a suitable space for settlement land use (De Groot, 2006). In this instance, to avoid double-counting of ecosystem services, the Carrier function and habitation ecosystem service was excluded in preference for to describe flood damage as it is predominantly linked to the hydraulic control that enables habitation and therefore more suitable. The magnitude of floods downstream can be reduced through storage of floodwaters on floodplains (Bullock & Acreman, 2003). Dutta et al. (2006) discussed that an increase in lateral connectivity i.e. lowering embankments in low frequency/ high magnitude flood events can promote flood inundation causing higher damages to infrastructure and residential and non-residential buildings limiting disturbance prevention than low lateral connectivity. Förster et al. (2008) discussed the importance of floodplain connectivity in terms of off-line storage of floodwaters to attenuate low/frequency/high magnitude flood event although based on flow control and timing of storage.

In the UK, annual groundwater abstraction is 10% of a total of 16.8 billion m^3 to include tidal and surface waters and is vital to maintain water supplies especially in times of drought and dry summers (Matlby et al., 2011; Acreman et al., 2000). Kazama et al. (2007) discussed that the effects of decreasing lateral connectivity by raising flood embankments can impact on water supply i.e. groundwater recharge through the prevention of flood inundation.

4.2.1.2 **Habitat**

Floodplains can function as ecotones which are a transition between terrestrial and aquatic environments through hydrological connections thus influencing biological and ecological productivity (Duranel et al., 2007; Brunke, 2002; Thoms, 2003). The maintenance of habitats is an essential pre-condition to the provision of direct or indirect ecosystem goods and services and concerned with carrying capacity and spatial needs for the provision of ‘refuge’ and ‘reproduction-habitat’ of the ecosystem (De Groot et al., 2002). Table 4.2 provides a list of floodplain ecosystem habitat functions/services, ecosystem processes and components with examples of their benefits.

Table 4.2 Habitat function/services, process and components and their benefits

	Functions/Services	**Ecosystem processes and components**	**Benefit (examples)**
2	***Habitat***	The floodplain is a habitat and ecotone for terrestrial and aquatic species with both lateral and vertical connectivity playing an important role to control the hydrological regime	Providing habitat (suitable living space) for wild plant and animal species
2.1	Terrestrial	Refugium: Suitable living space for wild plants	Maintenance of biological & genetic diversity and abundance
2.2	Freshwater fish	Refugium: Suitable living space for wild animals	Maintenance of biological & genetic diversity and abundance.
		Nursery: Suitable habitat-reproduction and development	Maintenance of fauna species through their respective life-cycle e.g. fish

Source: after De Groot (2006, p. 396); MA (2005b)

Floodplains provide a refugium service as a living space for resident and transient species e.g. wild flora and fauna in order to also maintain species and habitat diversity as a pre-condition to the provision of all ecosystem services (De Groot, 2002)

Floodplains can provide a nursery service for several species of flora and fauna whether for subsistence or commercial harvest (trees) or conservation of flora species diversity and abundance (De Groot et al, 2002). Several authors have emphasised the importance of river-floodplain floodplain connectivity and floodplains as a habitat for the maintenance and conservation of aquatic species e.g. fish (Funk et al., 2009; Henning et al., 2007; Lasne et al., 2007; Nunn et al., 2007; Grosholz and Gallo, 2006; Aarts et al., 2004; Lusk et al., 2003; Grift et al., 2003; Brunke, 2002). Several authors have discussed the importance of river-floodplain floodplain connectivity for the conservation of wet grassland species through the application of increasing lateral connectivity e.g. lowering of embankments or presence of natural embankments (Duranel et al., 2007; Thompson et al., 2004; Bissels et al., 2004).

4.2.1.3 **Production**

This function is concerned with biotic resources and products that are cultivated or naturally available in floodplains, as they are renewable and thus sustainable (De Groot et al., 2002). This research focuses specifically on food production from floodplains since they are the most fertile and productive areas of land and naturally fertilized by rivers as a result of flooding and also therefore amenable to arable production and seasonal grazing (Matlby et al., 2011).

Table 4.3 provides a list of floodplain ecosystem production functions/services, ecosystem processes and components with examples of their benefits.

Table 4.3 Production function/services, process and components and their benefits

	Functions/goods and services	**Ecosystem processes and components**	**Benefits (examples)**
3	***Production***	Control of floodplain connectivity to manage the hydrological regime to enable food productivity	
3.1	Agricultural productivity	Lateral connectivity controls the level of inundation that may enhance nutrient enrichment from floodwaters. Vertical connectivity controls the water table level thus enabling farm activities.	Food production i.e. - Intensive arable e.g. sugar beet and potatoes - Extensive arable e.g. cereals , beans and oil seeds - Intensive, improved grass typically dairy cows - Extensive grass usually cows and sheep

Source: after De Groot (2006, p. 396); MA (2005a); Penning-Rowsell et al. (2005)

In England for example, 9% of total agricultural area in based in floodplains with 57% of Grade 1 agricultural land e.g. intensive arable land use with a capital value of £15 billion based on 2008 values (Matlby et al., 2011)

The control of floodplain connectivity is essential to limit damages to agricultural productivity. Alkema and Middlekoop (2005) and Kazama et al. (2007) discussed that increasing lateral connectivity in low frequency/ high magnitude flood events can cause higher damage to agricultural productivity than decreasing lateral connectivity. Vertical connectivity i.e. land drainage is also essential and key to the management of the floodplain hydrological regime to maintain agricultural productivity (Matlby et al., 2011).

4.2.1.4 **Information**

The natural landscape has the potential to offer opportunities for recreation and also aesthetic experiences. This function is primarily attached to the non-material benefits that people can obtain from the ecosystem (MA, 2003; De Groot, 2002). Table 4.4 provides a list of floodplain ecosystem information functions/services, ecosystem processes and components with examples of their benefits.

Table 4.4 Information function/services, process and components and their benefits

	Functions/Goods and Services	Ecosystem processes and components	Benefits (examples)
4	***Information***	Role of floodplains to provide opportunities for cognitive development.	
4.1	Recreation	Land accessibility and attractive landscape features are a function of the control of floodplain connectivity.	Enjoyment of scenery i.e. rest, refreshment and relaxation (scenic roads, landmarks, Eco-tourism e.g. camping, trail hiking, nature walks.

Source: after De Groot (2006, p. 396); Morris et al. (2010); MA (2005)

Gallagher (1995) described that well-being is strongly linked to the experience that natural landscapes provide. Bolund and Hunhammar (1999) discussed that recreation is especially highly valued especially in urban areas promoting physical and psychological well-being as a function of accessing the natural landscape. Floodplains have an enormous merit as areas that deliver a wide range of activities yet these are largely based on controlling floodplain connectivity to reduce the incident of flood inundation and waterlogging (Woolsey et al., 2005; Gren, 1995).

4.2.2 **Multi-functional land use**

Multifunctional land use involves the creation of synergy amongst ecosystem services where the provision of one ecosystem service can enhance the delivery of other ecosystem services (Hasse et al., 2010). As ecosystem services are quite varied in typology and requirements to enable delivery, trade-offs can occur where the provision of one ecosystem service can affect the delivery of other ecosystem services (Rodriquez et al., 2006). An example of this is where the floodplain water table is managed to increase drainage to deliver agriculture benefits for food production yet this may cause a trade-off with the loss and decline in habitats for biodiversity (UKNEA, 2011).

The ecosystems approach is consistent with the concept of multi-functionality in order to provide a diverse range of services generated by a natural (MA, 2005; De Groot, 2006; UKNEA, 2011). Floodplains have the potential for multi-functional land use to provide a wide range of ecosystem services providing benefits to range of stakeholders. Trends in land ownership and management have tended more often to focus on single land use as a result of dominant market and/or policy drivers (FLUFP, 2010). Although, there are many examples in the UK of floodplains being managed as ‘washlands’ for flood alleviation, biodiversity enhancement and where possible permitting extensive agriculture (Morris et al., 2004).

In the long term, multifunctional land use to deliver multiple ecosystems services will provide a more resilient and sustainable use of floodplains (UKNEA, 2011). While nature is resilient to change, current floodplain management practises will further diminish the possibility for sustainable development. The outcome of the Millennium Ecosystem Assessment (2005) discussed that the current demands for ecosystem services are so great that already outstrip the capacity of ecosystems with trade-offs amongst ecosystem services becoming the rule. The integrity of floodplains throughout history and their benefits have been inadequately identified, underestimated and valued and this has led more emphasis placed on production and carrier ecosystem functions and their services causing trade-offs for other ecosystem services e.g. habitat and information ecosystem functions (UKNEA, 2011). The challenge remains not only to identify and evaluate but also to assess the interaction of ecosystem services in multiple dimensions e.g. floodplain connectivity in order to protect the ecosystem for the provision of well-being as part of sustainable development.

Winn et al. (2011) discussed that sustainable management of floodplains is dependent on a number of ways to include better legislation use, improved planning and better decision-support tools that capture ecosystem service delivery. A careful combination of scenarios i.e. floodplain connectivity and indicators (hydrological) can help to assess the options for the management of multiple ecosystem services (Posthumus et al., 2010). This will enable a consistent application of the ecosystem services approach to satisfy the provision of a comprehensive scientific description of the multiple relationships and feedback flows among the different ecosystem services (Haines-Young and Potschin, 2010). Greater understanding of floodplain processes and functions will enable the potential to optimize ecosystem services delivery (Matlby et al., 2011).

4.3 Drivers of change

A ‘driver of change’ is defined by MA (2005, p. 87) as ‘any natural or human-induced factor that directly or indirectly causes a change in an ecosystem’. A direct driver unequivocally influences ecosystem processes and also the services it provides while indirect drivers operate diffusely and more than often can alter one or more of the direct drivers (MA, 2005a). These drivers may interact in multiple ways and in combinations to cause changes in ecosystem services either with the provision or loss of ecosystem services. Table 4.5 provides a list of direct and indirect drivers of change to the floodplain ecosystem along with a brief description. The relevance of the interaction and the impacts of these drivers on the floodplain ecosystem in a UK perspective will be discussed further throughout this section.

Table 4.5 Drivers of change

Driver			**Description**
Name		**Type**	
1	Land use change	Direct	▪ Agriculture conversion ▪ Urbanization
2	Technology development	Direct	Precision agriculture
3	Harvest and resources consumption	Direct	▪ Arable crop production ▪ Water for consumption
4	Climate variability and change	Direct	Increase mean temperature e.g. climate variability and extreme weather events
5	Extreme weather events	Direct	Climate variability e.g. extreme weather events
6	Demographic	Indirect	▪ Population growth (rate of change, birth and death rates) ▪ Age and gender structure ▪ Household distribution by size and composition ▪ Spatial distribution (urban 'vs' rural) ▪ Migration patterns ▪ Education level attainment
7	Behaviour change	Indirect	Choices individuals make about what, how much they consume, and what they value.

Source: after UKNEA (2011); MA (2003); MA (2005b).

In the UK, as early as the 12th century, the natural attributes of a floodplain e.g. flat terrain, fertile and workable land encouraged the conversion of land from a natural landscape to both agricultural land and settlement areas to meet the demographic demands i.e. growing population and migration (Werrity, 2006; Fleming, 2002).

Rapid improvements in technology especially in the last 60 years brought about improvements in farming practices and techniques e.g. mechanized farming, pumping water and subsurface drainage leading to extensive land conversion from natural habitats to intensive or extensive farming (Winn et al, 2011).

The conversion of floodplain land for agricultural use continued to become intensified from the 1930s for the drive for food production, economical food supply and boost rural economy with publicly funded flood defence schemes e.g. embankments and land drainage as major features of support for farming (Werrity, 2006). The control of floodplain connectivity in separating rivers from floodplains by embankments and the addition of drainage systems on floodplains while providing agricultural productivity and habitation has led to the loss and deterioration of habitats and a natural means of flood regulation i.e. flood alleviation ecosystem services (UKNEA, 2011).

Floodplains in the UK do not necessarily constitute a single habitat type and may be composed of many habitats e.g. wet woodlands and grasslands and in many cases, a mosaic of habitat types (Matlby et al., 2011). A river habitat survey conducted on floodplains for the UKNEA (2011) described that a third of floodplains in the UK are rough pasture, another third are made up of improved grasslands and the remaining third are made up of other habitat types e.g. woodland, wetland, fen and lowland raised bog (Matlby et al., 2011). These habitats are described in six priority habitats as emphasized in the United Kingdom Biodiversity Action Plan (UK BAP) namely rivers, lowland meadows, grazing marsh, fens, reedbed and lowland raised bogs (Matlby et al., 2011). In England, Wales and Scotland, there are more than 389,0000 kilometres of rivers while in England and Wales an estimate of floodplain area is given at 1,658,000 ha with 42% of this area lost by flood defence embankments i.e. 694,000 ha (UKNEA, 2011). Rivers are dynamic and continually changing as a habitat yet flood defence structures e.g. embankments have reduced their capability to act as an ecotone leading to fragmented and isolated floodplain habitats (Matlby et al., 2011). The floodplain grazing marsh extent has had significant losses occurring in the last 60 years mainly as a result of river embankments preventing flood inundation and drainage in floodplains (BMRC, 2009). It is estimated that there is 230,000-300,000 ha left in the UK yet only an estimated 10,000 ha of this habitat is semi-natural to support high diversity of native plant species (Maddock, 2008a). In recent decades in the UK, Wet woodland has been subject to losses and destruction as a result of land drainage and massive clearance for agricultural production, afforestation and poor management practices or neglect. Current estimates of total wet woodland is in the region of 50,000-70,000 ha (The Wildlife Trusts, 2013; Maddock, 2008b). Fens have declined historically from 310,000 ha to 26,000 ha and remain widespread yet scattered, fragmented and isolated (Matlby et al., 2011). In intensively farmed lowland areas, fens are more isolated and smaller in size than in other parts of the UK although the largest base-poor fen in the UK is the Insh Marshes in the floodplain of the River Spey in Scotland covering 300 ha (Maddock, 2008c). Reedbeds have declined historically from 10,000 ha to 5,000 ha and mainly scattered across the UK although most are concentrated in

South East England and continue to decline slowly. Between 1979-1993, the area of reedbed had declined by 5-10% due to drainage and lack of management (Maddock, 2008d). Lowland raised bogs since the 19th century have declined by 94% from 95,000 ha to 5,800 ha in the UK as a result of drainage activities to lower the water table level for agricultural intensification, afforestation and commercial peat extraction (Maddock, 2008e).

During the 1980s until 2000, concerns of agricultural subsidies and impacts of intensive farming on the environment led to CAP reforms to enhance the environment (Morris et al., 2008). Demographic drivers i.e. increasing population growth, household distribution and size (single person occupancy), settlement and high amenity value by proximity to a river e.g. industry transport logistics led to renewed urbanization and encroachment onto floodplains (Werrity, 2006).

Population growth and distribution in the UK has led to a 0.5-5% increase per decade especially from 1951 to 2009 with net migration being the main contributor although not necessarily specific to floodplains (Winn et al., 2011). Also this pressure has led to an increase in urbanization resulting in the increased pressure on land conversion to housing with also greater demands for water resources and impact on UK habitat loss and trade-offs in other ecosystem services e.g. flood alleviation (Winn et al., 2011).

Land conversion for housing and industrial development to meet the demographic needs has led to an increase in flood defences to protect these assets and reduce damage from floods to properties and infrastructure (Fleming, 2002). Knight (2006) described the outcomes of land conversion considering flood events and floodplain connectivity as follows:

- Embankment failures (breaching or overtopping of river flood defence embankments)
- Floodplain encroachment (building on floodplains reduces ground permeability and loss of storage)
- Inadequate drainage capacity (drainage into floodplains reduced through urbanization)

As a result of drivers 1-3 and 6 (Table 4.5) in regard to agricultural productivity, it was estimated that 97% of enclosed semi-natural grassland (including floodplain meadows) in England and Wales were modified and converted to farmland between 1930 and 1984 causing habitat losses (UKNEA, 2011). While priorities have switched to favour environmental enhancement, there still remains a requirement to maintain land in

‘Good agricultural and Environmental Condition’ and the provision of land for development to fulfil habitation and industry requirements (Winn et al., 2011; Defra, 2008a). The combination of changes in land use accompanied by more extreme rainfall events whether natural or as a result of climate change will make flooding a continuing problem in the UK resulting in significant social, economic and environmental costs (Pitt, 2008)

Behaviour change is a function of the values, beliefs, knowledge and attitudes shared by groups of people or individuals and an important factor to how groups and/or individuals perceive the world in terms of what they consume and value (Nelson et al., 2005). For example in terms of consumption, agricultural productivity could be favoured over other ecosystem services as it provides economically priced goods at low cost (Winn et al., 2011).

Climate variability and change has had a major impact on regulation and production ecosystem functions with more intense heavy precipitation events resulting in flood runoff (Nelson et al., 2005). In the past 50 years, the incidence of extreme stormy weather events has increased causing major impacts on ecosystem services e.g. regulation and production ecosystem functions (Met Office, 2014; Knight, 2006).

4.4 Floodplain assessment methods

In the last three decades, ecosystem services have undergone further classification and characterization and have been predominately valued in monetary terms (Gómez-Baggethun et al., 2010). There is a wide range of methods to assess ecosystem services, which can be described in general as monetary and non-monetary methods (Defra, 2007b; Eftec, 2006). Monetary methods attempt to calculate a value based on the natural environment input, the effects of the environmental amenity as a function of property prices and factors affecting choices people make and choices individuals make between different environmental outcomes with different prices attached (Eftec, 2006). Non-monetary methods refer to ecosystem services, which cannot be robustly valued through economic analysis and can be important to compliment services that are non-amenable to economic appraisal (Bateman et al., 2011). There are two main approaches to non-monetary methods namely deliberative and participatory valuation methods and decision support systems (Defra, 2007b). Deliberative and participatory methods can range from discussion groups and processes in terms of presenting members of the public with an expert opinion and then asking them to make a verdict as a means to synthesize expert opinion (Eftec, 2006). The aim is to explore how opinions are formed and/or the preferences expressed but in units. These approaches are based more on understanding people preferences or opinions for the decision-making processes. Multi-Criteria Analysis (MCA) is an alternative method to define the benefits of ecosystem services when economic methods are impractical and establishes measureable criteria to provide indicators to measure performance of these services (DCLG, 2009).

A research synthesis of ecosystem services assessments applied to floodplains (Table 1.2) described that in general, decision support systems methods were applied and in particular Cost Benefit Analysis (CBA) and Multi-Criteria Analysis (MCA). Both these methods are described as decision support methods which allow comparison of options by assessing the impact of ecosystem services of an option (Posthumus et al., 2010; Eftec, 2006; Brouwer and van Ek, 2004). An example of this may include a management scenario in order to develop an understanding of the issues and insight to the research community for prioritization of a study and for decision making e.g. stakeholders, policy makers and planners for land use management options. The following section will describe CBA and MCA decision support methods commonly applied for floodplain ecosystem service assessment. Examples of their application, advantages and limitations of their use are also included. Finally, the choice of method applied for this research shall be described with justification.

4.4.1 **Cost-benefit analysis**

Cost-benefit analysis (CBA) is a monetary decision support method, which compares the benefits and costs of an option, proposal, policy, project or programme and feasibility to include the impacts upon ecosystem services (Defra, 2007; Eftec, 2006). In principle, it can be applied prior or post an event with its application mainly limited to the availability of necessary data (Eftec, 2006). The HM Treasury’s Greenbook: Appraisal and Evaluation in Central Government recommends its application in the public sector to support decision making for public projects, polices and programmes (HM Treasury, 2003).

Simpson and Vira (2010) also described CBA as a form of trade-off analysis that can reduce different outcomes to a common unit of measurement e.g. money. This form of analysis typically works by multiplying certain quantities (benefits) by positive weights (prices), while also certain other quantities (costs) are multiplied by the negative weights (prices). Then all the weighted quantities are summed in order to derive the net benefits of an option, proposal, policy, project or programme under consideration.

The difference between CBA and other forms of trade-off analysis in that the weights, which are placed on the quantities in the analysis, are inferred from observed data rather than assigned from the basis of priori judgments or moral principles. CBA can be utilised as a tool for negotiation between different stakeholders and allows for a systematic presentation of the impacts and valuation information (Eftec, 2006). CBA forms outcomes such as if the benefits outweigh costs and if an option is worth undertaking and which option offers the most benefits per unit costs in order to select which option among the competing alternatives is worth undertaking.

In some cases, ecosystem services are not traded in markets and no market price is available reflecting their economic value e.g. clean air and biodiversity (Eftec, 2006). These services are public goods that accrue to many people in which damages to the environment or impact on ecosystem services are difficult to measure. In this instance, there are a number of techniques to infer the value of ecosystem services that are not traded in markets described by Simpson and Vira (2010) as follows:

1. Revealed preference methods: rely on behaviour observations in related markets and include:

    a. Hedonic pricing: makes inferences in regard to the value of component attributes of the market good from the price of the good. Estimates the value of the non-market good by examining the relationship between the non-market good and demand for a market good (complementary) e.g. landscape amenity and air quality in the property market.

    b. Travel cost methods: examine people's desire to travel to a recreational or attractive landscape site and is assumed to be a function of ecological attributes of the site. For example, where an admission price is not charged, the willingness to pay (price) in terms of travel expenditure and time to visit the site is inferred.

    c. Production function approaches: these involve the treating of an ecosystem service as an unpriced input production processes e.g. land leading to the output of a marketed good or service e.g. products of agriculture. The price of the input is imputed from the contribution to the production of the marketed good.

2. Stated preference methods: involve the application of carefully constructed questionnaires in order to elicit an individual’s preferences for a given change in either a natural resource or environmental attribute even when they are neither consumed or used e.g. preservation of wild species. Methods may include contingent valuation and choice modelling.

The process to implement a CBA for a project for example was summarised by HM Treasury (2003) as follows:

1. Define the overall objective of the project, programme or policy.
2. Identify and define the baseline situation e.g. existing situation.
3. Identify and define the options.
4. Identify the costs and benefits that may arise over the lifetime of the project, programme or policy.
5. Quantify the costs of each option.
6. Quantify the benefits of each package.
7. After estimating all costs and benefits, aggregate and compare in order for estimation of net benefits for each option.
8. Conduct sensitivity analysis in order to assess the relative importance of key parameters.

In floodplains, CBA is commonly applied to certain aspects of floodplain management i.e. agricultural development, commercial fisheries and flood protection (RPA, 1998). The ability to derive robust monetary valuations for different uses in floodplains especially with non-use related ecosystem functions and services is varied and described in Table 4.6. Valuation of many ecosystem functions and services as in Table 4.6 requires application of some form of modelling (hydrological or economic) in order to allow links between the ability of a floodplain to provide a particular function and service and the changes in that ability following the adoption of alternative management options e.g. floodplain connectivity.

Table 4.7 provides further information on CBA methods, the total economic value element, examples of ecosystem services value, benefits of the valuation approaches and their limitations.

Table 4.6 CBA valuation of floodplain functions and services

Ecosystem		**Ease of valuation**	**Valuation issues**
Function	**Service**		
Regulation	Flood defence	Relatively straightforward in regard to protection of property based on market price data.	Role of floodplains in relation to flood embankments may not be clear.
	Water Supply	Valuation through effects on productivity and market price approaches where related to water supply.	Models required to link the impacts of different management options to resource requirements, changes in recharge may also impact on other functions/services.
Production	Agricultural productivity	Valuation though the effects on productivity approaches.	Impacts of general management activities may affect productivity e.g. sediment loss.
Habitat	Terrestrial	Indirectly through importance to direct uses of floodplains, valuation through the use of survey techniques.	Models required to link the impacts of the particular ecosystem to other uses; valuation of conservation and biodiversity functions is complicated by embedding and unfamiliarity issues.
	Fisheries	Valuation through effects on productivity approaches.	Bio economic model relationships required to link changes in management to productivity may not be available.
Information	Recreation	Valuation through Travel Cost Method.	Values are likely to be more robust where realistic payment vehicles can be defined e.g. entry fee.

Source: after RPA (1998, p. 21)

Table 4.7 Monetary valuation method choice

Valuation method	Element of TEV captured	Ecosystem service(s) valued	Benefits of approach	Limitations of approach
Market prices	Direct and indirect use	Those that contribute to marketed products e.g. timber and fish.	Market data readily available and robust.	Limited to those ecosystem services for which a market exists.
Cost based approaches	Direct and indirect use	Depends on the existence of relevant markets for the ecosystem service in question. e.g. man-made defences being used as proxy for wetlands and. storm protection.	Market data readily available and robust.	Can potentially overestimate actual value.
Production function approach	Indirect use	Environmental services that serve as an input to market products e.g. effects of air or water quantity and/or quality on agricultural productivity.	Market data readily available and robust.	Data-intensive and data on changes in services and the impact on production are often missing.
Hedonic pricing	Direct and indirect use	Ecosystem services that contribute to air quality, visual amenity, landscape, quiet i.e. attributes that can be appreciated by potential buyers.	Based on market data, so relatively robust figures.	Very data-intensive and limited mainly to services related to property.
Travel cost	Direct and indirect use	All ecosystems services that contribute to recreational activities.	Based on observed behaviour.	Generally limited to recreational benefits. Difficulties arise when trips are made to multiple destinations.
Contingent valuation	Use and Non-use	All ecosystem services.	Able to capture use and non-use values.	Bias in responses, resource-intensive method, hypothetical nature of the market.
Choice modelling	Use and Non-use	All ecosystem services.	Able to capture use and non-use values.	Similar to contingent valuation above.

Source: after Defra (2007a, p. 37)

In general, the limitations of applying CBA include data, expertise and time frame requirements (Eftec, 2006). These limitations specifically refer to the collection of available data, defining costs and benefits and to avoid double counting. The time frame for data collection, subsequent sensitivity analysis and discussion of impacts to the stakeholders can be very time consuming. Simpson and Vira (2010) identified a number of controversial issues in regard to implementation of CBA methods as follows:

- Measurement of non-marginal changes: prices are related to marginal well-being i.e. the improvement in welfare as a response to small change in the provision of an ecosystem service. CBA is largely applicable for consideration of large changes rather than trivial changes.
- Discounting: this refers to the assignment of a lower value to costs or benefits that would accrue in the future than would be assigned immediately. Arguments for the adoption of discounting include the following:

    - People have a preference for services sooner rather than later.

    - Capital is productive; the case of benefits forgone today for the increase in production in the next year will lead to an increase in future production over the current consumption is sacrificed.

    - People become wealthier with time. If the current investment will pay off in an increase in future consumption, it will be less valuable to wealthier future recipients than the today’s same quantity of consumption.

The research synthesis in regard to ecosystem assessment methods applied to floodplains (Table 1.2) described four CBA methods. Table 4.8 lists the CBA method applied with a brief description of method and study context, the ecosystem services assessed and the issues encountered for each respective research paper.

Table 4.8 Floodplain CBA ecosystem services assessment methods in research

Method	Ecosystem	Brief description	Issues	Source
▪ Household production function ▪ Contingent valuation	▪ Agricultural productivity ▪ Water storage	Economic analysis of groundwater recharge function from flooding derived for ecosystem services consumption benefits capturing direct and indirect use values.	▪ Competing uses of groundwater can have implications on the imputed value. ▪ Present values may be higher than reported. ▪ Present trend in groundwater abstraction for use may reveal bias.	Acharya (2000)
Cost based Household production	▪ Flood damage ▪ Agricultural productivity ▪ Transport ▪ Recreation ▪ Habitat	▪ Economic and financial costs of options e.g. dike-strengthening and land use change for protection of infrastructure, residential /industrial areas and damage to agricultural productivity as a result of flooding ▪ Direct and indirect use.	▪ Uncertainty in the exact size and value of predicted impacts from land use change over long periods. ▪ Highly sensitivity to assumptions made on costs and benefits especially over time.	Brouwer and Van Ek (2004)
Cost based	Agricultural productivity	Economic and financial benefits of river maintenance for flood alleviation and drainage benefits to agriculture.	Costs and benefits ▪ based on estimates ▪ specific for a given year not over time.	Dunderdale and Morris (1997)
Cost based	▪ Flood alleviation ▪ Agricultural productivity ▪ Habitat	Economic assessment of agri-environment schemes and flood management in floodplains.	Costs estimates require further information to provide more meaningful results.	Morris et al. (2008)
Cost based	▪ Agricultural productivity ▪ Financial return ▪ Transport ▪ Settlement	Assessment of floodplain ecosystem services with combined CBA and MCA methods i.e. indicators under land use scenarios.	▪ Cost based estimates with assumption basis implied Sensitivity to price fluctuations e.g. income. ▪ Prices reflect market conditions of a given year only not over time.	Posthumus et al. (2010)

Source: after Posthumus et al. (2010); Morris et al. (2008); Brouwer and Van Ek (2004); Acharya (2000); Dunderdale and Morris (1997).

Past studies described in Table 4.8 have been successfully applied to assess the economic impacts of problems and the effects of options. The advantages of the CBA methods are that they generally provide good estimates, reliable and repeatable and in some cases relatively easy to compute with information and readily available as of market prices e.g. agricultural production and flood defence to enable decision making process for a project e.g. options (Posthumus et al, 2010; Brouwer and van Ek, 2004). The common issues among the studies reviewed related to the application of costs , which were based on market prices for a given year only, and these values are less certain over time. Although the CBA methods applied were based on well-established methods and datasets, uncertainty in estimates is still the subject to variation in local conditions e.g. weather, floodplain management, floodplain connectivity (Posthumus et al., 2010).

4.4.2 **Multi-criteria analysis**

Multi-criteria analysis (MCA) is a term that covers a wide range of methods to assess decisions in the context of when there are multiple options that cannot be reduced to a single monetary measure (Simpson and Vira, 2010). In general, MCA methods as described by Eftec (2006) to involve the following processes:

(i) developing a set of criteria to compare options
(ii) evaluating the performance of each option against each criterion
(iii) weighting each criterion according to its relative importance
(iv) aggregating across options to produce an overall assessment

MCA has an early basis in economic utility theory with a utility defined as the satisfaction that is derived by an individual or group of individuals as of a particular situation from ecosystem services consumption (RPA, 1998). The level of satisfaction is expressed in terms of a relative ranking of preferred combination of the commodities rather than an absolute utility measure e.g. money. This is important for ecosystem services evaluation in regard to choosing options for floodplain management as it equates to the need for account of trade-offs between different ecosystem services or impacts in order to screen out the ‘worst’ options and possibly identify the ‘best’ or ‘preferred’ option (Simpson and Vira, 2010). Measures of options and/or impacts are in different units e.g. score and/or rank allowing for the examination of impacts separately in the first instance where values are incommensurable. Although, where a final weighting system is applied, the impacts may be commensurated via the weights placing emphasis on one set of criteria (Eftec, 2006).

There is a wide range of MCA methods to assess decision problems, which are characterised by a large number of diverse attributes that do not need to be expressed in monetary terms (RPA, 2004). These methods range from simple to complex techniques with the aim of providing a means for aggregating information into a single indicator describing relative importance. In addition, these methods can be classified in terms of three distinct characteristics as follows:

- Set of alternatives: this refers to discrete or continuous problems in terms of representation in a multi-dimensional space. Discrete problems involve a finite set of options i.e. flood management option from several options e.g. flood storage area, channel engineering, flood embankment. Continuous decision problems are characterised by non-exhaustive possible alternatives i.e. selection of design SOP for a flood embankments and crest elevation.

- Measurement scale: applying quantitative and/or qualitative attribute scales. Some MCA methods can be applied with mixed quantitative and qualitative information to assess decision problems

- Valuation function: this refers to quantitative scores that can be measured in a variety of measurement units. Scores can be made comparable by transformation into a common dimension or dimensionless unit. They may also be standardised with a value and/or utility measured on a physical measurement scale to a utility or value index.

The MCA methods described by RPA (2004; 1998) namely simple methods and complex methods with a brief description and issues are described in Tables 4.9-4.10.

Table 4.9 Simple MCA methods

Method	Description	Key Issues
Ranking	▪ The ordering of options or impacts into ranks utilising verbal or alphabetical or numerical scales. ▪ Provides an indication of relative performance. ▪ Value judgements (e.g. decision maker expert opinion) may be used to decide on preference order for the different options or impacts. ▪ Simple method to evaluate performance of different options over a range of criteria.	▪ When applied on their own, they provide little information on the magnitude of any differences in impact between the options. ▪ They may hide uncertainty that may exist in regard to extent the of such differences. ▪ Where there are several options under consideration, difficultly may occur in selecting a preferred option. ▪ Tendency to add ranks which is mathematically invalid unless decision makers place an equal value on impacts falling under the various criteria and all trend scores or ranks will reflect proportional changes in the impact level. If this is the case, descriptive information must be provided to paint an accurate picture of implications associated with alternative options e.g. flood embankments.
Pairwise comparison	▪ The listing of the criteria and comparison of options in pairs against these criteria to indicate a preference of one option over another. ▪ Results presented in a table to identify overall preferences to highlight trade-offs in selection of one option over another. ▪ Decision makers make a judgment of the relative importance to be assigned to the different criteria and then determine the best option.	▪ No attempt made for incorporation of the relative importance of different magnitudes of impacts or of the different criteria. ▪ Increasing complexity with undertaking comparisons and to ensure consistency as numbers of criteria and the options increase. ▪ Requires use of a sophisticated mathematical approach e.g. AHP, where the numbers of criteria and options increases to effectively achieve assessment.

Source: after RPA (2004, p. 1).

Table 4.10 Complex MCA methods

Method	**Description**	**Key Issues**
Weighed summation	▪ Simplest form of multi-attribute utility analysis. ▪ Applies a linear relationship involving standardizing the scores across all criteria, assignment of preference weights which are multiplied by scores and added to give final scores. This provides the total weighted score for each option to determine the rank of the total weighed scores. ▪ The method requires quantitative information on scores and priorities and only relative values are used in the assessment. ▪ Provides complete ranking of options and information on the relative differences between the options.	▪ Difficulty in choosing a good standardization method and the attribution of weights. ▪ If the range of scores is large or if the scores are in a range where the value is sensitive to changes, expert judgment needs to be applied to determine the shape of the value function. ▪ Less suitable method for the application of qualitative information although a well chosen standardization method with an underlying quantitative scales may be applied for weighted summation of scores.
Ideal point method	▪ Ranks the options in terms of the magnitude to achieve an ideal situation or prescribed target e.g. distance from the target outcome. ▪ An ideal level of impact must be assumed for the criteria of concern and the decision maker's utility decreases, moving away in either direction from this level. ▪ Options which are closer to the ideal are preferred to those which are further away. ▪ A scaling coefficient is applied to allow for inclusion of the relationship between the relative size of the effect and weight into a decision rule. ▪ Provides complete ranking of options and also information on the relative distance of each from an ideal solution.	
Evaluation by graphics	▪ A graphical interface on computerised models can facilitate the development and analysis of a decision problem with the use of multi-criteria analysis. ▪ Enables the analyst and/or decision makers to easily see the relative performance of options under the different weighting systems e.g. GIS software tools to assess geographical variation of risk management options.	

Method	Description	Key Issues
Outranking methods	▪ Various Electre methods i.e. concordance analyses are important to represent the class of outranking methods and widely used. ▪ They translate the criterion scores to an outranking relationship and then this relationship is analysed. ▪ Electre II for example is based on pairwise comparison of the alternative options and only uses the interval character of the scores for the evaluation of the effects table. The degree to which the scores and their associated weights either confirm or contradict the dominant pairwise relationship amongst the alternatives is measured. ▪ In this method, a dominant relationship of each alternatives pair is derived using two indices i.e. one for concordance and the other indicating discordance. ▪ Thresholds which are supplied by a decision-maker and combination of the concordance and discordance tables are applied to establish a weak and strong outranking relationship between each pair of alternatives. ▪ This method involves a stepwise elimination procedure to transform the weak and the strong graph which represent these outranking relationships into the overall ranking of alternatives.	▪ Training to apply this method is required due to interaction with decision makers, which can be a complicated task. ▪ Results are very sensitive to the threshold levels used to define the concordance and discordance relationships. ▪ The settings of threshold levels are not always transparent due to complex interactions between the analyst and the decision-maker to define the levels. ▪ Difficulty in trying to understand the role of various thresholds to determine the end ranking of options and the interpretation of weights which are assigned to different criteria. ▪ The procedure to generate final ranking may not always provide a complete ranking of the alternative options as some options cannot be ranked or two partial rankings may be produced. ▪ The method complexity makes it less transparent to communicate the results and less suitable for the purposes of flood defence appraisal for example.
Analytical hierarchy process (AHP)	▪ Pairwise comparisons form the basis for the AHP. ▪ Structures the decision problem into levels, which corresponds to the decision maker's goals, criteria and sub-criteria, options and understanding of the situation. This enables the decision maker to focus on a smaller set of decisions. ▪ The main aim is to derive quantitative scores and weights from qualitative statements in regard to the relative performance of the alternatives and relative importance of the criteria which is obtained through the comparison of all the pairs of the alternatives and criteria. ▪ An approximation of the weights must be generated making optimal use of information from decision makers available for the comparison matrix. ▪ This method is used to assess the relative criteria weights and assess the performance of the options through pairwise comparison. The pairwise comparison table of results are translated to weights and scores using the Eigen values of these tables.	▪ The AHP is widely used in many applications yet controversy surrounds the theoretical basis of the method. ▪ Although the method is easy to apply, the procedures for the processing of information obtained from decision makers is less transparent and less suitable for a situation with multiple stakeholders. ▪ An exception method involving group decisions by multiple stakeholder's negotiation and their position improves transparency. ▪ The number of pairwise comparisons can increase rapidly with increasing criteria and therefore a hierarchal structure for the criteria, goals and sub-goals provides a better option. ▪ Situations were decisions have ordinal information available is rare requiring the use of alternative methods e.g. permutation, regime method or evamix method to deal with mixed information. In this instance, the method becomes complicated and less transparent leading to the ambiguous interpretation of the results.

Method	Description	Key Issues
Regime method	▪ This method is based on pairwise comparison of the alternatives. ▪ All pairs of alternatives are compared for each criterion e.g. best alternative +1, Worst -1 and if the same, a 0 score. These scores are then combined with quantitative information on the weights that are attached to the criteria for determination of which of the two alternatives is preferred taking all criteria simultaneously into account. ▪ If quantitative weights are available, the method is straightforward, but were not available, qualitative weights are interpreted as unknown quantitative weights. This will involve defining sets of quantitative weights that conform to qualitative priority information. The distribution of weights is assumed to be uniform, therefore the relative size of the subsets are interpreted as probabilities which can then be aggregated to produce an overall ranking of the alternatives.	
Permutation method	▪ This method derives the alternative that is most in harmony with the ordinal information contained in the effects table of all possible ranking orders of the alternatives. ▪ Each permutation is numbered and ranked against ordinal information. Rank correlation coefficients are then used to calculate the statistical correlation between the rank order and the effects table. The weighed sums of the rank correlation coefficients are then used for the determination of the most attractive of the total permutations.	
Evamix method	▪ Designed to deal with the effects table containing qualitative and quantitative criteria. ▪ In the effects table, a set of criteria is divided into a set of ordinal criteria and as a set of quantitative criteria, with both sets, the dominance criteria are calculated. ▪ A total dominance score is derived by combining the indices and calculating separately for the quantitative and qualitative scores with both indices standardised in the first instance ▪ The total dominance score is effectively calculated as the weighted sum of the quantitative and qualitative dominance scores.	

Source: after RPA (2004, p. 12 -17)

Table 4.11 summaries the key characteristics of the MCA methods specifically describing the key components of when to consider the application of an MCA method.

Table 4.11 Multi-Criteria Analysis methods and characteristics

Method	Information	Result	Transparency	Computation
Weighed summation	Quantitative	Performance scores/ranking	High	Simple
Ideal point method	Quantitative	Distance to target/ranking	Medium	Simple
Evaluation by Graphics	Qualitative, Quantitative and Mixed	Visual presentation	High	Simple
Outranking methods	Quantitative	Ranking/incomplete ranking	Low	Very complex
Analytical Hierarchy process (AHP)	Qualitative	Performance scores/ranking	Low	Complex
Regime	Qualitative, Quantitative and Mixed	Ranking/probability	Low	Very complex
Permutation	Qualitative	Ranking	Low	Very complex
Evamix	Mixed	Ranking	Low	Simple

Source: after RPA (2004, p. 9)

The principal outputs of MCA are weighted scores for different options either individually or over a group. The advantages of applying MCA methods in general is that they provide clear outputs either as scores or graphical outputs, the outputs are relatively transparent i.e. easy to see the consequences of a given impact for alternative options and the computation required is relative simply (Eftec, 2006)

Limitations involve some methods being process complex and can lack transparency, while the scoring with numerical or ordinal measurements can be relatively subjective (RPA, 2004). Other limitations refer to weighting of options which are usually relative rather than absolute with difficulty to maintain consistency between decisions and groups of judges.

The research synthesis in regard to ecosystem assessment methods applied to floodplains (Table 1.2) described three MCA methods applied. Table 4.12 describes the MCA method applied with a brief description of method and study context, the ecosystem services assessed and the issues encountered for each respective research paper.

Table 4.12 Floodplain MCA ecosystem services assessment methods in research

Method	Ecosystem	Brief description	Issues	Source
Weighed summation	Flood defence	Hydrological indicators applied for flood hazard/damage assessment of embankment scenarios.	No measure of absolute risk, damage of casualty values only hazard class based on an ordinal scale.	Alkema and Middelkoop (2005)
Weighed summation	▪ Flood defence ▪ Agricultural productivity ▪ Transport ▪ Recreation ▪ Habitat	Ecological and economic criteria to ranking scores of options e.g. dike-strengthening and land use change Direct and indirect use.	Sensitive to inclusion of qualitative scores e.g. social impacts of land use change - stakeholder influence bias.	Brouwer and Van Ek (2004)
Weighed summation	▪ Employment ▪ Soil quality ▪ Floodwater storage ▪ Water quality ▪ Greenhouse gas balance ▪ Habitat provision ▪ Wildlife ▪ Space for water, ▪ Recreation ▪ Landscape	Assessment of floodplain ecosystem services with combined CBA and MCA methods i.e. indicators under land use scenarios.	▪ Limited empirical research basis. ▪ High degree of uncertainty ▪ Value subject to assumptions.	Posthumus et al. (2010)

The MCA methods applied in research for floodplains (Table 4.12) although not directly stated had a basis in weighed summation MCA methods. It is important to note that all of these studies either applied hydrological based models and/or data as quantitative indicators to value impacts for the respective ecosystem services against alternative options e.g. floodplain connectivity and/or floodplain land use management. Posthumus et al., (2010) and Alkema and Middelkoop, (2005) discussed that the common issues in regard to applying MCA methods were in regard to uncertainty of estimates from indicators through the assumptions made in regard to understanding the system, limited empirical research with estimates providing relative rather than absolute values. The qualitative scores applied by Brouwer and van Ek, (2000) e.g. social impacts were found to be very sensitive with issues largely related to weights attached as derived from stakeholder response.

4.4.3 **Research ecosystem services assessment method selection**

The preceding sections provided descriptions of decision support systems i.e. CBA and/or MCA methods including the advantages and disadvantages of their implementation. Both these methods allow for the comparison of options by assessing the impact of ecosystem services delivery based on an option e.g. management scenario. Brouwer et al. (2004) discussed that the choice of either use of CBA or MCA as part of an integrated assessment depends on a number of factors e.g. evaluation criteria for the specific problem and available information about the expected effects of alternative options e.g. solutions (quantitative or qualitative, in monetary terms of otherwise). The nature of an assessment will also depend on available time, financial resources and information. Brouwer and van Ek (2004) also discussed that the application of both methods is rare in a water related context although Posthumus et al. (2010) has applied both methods to assess the impacts of hydrological management options in floodplains.

Monetary valuation techniques are widely used approaches to assess ecosystem services especially CBA considering multiple ecosystem services (Ansink et al., 2008; Posthumus et al., 2010). The application of attaching a monetary value to ecosystem services can facilitate this value as a public good and can be instrumental to support decision-making (Soma, 2006; Turner et al., 2003). Yet, not all ecosystem services are captured in commercial markets or quantified adequately in terms that are comparable with economic services or manufactured capital e.g. habitat and information ecosystem functions (Costanza et al., 1997). In floodplains, habitat and information ecosystem functions tend to be associated as both non-market and partial/gleaned market goods with objective values difficult to derive (Posthumus et al., 2010; Defra, 2007a). Monetisation of ecosystem services can generate massive uncertainties in ecosystem service values largely generated through manipulation of markets as a function of an institution or individual’s notion of property, ownership and rationality (Gómez-Baggethun et al., 2010). The adoption of CBA methods which apply revealed and stated preference methods for non-market goods e.g. habitat and information can suffer from complexities in application; data intensive, bias in responses in regard to rationality e.g. institutional structures having the ability to modify behaviour patterns and motivations. (Eftec, 2006). Economists frequently argue that the failure to place a monetary value on wider ecosystem functions and services, which are provided by floodplains, may lead to benefits being ignored and thus leading to conversion for other uses and/or overexploitation in general (RPA, 1998).

This research will adopt an MCA approach in order to assess the impacts of floodplain connectivity on ecosystem services delivery for the following reasons. Prato and Herath (2007) discussed that MCA rather than CBA methods are more appropriate to assess the impacts of alternative management systems in consideration of landowner preferences i.e. weights and also superior for the following reasons:

- Recognizes within a catchment that human activities are motivated by multiple and competing criteria and/or constraints.
- Monetary valuation of criteria is not required.
- Allows trade-offs between criteria to be measured and assessed.
- Comprehensive, knowledge based and stakeholder orientated which will aid to increase the likelihood to resolve catchment problems.
- Allows the consideration of objective and sustainable land and water resource management decisions.

Several authors have successfully applied MCA methods using observed and modelled hydrological (quantitative) data to assess the impacts of alternative options on ecosystem services (Posthumus et al., 2010; Alkema and Middelkoop, 2005; Brouwer and van Ek, 2004). Initially the 'ranking' method as recommended by RPA (2004) for flood management will be applied as it's the most appropriate method in the context of this research and also simple to apply, retains a high level of transparency and has a low cost.

Posthumus et al. (2010) discussed that the critical aspect of assessing ecosystem services in floodplains is the identification of the most appropriate set of indicators. Both Simpson and Vira (2010) and Posthumus et al. (2010) described that the indicators must be:

- Sensitive to relevant changes in the ecosystem service.
- Objectively verifiable, generating results, which are repeatable by others.
- Practical in regard to convenience, easiness of estimation and easily understood
- Reliable in most conditions i.e. little interference from other factors with an acceptable degree of uncertainty.
- Suitable for aggregation and disaggregation in regard to boundaries and space or time.
- Usable for future scenario projections i.e. quantifiable cause effect relationships and projected forward for alternative options and scenario analysis.
- Sets of indicators: no single indicator will provide information on a relevant option changes. Assessment of an ecosystem service ideally will have a relatively small number of individual representative indicators which lowers costs and easier to communicate outcomes of options to the wider community. However, the set of indicators should not be too small or simple as to ignore the important aspects of the impacts/options being assessed.

Modelled data outputs generated by the lateral and vertical connectivity models also meet the criteria as stated above in order to generate suitable and appropriate hydrological based ecosystem services indicators. The application of appropriate and suitable ecosystem services indicators is in continual development with mainly production and regulation ecosystem functions benefiting from well-established methods and data sets (Posthumus et al., 2010). Although the application of hydrological indicators for other ecosystem functions e.g. habitat and information are proving more challenging due to the limited understanding of the hydrological processes by which the values are formed, lack of methods and data to support floodplain management.

A methodology will be developed using initially modelled data from the integrated modelling system to develop hydrological based indicators as they met the criteria as described by Simpson and Vira (2010) and Posthumus et al. (2010). The assessment of ecosystem services is quite complex but the thresholds of scientific information, standards and verification have yet to be met for integration into policies and legislation (Cox and Searle, 2009). Further developing methodologies especially of indicators while challenging is necessary in order to take the ecosystem approach forward (Posthumus et al., 2010). Assessing impacts of ecosystem services from alternative floodplain connectivity options utilising an MCA method will allow for greater understanding, interpretation and transparency to communicate the impacts on ecosystem services, synergies and trade-offs (RPA, 2004; Alkema and Middelkoop, 2005).

5 CASE STUDY SITE

5.1 Introduction

The case study site was described in two ways i.e. the case study and the field study site. The following section will describe the choice and selection of the case study site along with the methods to describe the site characteristics.

5.2 Methodology and discussion

5.2.1 **Case study site selection**

The case study site (NGR, TL15444 52643) was located on the River Ivel between Blunham and the confluence with the River Great Ouse at Tempsford, Bedfordshire, United Kingdom (Figure 5.1).

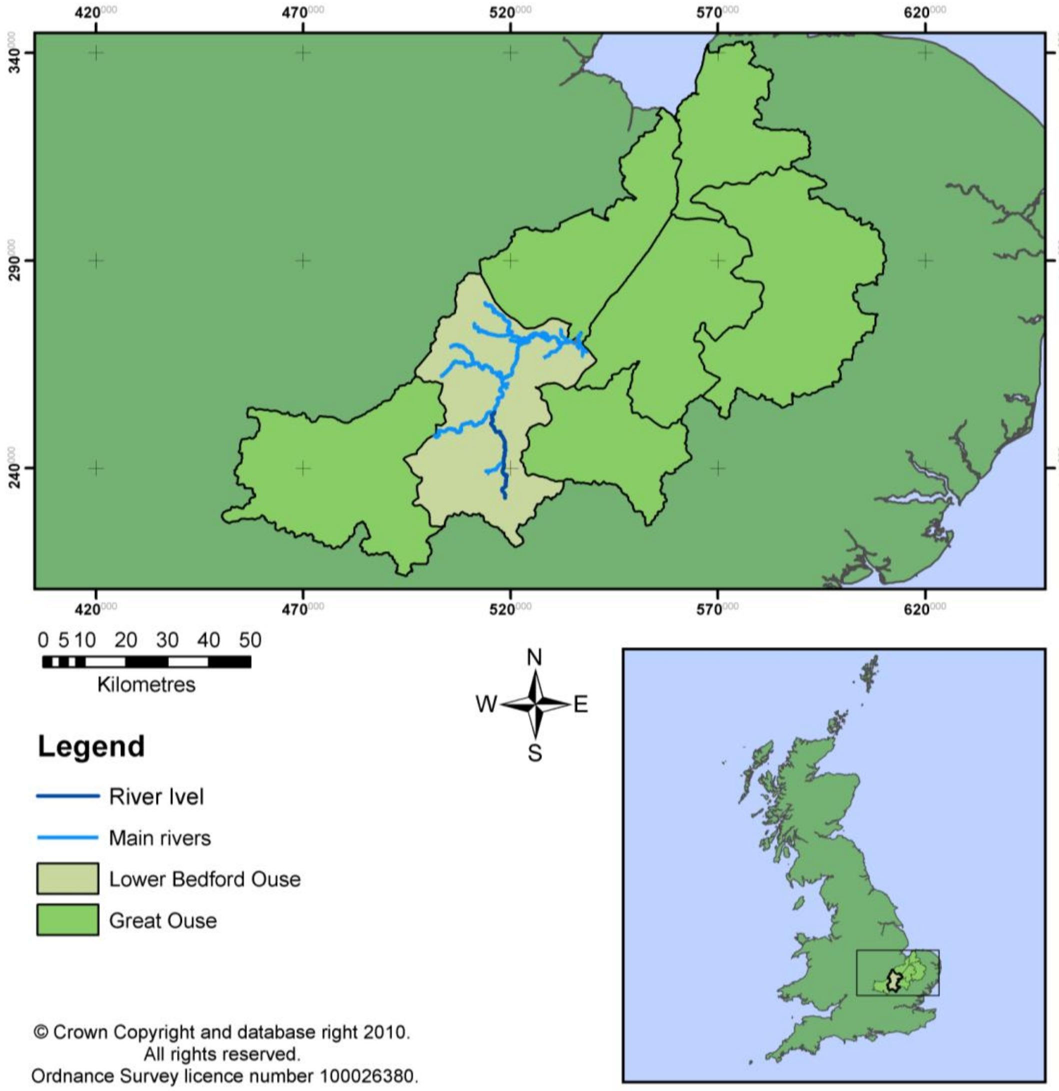

Figure 5.1 Case study site location

The case study floodplain refers to the model boundary for the linked ISIS 1D-2D model and the field study site refers to the model boundary for the WaSim model boundary. The River Ivel is one of the main tributaries of the River Great Ouse located in the Lower Bedford Ouse, which is a sub catchment of the River Great Ouse. The selection of the case study site on the River Ivel was based on the location of earth embankments and surface drains representing opportunities to study the existing and alternative floodplain connectivity options for floodplain management to enhance ecosystem service delivery.

Floodplain connectivity features were identified on the River Ivel in order to study the impacts upon ecosystem services delivery. Ordnance Survey maps (OS, 2009a, 2009b) and surface drain maps from Bedford Group Internal Drainage Board (Bob Spendlove, Pers. Coms, 15 August 2010) were analysed to identify surface field drains along the River Ivel. The embankments were analysed to identify a specific location for the case study site. Earth embankments were identified as they have the potential to act as hydraulic controls to flooding. These can be formed from natural deposition processes as a result of historic flooding or constructed through the placement of river dredging for example (Charlton, 2007; Tom Flint, Environment Agency, Pers Coms, 20 September 2010). They also allow uncontrolled inflow and uncontrolled gravity return flow as a function of the rising and falling river stage (Morris et al., 2004). A series of earth embankments on the River Ivel are only located between Blunham and the confluence of the River Great Ouse with a 10% AEP standard of protection as identified for 'raised defences' asset type using the National Flood and Coastal Defence Database (NFCDD) to identify potential locations (Figure 5.2). In addition, the embankments at this location are placed at different sections on the River Ivel with the remaining river sections containing natural embankments representing varied existing lateral connectivity and hydraulic controls (Figure 5.2). More importantly, this section of the River Ivel also contains embankments with irregular bankside elevations as a result of natural accretion from historic flooding and also placement from river dredging known as 'scradge' banks as advised by Tom Flint, Environment Agency, Pers Coms (20 September 2010) and based on a field walk over survey.

The boundary of the case study floodplain was defined by the flood zone 2 i.e. 1% AEP flood event extent for the River Ivel and floodplain between Blunham and Tempsford villages. Flood zone 2 was selected as it is the maximum flood defence standard of protection present on rivers within the Lower Bedford Ouse sub catchment (EA, 2010c). The length of the case study site was based on the length of the river between

Blunham village and the confluence of the River Great Ouse marking the end of the River Ivel. The width of the case study site was extended slightly beyond the 1% AEP flood event extent for this section of the River Ivel for modelling purposes as the flood zone 2 extent was based on modelled outputs for flood risk assessments conducted for the Environment Agency (Figure 5.2).

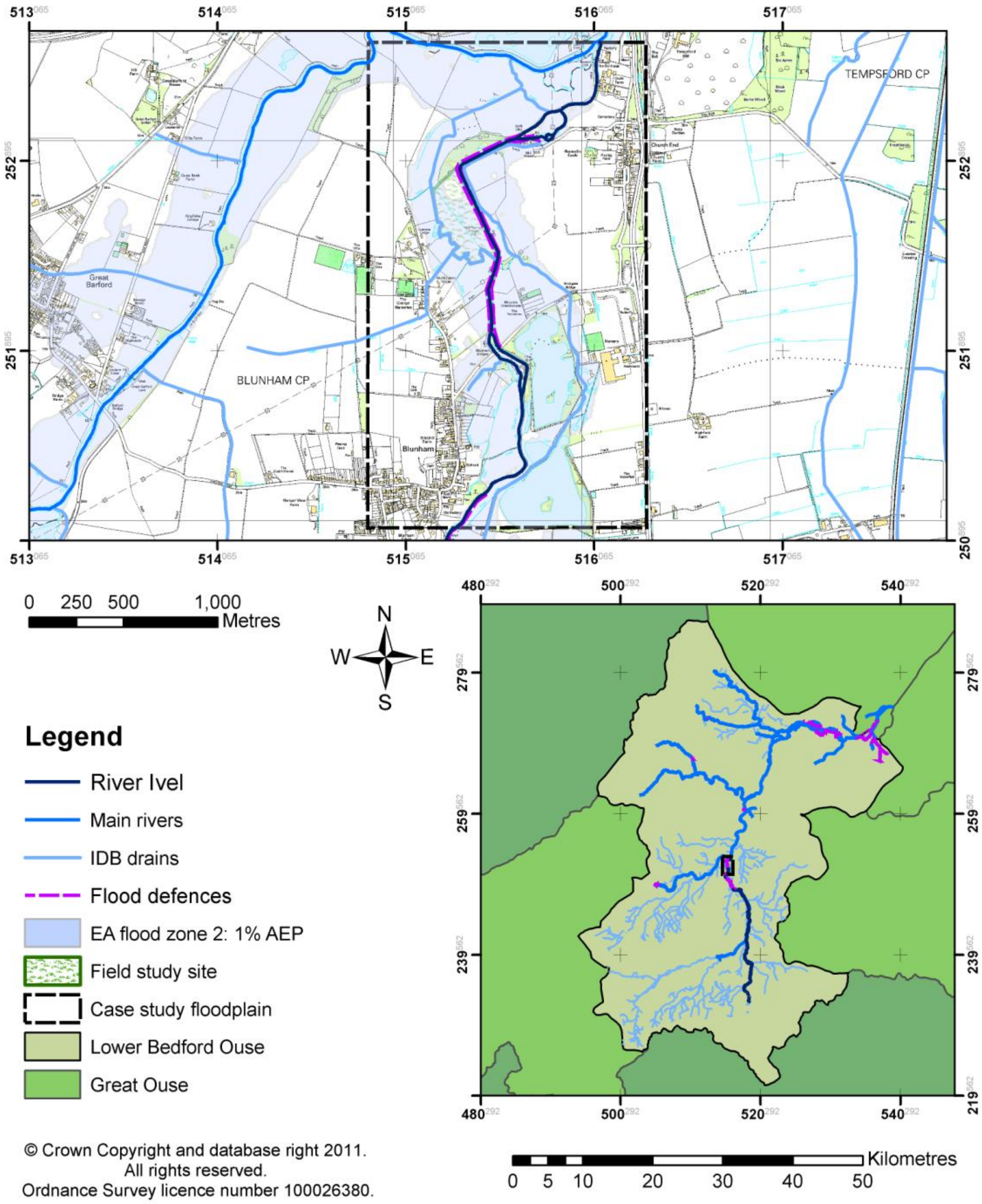

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Figure 5.2 Case study floodplain and field study site

The field study site (Figures 5.3-5.8) was located within the case study floodplain at NGR (TL15444 52643), 800 m east of Tempsford (Figure 5.2). This site was selected as it was located proximate to the earth embankments in the case study floodplain and also contained examples of surface drains (Figure 5.2)

Figure 5.3 River Ivel: facing upstream of field study site

Figure 5.4 Field study site: River Ivel, west embankment and west side floodplain facing downstream

Figure 5.5 Field study site: River Ivel, west and east embankments facing downstream

Figure 5.6 Field study site: west side floodplain facing downstream

Figure 5.7 Field study site: River Ivel, west and east embankments facing upstream

Figure 5.8 Field study site: east side floodplain facing downstream

The images of the field study site (Figures 5.3-5.8) provide an indication of the level of lateral connectivity imposing a hydraulic control upon the river channel discharge into the floodplain. In addition, it is clear from the images that the floodplain is quite flat displaying minimal variation in topographic elevation across the floodplain.

5.2.2 **Case study floodplain and field site characterization**

A set of criteria (Table 5.1) were applied as per Gordon et al. (2004) in order to characterize the case study floodplain and the field study site which form the model boundaries for the linked ISIS 1D-2D model and the WaSim model. Where appropriate, the impacts of the site characteristics upon ecosystems services delivery are discussed for the case study floodplain and field study site. The criteria were divided into hydrology/morphology, hydrogeology and ecosystem services with sub criteria to characterize both the case study floodplain and field study site. In Table 5.1, the hydrological flows and systems are listed and the types of methods applied for each criterion. Finally, the data source from where the information was collated is listed.

Figure 5.9 displays a conceptual diagram of the hydrological transfer flows and the hydrogeological matrix drawn to scale for the case study floodplain and field study site. The surveyed IV-01574 cross section on the River Ivel study reach (TL15469 52517) was utilised as the nearest surveyed cross section located 37 m northeast from TEM 1 dipwell. The ground surface elevation, superficial thickness and bedrock at the western boundary of the field study site was derived from British Geological Survey borehole records for TL15SE21 (Table 5.6 and Figure 5.12) for the case study site (BGS, 2014). The superficial thickness at the dipwells was based on the vertical soil profile and soil texture field assessments (Section 5.2.2.2). The water table level was conceptualised based on manual dipwell measurements and the derived river stage level for the 11/05/2011 coinciding with automated level logger field calibration.

Table 5.1 Case study site characterisation criteria, dominant water transfer flows, methods and information sources

	Criteria	Hydrological systems and transfer flows	Method				Data source
			Literature review	Map Analysis	Field Work	Laboratory analysis	
1	Hydrology/Morphology	Surface					
1.1	Drainage area	▪ Overland flow ▪ Channel discharge	✓	✓	✗	✗	River Great Ouse Catchment Flood Management Plan (EA, 2010c)
1.2	Drainage density	▪ Overland flow ▪ Channel discharge	✗	✓	✗	✗	Ordnance Survey (2009a,b)
1.3	Main watercourse length and slope	▪ Channel discharge ▪ Seepage	✗	✓	✗	✗	Ordnance Survey (2009a,b)
1.4	Floodplain connectivity	▪ Overbank flow ▪ Overland flow ▪ Channel discharge ▪ Evapotranspiration ▪ Surface runoff ▪ Groundwater recharge	✗	✓	✗	✗	▪ NFCDD ▪ EA (2010c) ▪ Ordnance Survey (2009a,b)
2	Hydrogeology	Sub-surface					
2.1	Soil	▪ Infiltration ▪ Evapotranspiration	✗	✓	✓	✓	NSRI (2012)
2.2	Superficial deposits	▪ Infiltration ▪ Groundwater recharge ▪ Seepage	✗	✓	✗	✗	British Geological Survey (2003)
2.3	Bedrock	▪ Groundwater recharge ▪ Seepage	✗	✓	✗	✗	
3	Ecosystem services	Surface and sub-surface					
		NA	✓	✓	✓	✗	▪ River Great Ouse CFMP (EA, 2010c) ▪ Ordnance Survey (2009a,b) ▪ Defra (2012)

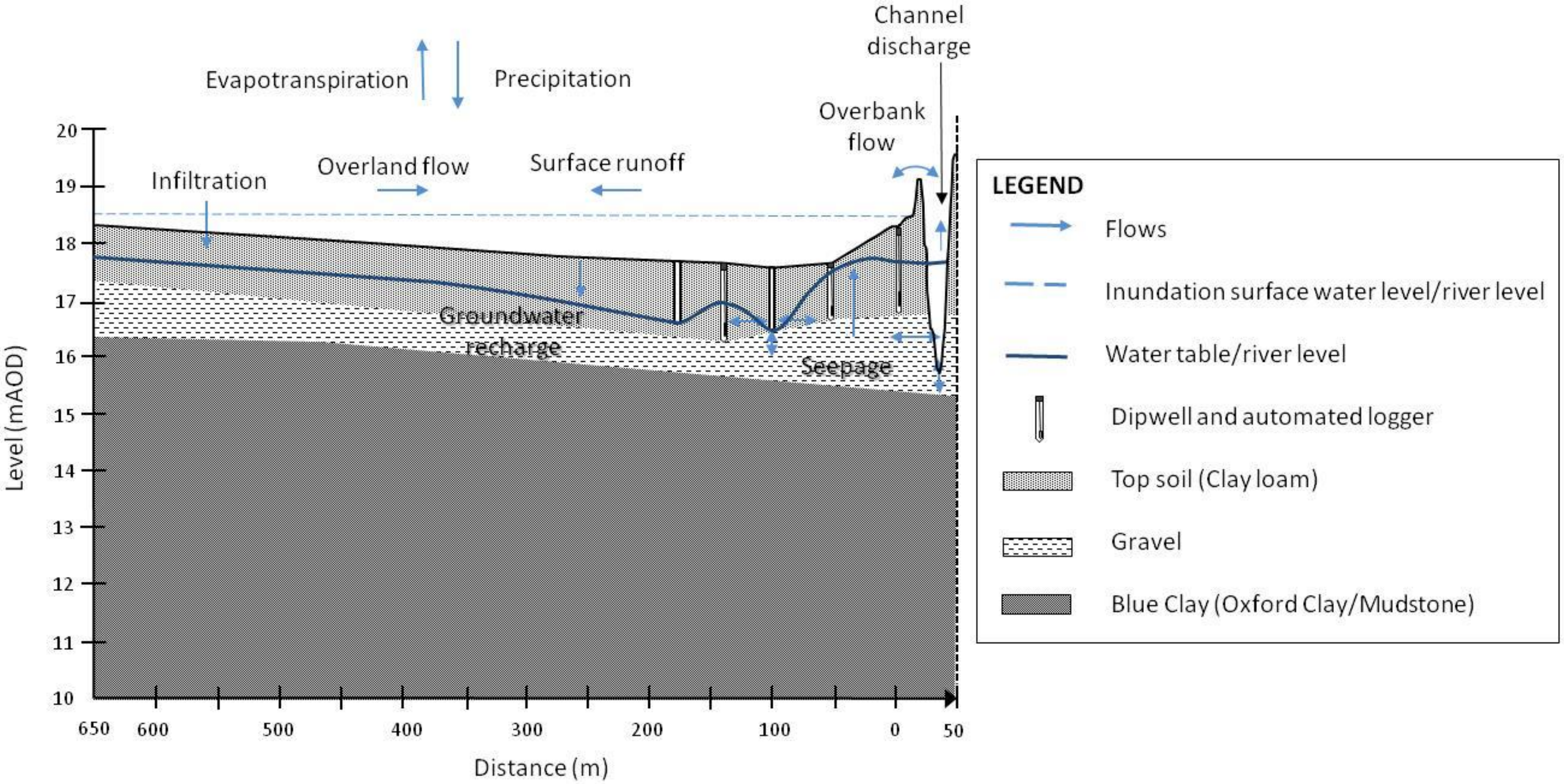

Figure 5.9 Conceptual diagram of floodplain and river hydrological transfer flows and hydrogeology at the case study site

5.2.2.1 **Hydrology/Morphology**

A number of sub criteria were identified to aid in describing the hydrology of the site namely the drainage area, drainage density, mean watercourse length and slope and the hydrological connectivity. The hydrology/morphology criteria are based on the drainage basin characteristics. These criteria will enable further understanding to the prediction of flood patterns and dominant hydrological flows, which influence the hydrology and morphology characteristics of rivers and floodplains. For the case study floodplain, large-scale features such as the drainage area and density and also small-scale features such as the channel length and slope were measured.

The drainage area is an important descriptor in terms of hydrology as it represents the area that can influence the number and size of watercourses (Leopold et al., 1964). This sub criterion was assessed by two desktop methods, sourcing information from the River Great Ouse Catchment Flood Management Plan (EA, 2010c) and interrogating features from Ordnance Survey maps of the case study site at 1:50,000 scale (OS, 2009a,b). The drainage area of the case study site is 365 ha based on the boundary area (Figure 5.2) that represents only a small fraction of the River Ivel drainage area at 54,069 ha. The case study site contains only the main river i.e. River Ivel with no tributaries present (OS, 2009a,b). As the case study site consists of a small reach and its floodplain, the contribution of precipitation in this area would potentially be small which would have minimal impact on overland flow and infiltration.

The ground elevation for the case study site ranged from 14.69-34.54 mAOD as displayed in Figure 5.10 (EA, 2011; OS, 2009a,b). The highest elevation was observed in the south west at Blunham Village while the lowest elevation was observed northeast near the confluence of River Ivel and River Great Ouse in the case study floodplain (Figure 5.10). The average elevation in the case study floodplain was calculated as 19.75 mAOD, which has a minimum variation in the majority of the case study floodplain and especially at the field study site (Figure 5.10).

Taking a cross section of the floodplain from TL15SE21 to TEM 1 dipwell and the River Ivel study reach (Figure 5.12), there is a small slope present from the borehole site towards the river embankments (Figure 5.10). The elevation drops from 18.29-17.72 mAOD from the western boundary of the field study site towards dipwell 2 and rises to 18.29 mAOD at the TEM 1 dipwell proximate to the river embankment. Overland flow as a result of precipitation will increase towards the surface drains and the river embankment and potentially collect behind the embankment until overbank flow is possible from the floodplain to the river. The slope in the floodplain resembles a concave shape, which will cause deeper ponding of water as a result of overland flow from precipitation in the floodplain and overbank flow through channel discharge from the river to the floodplain.

The case study site is located in a rural area with the land cover vegetated by sparse trees and bushes yet mainly grass cover (Figure 5.2-5.8). The roughness of the case study site is likely to have minimal impact on the velocity of overland flow or surface runoff. The loss of water through evapotranspiration will occur as the ground cover is vegetated. Open water evaporation (Figure 5.9) is likely to influence the partial removal of water to reduce the extent, depth of open water in the floodplain and channel discharge in the river. The drainage density (R_D) is an important indicator of surface runoff and reflects the climate, geology, soils and vegetation cover within a catchment (Gordon et al., 2004). High drainage density indicates a denser network of watercourses with shorter river lengths and steep valley sides creating greater surface runoff hence river discharge and potentially larger floods.

The drainage density was calculated by using Equation 5.1 (Leopold et al, 1964). The drainage area and river length were extracted from Ordnance Survey maps (OS, 2009a,b)

$$R_D = \frac{\sum L}{A} \qquad \textbf{5.1}$$

where:
R_D = Drainage density (km.km^{-2})
L = Stream length (km)
A = Catchment area (km^2)

The River Ivel is 38 km in length and is one of three main tributaries of the River Great Ouse and has two tributaries namely the River Flit and Hiz located in the mid section of the River Ivel (EA, 2010c). The River Ivel study reach is 3.36 km, located at the downstream section of the River Ivel, and has no tributaries. The drainage density was calculated as 0.92 km.km^{-2} representing the amount of river channel that is required to drain a unit of drainage area. This value is quite high as the density is constrained by the case study site drainage area/boundary but serves as an example of the drainage density at reach scale. The larger the drainage network in terms of channels within a drainage basin equates to a greater drainage density. The River Ivel catchment has only two smaller tributaries draining into the main river over a large catchment area (54,069 ha), (Figure 5.2) and resembles a drainage area of low density. In the wider catchment, this indicates that overland flow would be low hence lower river discharges and less flooding.

The mean watercourse slope is an indicator of timing in response of peak discharges with steeper slopes producing greater peak discharges hence higher magnitudes of flooding (Gordon et al., 2004). The main watercourse slope was calculated using Equation 5.2, which was adapted by considering the upstream and downstream bed elevation of the study reach rather than the total length of the River Ivel.

$$S_c = \frac{(U/S - D/S)}{L} \qquad \textbf{5.2}$$

where:
S_c = Main watercourse slope (m.m^{-1})
U/S = Upstream elevation (m)
D/S = Downstream elevation (m)
L = Stream length (m)

Source: after Gordon et al. (2004, p. 64)

The upstream and downstream bed elevations of the River Ivel study reach were derived by calculation of the minimum bed elevation of IV-03418 and IV-00052 cross sections from channel surveys in the case study site (Table 5.2).

Table 5.2 River Ivel study reach upstream and downstream cross section bed elevations

Reach cross sections	IV-03418	IV-00052
Bed Elevation (mAOD)	17.52	14.16

The mean watercourse slope was calculated as 0.0009 m.m^{-1} indicating that this section of the River Ivel would have a slower prolonged hydrograph response in regard to river discharge.

Floodplain connectivity is an important indicator of the hydrological process that occur in riverine floodplains. Two types of floodplain connectivity as displayed in Figure 5.10 were identified for the case study site as follows:

1. Lateral connectivity, which links a river with the floodplain at the ground surface e.g. embankments.
2. Vertical connectivity, which links the floodplain surface and subsurface e.g. surface drains.

The River Ivel study reach was observed to have mainly irregular lateral connectivity earth embankments across 3.36 km of case study site. A 10% AEP standard of protection uniform structural earth embankment is present for 1.7 km on each bank side of the River Ivel study reach extending from the field study site to the confluence of the River Great Ouse based on map analysis from the NFCDD (Figure 5.10). This would contribute to impeding overland flow and overbank flow from the floodplain to the river and channel discharge and overbank flow from the river to the floodplain based on the 10% AEP SoP embankment present at the case study floodplain.

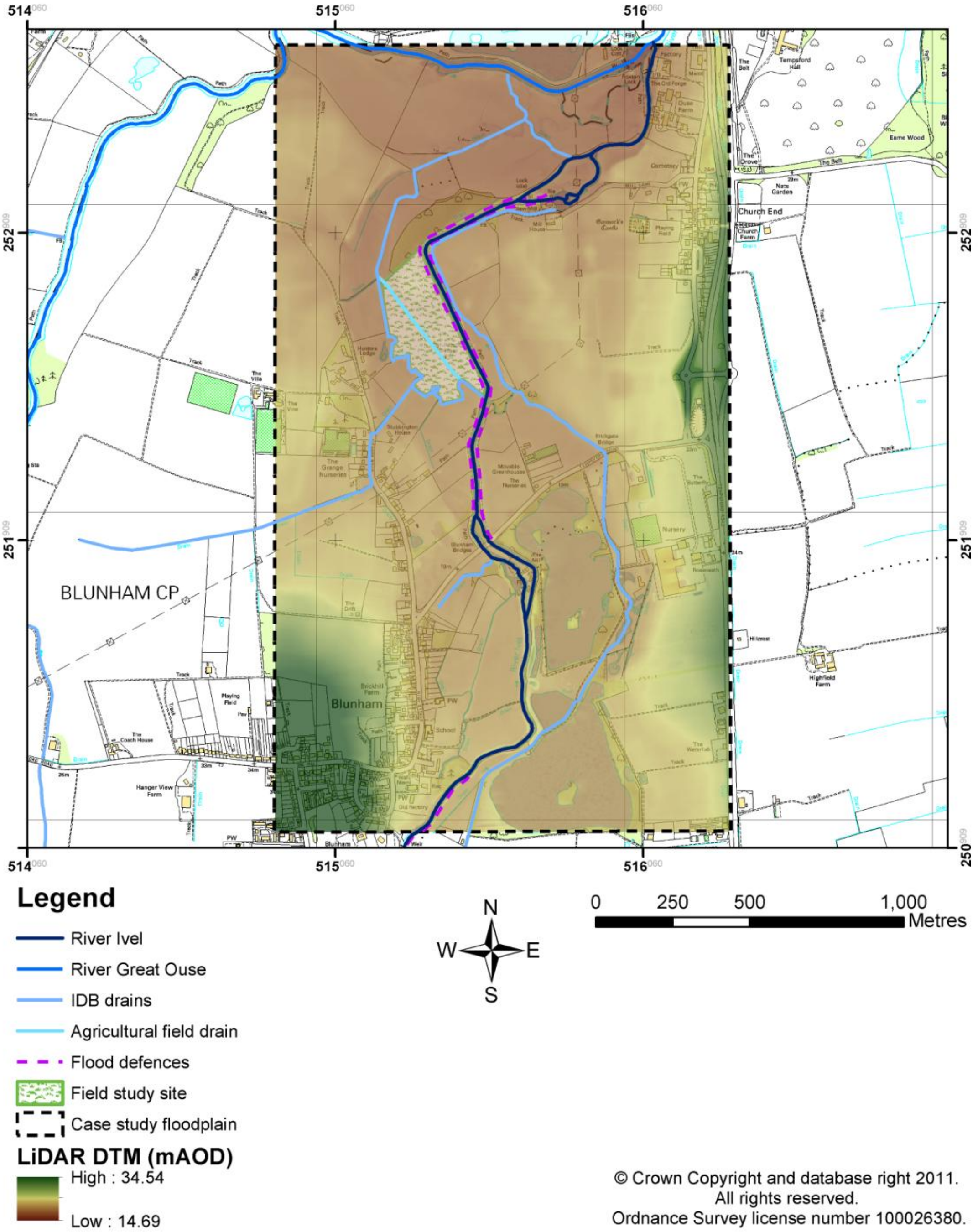

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Figure 5.10 Case study floodplain and field study site lateral and vertical hydrological connectivity map

The case study floodplain contains extensive networks of artificial surface drains as observed from Ordnance Survey maps (OS, 2009a,b). The surface drain network at the field study site comprises of a single agricultural field drain and IDB surface drains (Figure 5.10 and Figure 5.11).

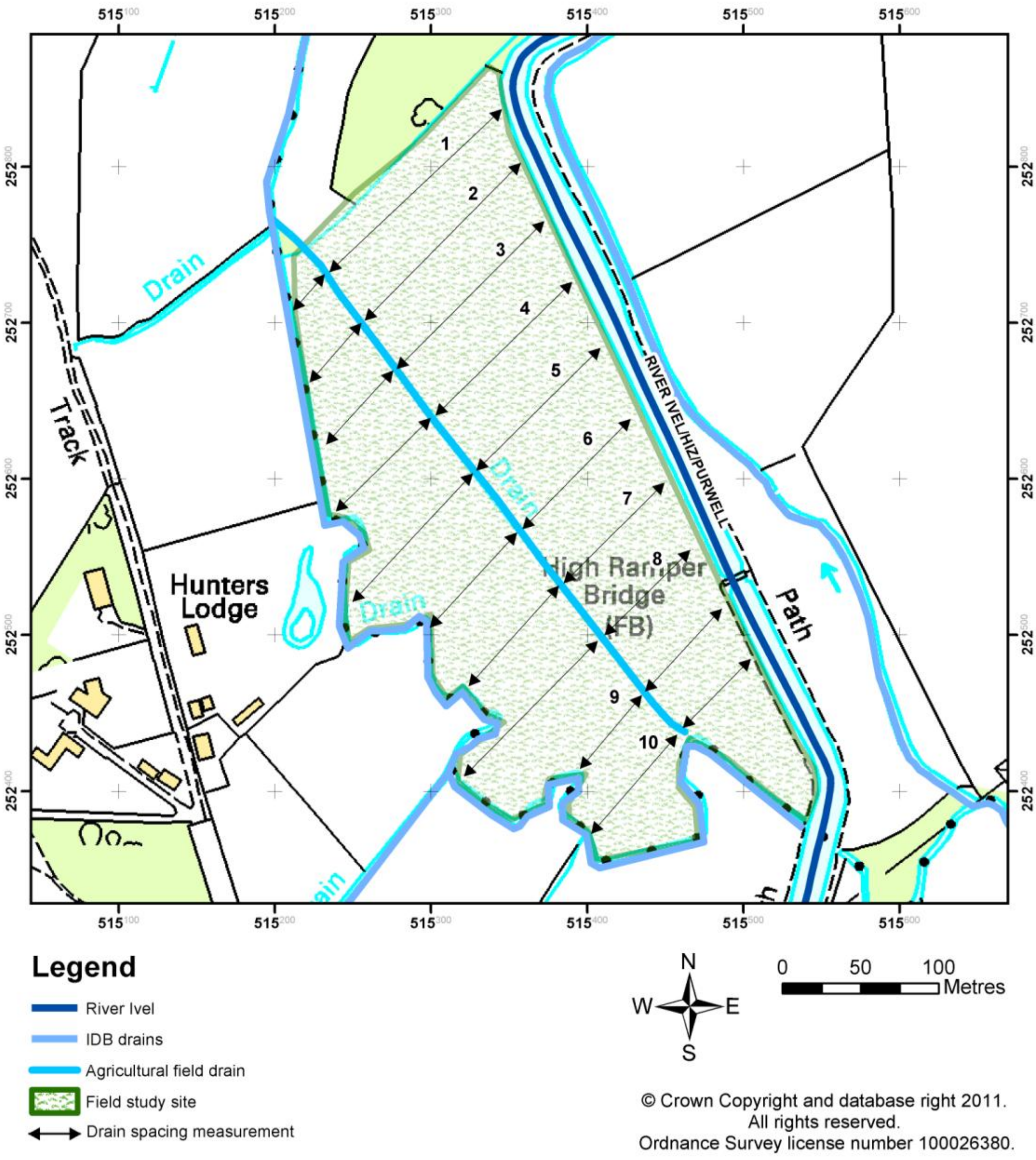

Figure 5.11 Field study site drainage system spacing

The agricultural field drain functions to control and lower the water table to allow timely field operations with greater access to vehicular and/or foot traffic. The IDB drains function to manage surface waters for flood risk control and water level management plans to enhance the conservation of wildlife and terrestrial habitats (Bob Spendlove, Pers Coms, 25 March 2011). No subsurface drains were present at the field study site based on a field survey. As the drain networks are quite extensive, the drain depth and width were measured at the field site with the drain spacing derived from an ordnance survey map of the case study site (OS, 2010). The drain networks contribute to the control of the water table position and control of channel discharge in the surface drains. Also, the collection of surface water in the drains from the floodplain due to overbank flow, surface runoff or precipitation and overland flow may contribute to potential groundwater recharge (Figure 5.9).

Both surface drains at the field study site were inaccessbile with the IDB main drain and the agricultural drain both fenced off and the agricultural drain was heavily overgrown with vegetation. Subjective estimates of both drains was derived with the IDB main drain as having a 2 m width and 1 m depth and the agricultural drain having a 1m width and 1m depth. The drain spacing was derived by drawing 10 transect lines perpendicular to the river channel on a map of the field study site and measuring the distance from the river to the IDB drain and the agricultural field drain (Figure 5.11). The drain spacing between the river channel and IDB drain had a range of 183 m to 224 m width and a mean width of 188 m. While, the drain spacing between the river channel and the agricultural field drain had a range of 64 m to 156 m width and a mean width of 109 m. The drain depths were likely excavated deep enough to intercept both surface and groundwater flows and due to the poor permeability of the top soil at the field study site. The mean measurement of both drains were extracted as the final drainage spacing. The drain spacing is wide indicating that there is less control of the water table thus maintaining a lower water table for agricutlural purposes. The field study site is utilised for a pasture land for dairy/beef farming. In this instance, lower water tables are preferable to enhance soil bearing strength to allow trafficability and reduce poaching of the soil (Brady and Weil, 2008). The drains were possibly sited in natural lows in the floodplain based on the topography with a view to removing surface runoff and overland flow rather than water table control.

5.2.2.2 **Hydrogeology**

The hydrogeology of a site is important as it emphasises the occurrence, distribution and geological interaction of water in the ground (Hiscock, 2005). The soil texture is the key characteristic to assess the effects of infiltration in the case study site. Initially a desktop survey was conducted for the case study site to assess the potential for drainage from precipitation or flooding from overbank flow. A soil survey report was generated for the case study site with the results for the floodplain and river displayed in Table 5.3.

Table 5.3 Case study site soil site report

Feature	Soil Association	Hydrogeological rock type	HOST class and description
Riverbed	Thames (814a) – stoneless mainly calcareous clayey soils affected by groundwater.	River alluvium	9 - Soils seasonally waterlogged by fluctuating groundwater and with relatively slow lateral saturated conductivity.
Floodplain	Efford 1 (571s) – Well drained fine loamy soils often over gravel.	Loam drift	5- Free draining permeable soils in unconsolidated sands or gravels with relatively high permeability and high storage capacity.

Source: NSRI (2010)

Further assessment of the soil texture was derived from fieldwork and laboratory analysis. Soil sampling was carried out by taking 20 soil samples from the top spoil (30 cm below ground level) in a W shape pattern across the length of the field study site (Rowell, 1994). Particle size distribution analysis was conducted on the bulked soil sample (BSi, 1998). The analysis was performed in triplicate in order to confirm the soil texture at the field study site. Table 5.4 displays the particle size distribution results describing the soil texture at the field study site.

Table 5.4 Particle size distribution analysis results and derived soil texture for the field study site

Texture	**Particle size**	**Tempsford 1**	**Tempsford 2**	**Tempsford 3**	**Tempsford Mean**
Coarse Sand	0.6 mm – 2 mm (%)	6.27	6.64	3.72	5.54
Medium Sand	0.212 mm - 0.6mm (%)	26.82	25.34	31.08	27.75
Fine Sand	0.063 mm - 0.212 mm (%)	12.42	12.73	14.09	13.08
Total Sand	*0.6 mm - 0.063 mm (%)*	*45.51*	*44.70*	*48.89*	*46.37*
Silt	*0.002 mm - 0.063 mm (%)*	*21.36*	*22.39*	*20.24*	*21.33*
Clay	*<0.002 mm (%)*	*33.14*	*32.91*	*30.87*	*32.30*
Soil Texture		**Clay loam**	**Clay loam**	**Clay loam**	**Clay loam**

The analysis confirmed the soil type as a clay loam. This type of soil texture has a low infiltration rate of 5-10 mm/hr and hydraulic conductivity of 0.01-0.1 m.d^{-1} (Van der Molen, 2011; Brouwer et al., 1988). The results indicate that the top soil has poor drainage characteristics such that water flow from precipitation and overbank flows will take longer to drain through the ground surface, which may lead to ponding of waters and increasing overland flow and surface runoff in the floodplain. Flow of water beneath the ground surface would also be slow potentially leading to steady water table fluctuations were the water table meets the top soil. Once the water has infiltrated the soil, the next dominant flows are percolation, seepage and groundwater recharge in the unsaturated and saturated zones (Brady and Weil, 1996).

Three vertical soil profiles were assessed for soil texture at depth in the field study site as part of the assessment to monitor the presence and depth of the water table and monitor seasonal water table fluctuations (BSI, 2011). A hand auger rotary method was applied to assess the soil textures at depth. The material at depth was initially described as having a clay loam topsoil with river alluvium and river terrace gravel soil parent and hydrogeological rock type (NSRI, 2010).The ground at each sampling point was augured to achievable depths (BSI, 2014) based on the following:

- To detect the presence of the water table
- To account for the minimum and maximum water table depth and monitor seasonal fluctuations
- To assess the soil profile and permeability at limited depth until an obstruction e.g. gravels limited auguring depth.

A field soil texture method as described in Rowell (1994) was applied to assess the soil texture of spot disturbed soil samples over layers at sample depth intervals of 0-0.12, 0.12-0.85 and 0.85 + mbgl to the achievable augured depth (BSI, 2011; Pennock et al., 2008). The soil texture can have an impact on the infiltration rate from the ground surface thus affecting storage of soil water leading to overland flow and ponding of surface waters. The soil texture can also affect percolation in the soil matrix and seepage flows between the river, surface drains and groundwater affecting the water table position leading to seepage to the ground surface causing ponding and/or increased or reduced channel discharge in surface drains and the river (Figure 5.9).

The vertical soil profiles were located in a linear transect perpendicular to the river and surface drains to assess the hydraulic gradient of the river and floodplain. Figure 5.12 displays the locations of the vertical soil profiles taken across the floodplain. The field study site and Table 5.5 provides a description of the ground cover and soil profile depths and textures/structure present.

Table 5.5 Field study site ground cover, vertical soil profile and texture description

Dipwell	Ground cover	Soil profile depth (mbgl)	Soil texture and structure description
1	Pasture grassland	0-0.12	Clay loam, fine, angular blocky with medium cobble stones (5-10 cm)
		0.12-0.85	Clay loam, fine, angular blocky
		0.85-1.47	Clay loam, fine, with medium angular blocky gravels were found at 1.47 mbgl
2	Marshland, tussocks of sedge	0-0.12	Sandy clay loam, fine, angular blocky
		0.12-0.85	Sandy clay loam, fine, angular blocky
		0.85-1.01	Sandy clay loam, fine with medium angular blocky flint gravels found at 1.01 mbgl
3	Pasture grassland	0-0.12	Clay loam, fine, angular blocky
		0.12-0.85	Clay loam, fine, angular blocky
		0.85-1.42	Clay loam, medium, fine with medium angular blocky flint gravels found at 1.42 mbgl

The infiltration rate for each vertical soil profile can be described in general for a clay loam soil and having a basic infiltration rate of 5-10 mm.hr^{-1} based on standard values as per Brouwer et al. (1986). In some instances, the presence of sand and stones may increase the infiltration rate to greater than 10 mm.hr^{-1} based on standard values as per Brouwer et al. (1986). The hydraulic conductivity of the field soil textures can be described by 0.01-0.1 m.d^{-1} for depths 0-0.85 mbgl and 0.1-0.4 m.d^{-1} for depths greater than 0.85 mbgl based on standard values as per van der Molen et al. (2007). There is greater potential for percolation, groundwater recharge and seepage with depth. At the maximum depths for each vertical profile, a greater abundance of medium gravels with the clay and sandy clay loam soil was present which likely represents the river deposits as part of the superficial layer. The lithology of the geological materials was further investigated to enable an understanding of the occurrence of groundwater and flows that can have an effect on the surface and groundwater hydrology (Hiscock, 2005). The superficial deposits for the case study site are displayed in Figure 5.12 and described in Table 5.6 based on the borehole records.

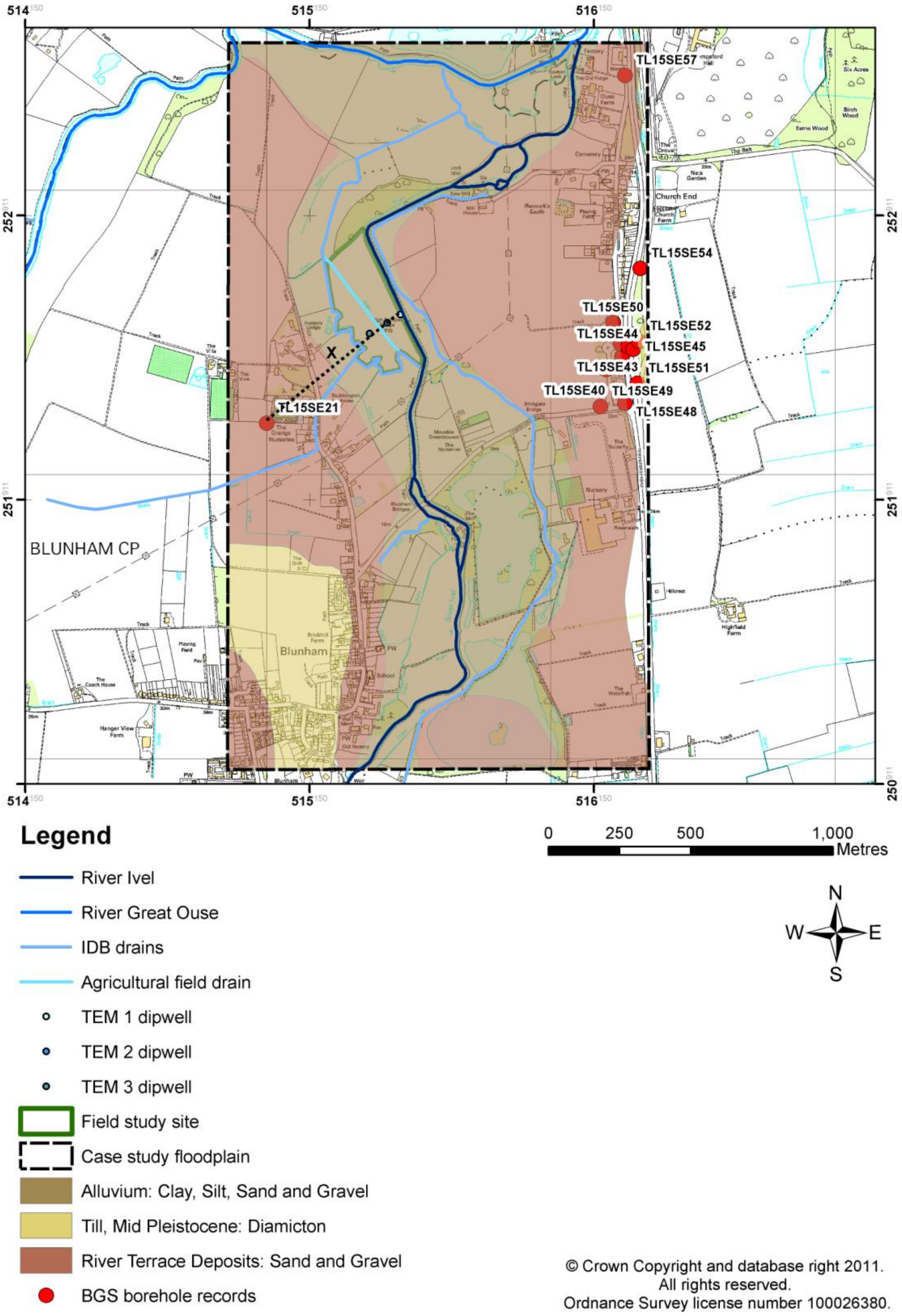

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Figure 5.12 Superficial geology and borehole records of the case study floodplain

Table 5.6 British Geological Society borehole records at the case study floodplain

Borehole ID	Description	NGR	BH depth (mbgl)	Top of casing (mAOD)	Superficial layer	Bedrock layer	Depth to impermeable layer (m)	Distance from Field study site (m)	Direction from field study site
TL15SE21	BLUNHAM GRANGE	TL15000 52180	42.67	18.288	River Terrace Deposits - Sand and gravel	Oxford Clay formation-Mudstone	1.676	550	SW
TL15SE40	A1 TEMPSFORD GRADE SEPARATION 10	TL16194 52369	10.45	21.806	River Terrace Deposits - Sand and gravel	Oxford Clay formation-Mudstone	NA	791	E
TL15SE41	A1 TEMPSFORD GRADE SEPARATION 20	TL16250 52415	24.5	23.333	River Terrace Deposits - Sand and gravel	Oxford Clay formation-Mudstone	NA	837	E
TL15SE42	A1 TEMPSFORD GRADE SEPARATION 30	TL16245 52460	15.15	23.131	River Terrace Deposits - Sand and gravel	Oxford Clay formation-Mudstone	NA	826	E
TL15SE43	A1 TEMPSFORD GRADE SEPARATION 40	TL16271 52451	15	24.058	Till, Mid Pleistocene - Diamicton	Oxford Clay formation-Mudstone	NA	848	E
TL15SE44	A1 TEMPSFORD GRADE SEPARATION 50	TL16289 52440	15	24.897	Till, Mid Pleistocene - Diamicton	Oxford Clay formation-Mudstone	NA	867	E
TL15SE45	A1 TEMPSFORD GRADE SEPARATION 60	TL16290 52494	20	24.816	Till, Mid Pleistocene - Diamicton	Oxford Clay formation-Mudstone	NA	871	E
TL15SE47	A1 TEMPSFORD GRADE SEPARATION 80	TL16359 52924	15.5	25.758	River Terrace Deposits - Sand and gravel	Oxford Clay formation-Mudstone	13	850	E
TL15SE48	A1 TEMPSFORD GRADE SEPARATION TP 100	TL16259 52250	3	23.144	River Terrace Deposits - Sand and gravel	Oxford Clay formation-Mudstone	NA	883	E
TL15SE49	A1 TEMPSFORD GRADE SEPARATION TP 110	TL16174 52239	3	21.155	River Terrace Deposits - Sand and gravel	Oxford Clay formation-Mudstone	NA	811	E

Borehole ID	**Description**	**NGR**	**BH depth (mbgl)**	**Top of casing (mAOD)**	**Superficial layer**	**Bedrock layer**	**Depth to impermeable layer (m)**	**Distance from Field study site (m)**	**Direction from field study site**
TL15SE50	A1 TEMPSFORD GRADE SEPARATION TP 120	TL16219 52534	5	22.291	River Terrace Deposits - Sand and gravel	Oxford Clay formation-Mudstone	NA	796	E
TL15SE51	A1 TEMPSFORD GRADE SEPARATION TP 130	TL16304 52320	3.6	25.291	River Terrace Deposits - Sand and gravel	Oxford Clay formation-Mudstone	NA	905	E
TL15SE52	A1 TEMPSFORD GRADE SEPARATION TP 135	TL16309 52469	3	25.594	Till, Mid Pleistocene - Diamicton	Oxford Clay formation-Mudstone	NA	886	E
TL15SE54	A1 TEMPSFORD GRADE SEPARATION TP 150	TL16314 52725	3.1	25.840	NA	Oxford Clay formation-Mudstone	NA	913	E
TL15SE57	A1 TEMPSFORD GRADE SEPERATION TP180	TL16260 53404	3.0	19.796	River Terrace Deposits – sand and gravel	Oxford Clay formation-Mudstone	NA	1000	NE

The ground lithology is made up of the superficial deposits overlaying bedrock. The lithology was derived from analysing British Geological Survey maps of the superficial deposits and bedrock present at the case study site and the assessment of borehole records (BGS, 2014; 2013). The lithology for the superficial deposits and bedrock was then compared to standard values of hydraulic conductivity and permeability (Lewis et al., 2006; Freeze and Cherry, 1979) to describe the dominant flows at the case study site.

The River Ivel and its riparian corridor are composed of Alluvium – clay, silt and sand and river terrace deposits (undifferentiated) – sand and gravel likely formed as a result of overbank floods. These materials have a high permeability and storage capacity (Freeze and Cherry, 1979; Lewis et al., 2006). There is a greater potential for groundwater movement with fluctuating water table levels and high seepage potential between the river and floodplain (Figure 5.9). The vertical superficial thickness in the case study floodplain ranges from 1.68 – 3+ metres from the south west to north east based on British Geological Survey borehole records TL15SE21 and TL15SE57 (Table 5.6 and Figure 5.12) for the case study site (BGS, 2014).

The east side of the case study floodplain considering the TL15SE57 borehole record is made up of 0.85 mbgl of silty fine sand topsoil and medium angular flint gravel. Alluvial Clay and sand with coarse angular flint gravel and occasional cobbles are found from 0.85-2.60 mbgl. Glacial till formed of silty clay and coarse angular flint gravel is found from 2.60-3 mbgl. These materials are indicative of high permeability hydraulic conductivity and storage capacity based on standard values (Freeze and Cherry, 1979; Lewis et al. 2006). There is a greater potential for groundwater movement with fluctuating water table levels and high seepage potential between the river and floodplain and between the surface drains and floodplain. These superficial deposits were likely formed as a result of overbank flooding and deposition.

The west side of the case study floodplain which contains the field study site is mainly composed of Alluvium – clay, silt and sand and river terrace deposits (undifferentiated) – sand and gravel likely formed as a result of overbank floods. To a smaller extent, Till – diamicton material is located further south west of the field study site. The alluvium and river terrace deposits would have a high permeability and storage capacity (Freeze and Cherry, 1979; Lewis et al., 2006). There is a greater potential for groundwater movement with fluctuating water table levels and high seepage potential between the river and floodplain across the majority of the case study floodplain and especially at the field study site (Figure 5.9, 5.12). Till-diamicton materials are described by a moderate permeability and storage capacity based on standard permeability values (Freeze and Cherry, 1979; Lewis et al., 2006). Further investigation of the superficial thickness was examined with TL15SE21 borehole record and found to be made up of several materials and layers extending to 42 mbgl (Table 5.6). The borehole record describes the layers as follows: topsoil forms 0.80 mbgl, gravel is found from 0.8-1.68 mbgl and below blue clay extends from 1.68-27 mbgl and below sea level. The field study site soil vertical profile indicates that the topsoil layer is deeper towards the river (Figure 5.9). A conceptual scaled diagram of the lithology of the materials on the west side of the floodplain based on borehole records and field site vertical soil profile is displayed in Figure 5.9. The percolation of water flows from infiltration in the top soil would be slow as the soil is predominantly a clay loam and a metre or less shallow in the floodplain based on standard permeability values (Freeze and Cherry, 1979; Lewis et al., 2006). Percolation and the potential for groundwater recharge is significantly higher as a result of the river terrace gravels 1-1.47 mbgl from east to west in the floodplain (Figure 5.9) and based on standard permeability and hydraulic conductivity values (Freeze and Cherry, 1979; Lewis et al., 2006). Figure 5.9 also provides a conceptual positioning of the water table level based on manual measurements and the derived river stage for 11/05/2011. The presence of gravels in the superficial deposits layer reinforces the potential for seepage to affect the position of the water table and potentially contribute to the maintenance of a constant water table level.

There is greater potential for seepage of water from the gravels upwards into the topsoil and potentially above the ground surface. The movement of water between both materials will be fast to slow based on standard permeability and hydraulic conductivity (Freeze and Cherry, 1979; Lewis et al., 2006). Seepage between the surface drains and water table will be lower due to the position of the drains and presence of clay loam soil in the vertical profile (Figure 5.9). Seepage from the river to the water table would be potential high as the river is potentially connected directly to the gravels (Figure 5.9).

Oxford Clay Formation (Mudstone) sedimentary rock extends across the case study site (BGS, 2003). This rock would have been formed in shallow seas and comprising fragments of silicate minerals deposited as mud, silt, sand and gravel. These materials have low permeability and storage capacity (Freeze and Cherry, 1979; Lewis et al., 2006). The bedrock layer is likely to be the confining layer indicating that an unconfined aquifer is present due to the permeability of the superficial deposits layer. Examining the TL15SE21 borehole record found that blue clay i.e. Oxford Clay formation – Mudstone is present at 1.68 mbgl.

5.2.2.3 **Ecosystem services**

There are three ecosystem services present in the case study floodplain namely flood defence, terrestrial habitat and agricultural production (EA, 2010c). In terms of flood defence and agriculture, a 10% AEP standard of protection to select sections on the River Ivel is present mainly at a 1.7 km stretch located between Blunham village and the field study site on both banksides (Figure 5.2). Blunham and Tempsford villages are the main locations of properties at risk from flooding while agricultural related properties are in smaller numbers and sporadically spaced within the case study site (Figure 5.2). The main types of agriculture within the case study site are pasture farming and in fewer instances arable farming. The agricultural land classification ranges from grades 1-4 with grade 1 and 3 being the dominant agricultural land classification (Natural England, 2012b). The Biodiversity Action Plan (BAP) priority habitats present at the case study site are namely rivers and floodplain grazing marshes (Natural England, 2012b). The Bedfordshire and Luton BRMC (2009; 2008) described that physical alteration of River Ivel by installation of flood defences e.g. embanked sections has led to lateral hydrological disconnection of the river and floodplain thus leading to isolation and fragmentation of habitats and species and habitat decline. Deciduous woodland is present in small land parcels mainly to the south of the field study site while the floodplain grazing marshes are located between Blunham and Tempsford village on the west side floodplain facing downstream of the River Ivel (Natural England, 2012b).

The case study site also forms part of the Environment Agency strategic policy management unit for Biggleswade, Sandy and Blunham (EA, 2010b). The management plan intends ‘to continue with existing or alternative actions to manage flood risk at the current level’ to seek opportunities for the following:

- Utilize natural methods for flood alleviation by attenuation to increase flood storage where possible to reduce flood risk by increasing floodplain connectivity.
- Improve flood defence by localized protection measures i.e. remove set-back, maintain or increase defences.
- Ecological enhancement and floodplain restoration by looking for opportunities for floodplain connectivity and utilising existing designated or non-designated conservation sites to improve ecological networks which link to the Great Ouse

Wetland Vision. The restoration opportunities would involve increasing lateral connectivity by lowering flood banks to:

- create and/or enhance recreational opportunities.
- enhance access to aquatic habitat in floodplain for fisheries.
- create and/or enhance floodplain terrestrial habitat e.g. wet woodland and floodplain grazing marshes.

6 FLOODPLAIN HYDROLOGY AND INTEGRATED MODELS

6.1 Introduction

The following chapter is primarily composed of methods, results and discussion for the further characterization of the hydrology at the field study site, the hydrological events and the integrated modelling of floodplain connectivity.

The floodplain hydrology of the field study site is described by primary and secondary data sources for rainfall, evapotranspiration, river stage, water table level, hydraulic gradient and seepage. These hydrological variables provide important information on characterising the impacts of the hydrological transfer flows that can influence the hydrological regime at the field study site.

The hydrological events are comprised of design flood events for lateral connectivity modelling and seasonal year rainfall events for vertical connectivity modelling acting as hydrological inputs for the integrated models to study the impacts of hydrological events on the hydrological regime at the case study site.

Floodplain connectivity is described for the lateral (embankments) and vertical (surface drains) configurations and their application for each respective model and as part of the integrated modelling system to study the impact of the hydraulic controls on ecosystem service delivery.

The remaining sections describe the methods for the model schematisation, parameterization, calibration, validation, sensitivity testing and simulation of the scenarios for the two models making up the integrated modelling system. Finally, the model results and discussion of the hydrological events and floodplain connectivity scenarios are presented.

6.2 Floodplain hydrology

6.2.1 **Methodology**

6.2.1.1 **Rainfall and evapotranspiration**

Daily rainfall and evapotranspiration for the case study site were collected during the water table monitoring period 31/03/2011-31/07/2012. Secondary data for the rainfall and evapotranspiration was collated from the Environment Agency. A single rainfall gauging station at Great Staughton at TL3040445, 12.2 km north west of the case study floodplain was selected for the daily observed rainfall data since:

- Proximate to the field study site.
- Covers a small spatial area and there is an irregular and low density of rain gauges proximate to the case study site (Mansell, 2003).
- The historic record extended from 1984-2012 with quality controlled data.

The daily potential grass evapotranspiration for MOSES square 139 (40 km^2) of which the field study site is located was acquired from the Environment Agency to correspond with the rainfall data records of Great Staughton. The net rainfall i.e. the rainfall that reaches the ground that is not lost through evapotranspiration was calculated to gain an understanding of the potential for rainfall to influence the position of the water table (Shaw et al., 2011). The results were displayed as daily rainfall and monthly net rainfall and divided into seasonal periods to represent hydrological winter and summer to study seasonal variations and patterns of the impacts of precipitation and evapotranspiration transfer flows at the case study site. Monthly net rainfall was calculated by subtracting the sum total rainfall from the sum total evapotranspiration for each month during the monitoring period.

6.2.1.2 **Water table level**

Water table level position was measured for the following reasons:

- Gain an understanding of the baseline condition at the field study site.
- To understand the influence of hydrological transfer flows on the water table position at the field study site.

The position of the water table at the field study site was monitored from 31/03/2011-31/08/2012. Three dipwells were installed with automated water table leveloggers. A Schlumberger micro-diver (DI 601) was applied to measure the water table level at TEM 1 and TEM 2 dipwells. This unit has an operating measurement range of 10 m and an accuracy of ±0.01 m (SWS, 2014). A Solinst levelogger (F30, M10) was applied to measure the water table level at Tempsford 3 dipwell (TEM 3). This unit has an operating measurement range of 10 m and an accuracy of ±0.05 m (Solinst, 2007).The dipwells and automated leveloggers were located perpendicular to the River Ivel as a transect across the floodplain. Figure 6.1 displays the position of the dipwells and automated leveloggers at the field study site.

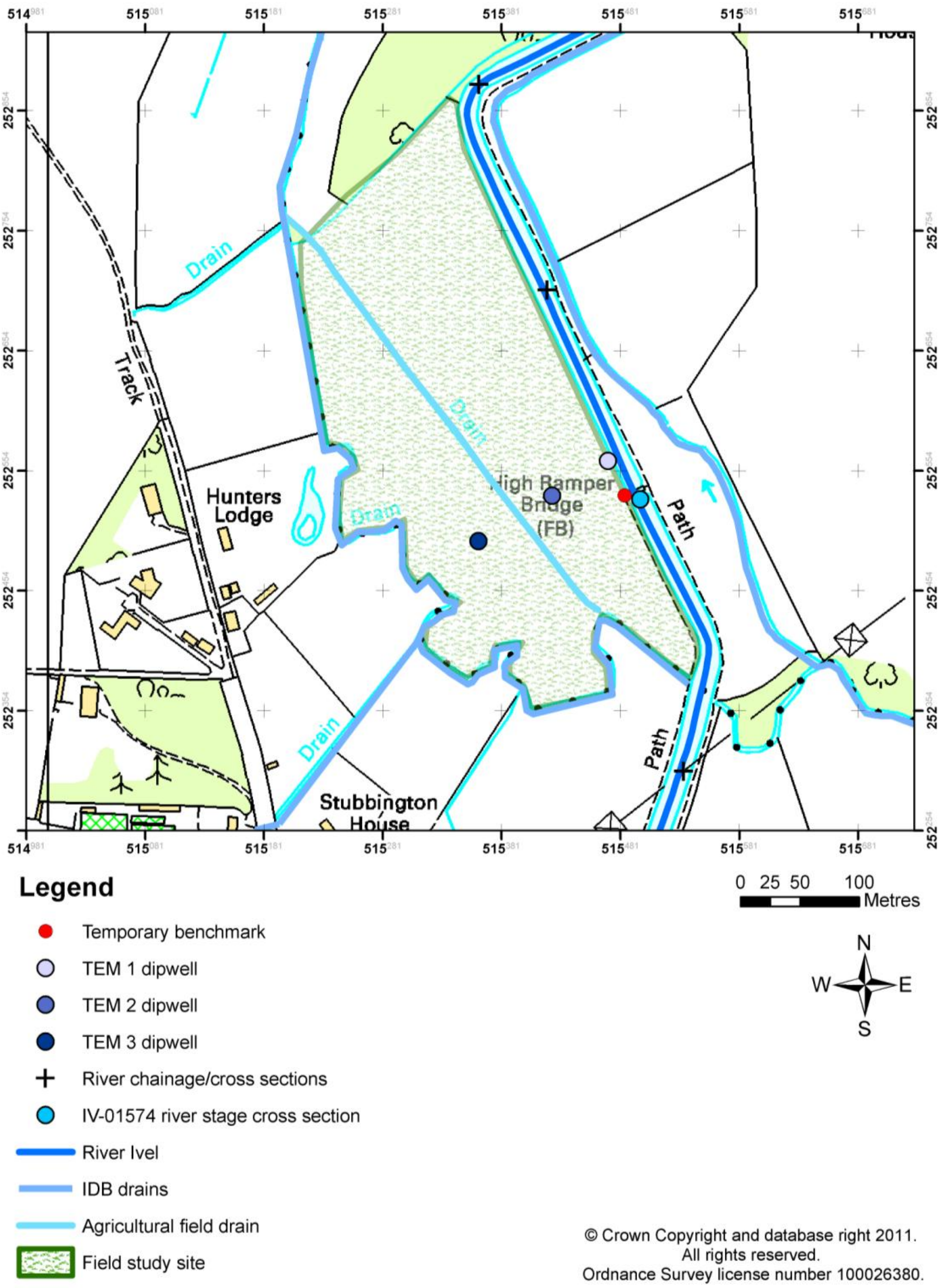

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Figure 6.1 Field study site dipwell and levelogger installation location map

Figure 6.2 displays a vertical cross section of the floodplain, river channel and the dipwell installation locations. This diagram also includes the position of the dipwells in relation to the river and the surface drains at the field study site including a hypothetical water table position.

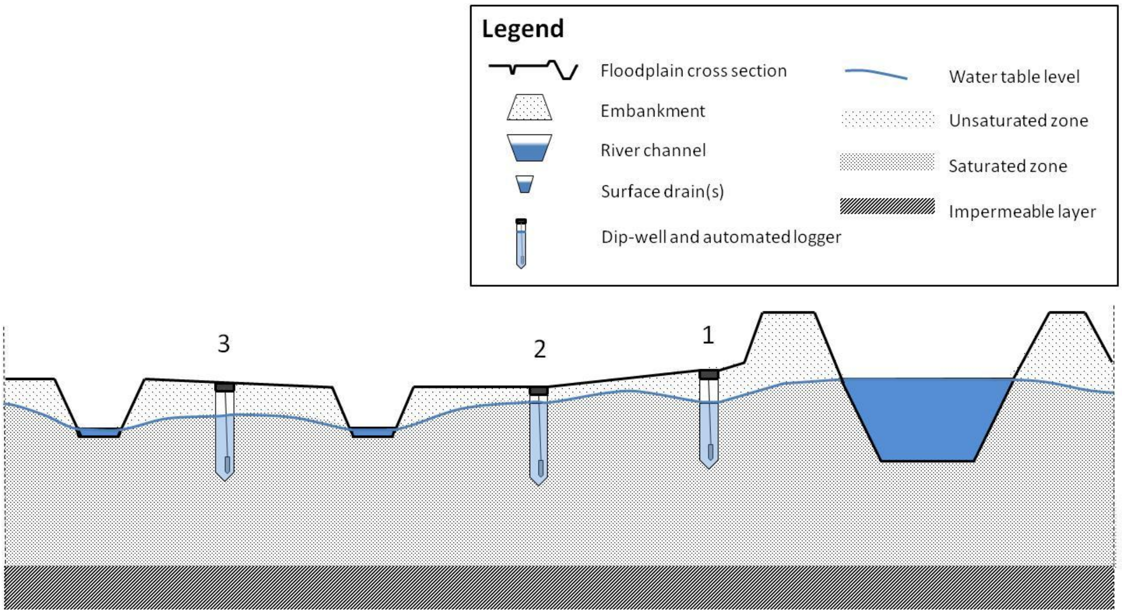

Figure 6.2 Schematic diagram of dipwell and levelogger installation at the field study site

The leveloggers were set up and installed as per methods described in Solinst (2007). A Solinst barologger was set up to measure barometric pressure as per methods described in Solinst (2007) and placed at Cranfield University, Bedfordshire, UK, approximately 16 km southwest of the field study site. The barologger location is within the allowable maximum distance range of 30 km and maximum elevation change of 300 m to allow for accurate manual barometric compensation of the levelogger results (Solinst, 2007). Table 6.1 provides further information on the installation and operation details of each levelogger and the barologger.

Table 6.1 Levelogger and Barologger installation and operation details

ID	Name	Serial number	Geographic location	Sample frequency	Installation depth	Initial reference level	Elevation
		No.	NGR*	minutes	mbgl	mbgl	mAOD
TEM 1	Schlumberger DIVER	80130	TL515471 252562	30	1.47	0	18.29
TEM 2	Schlumberger DIVER	52742	TL515424 252533	30	1.01	0	17.72
TEM 3	Solinst Levelogger	48432	TL515362 252495	30	1.42	0	17.88
Cranfield University	Solinst Barologger	62958	SP940887 423832	30	0	0	110

*National Grid Reference (NGR)

A linear sampling mode was applied at a 30 minute sampling rate interval to measure the water table levels over the monitoring period. This high resolution sampling time was applied in case of the occurrence of an observed flood at the field study site which could be also be utilised to characterize the impacts of hydrological events at the field study site. The installation depth for each logger was the maximum depth achievable through hand auguring of the clay loam soil at the field study site.

Level surveys were also performed for each dipwell in order to establish the position of the water table level in relation to the ground surface datum. The position of the water table can then be used in conjunction with the river stage to establish the hydraulic gradient between the dipwells to understand the interaction between the River Ivel and the floodplain water table level. In the first instance, a local temporary benchmark was created at the field study site since no benchmark was present in order to mark as point of elevation reference. A Global Navigation Satellite System (GNSS) based height method was applied to establish a physical benchmark as a fixed reference point on the ground using methods as per RICS (2011). A corner point on the concrete steps of the ‘High Ramper Bridge’ TL15485 52533, 40 m south of the dip-well installation transect was selected at the field study site to measure elevation data using a Handheld Trimble GeoXT GPS receiver (Trimble, 2012). Data was collected for a period of one hour or more logging time to increase measurement accuracy (Trimble, 2003). The field measurement was then post-processed against the nearest OS NET® GPS active station at St. Neots (SNEO) TL2955, 22 km north east from the field study site for the same date and time period. This was in order to convert the field measurement elevation to metres above ordnance datum (mAOD) and to maximise the elevation measurement accuracy (Trimble, 2003). The top casing of the dipwells at the field study site were then level surveyed against the local temporary benchmark using a ‘rise and fall’ method (Irvine, 1995) with a Leica Sprinter 50 digital level and levelling staff.

The barometrically compensated water table level (BC) was calculated as described by Solinst (2007) in Equation 6.1.

$$CWL = L - B \qquad (6.1)$$

where:
CWL = barometrically compensated water table level (mbgl)
L = Levelogger measurement (m)
B = Barologger measurement (m)

Manual water level measurements (M) were taken throughout the monitoring period to initially calibrate the leveloggers to a field zero reading and then to assess and eliminate the potential effects of pressure sensor drift. Each levelogger was calibrated using a selected manual measurement as a correction factor, e.g. offset. The correction factor (CF) for each manual measurement and corresponding CWL measurement was calculated as displayed in Equation 6.2.

$$CF = M - CWL \tag{6.2}$$

where:
CF = Correction factor (m)
M = Manual measurement (m)
CWL = Barometrically compensated water table level (mbgl)
B = Barologger measurement (m)

The actual water table level is the barometrically compensated water table adjusted with the correction factor as described by Solinst (2007) and was calculated as described in Equation 6.3. This correction factor was applied to all subsequent barometrically compensated water table levels from the levelogger calibration point to enhance accurate recording of the water table levels at the field study site.

$$AWL = CF + CWL \tag{6.3}$$

where:
AWL =Actual water table level (mbgl)
CF = Correction factor (m)
CWL = Barometrically compensated water table level (mbgl)

As the initial ground surface (GS) reference level for each dipwell was set to 0 m (Table 6.1), the levelogger readings at each dipwell were then subtracted from each 0 m to establish the water table position in metres below ground level (mbgl). The Levelogger readings were then subtracted from the final surveyed level for the top casing of each dipwell to establish the water table position in metres above ordnance datum (mAOD). Figure 6.3 provides a conceptual diagram of the measurement indices to calculate the position of the water table at the field study site.

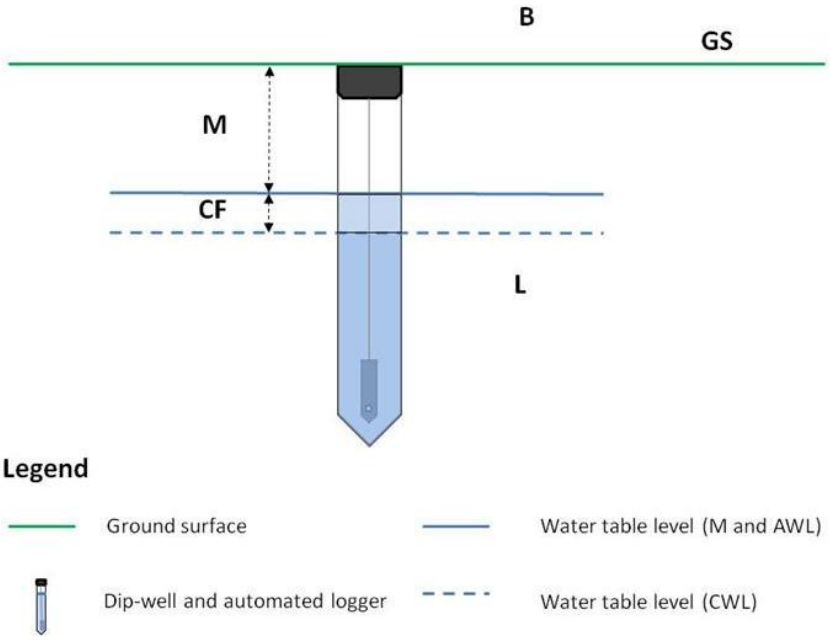

Figure 6.3 Water table level calculation conceptual diagram

Five manual measurements were taken over the levelogger sampling period. Initially, the levelogger readings of the water table depths in relation to the ground surface was were assessed between the 31/03/2011 and 11/05/2011 as a pilot test to ensure the leveloggers were functioning properly. This period was also used to identify the frequency of manual measurements, calibrate the levelogger to a field zero reading were necessary. Based on the pilot test period, this research established a quarterly monitoring schedule since the water table position for each levelogger displayed minimal fluctuation. Also, since the loggers are automated, water table data could be extracted at any time. The levelogger readings and the manual measurement depth for each dipwell was taken for each of the leveloggers and dates as displayed in Table 6.2.

Table 6.2 Manual measurement monitoring period at the field study site

Date	**Dipwell**		
	TEM 1	**TEM 2**	**TEM 3**
31/03/2011	✓	✓	✓
11/05/2011*	✓	✓	✓
09/11/2011	✓	✓	✓
22/03/2012	✓	✓	✓
16/08/2012	✓	✓	×
31/08/2012	×	×	✓

*calibration point

The leveloggers were calibrated based on the manual measurement taken after the pilot test on 11/05/2011 as calibrating the leveloggers based on the manual measurement taken on the 31/03/2011 would be prone to bias as the water table had not equilibrated after installation of the dipwells and automated leveloggers. These manual measurements were also compared to the barometrically compensated water table levels to assess the accuracy of the levelogger measurements. The water table levels for the field study site will be displayed in mAOD to allow comparison of the water table position and river stage results in order to derive the hydraulic gradient at field study site and to determine the seepage between the river and water table or vice versa.

6.2.1.3 River stage

The river stage is an important element in conjunction with the water table position at the riverbank in order to define the vertical hydraulic gradient and the direction of flow between the river and the water table (Simonds and Sinclair, 2002). It can also be an important flow to study the impact of rainfall directly onto the river channel or floodplain causing overland flow to increase the river stage or overbank flow and surface runoff to increase the ponded surface water in the floodplain. Figure 6.4 displays the hydrological data source locations at the case study site.

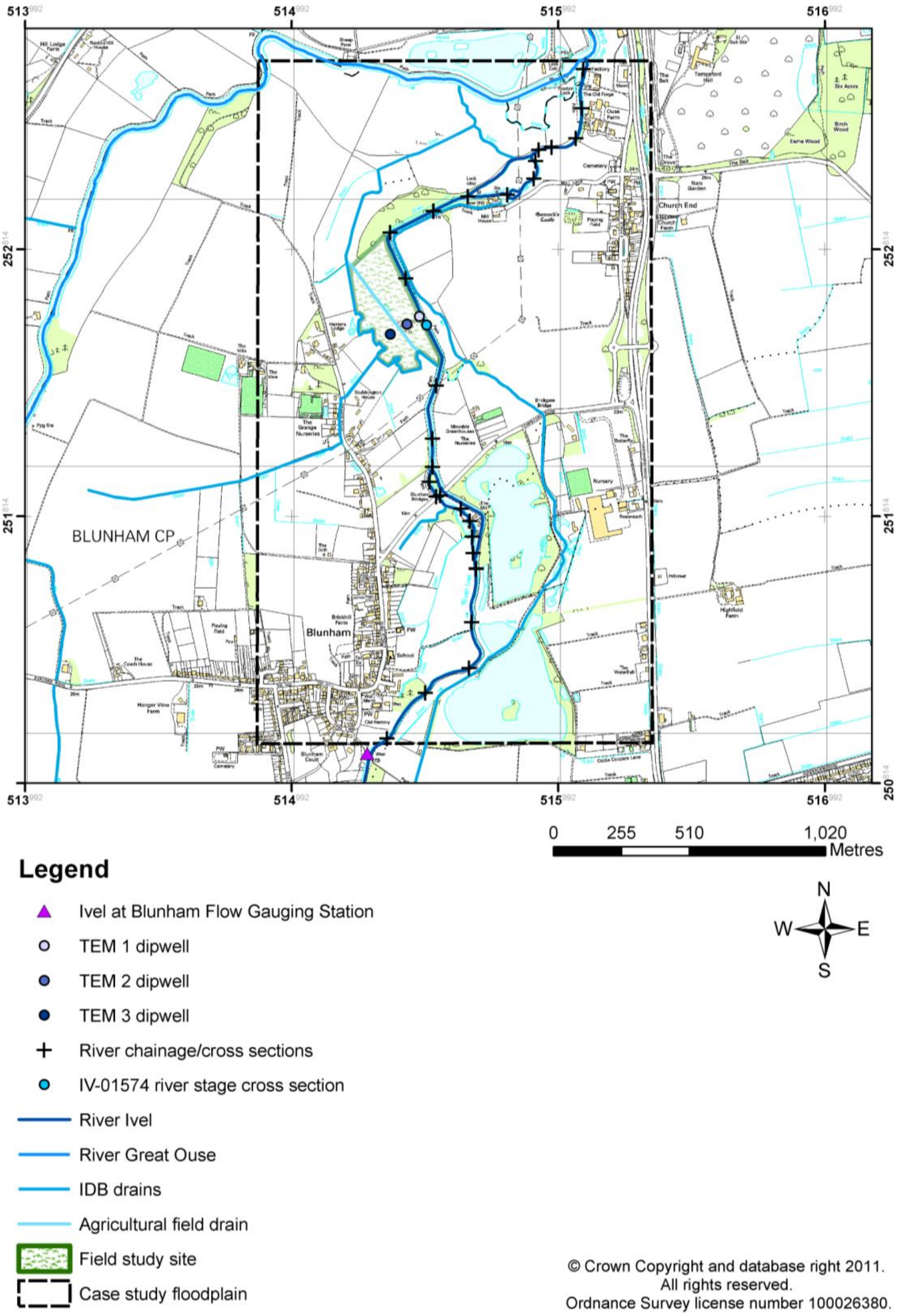

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Figure 6.4 Hydrological data source locations of the case study site

The river stage at the field study site was not measured due to health and safety reasons since the embankments at the river channel were quite steep and access to take measurements would be precarious. As an alternative, the river stage for the field study site was derived from secondary data described by applying a correction factor between a surveyed water level at a cross section proximate to the dipwells in the field study site and the nearest flow gauging station river stage levels for the same period of water table monitoring.

The flow gauging station (FGS) at Blunham (TL15260 50921) was selected for river stage records since it is located on the River Ivel at 1.7 km upstream of the field study site. IV-01574 cross section on the River Ivel study reach (TL15469 52517) was selected since it was the nearest surveyed cross section located 37 m northeast from the TEM 1 dipwell (12 m horizontally from river stage) and included a river stage level (Figure 6.4). The river stage level for the IV-01574 was surveyed on 27/01/2009 at 12:00 by Cartographical Surveys Ltd. on behalf of the Environment Agency as part of the River Ivel & Ivel Navigation survey for flood risk management purposes (EA, Pers. Coms, 12 March 2011). This surveyed river stage level was then compared to the river stage level at the Ivel at Blunham FGS for the same period. The difference between the Ivel at Blunham river stage and IV-01574 cross section was calculated as the correction factor. This correction factor was then applied to the river stage data for Ivel at Blunham FGS for the water table monitoring period by subtracting the correction factor from each daily river stage record to estimate the potential river stage level at the field study site i.e. IV-01574. A sensitivity test was carried out to incorporate the impacts of seasonality on the river stage level since the correction factor for the derived river stage was based on a surveyed river stage level taken in February (winter). This is also a critical factor in order to assess the hydraulic gradient between the river and floodplain. Seasonal growth of aquatic vegetation in lowland rivers alters the channel roughness and in turn can impact on the flow resistance resulting in controlling the river discharge and hence the river stage. Vegetation growth in the summer can increase the channel roughness and lead to an increase in the river stage for a given discharge and vice versa (Sear et al., 2000). The channel roughness for IV-01574 cross section was surveyed on 27/09/2009 at 12:00 as Mud/Gravel. A parameterized global roughness value of ‘0.040’ corresponding to the surveyed channel roughness was used as an ‘excavated or dredged river channel, made of earth, winding and sluggish based on Chow (1959) channel roughness values. The channel roughness ‘n’ values for ±20% were calculated at 0.032 and 0.048 representing a winter and summer channel roughness respectively. This research utilised estimated Manning’s ‘n’ roughness values based on ±20% to assess the effects of changing aquatic vegetation on seasonal river stage (Table 6.3).

Table 6.3 ISIS 1D River Ivel study reach Manning’s ‘n’ channel roughness sensitivity test values and description

Manning’s ‘n’ value		**Type of Channel**	**Description**
Normal	0.03	C. Excavated or dredged	b. Earth, winding and sluggish 5. Stony bottom and weedy banks
Maximum	0.05	C. Excavated or dredged	b. Earth, winding and sluggish 6. Cobble bottom and clean sides

Source: Chow (1959, p. 112)

An ISIS 1D model was applied for the River Ivel study reach using the global roughness Manning’s ‘n’ values of 0.040, 0.030 and 0.05 to simulate the impact of increasing or decreasing the channel roughness on the river stage level. The mean absolute error (Moriasi et al., 2007) was applied to test the change in river stage as a result of seasonal growth and channel roughness in the river channel.

6.2.1.4 **Hydraulic gradient and seepage rate**

The hydraulic gradient for the field study site was derived in order to assess the hydrological interaction and exchange dynamics between the River Ivel and the water table level. This interaction may involve whether the river losses water through channel discharge i.e. seepage from the river to the water table or where the river gains water through groundwater discharge i.e. seepage into the river from the water table (Rushton, 2007) as displayed in Figure 6.5.

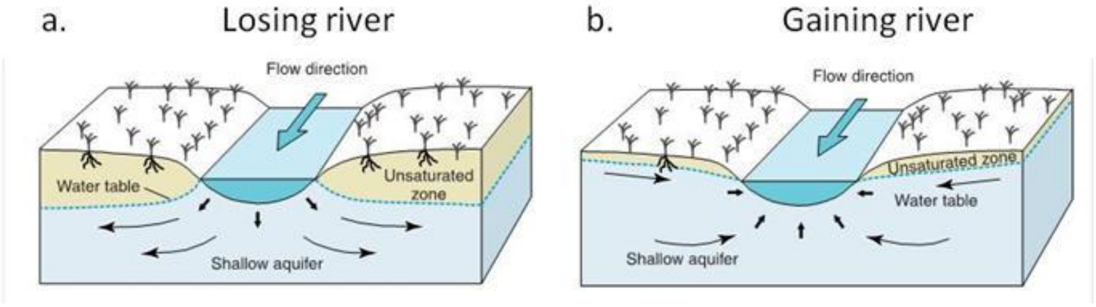

Figure 6.5 Interaction between the river and water table to form a losing river or gaining river
Source: Simonds and Sinclair (2002, p. 24)

The hydraulic gradient was then calculated using Equation 6.4 (Freeze and Cherry, 1979).

$$I = \frac{dh}{dl} = \frac{h_1 - h_2}{l}$$

where: **6.4**

I = hydraulic gradient (dimensionless)
dh = difference between two hydraulic heads
dl = horizontal flow path length between two hydraulic heads
h_1 = hydraulic head 1 i.e. TEM SG river stage (m)
h_2 = hydraulic head 2 i.e. TEM 1 levelogger reading (m)
l = length of the flow path between TEM SG and TEM 1 (m)

The distance (*l*) between the TEM 1 levelogger and the river was measured as 11.8 m from OS maps of the field site (OS, 2009a,b). The hydraulic gradient (I) was calculated for each day over the monitoring period i.e. 31/03/2011-31/07/2012. The hydraulic gradient between the river and floodplain was calculated for three event periods based on seasonal rainfall events as per Section 6.2.1.1. This was to indicate the duration and direction of seepage between the river and dipwell and vice versa. The sum total of days and the percentage for the hydraulic gradient for TEM SG>TEM 1 were calculated for each event period to confirm whether the hydraulic gradient indicated that seepage occurs from the river to the groundwater or vice versa. Where the percentage is > 50% indicates that seepage occurs between the water table and river to increase the river stage (gaining river).

The seepage rate is an important measurement to understand the influence of the transfer of water in the river-aquifer interaction. The seepage rate per unit width of river/floodplain was derived from Darcy's law (Equation 6.5).

$$q = \frac{KIb}{A} \times 1000$$

where: **6.5**

q = Seepage rate ($mm.d^{-1}$)
K = Hydraulic conductivity ($m.d^{-1}$)
I = Hydraulic gradient (dimensionless)
b = Aquifer thickness (m)
A = Plan area of the unit width of river/floodplain (m^2)

The plan area of the unit width of river/floodplain (*A*) was derived by multiplying the distance between the river and dipwell (TEM 1) i.e. 11.8 m by the unit length of river channel i.e. 1 m. The aquifer thickness (*b*) was derived as 1.68 m based on BGS borehole record TL15SE21 (Table 5.6 and Figure 5.12) proximate to the field study site. The seepage rate (*q*) was calculated for the water table monitoring period 31/03/2011-31/07/2012 for a range of hydraulic conductivities based on a clay loam soil at the field study site. The hydraulic conductivities (*K*) for a clay loam soil were derived from a secondary data source (Smedema et al., 2004) and displayed in Table 6.4.

Table 6.4 Hydraulic conductivity values for a clay loam soil

Soil Type	**Hydraulic conductivity (K)**		
	Range ($m.d^{-1}$)	**Min ($m.d^{-1}$)**	**Max ($m.d^{-1}$)**
Clay Loam/Clay poorly structured	0.02-0.2	0.02	0.2
Loam/Clay loam/ Clay ,well structured	0.5-2	0.5	2

The average seepage rate was then calculated for each seasonal event period. Where the seepage rate was >0 indicates the flow from the river to the water table and vice versa.

6.2.1.5 **Field site hydrology**

The net rainfall, river stage and water table results from the previous sections were then integrated and analysed to assess the impacts of hydrological flows on the observed water table levels. The rise or fall in the water table position was calculated for each net rainfall period to analyse the impact of net rainfall on the water table position (Equation 6.6). The river stage and observed water table level were also displayed to highlight the hydraulic gradient to assess the impact of seepage to influence the water table position.

$$\Delta H = \frac{I}{D.P.} \qquad \textbf{6.6}$$

where:
ΔH = Rise (or fall) in water table position (mm)
I = Inputs to the watertable e.g. net rainfall (mm.month^{-1})
$D.P.$ = Drainable porosity of a clay loam soil e.g. 0.143 cm^3.cm^{-3}

6.2.2 **Results and Discussion**

6.2.2.1 **Rainfall and evapotranspiration**

Figure 6.4 displays the daily evapotranspiration and rainfall data for the case study site from April 2011- July 2012.

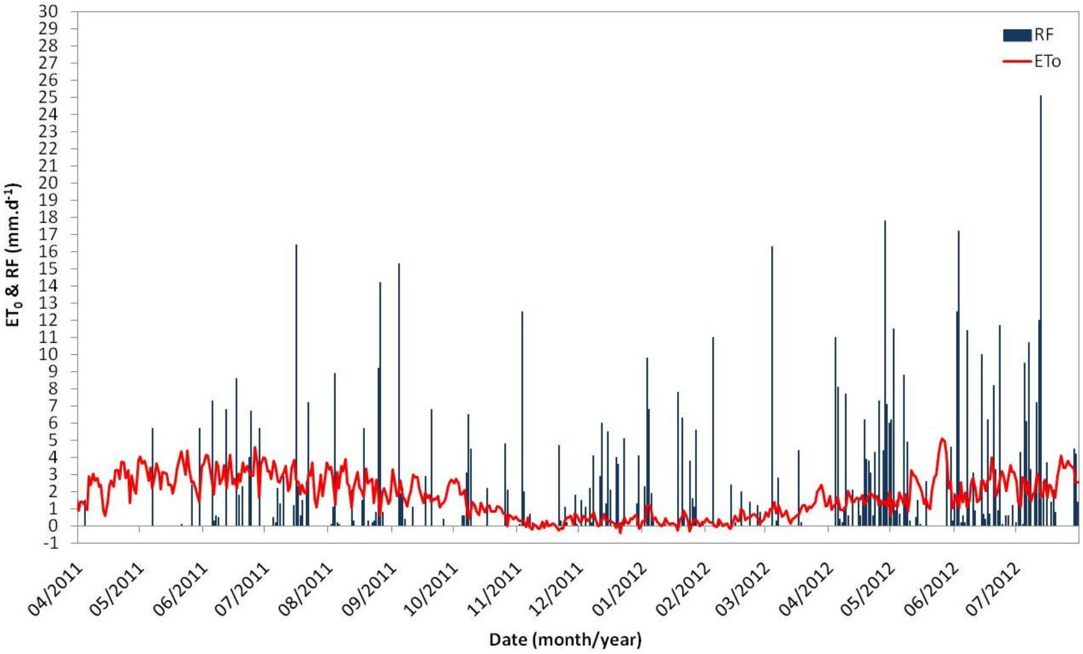

Figure 6.6 Case study floodplain monthly net rainfall (April 2011 – July 2012).

The monthly net rainfall from April 2011-July 2012 (Figure 6.7) was calculated for the case study site and divided into three event periods i.e. April-October 2011, November 2011-February 2012 and March-July 2012 based on the different patterns of net rainfall observed and winter and summer seasons.

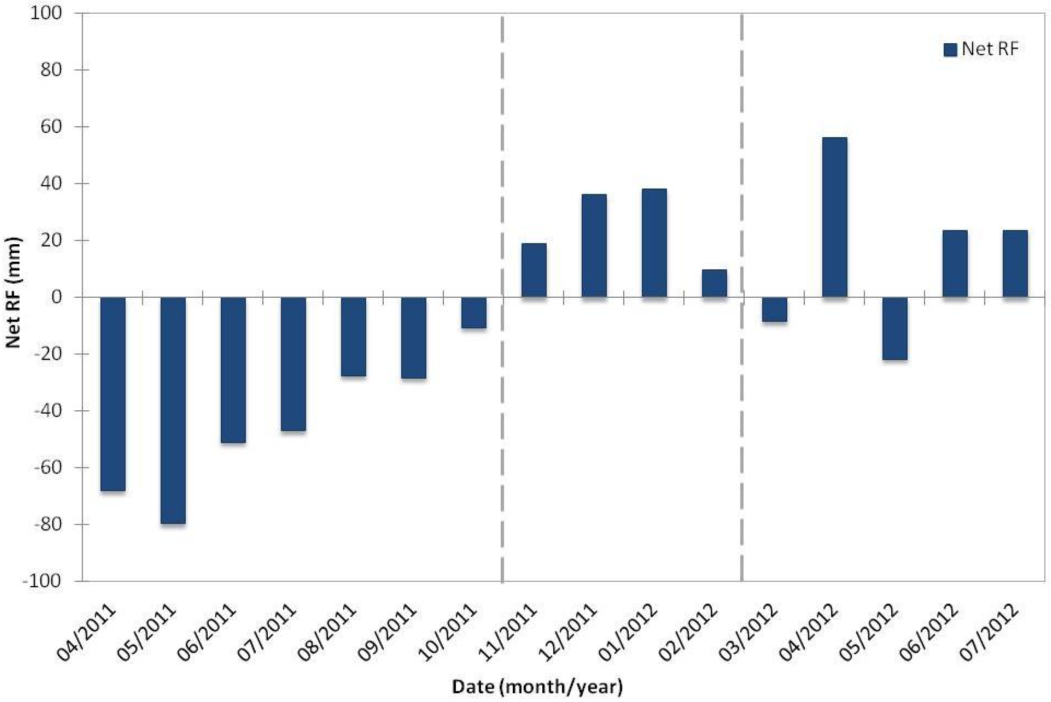

Figure 6.7 Case study floodplain monthly net rainfall (April 2011 – July 2012).

The following observations were made from the monthly net rainfall data:

- In April-October 2011 (Hydrological summer 1), the evapotranspiration was greater than the rainfall. The net rainfall gradually increases over the same period. These observations are considered normal for any given spring/summer season indicating drier periods. The lack of rainfall provides less opportunity for groundwater recharge through infiltration and percolation. Higher evapotranspiration rates lead to the removal of water from the soil surface affecting infiltration and percolation for groundwater recharge. The evapotranspiration may have an impact to the water table receding with little opportunity for groundwater recharge.
- In November 2011-February 2012 (Hydrological winter 1), the rainfall was greater than the evapotranspiration. The rainfall had risen to a peak in December 2011/January 2012 and declined towards February 2012. Low evapotranspiration and high rainfall rates may influence groundwater recharge and raise the water table level through infiltration and percolation from rainfall.
- In March-July 2012 (Hydrological summer 2), overall indicates that the evapotranspiration was greater than the rainfall except for the months March and May 2012. The net rainfall during indicating a wetter spring/summer and is in sharp

contrast to 2011 over the same period. While evapotranspiration is greater than the rainfall, there is still potential for groundwater recharge as a result of rainfall, infiltration and percolation. As the dominance of rainfall and evapotranspiration changes between the months, it is likely that the water level will rise and fall in direct response to these hydrological flows.

6.2.2.2 **Water table level**

Table 6.5 provides the results of the measurement of the local temporary benchmark at the field study site in order to generate a reference datum point to level survey the leveloggers/dipwells to establish the water table level position across the floodplain transect.

Table 6.5 Local temporary benchmark at the field study site

GPS date and time	Logs	GPS Elevation (mAOD)	Precision			Northing	Easting
			Vertical (m)	Horizontal (m)	Std. Dev.		
17/08/2011 11:24:26am	710	19.534	0.1	0.1	0.129201	252533.317	515485.003

The local temporary benchmark was derived as 19.53 mAOD from the post processed field measurements at the field study site with 0.1 m precision in the vertical and horizontal dimension. Appendix A displays the level surveying booking and reduced readings for the local temporary benchmark and dipwells. The final elevations of the top casing for each dipwell are displayed in Table 6.6.

Table 6.6 Dipwell elevations

Dipwell	Elevation (mAOD)
1	**18.3**
2	**17.7**
3	**17.9**

The barometrically compensated levelogger readings were compared to the manual measurements of the water table at the field study site for each levelogger to assess the accuracy of the levelogger readings and the susceptibility of the levelogger pressure sensors to drift during the monitoring period. Drift can occur incrementally over time with the assumption that it increases from the initial calibration point to the next calibration point. The correction and adjustment of data for drift needs to be determined at the correct manual measurement for example based on a trend of manual measurements moving in a positive or negative direction away from the field zero point. There are many factors contributing to drift such as temperature extremes, material responses of the unit to environmental changes e.g. pressure and temperature cycles (Solinst, 2007). Figures 6.8-6.10 displays the TEM 1-TEM 3 barometrically compensated water table levels referenced to mAOD and the manual measurements taken over the monitoring period.

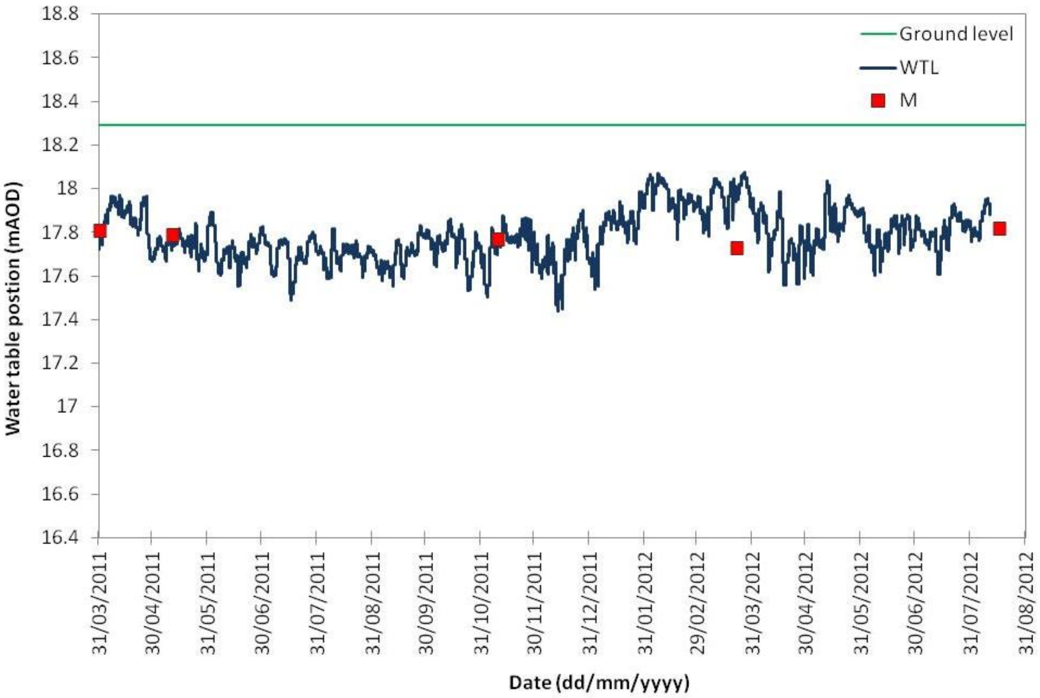

Figure 6.8 TEM 1 automated logger and manual measurement water table levels

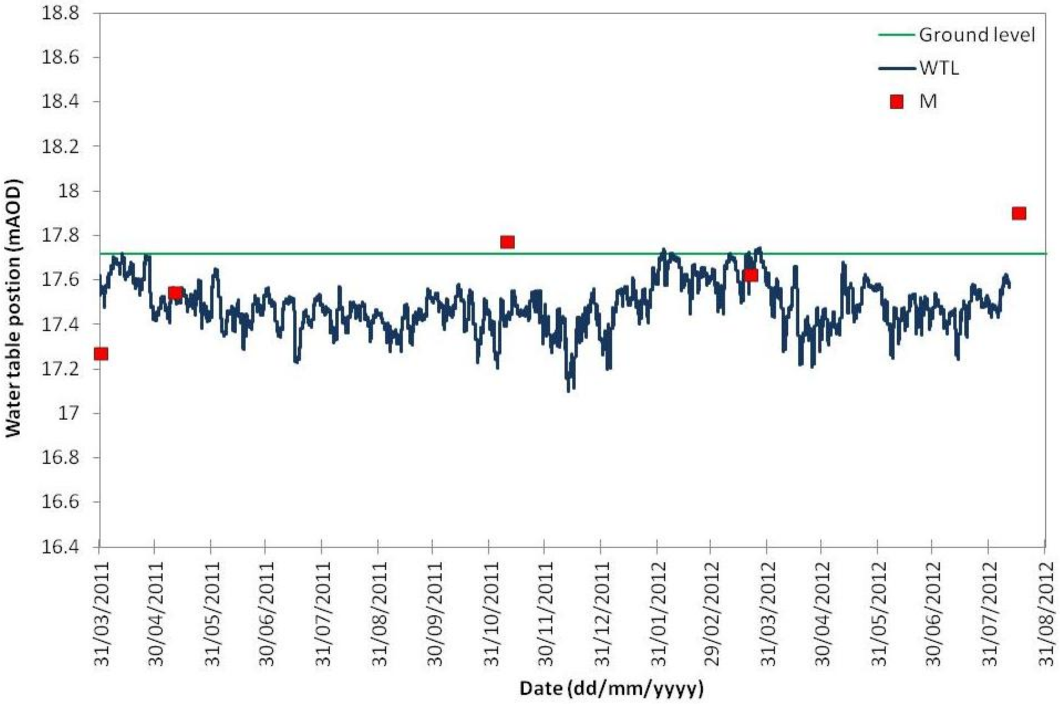

Figure 6.9 TEM 2 automated logger and manual measurement water table levels

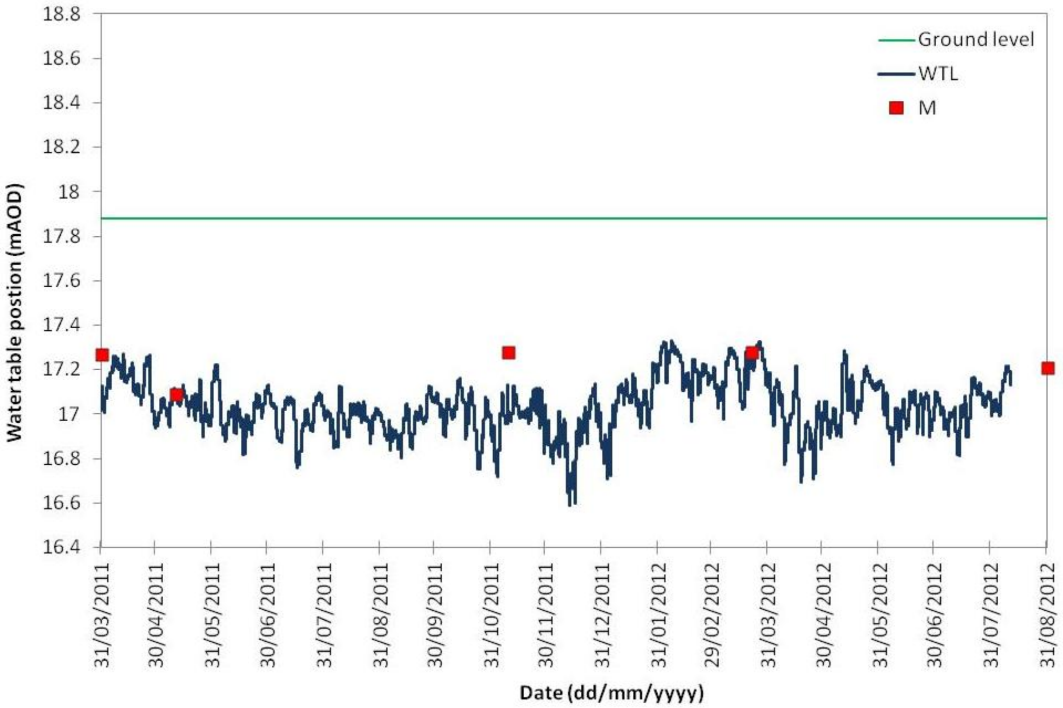

Figure 6.10 TEM 3 automated logger and manual measurement water table levels

The pressure sensors for all the three leveloggers were designed to be durable, corrosion resistance and provide long-term stability and accurate measurements (SWS, 2014; Solinst, 2007). The temperature cycles for the levelogger and barologger were assessed and found to be well within operating limits (SWS, 2014; Solinst, 2007). The difference between the levelogger water level and the manual measurement observed on 31/03/2011 can be ignored as the water table level would not have equilibrated upon installation of the automated leveloggers. The correction factor was applied to the levelogger water level based on the manual measurement for the 11/05/2011 as a calibration point taken after the pilot test were both the levelogger water level and manual measurement are the same value.

Assessment of the two subsequent manual measurements for each levelogger revealed a random pattern for the difference between the levelogger readings and manual measurements (Figure 6.8-6.10). The levelogger water levels were observed to be either above or below the manual measurements and beyond the acceptable accuracy range for each unit (SWS, 2014; Solinst 2007). The levelogger readings ranged from -0.06 to +0.31 m below or above the manual measurements.

The raw barologger level data was assessed and displayed a large pattern of variation with minimum and maximum range of 0.6 - 1.3 m. The pattern of variation was found to be in stark contrast to the water table levels of each levelogger which displayed diurnal fluctuations yet more stable water table levels. The barologger levels were then compared to the atmospheric pressure at Bedford and displayed the same pattern of fluctuation. Comparing the barologger measurement for each manual measurement on the 09/11/2011, the pressure had dropped by 0.1 m from a peak in pressure 3 days prior. On 22/03/2012, the pressure had dropped by 0.03 m from a peak in pressure 3 days prior. It is possible that the random pattern and variation of pressure may have had some influence on the calculated water table levels yet a conclusive reason for the differences cannot be confirmed.

The largest variation between the manual measurement and the levelogger water table level was observed on 09/11/2011 for TEM 2 where the levelogger water table level was 0.37 m above the manual measurement (Figure 6.9). This dipwell and levelogger was installed in a low depression of marshy grassland at the field study site. Over the course of the monitoring period, this depression became inundated from ponding water on the ground surface identified as a result of rainfall and potentially groundwater recharge and seepage. On 09/11/2011, ponded surface water was present. While, the dipwell and levelogger were located, the manual measurement was taken using a meter ruler with the distance measured from the top of the dipwell casing to the ponded water surface. The large difference could possibly be a product of movement of the dipwell or error in taking the manual measurement as the top of the dipwell casing was difficult to locate. The automated loggers all stopped recording data on 11/08/2012 just short of the designated monitoring period of the 31/08/2012. This was discovered after taking a manual measurement on the 16/08/2012 for TEM 1 and TEM 2 and 31/08/2012 for TEM 3 after downloading the water level data. TEM 3 dipwell could not be located on 16/08/2012 due to overgrown grass cover. Since only five manual measurements were taken, it was not possible to establish a trend of instrument drift, therefore the levelogger readings were not further adjusted since calibration applied on 11/05/2011. The mean absolute error between the manual measurements and the levelogger readings for all three dipwells at 11/05/2011, 09/11/2001 and 22/03/2012 was calculated as ±0.1 m in the water table position. These levelogger readings/manual measurements represented the water table levels taken since calibration of the leveloggers. Figure 6.11 displays the water table levels from TEM 1, 2 and 3 leveloggers observed at the field study site over the monitoring period from 31/03/2011 to 11/08/2012. The observed water table levels in Figure 6.11 were divided into three event periods i.e. April-October 2011, November 2011-March 2012 and April-July 2012 based on the pattern of observed net rainfall and hydrological seasons (Figure 6.7).

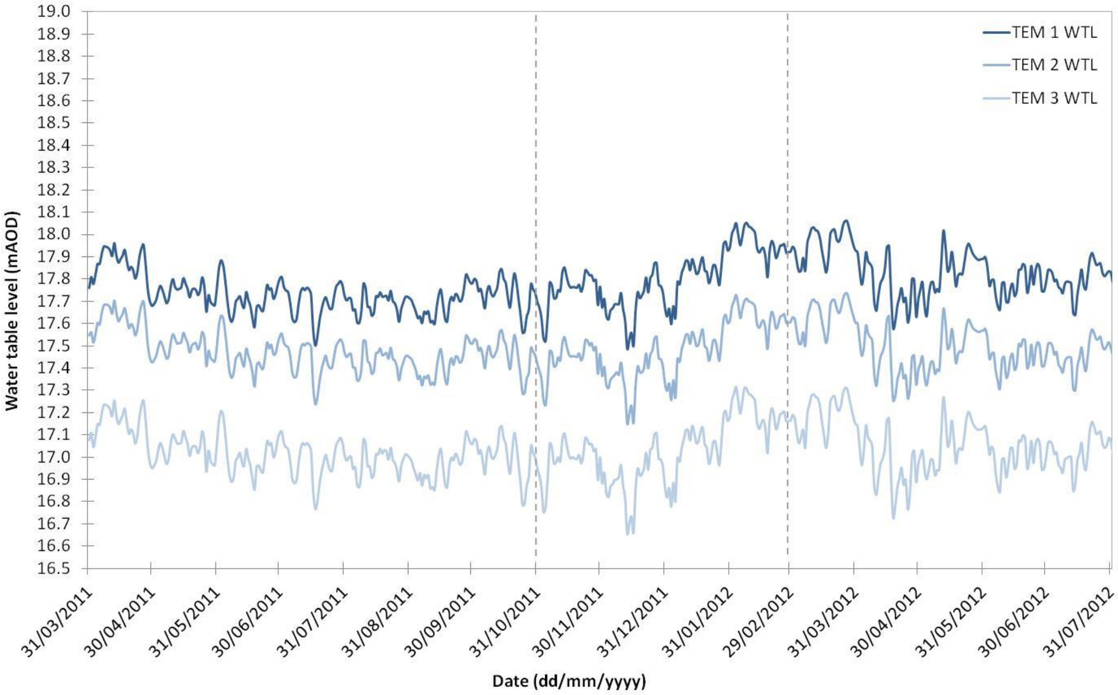

Figure 6.11 Field study site water table levels in ordnance datum

From April-October 2011 (Hydrological summer 1), the water table levels for all dipwells displayed the same pattern and fluctuate by ±0.1 m. The water table displays a steady decline between 0.1 and 0.2 m over the same period. From November 2011-February 2012 (Hydrological winter 1), the water table levels displayed the same patterns and fluctuate ±0.2 m and rise to a peak in February 2012. From November 2011-March 2012 (Hydrological summer 2), there is a slow decline in March 2012 onwards and the water table levels display the same patterns and fluctuate ±0.2 m with levels remaining high similar to the hydrological winter 1 period.

6.2.2.3 River stage

Table 6.7 displays the observed river stage (SG) on the River Ivel at 'Ivel at Blunham' FGS i.e. IV-03516 cross section and the modelled river stage at IV-01574 cross section at the field study site. The derived river stage data at the field study site for IV-01574 cross section is displayed in Figure 6.12.

Table 6.7 River stage field site correction factor

Survey Point	Description	National Grid Reference	Date and time	Observed river stage (mAOD)
IV-03516	Ive at Blunham FGS	TL15260 50921	27/01/2009 12:00	19.367
IV-01574	XS upstream of High Ramper Bridge	TL15469 52517	27/01/2009 12:00	17.960
			Correction factor	**1.407 m**

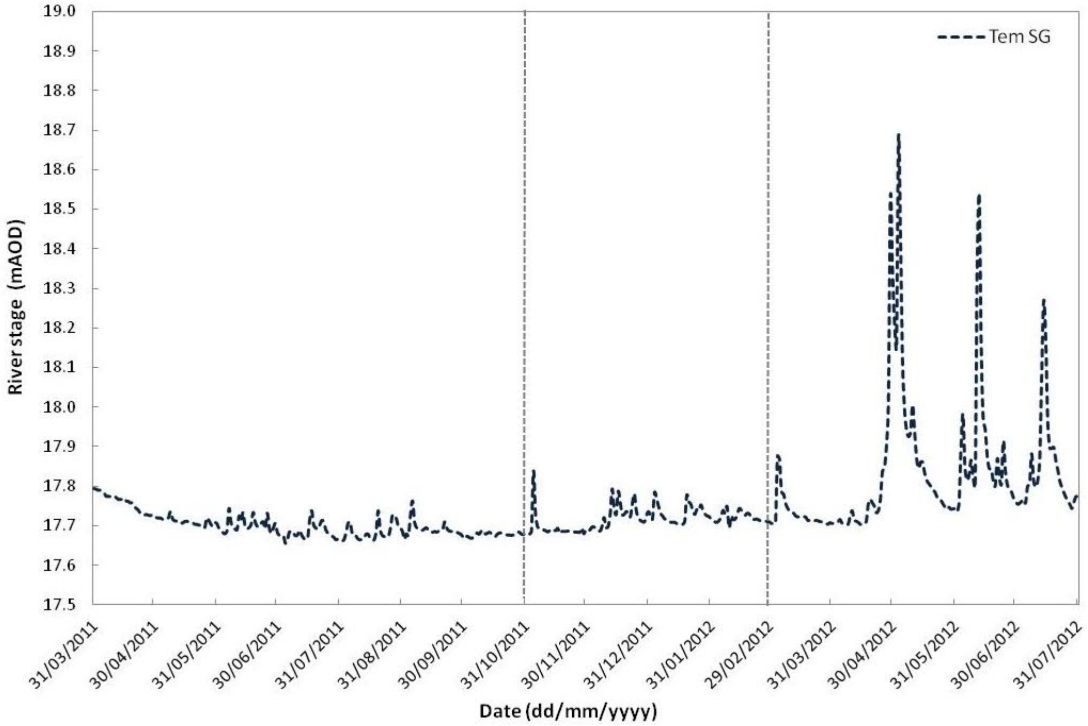

Figure 6.12 IV-01574 cross section derived river stage (TEM SG)

The derived river stage data for IV-01574 cross section on the River Ivel at the field study site were quite consistent and stable at 17.7 mAOD with minor fluctuations ranging from +10 to +20 cm from 31/03/2011 to 25/04/2012. From 25/04/2012 onwards the river stage had notable fluctuations rising from 17.7 mAOD to greater than 18.3 mAOD on three occasions. Comparing the same period for net rainfall (Figure 6.7),the rise in the river stage could potentially be a product of overland flow in the floodplain flowing into river channel leading a rise in the river stage. Table 6.8 displays the modelled river stage results for IV-01574 cross section on the River Ivel study reach at the field study site to assess the impacts of winter and summer seasonal vegetation growth on river stage levels.

Table 6.8 IV-01574 cross section Manning's ‘n' ±20% modelled river stage seasonal channel roughness results

Manning's 'n'		Hydrological Season	Modelled river stage (mAOD)	MAE (m)
ID	'n' value			
C.b.5 Max	0.04	Average	17.87	0
C.b.2 Normal	0.03	Winter	17.86	-0.008
C.b.6 Max	0.05	Summer	17.88	0.011

The modelled river stage was derived as 17.87 mAOD based on a Manning’s ‘n’ river channel roughness value of 0.04 (Table 6.8). Increasing or decreasing the Manning’s ‘n’ river channel roughness based on winter or summer vegetation growth displayed negligible results (Table 6.8).

6.2.2.4 **Hydraulic gradient and seepage rate**

The following section provides the hydraulic gradient calculated from the derived river stage at IV-01574 cross section in the River Ivel study reach and the observed water table levels at the field study site. Figure 6.13 displays the derived river stage (SG) and the observed water table levels (TEM 1, 2 and 3 WTL) at the field study site.

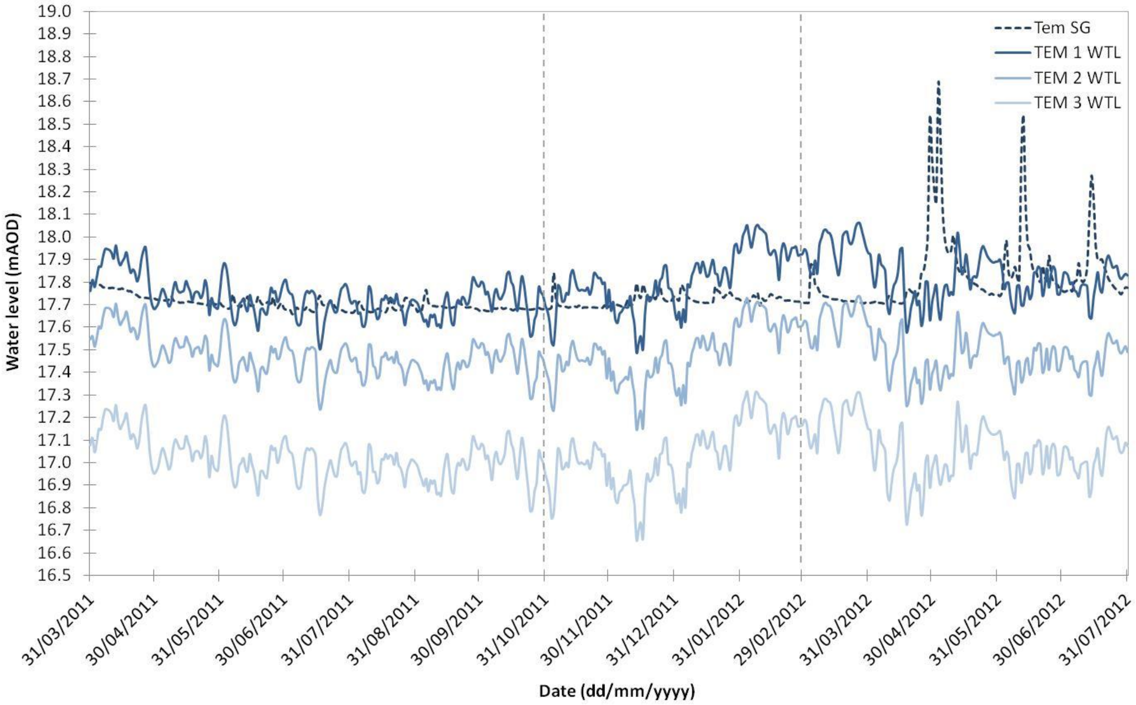

Figure 6.13 River stage and logger water table levels at the field study site

It is quite clear from Figure 6.13 that the hydraulic gradient of the water table is flowing away from the river especially from TEM 1 to TEM 2 to TEM 3, although the hydraulic gradient between the river and TEM 1 is more dynamic. TEM 1 flows towards the river and vice versa interchangeably throughout the monitoring periods. TEM 1 is 11.8 m from the river and the difference in head is potentially within a margin of error as the river stage was derived and not directly measured at the field study site. Table 6.9 displays hydraulic gradient results between the river and floodplain to indicate the duration and direction of seepage.

Table 6.9 % Hydraulic gradient of the river stage (TEM SG) and the water table (TEM 1).

Event	Time Period		Hydraulic gradient	
	Date range	Total Days	TEM SG > TEM 1	
			Days	%
Period 1	31/03/2011 to 31/10/2011	213	70	33
Period 2	01/11/2011 to 29/02/2012	120	29	24
Period 3	29/02/2012 to 31/07/2012	153	66	43

The hydraulic gradient results (Table 6.9) indicate that the groundwater is feeding the river through seepage from TEM 1 throughout the monitoring period. It is also evident that seepage occurs from the river to TEM 1 within each period yet occurring at different times (Figure 6.13). As the river stage was derived and not directly measured, there is a potential margin of error since TEM 1 is located 11.8 m from the river. Considering the water table and river stage (Figure 6.13) and the net rainfall (Figure 6.7), the river stage could potentially be equal to the water table level in periods 1 and 3. However, in period 2 (Figure 6.13), the observed increase in the net rainfall (Figure 6.7) may cause groundwater recharge in the floodplain causing seepage from the water table to the river channel. The seepage rates results for a range of hydraulic conductivity of a clay loam soil over the 3 seasonal event periods are displayed in Table 6.10.

Table 6.10 Seepage rates (mm.d^{-1}) from the river to the water table at the field study site

Soil Type	Hydraulic conductivity (m.d^{-1})	Seepage rates (mm.d^{-1})		
		Period 1 (summer 1)	Period 2 (winter 1)	Period 3 summer 2)
Clay Loam/ Clay poorly structured	0.02	-0.008	-0.021	0.000
	0.2	-0.079	-0.212	0.004
Loam/Clay loam/ Clay ,well structured	0.50	-0.197	-0.531	0.011
	2.0	-0.788	-2.125	0.043

The overall results (Table 6.10) indicate that the seepage rate increase with hydraulic conductivity values of 0.02, 0.2, 0.5 and 2.0 m.d^{-1} over all three periods. The negative values indicated that seepage occurred from the water table to the river channel and vice versa. The results confirmed that the seepage rates were generally low in all event periods. There was an increase in the seepage rate through the aquifer when higher hydraulic conductivity values were applied in all event periods. In period 2, the seepage rates were higher than in periods 1 and 3. This effect was likely the result of greater net rainfall (Figure 6.7) observed in period 2 leading to infiltration and percolation to recharge the water table causing greater seepage than in periods 1 and 3.

6.2.2.5 **Field site hydrology**

Figure 6.14 displays the daily net rainfall, derived river stage and levelogger water table levels at the field study site.

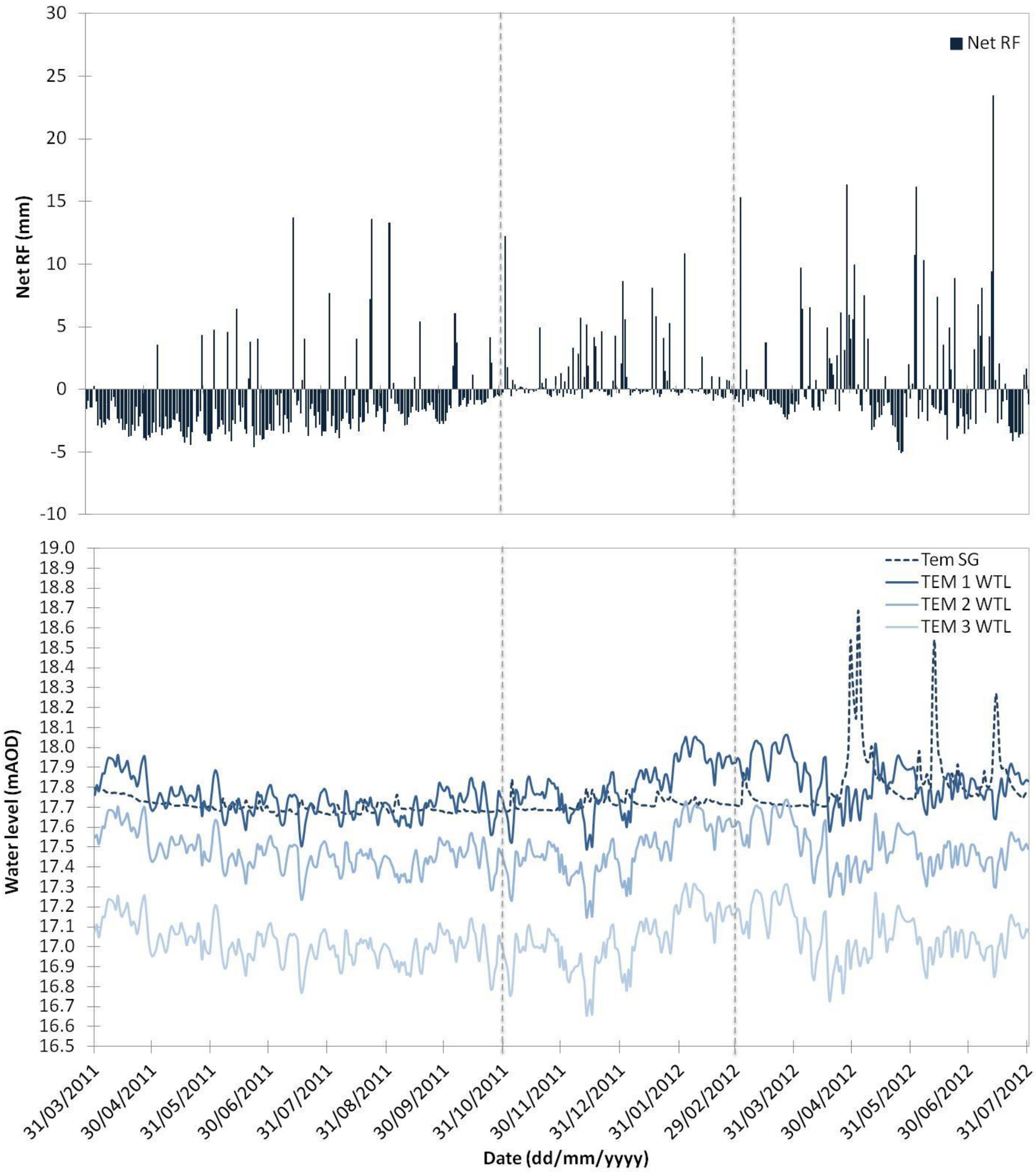

Figure 6.14 Daily net rainfall, levelogger water table levels and river stage for the monitoring period

From March-October 2011 (Hydrological summer 1), the net rainfall indicates that evapotranspiration > rainfall which will explain the slow decline in the water table position. A fall of -0.47 m in the water table position was calculated based on the April 2011 monthly net rainfall in event period 1. It is quite clear from Figure 6.14 that this did not occur with a potential fluctuation in the water table was observed as ±0.10 m.

For the same period, the hydraulic gradient results indicated that seepage occurred at 33% of the time from the river (Table 6.9). The hydraulic gradient between TEM 1 dipwell and the river is likely to be dynamic as the river stage was derived and TEM 1 dipwell is proximate to the river channel. Seepage will occur interchangeably between the river and TEM 1 dipwell (Figure 6.14). Seepage from the river potentially contributes to stabilising the water table level. The slow decline in water table level is a likely response to lower rainfall and higher evapotranspiration (Figure 6.14).

From November 2011-February 2012 (Hydrological winter 1), the net rainfall indicates that rainfall > evapotranspiration which will explain the increase in the water table position as result of infiltration and percolation. A rise of 0.13 m in the water table position was calculated based on the November 2011 monthly net rainfall and a rise of 0.26 m in the water table position based on January 2012 monthly net rainfall. For the same period, the hydraulic gradient results (Table 6.9) indicated that seepage occurred at 24% of the time from the river (Figure 6.14). It can be deduced from Figure 6.14 that the water table fluctuations are in response to the increase in rainfall causing a rise in the water table.

From March-July 2012 (Hydrological summer 2), the net rainfall indicates that rainfall > evapotranspiration over the whole period. The water table position was calculated based on net rainfall considering three examples as follows:

- a drop of -0.05 m in the water table position based on the March 2012 monthly net rainfall.
- a rise of 0.39 m in the water table position based on April 2012 monthly net rainfall.
- a rise of 0.16 m in the water table position based on June 2012 monthly net rainfall.

This rise in the water table position is possibly the result of infiltration and groundwater recharge from rainfall in the floodplain and seepage from the river due to a rise in the river stage as a result of direct rainfall and potentially overland flow. The fall in the water table position is due to evapotranspiration occurring in general every second month during the event period and seepage from the groundwater to the river. For the same period, the hydraulic gradient results indicated that seepage occurred at 43% of the time from the river (Table 6.9). The hydraulic gradient between TEM 1 dipwell and the river is likely to be dynamic as the river stage was derived and TEM 1 dipwell is proximate to the river channel. Seepage will occur interchangeably between the river and TEM 1 dipwell (Figure 6.14). This will lead to stabilising the water table position and causing a rise and fall in response to the change in rainfall and evapotranspiration.

6.3 Hydrological events

6.3.1 Design flood events

6.3.1.1 Introduction

A range of design flood events in percentage annual exceedance probability (% AEP) i.e. the probability of a flood event being equalled or exceeded in any year was selected (EA, 2013). These % AEP design flood events are described by high to low frequency/magnitude flood events i.e. 50, 20, 10, 4, 2, 1.33 and 1% AEP for flood routing. This particular range of design flood events were selected to represent natural conditions in a floodplain (50% AEP) to extreme conditions (1% AEP) with regard to flood frequency and magnitude.

Flood events can have an impact on the delivery of ecosystem services to create synergies and trade-offs amongst multiple ecosystem services (Tockner and Stanford, 2002). In particular, the flood frequency and magnitude can also have contrasting impacts on the delivery of benefits and disbenefits in ecosystem services with examples as follows:

- Tockner and Stanford (2002) discussed that high frequency/low magnitude flood events are necessary to maintain habitat diversity and functionality in the floodplain. Kazama et al. (2007) discussed that larger floods lead to greater inundation in the floodplain and groundwater recharge providing greater water resources. Although, the same study also discussed that larger magnitude flood events can destroy agricultural productivity as a result of floodwater inundation in the floodplain.
- MAFF (1999) provided indicative standards of protection for land use describing that the greater the density of properties and productivity of agricultural land requires greater protection especially from low frequency/high magnitude flood events.
- Penning-Rowsell et al. (2005) discussed that flood probability is a crucial factor for land use and crop tolerance (Table 6.11). If the flood frequency and magnitude for each land use is outside the tolerance flood probabilities, this leads to a reduction in crop yield.

Table 6.11 Maximum flood probability tolerance by different agricultural land uses and crop source

Land use	Whole year	Summer (April-October)
	%AEP	
Horticulture	5%	1%
Intensive arable including sugar beet and potatoes	10%	4%
Extensive arable: cereals, beans, oil seeds	20%	10%
Intensive, improved grass, typically dairy cows	50%	20%
Extensive grass: usually cattle and sheep	≥100%	33%

Source: Penning-Rowsell et al. (2005, p. 62)

The selection of these design flood events is critical for the assessment of the impacts of floodplain connectivity configurations to deliver ecosystem services. These flood events were applied as hydrographs to represent the upstream boundary describing the change in discharge over time to enable flood routing with the linked ISIS 1D-2D hydrodynamic model (Halcrow, 2010).

6.3.1.2 **Methodology**

The application of flood estimation handbook (FEH) methods were reviewed in order to generate the range and series of design flood event hydrographs. The Revitalised FSR/FEH rainfall-runoff method involves the application of the Revitalised flood hydrograph (ReFH) rainfall-runoff model to derive flood event hydrographs (Kjeldsen, 2007). This method was applied as the preferred option in the context of this research and as it meets the following FEH guidelines and recommendations, Table B.1 (Bayliss, 1999; Reed and Houghton-Carr, 1999).

- A hydrograph was required for the 1D hydrodynamic model.
- The catchment is smaller than 1000 km^2 and not highly permeable e.g. (BFIHOST<0.65).
- The catchment is slightly urbanised (URBEXT$_{1990}$: 0.0441).
- Non-gauged catchment.
- Research requires flood storage and routing.
- ReFH model is adequately calibrated to catchment areas: 500-750 km^2
- Model has been calibrated for flood events up to 0.66% AEP.

A point upstream on the River Ivel (TL15450 52600) was selected to extract the catchment descriptors and depth, duration, frequency (DDF) model parameter values for the case study site using the FEH CD-ROM version 3 (CEH, 2006). These values are presented in Appendix B, Table B.1.1. The catchment descriptors and DDF model parameters for the case study site were then exported to the ReFH spreadsheet in order to create hydrographs for the design flood events utilising the Revitalised FSR/FEH rainfall-runoff method (Kjeldsen, 2007).

6.3.1.3 **Results and Discussion**

In order to run the ReFH model, calculation of the design rainfall inputs i.e. Duration (hr) and Time to peak (T_p) were required (Kjeldsen (2007). The winter season was automatically selected based on the URBEXT value of less than 0.125 (Kjeldsen, 2007). All other parameters for the ReFH model utilised the catchment descriptors and ReFH design standard in order to generate the design flood event hydrographs. The ReFH model calculated the rainfall, net rainfall, total flow, direct runoff and baseflow for each respective flood event. The total flow as per ReFH shall be referred to as 'discharge' in this research. The ReFH model parameters were applied for each design flood event in the ReFH model to generate a flood hydrograph. T_p was calculated as 15 hours, ΔT was calculated at 3 hours and the duration was calculated at 5 hours. A summary of model parameters and all design flood event hydrograph simulation results are displayed in Appendix B.2. The discharge hydrographs for each design flood event were extended from the initial 69 hours to 90 hours on the falling limb to meet the initial discharge of the rising limb and to extend the discharge to evaluate the effects of flood routing for an extended hydrograph. Extending the total flow also accommodates any potential effects that may be observed from the linked ISIS 1D-2D hydrodynamic model simulations on the falling limb and depletion curve of the design flood event hydrographs. An exponential decay calculation was applied to the baseflow for each flood event at the 69th hour to extend the discharge hydrograph to 90 hours where the baseflow meets the discharge (Appendix B.2). Figure 6.15 displays the discharge for all design flood event hydrographs for a 90-hour period.

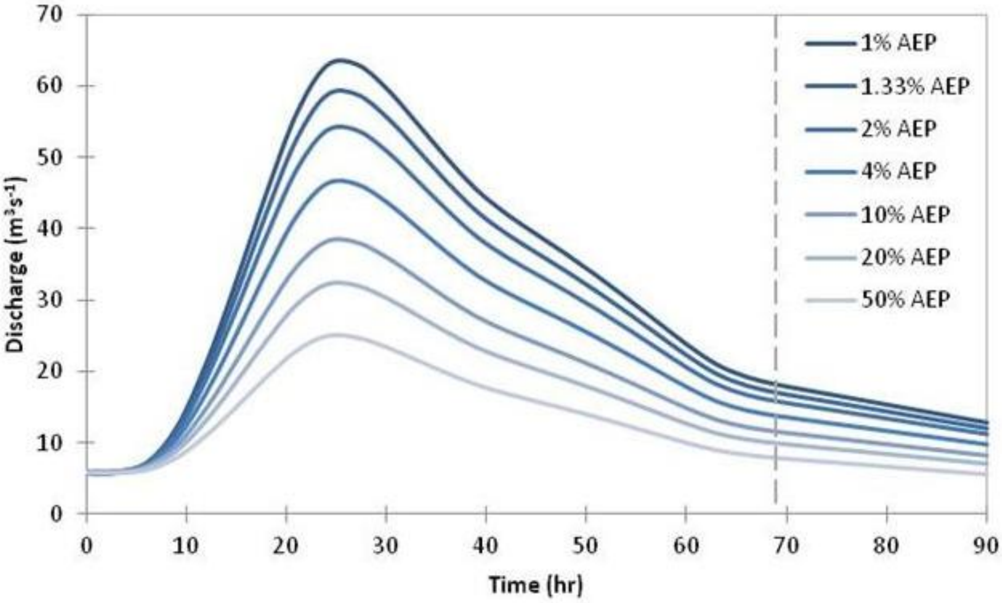

Figure 6.15 % AEP design flood events discharge hydrographs

It was observed that the initial discharge of the design flood event hydrographs in the ReFH models vary substantially from the discharge at the inflection point on the recession limb for each flood event hydrograph (Figure 6.15, Appendix B.2). The baseflow represents a linear relationship from the initial discharge where hydrograph separation occurs on the rising limb between the surface and baseflow and then meets at the inflection point on the recession limb (Shaw et al., 2011). The discharge difference between the baseflow separation and the inflection point of the design flood event hydrographs were a result of the short storm design duration e.g. 15 hours and the estimated baseflow parameters (BL and BR) which are a constraint of the ReFH method applied. Reed and Houghton-Carr (1999) and Kjeldsen (2007) discussed that estimates of the ReFH model parameters made in this form in order to produce design flood event hydrographs may be accompanied by relatively large uncertainties. This is largely due to the utilisation of regression relationships, limited data and imperfection on the regression models and thus a constraint and limitation of the model design (Kjeldsen, 2007).

6.3.2 Seasonal years

6.3.2.1 Introduction

Seasonal years were classified in this research as wet, dry and average years based on the four seasons of the year in accordance with FAO guidelines (Dunderdale and Morris, 1997). The seasonal year events in this research are representative of rainfall which may cause infiltration and groundwater recharge to impact on the water table position in the floodplain. Figure 6.16 provides a conceptual diagram of the impacts on the water level in the river and the position of the water table in the floodplain in response to seasonal year events.

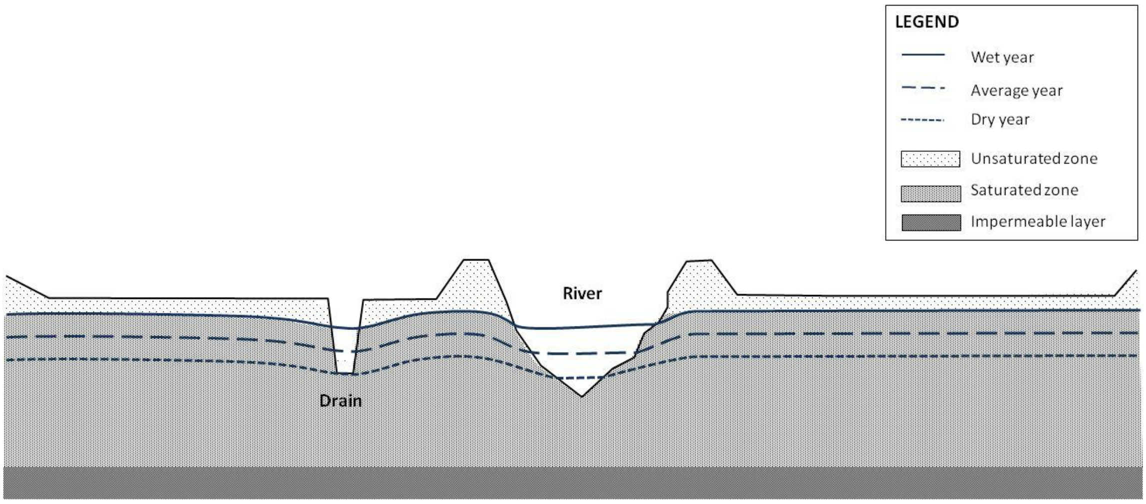

Figure 6.16 Conceptual diagram of seasonal year event impacts on the water table position in a floodplain

The wet, average and dry years can have an impact on the drainage status and water table position hence affecting agricultural productivity (Dunderdale and Morris, 1997). Wheeler et al. (2004) discussed the importance of the impact of water table depths throughout a calendar year and encompassing seasons for the conservation of lowland wetland plant communities. The same study described how water table depths outside of the desirable or especially tolerable limits may lead to gradual loss of a plant community characteristic and/or a change in community composition due to low or high water tables. Water table control during seasons can be critical to deliver agricultural productivity and terrestrial habitat ecosystem services. These hydrological events were also derived to apply as climate input data for the WaSim model for vertical connectivity modelling as part of the integrated modelling system to assess the impacts of floodplain connectivity controls on ecosystem service delivery.

6.3.2.2 **Methodology**

The total rainfall for each given hydrological year (1 October – 30 September) was calculated within the historic rainfall data period 1984-2012 for Great Staughton rainfall station. The calculations for each seasonal year were selected and based on methods described in Dunderdale and Morris (1997) as follows:

- Wet year: the hydrological year with total rainfall more than 125% of the mean representing the highest total rainfall for the wet seasonal year event scenario.

- Average year: the hydrological year for the calculated average total rainfall representing the average seasonal year event scenario.
- Dry year: the hydrological year with total rainfall less than 75% of the mean representing the lowest total rainfall for the dry seasonal year event scenario.

6.3.2.3 **Results and Discussion**

Figure 6.17 displays the total rainfall for each hydrological year in the historic data period at Great Staughton rainfall gauge.

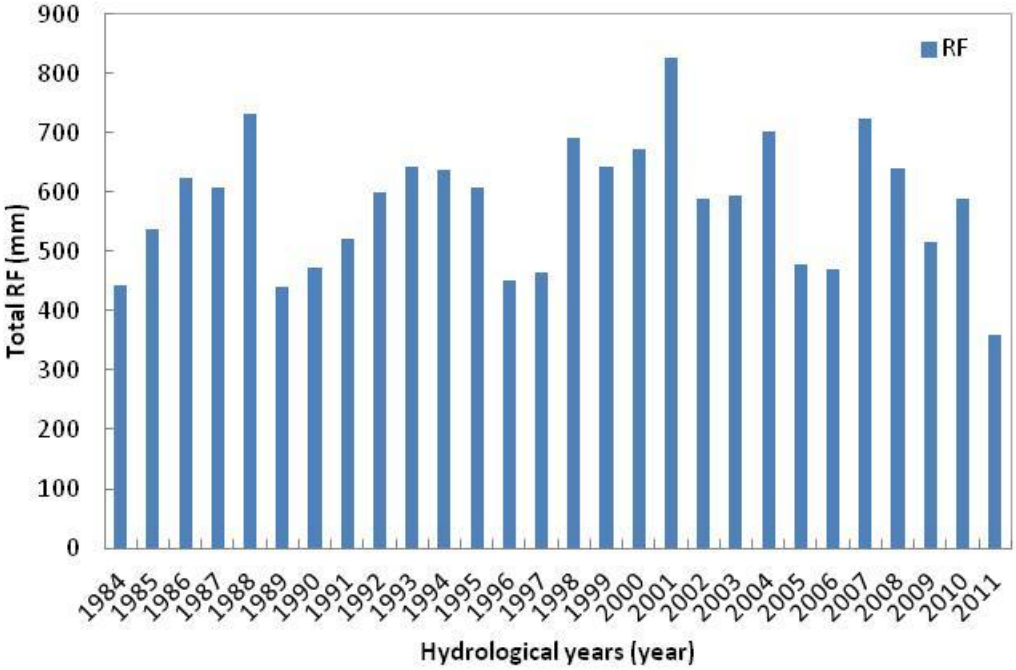

Figure 6.17 Total rainfall for each hydrological year from historic records at Great Staughton rainfall gauge

The seasonal year scenarios and their corresponding hydrological year and total rainfall are displayed in Table 6.12.

Table 6.12 Seasonal year scenario, hydrological year and corresponding total rainfall

Seasonal year event scenario	Hydrological Year	Rainfall (mm)
Wet	2007	726.5
Average	2002	581.2
Dry	1989	435.9

6.3.3 **Floodplain connectivity scenarios**

This research will apply a range of lateral and vertical connectivity scenarios in the integrated modelling system to understand the impacts of floodplain connectivity on ecosystem service delivery. The floodplain connectivity scenarios will be simulated for each lateral connectivity scenario under a range of vertical connectivity scenarios to also assess the interaction of both types of connectivity to enable ecosystem service delivery while exploring the effects on synergy and trade-offs amongst multiple ecosystem services.

The lateral connectivity scenario configurations applied in this research are as follows:

- A bankfull stage: The bankfull stage describes the riverbank elevation point of incipient flooding. Leopold et al. (1964) described that the bankfull stage of a natural riverbank at a floodplain represents a 50% AEP flood event.
- Embankment/flood wall (uniform longitudinal crest): crest elevation for a standard of protection based land use (MAFF, 1999). The embankments/flood walls have uniform crest elevations along the river channel.
- Embankment/flood wall (non-uniform longitudinal crest): This type of embankment is based on channels with variable bank crest elevations, which could partly be as a result of natural avulsion or artificial modification due to river dredging placement.

Four different lateral connectivity scenarios were applied in this research as an example to study the impacts of lateral connectivity on ecosystem service delivery as described in Table 6.13.

Table 6.13 Lateral connectivity scenarios for the flood inundation models

ID	Lateral connection type	Standard of protection	Description
1	No embankment (50% AEP)	50% AEP	Natural riverbank: Riverbank elevation based on the bankfull stage and floodplain topography at river banksides
2	SOP embankment (20% AEP)	20% AEP	Embankment (Uniform longitudinal bank crest): Artificially modified embankment based on SOP for Land use band C
3	Existing embankment (10% AEP)	10% AEP	Embankment (Mixed bank crest uniformity): Existing embankment made up of 10% AEP SOP for 1.7 km uniform crest and non-uniform crest along the river from natural and artificially modified processes
4	SOP embankment (4% AEP)	4% AEP	Embankment (Uniform longitudinal bank crest): Artificially modified embankment based on SOP for Land use band B

These lateral connectivity scenarios serve as examples of decreasing connectivity i.e. raising embankments for hydraulic control and considering natural and artificially modified riverbanks and embankments. Scenario (1) is of particular importance to the habitat ecosystem service. Amoros and Bornette (2002) described how permanent and episodic links between the river and floodplain and frequent flooding are preferable to increase habitat productivity i.e. plant species diversity and heterogeneity and for the recruitment and sustainability of fish populations. Scenarios (2-4) are of particular significance to lateral connectivity and hydraulic controls to protect against impacts of flooding to agricultural productivity and flood damage ecosystem services as based on indicative standards of protection (MAFF, 1999). An illustrated example of the lateral connectivity scenarios applied in this research is displayed in Figure 6.18 (1, 2, 3 and 4).

- No embankment (50% AEP): Figure 6.18 (1)
- SOP Embankment (20% AEP): Figure 6.18 (2)
- Existing Embankment (10% AEP): Figure 6.18 (3)
- SOP Embankment (4% AEP): Figure 6.18 (4)

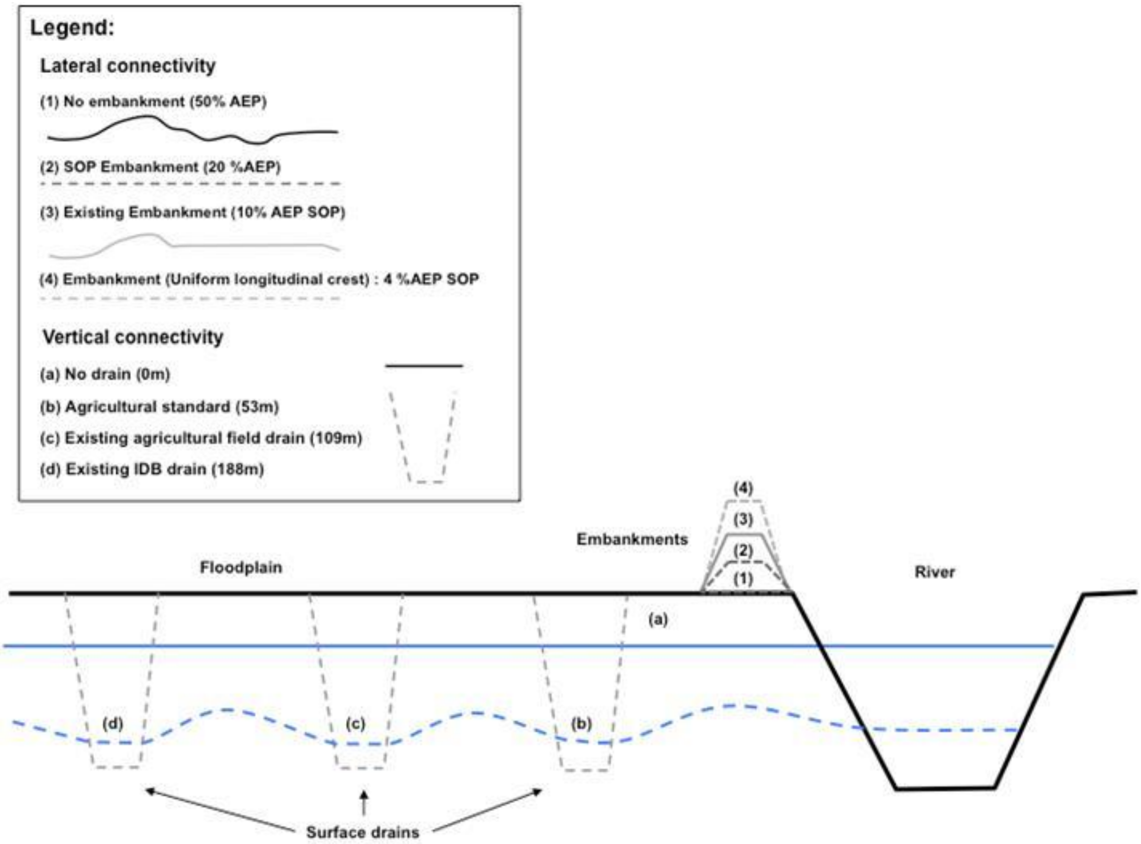

Figure 6.18 Lateral and vertical floodplain connectivity scenarios diagram

The vertical connectivity scenario types applied in this research are as follows:

- Natural: a floodplain with no drainage system.
- Artificial: application of design surface drains for multiple purposes i.e. agricultural productivity, flood inundation surface runoff control, habitat conservation/maintenance and the existing surface drains.

Surface drainage systems were chosen as they are traditional drainage systems applied to fields to manage and control the water table for agricultural purposes. (Castle et al., 1984). They function through the collection of surface flows to alleviate ponding as a result of direct rainfall and/or flood inundation providing a dual function of intercepting surface and groundwater in the hydrological surface and subsurface systems. They are also applied to control surface runoff on sloping land or especially in soils with poor permeability (Smedema et al., 2004). Henderson and Farr (1992) discussed that surface drainage systems are also valuable wildlife habitats as they traverse numerous land environments acting as corridors for wildlife while also providing direct support for multiple species. Water table control is delivered through drain spacing, which is a function of drain depth and soil permeability (Youngs, 1992; Castle et al., 1984). The drain spacing is the critical component of water table control to lower or raise the water table by decreasing or increasing drain spacing respectively (Youngs, 1992). The drain spacing for each scenario is based on surface drainage for agricultural productivity and surface runoff management (Henderson and Farr, 1992; Castle et al., 1984). Four different vertical connectivity scenarios are applied in this research as an example to study the impacts of vertical connectivity on ecosystem service delivery as described in Table 6.14.

Table 6.14 Vertical connectivity scenarios for the agrohydrological model

ID	**Vertical connectivity scenario**	**Drain Spacing (m)**	**Description**
(a)	No drain	0	Natural: ‘no drainage system’
(b)	Agricultural standard	53	Artificial: Agricultural drainage ditch representing pasture land management based on the field study site soil type, hydraulic conductivity of soil and agro-climate area
(c)	Existing agricultural field drain	109	Artificial: Existing agricultural field drain for pasture land management
(d)	Existing IDB field drain	188	Artificial: Existing IDB surface field drain for water level management for ▪ agricultural land drainage, ▪ flood risk management ▪ surface water management i.e. amenity and biodiversity maintenance and conservation

These vertical connectivity scenarios serve as examples of increasing drain spacing for hydraulic control considering a natural floodplain system with no surface drains and an artificially modified floodplain with surface drains.

The natural scenario (a) considers a floodplain with no drainage system. This research defines a natural floodplain with no drainage as utilising the existing topography of the floodplain. This scenario allows the water table to be controlled naturally by the hydrological cycle through direct rainfall, flood inundation and soil and geological permeability. The artificial scenarios (b-d) are of particular significance to vertical connectivity and act as hydraulic controls to protect against impacts of waterlogging/ponding, surface runoff from direct rainfall or flood inundation, water table level management to promote crop yield, reduce trafficability and also habitat conservation and maintenance (Smedema et al., 2004; Castle et al., 1984).

An illustrated example of the vertical connectivity scenarios applied in this research is displayed in Figure 6.18 (a-d)

- Natural (no drainage system): Figure 6.18 (a)
- Artificial (Agricultural standard): Figure 6.18 (b)
- Artificial (Existing agricultural field drain): Figure 6.18 (c)
- Artificial (Existing IDB drain): Figure 6.18 (d)

6.4 Lateral connectivity modelling

6.4.1 **Methodology**

6.4.1.1 **River schematisation**

The upstream boundary of the River Ivel study reach chainage extends from TL15350 50981 for 3.36 km to the downstream boundary at TL16086 53487 (Figure 6.19). The River Ivel is anatomised at the upstream and downstream sections (Figure 6.19) and contains a number of bridges. Cross sections of the River Ivel study reach extending from IV-03418 to IV-00052 at upstream and boundary locations as specified above were provided as secondary data by the Environment Agency. These cross sections were surveyed from December 2008 to February 2009 by Cartographical Surveys Ltd for the purpose of flood risk modelling to generate flood maps by the Environment Agency. The horizontal extent of each cross section encompassed the river bed, river banks, and a few metres either side of the present embankments and high surface elevation from the river banks. The specific cross sections and their locations had been surveyed based on the following:

- All major flow obstructions e.g. bridges.
- Level and/or river flow gauging stations.
- Significant changes in the geometry of the river channel.
- Significant changes in the Manning's 'n' values in the river channel.
- At or near embankments.
- Locations just upstream and downstream of significant tributaries in the river system.
- Boundaries at the start and end points of a main river and at the ends of tributaries under study.
- Significant changes in the river slope or at or near control sections where critical depth may occur e.g. weirs.

There were 22 cross sections surveyed on the River Ivel at the case study site location with the average cross section spacing of 153 metres (Appendix C, Table C.1.1). The cross sections surveyed indicated that the spacing was reduced specifically at the location of bridges, which also functions to enable improved modelling of flow through the openings (Haestad Methods et al., 2007).

The river schematisation in the model excluded the anatomised river cross sections and only included the main river, replacing the bridges with weirs. This was to allow representation of a natural river system using the data from the River Ivel as an example and also to aid in model building efficiency. Round nosed broad crested weirs were applied at IV-2595 and IV-1013 cross sections to allow simulation of discharge representative to the natural system in place of bridges. The weir crests were designed with the geometry data extracted from the IV-02414 and IV-00805 cross sections (Appendix C, Table C.2.1). The length of the weirs was set at 1 m to represent the change from subcritical to supercritical flows in the natural system. Six interpolated cross sections (Appendix C, Table C.3.1) were added specifically at the weirs, where the cross section spacing was greater than 200 metres. This was to improve the hydraulic flow simulation ensuring a smooth graduation between cross sections and to minimize model errors and instability (Haestad Methods et al., 2007).

6.4.1.2 **Floodplain schematisation**

Light Detection And Ranging (LiDAR) Digital Terrain Model (DTM) data at 1 m grid cell resolution was extracted from OS tiles i.e. TL1453, TL1452, TL1451, TL1553, TL1552, TL1551, TL1653, TL165 and TL1651, from the Environment Agency geomatics group. This LiDAR DTM data was in the format of topographic data of the base terrain, which excludes tree canopy and buildings for example.

The floodplain boundary i.e. ISIS 2D active area was generated as per methods in Halcrow (2010) by creating a boundary following the riverbanks and extending the floodplain width beyond the EA flood zone 2: 1% AEP flood event from the upstream to the downstream cross sections of the River Ivel study reach (Figure 6.19). This enables the linked ISIS 1D-2D model to perform hydrodynamic computations across a structured square grid to model flood inundation to calculate the output variables e.g. water level, depth, flow and velocity within this area boundary and not beyond (Halcrow, 2010; Néelz and Pender, 2009).

The computational grid size of the LIDAR DTM in the floodplain boundary is an important parameter in regard to accuracy of model predictions, computation time and storage space requirements. In general, smaller grid sizes lead to higher accuracy in model predictions yet longer computations times and greater computational storage space is required for a model simulation (Chatterjee et al., 2008; Hunter et al., 2007). Small grid sizes are also useful to represent the flow dynamics of and within small features in a floodplain when investigating impacts of flood inundation (Chatterjee et al., 2008). This same study discussed that higher resolution grids e.g. 50 m in comparison to 25 m and 8 m grids can yield good results while providing a significant reduction in computational times and storage requirements. Bates and De Roo (2000) stated that grid resolutions of approximately 25-100 m would seem appropriate for most floodplain applications, although smaller resolutions are preferable. Model results can be overly dependent on timestep values with a given grid size requiring a small timestep to guarantee model run stability and increase convergence. The LIDAR DTM of the floodplain boundary displays mainly uniform topographic elevation especially over larger areas (Figure 6.19). For this research, the grid resolution of the linked ISIS 1D-2D model was resampled at 20 m and deemed suitable for its intended purpose to yield good results and reduce computational times.

The Manning’s ‘n’ roughness for the floodplain was described by predominantly pasture grassland surface roughness for the case study floodplain by interpreting Ordnance

Survey maps (OS, 2009a,b). The nearest corresponding Manning's 'n' value from Chow (1959, p. 113) was deduced as a floodplain, pasture, no brush with short grass. The Manning's 'n' normal value of 0.030 was selected and applied as the global roughness value for each floodplain connectivity scenario in the ISIS 2D model.

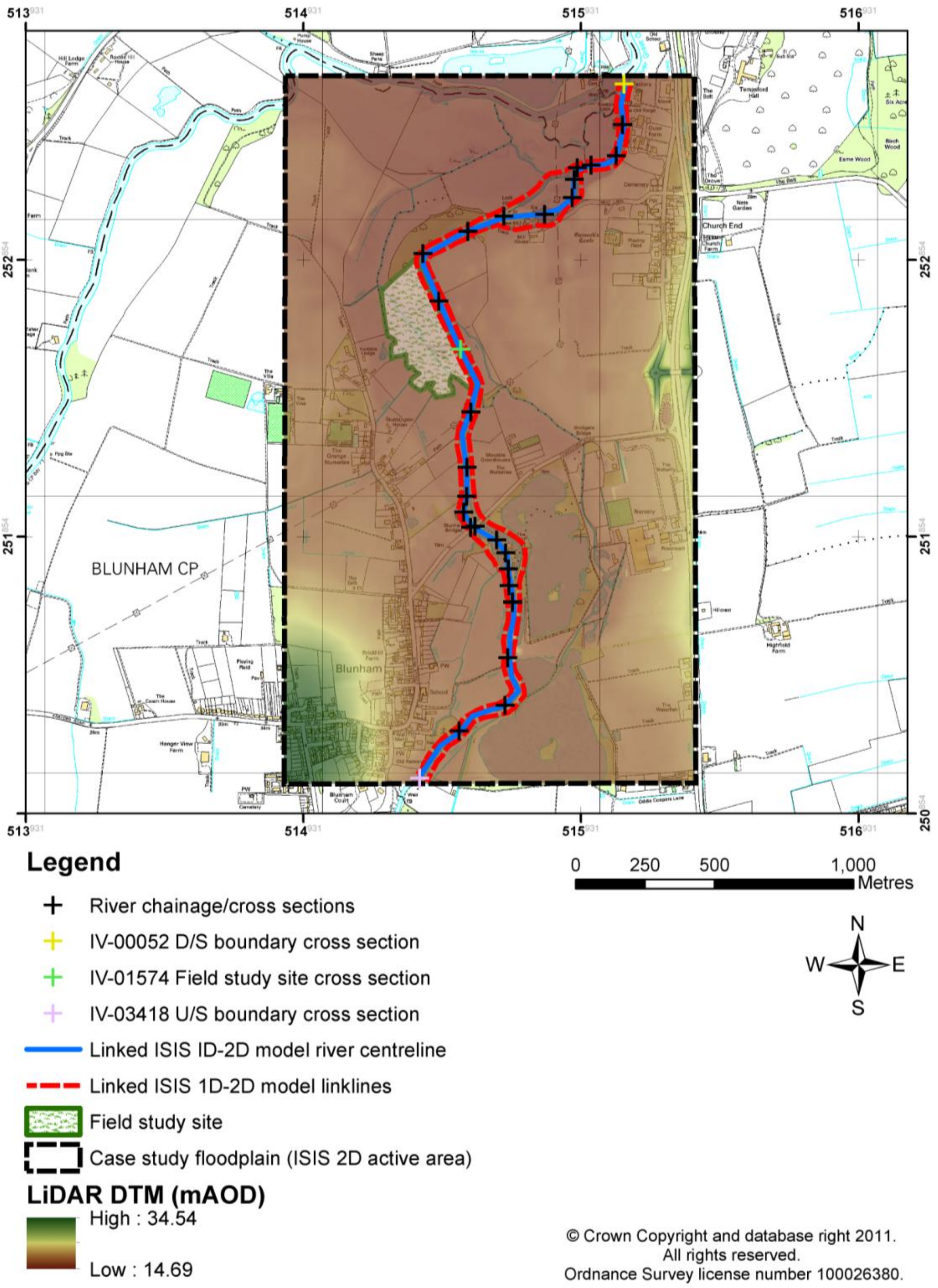

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Figure 6.19 Aerial view schematic of the linked ISIS 1D-2D model boundaries

6.4.1.3 **Lateral connectivity**

Modelling each lateral connectivity scenario in the linked ISIS 1D-2D model required the following:

- Editing the left and right bank points for each respective cross section corresponding to each ISIS 1D model lateral connectivity scenario.
- Creation of linklines in ISIS 2D to communicate the linking of the ISIS 1D and 2D hydrodynamic models and water transfer between the models.

The original chainage and cross section data of the River Ivel study reach was provided by the Environment Agency and included ground level elevations and the lateral distance between each elevation describing the riverbed, banks and partial extension into the floodplain as illustrated in Figure 6.20. For the ISIS 1D models, Table 6.18 describes the cross section editing method performed for each lateral connectivity scenario.

Table 6.15 ISIS 1D cross section editing method for each lateral connectivity design and description

Scenario	**Type**	**Method**	**Description**
1	No embankment (50% AEP)	Cross section trimming	Cross sections are trimmed to the riverbank level representing the floodplain elevation (Figure 6.20)
2	SOP Embankment (20% AEP)	Cross section trimming and bank elevation addition	Application of the bank elevations representing the 20% AEP flood event river stage results from an ISIS 1D model simulation (Figure 6.20)
3	Existing Embankment (10% AEP)	Cross section trimming	Cross sections are trimmed of values beyond existing the embankment crest (Figure 6.20)
4	SOP Embankment (4% AEP)	Cross section trimming and bank elevation addition	Application of the bank elevations representing the 4% AEP flood event river stage results from an ISIS 1D model simulation (Figure 6.20)

The riverbank elevations for scenario 2 and 4 were derived through modelling the river stage with the respective 20% and 4% AEP discharge peak flows using the ISIS 1D model. Figure 6.20 illustrates a cross section example for each lateral connectivity scenario applied in the ISIS 1D model.

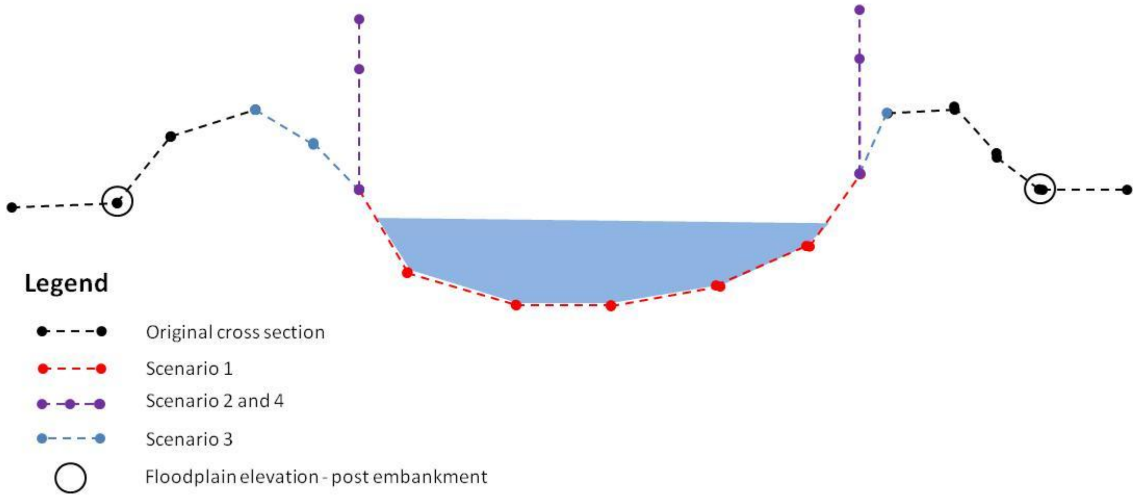

Figure 6.20 ISIS 1D river cross sections and lateral connectivity design

Scenario 1 lateral connectivity includes the river bed and then the river bank elevations corresponding to the floodplain elevation level post embankment e.g. Figure 6.20, red dashed line and black circle. Scenario 2 and 4 lateral connectivity is based on the existing scenario 1 which includes the river bed and then extends the bank elevations based on the river stage results from the ISIS 1D modelled 20% AEP and 4% AEP discharge peak flows e.g. Figure 6.20, purple dashed lines. Scenario 3 lateral connectivity includes the riverbed and bank elevations to the embankment crest e.g. Figure 6.20, red and blue dashed lines. Figures 6.21 and 6.22 provide a long view section of the riverbank elevations for each lateral connectivity scenario.

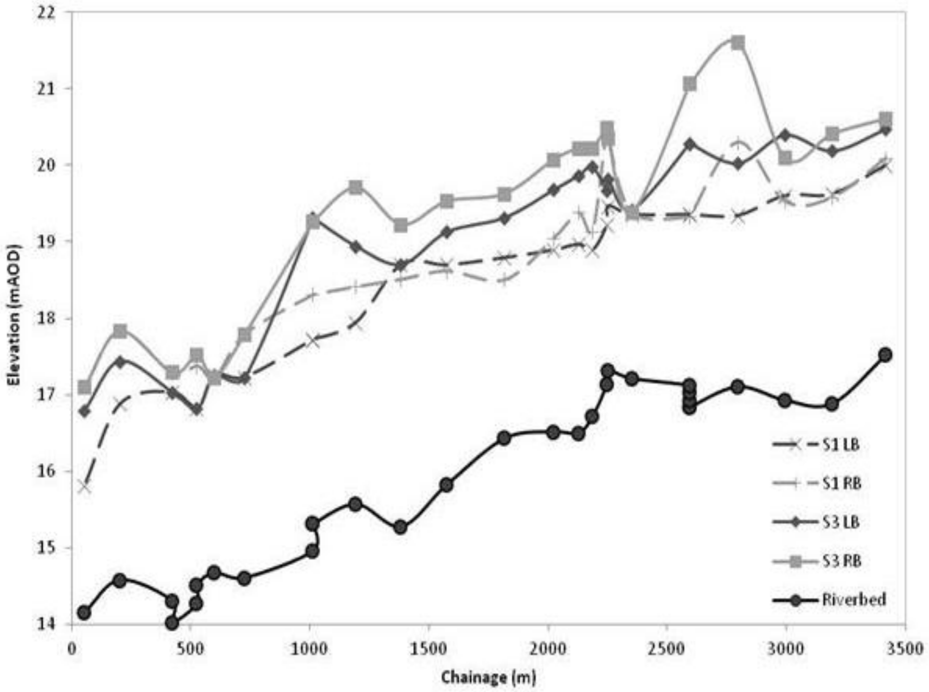

Figure 6.21 Scenario 1 and 3 linkline riverbank elevations and river chainage

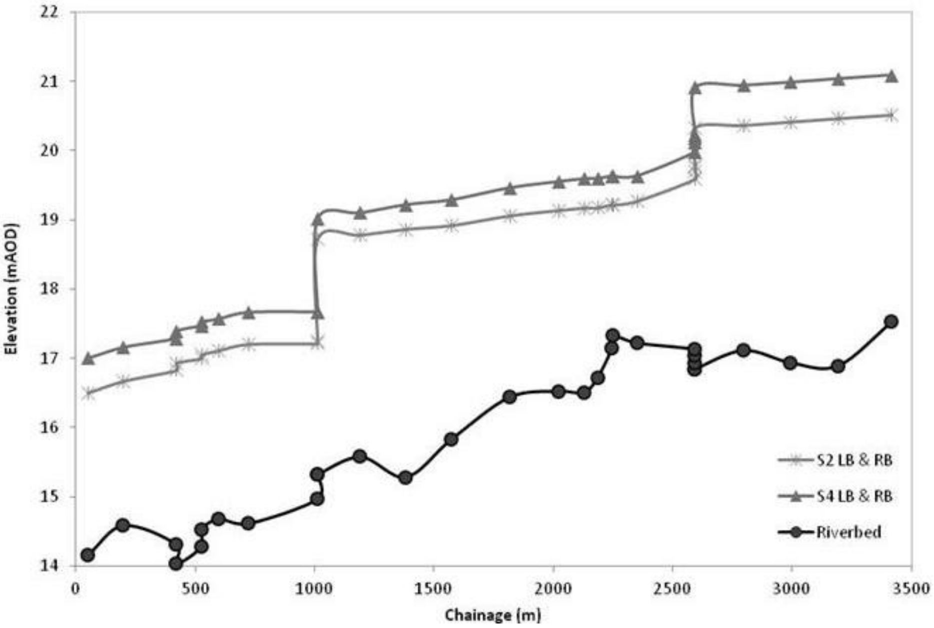

Figure 6.22 Scenario 2 and 4 linkline riverbank elevations and river chainage

There are three types of linking methods to exchange water between the ISIS 1D and 2D model i.e. water level, flow and weir (Halcrow, 2010). The water level linking method (Halcrow, 2010) was applied in order to represent the exchange of discharge from the river channel (ISIS 1D model) and the floodplain (ISIS 2D model), (Halcrow, 2010). This method uses the water levels from the 1D nodes (cross sections) and calculates the exchange of flow at these linked boundaries. The water levels of the ISIS 1D model at the 1D nodes are interpolated linearly between the water levels at the ISIS 2D model boundary with a shortest distance link method applied. River discharge is added or extracted from the ISIS 2D model at each 1D node based on the change in water levels between the river (ISIS 1D model) and the floodplain (ISIS 2D model).

The ISIS 1D-2D linking tool in ISIS Mapper was utilised to generate linklines for the left and right floodplains across all river chainage cross sections in Halcrow (2010). The elevation points for the linklines were based on the ISIS 1D model cross sections left and right bank boundary elevations for each lateral connectivity scenario. Figure 6.21 and 6.22 display the riverbank linkline elevations for the left and right bank for each floodplain and lateral connectivity scenario applied to the linked ISIS 1D-2D models. The computational area was selected as the active area shapefile with the Digital Elevation Model (DEM) selected as the LiDAR DTM as discussed in Section 6.4.1.2.

6.4.1.4 **Sensitivity**

Sensitivity analysis determines the rate of change in the model outputs with respect to the changes to the model input parameters (Moriasi et al., 2007). The sensitivity analysis was conducted on the Manning's 'n' roughness parameter and the downstream boundary, which are generally considered to have the most uncertainty of the hydrological variables in hydrodynamic models (Haestad Methods et al., 2007). The sensitivity of the Manning's 'n' roughness and downstream boundary were tested assessing the impacts to the river stage predicted variable in the ISIS 1D model to ensure that other model outputs are adequately simulated (Moriasi et al., 2007; Legates and McCabe Jr, 1999). In the linked ISIS 1D-2D model, the Manning's 'n' was tested on the discharge hydrograph, inundation area, volume, depth and velocity.

This research utilised a combination of both statistical and graphical model evaluation techniques as recommended robust statistics to test model efficiency and measure bias error (Moriasi et al., 2007; Ewen, 2011; McCuen et al., 2006; Legates and McCabe Jr, 1999). The error index statistics e.g. mean absolute error (Equation 6.7), the root mean square error (Equation 6.8) and Nash-Sutcliffe efficiency (Equation 6.9) statistics were applied to allow a complete assessment of the model performance. The results for each model parameter were graphed to enable a visual comparison of the simulated data to evaluate model performance.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}(m_i - o_i) \qquad \textbf{6.7}$$

where:

n = number of observations

m_i = model prediction for observation $_i$

o_i = observed value for observation $_i$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(m_i - o_i)^2} \qquad \textbf{6.8}$$

where:

n = number of observations

m_i = model prediction for observation $_i$

o_i = observed value for observation $_i$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(m_i - o_i)^2}{\sum_{i=1}^{n}(o_i - \bar{o})^2} \qquad \textbf{6.9}$$

where:

n = number of observations

m_i = model prediction for observation $_i$

o_i = observed value for observation $_i$

$\bar{o}$ = mean observed value

The MAE and RMSE measures of error describe the difference between the model simulations and observations with values of 0 representing the best agreement (Legates and McCabe, 1999). NSE evaluates the coefficient of efficiency and model performance based on ranging from – ∞ to 1, with values close to 1 indicating a better agreement and vice versa (Legates and McCabe, 1999)

This research estimated that the global value of the River Ivel study reach Manning's 'n' roughness from IV-03418 to IV-00052 was 0.04. The Manning's 'n' value was derived based on the River Ivel channel survey (Appendix C, Table C.1.1) and then applying a table lookup of the corresponding Manning's 'n' values for an excavated or dredged, earth, winding and sluggish river channel with a stony bottom and weedy banks, i.e. C.b.5 maximum (Chow, 1959, p. 112).

Haested methods et al. (2007) recommends varying the Manning's 'n' value as above by ±20% as part of sensitivity testing e.g. 0.032 and 0.048. This research applied values of 0.030 and 0.050 Manning's 'n' values as the respective lower and upper limits based on prescribed values by Chow, (1959, p. 112) and described in Table 6.16.

Table 6.16 ISIS 1D manning's n values

Manning's 'n' value		Type of Channel	Description
Normal	0.03	C. Excavated or dredged	b. Earth, winding and sluggish 2. Grass, some weeds
Maximum	0.05	C. Excavated or dredged	b. Earth, winding and sluggish 6. Cobble bottom and clean sides

An ISIS 1D model was created for each of the Manning's 'n' values using a steady state simulation and upstream boundary of 4.5 $m^3.s^{-1}$ based on the mean observed discharge flows at the field study site (Appendix C, Table C.1.1). Simulations were run to compare the modelled river stage for each cross section against the observed river stage from the River Ivel channel survey (Appendix C, Table C.1.1) and assessed using the statistical and graphical model evaluation techniques.

The downstream boundary of the 1D model was tested for sensitivity by varying the riverbed level by ±0.5 m (Figure 6.23). An ISIS 1D model was created for each downstream boundary value using a steady state simulation and upstream boundary of 4.5 $m^3.s^{-1}$ based on the mean observed discharge flows at the field study site (Appendix C, Table C.1.1). The modelled river stage for ±0.5 m riverbed elevations were compared to the river stage of the original downstream boundary elevation using statistical and graphical model evaluation techniques.

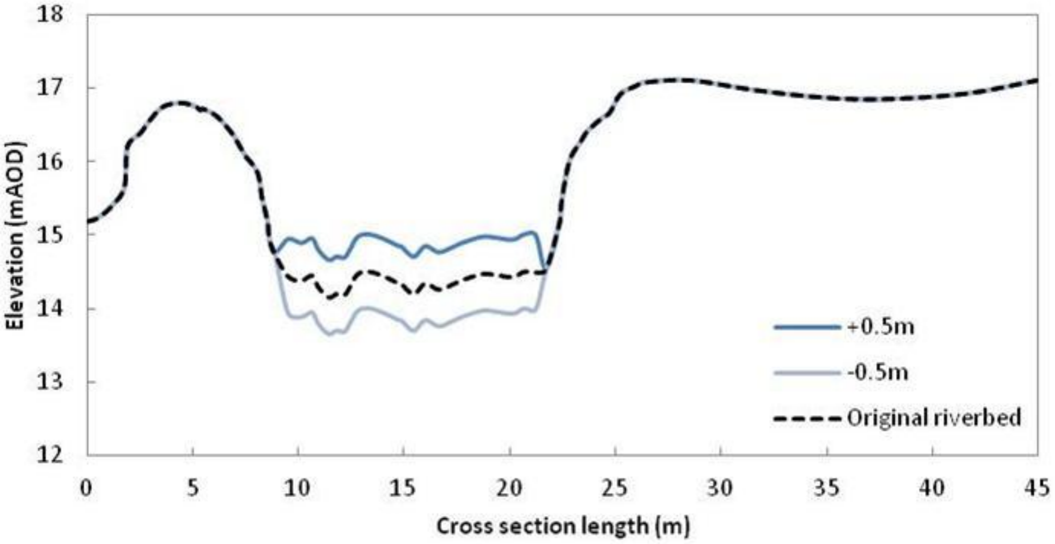

Figure 6.23 Schematic of IV-00052 cross section ±0.5 m downstream boundary bed level

This research estimated that the global value of the floodplain Manning's 'n' roughness was potentially 0.03. This value was based on deriving the Manning's 'n' value from a site visit of the case study floodplain and applying a table lookup of the corresponding Manning's 'n' values for a floodplain with pasture and no brush with short grass (Chow, 1959). Haested methods et al. (2007) recommends varying the 'n' value as above by ±20% as part of sensitivity testing e.g. 0.026 and 0.036. This research applied values of 0.025 and 0.035 Manning's 'n' values as the respective lower and upper limits and also as they represented prescribed values as in Chow (1959, p. 113).

An ISIS 2D model was created for each of the Manning's 'n' values using an unsteady state simulation and the 1% AEP design flood event (Figure 6.15) with a 90 hour run time and a 10 second fixed time step to maintain the stability of the hydraulic computations (Samuels, 1990). The 1% AEP flood event was chosen at it represented the most extreme design flood in order to highlight any sensitivity encountered while testing the Manning's 'n' value for the discharge hydrograph, inundation area, volume, depth and velocity modelled outputs. Linked ISIS 1D-2D simulations were run to compare the modelled river discharge, inundation area, volume, depth and velocity of the original linked ISIS 1D-2D Manning's 'n' value against the ±20% Manning's 'n' value simulations. The modelled floodplain inundation depth and velocity results were extracted for the discharge hydrograph peak and post flood peak based on maximum values to test the sensitivity of ±20% Manning's 'n' roughness values.

6.4.1.5 **Parameterisation and Validation**

Hydrodynamic models require robust and independent calibration-validation to establish both the quality of and the confidence in the hydraulic information generated (Hunter et al., 2007). In these models, the roughness parameter values for the riverbed are commonly parameterised to determine the robustness of the model design by comparing the modelled to an independent set of observed data (Hunter et al, 2007). The parameterisation of the model values may be conducted by measuring or estimating a priori e.g. adjusting the parameter value to get a better fit between modelled and observed variables. (Beven, 2001). Estimating a priori is a more commonly applied method to calibrate the modelled to observed data in models (Beven, 2001). Calibration of model parameters will be subject to uncertainty, involving trial and error and the concept of an optimal parameter set can be found to be ill-founded in models due to equifinality e.g. different models and parameter sets (Beven, 2001).

This research parameterised the manning's 'n' roughness value for channel cross sections IV-03418 to IV-00052 as the channel roughness descriptions were known and derived by Cartographical Surveys Ltd for the Environment Agency (Appendix C, Table C.1.1). Further benefits of parameterisation include the application of parameter values that reflect the significant and systematic variation of field data and by using representative parameter values (Refsgaard and Storm, 1996). The Manning's 'n' values derived from the roughness description for each cross section on the River Ivel study reach shall be defined as 'observed' data in this research.

Parameterisation of the Manning's 'n' roughness values in the ISIS 1D model for this research were defined in two ways i.e. global and local roughness.

- Global roughness: application of a single Manning's 'n' roughness value to all cross sections in the River Ivel study reach.
- Local roughness: application of unique Manning's 'n' roughness values for each individual cross section in the River Ivel study reach.

The global roughness value process involves a table look up of the Manning's 'n' roughness values as in Chow (1959, p. 112) which bear the closet resemblance to the river channel roughness (Haestad Methods et al., 2007). The local roughness value process involves the application of Cowan's equation, which generates an estimate of the Manning's 'n' value for each unique river cross section based on a variety of physical river channel components (Cowan, 1956).

The global roughness parameterisation shall be defined as the ‘Chow Table Lookup method’. This involved selecting Manning’s ‘n’ values from Chow (1959, p. 112) which correspond to the type of river channel and channel roughness description for each cross section as observed from the River Ivel cross section survey supplied by the Environment Agency (Appendix C, Table C.1.1). Two types of channel and description values were chosen (Table 6.17) to represent the nearest equivalent to the actual channel roughness (Appendix C, Table C.1.1). The minimum, normal and maximum values were then applied to the ISIS 1D model as a global roughness value for each respective cross section. The river discharge corresponding to the cross section survey date and time was derived from flow gauging records at the ‘Ivel at Blunham’ flow gauging station located 97 m upstream of the upstream boundary of the River Ivel study reach. The average river discharge of 4.5 $m^3.s^{-1}$ was applied as the upstream boundary of the 1D model (Appendix C, Table C.1.1).

Table 6.17 Chow table lookup method: channel type and manning’s ‘n’ description

	Type of Channel	**Description**
1	C. Excavated or dredged	b Earth, winding and sluggish 2 Grass, some weeds
2	C. Excavated or dredged	b Earth, winding and sluggish 5 Stony bottom and weedy banks

The local roughness parameterisation shall be defined as Cowan’s Equation and was applied to generate an estimate of the Manning’s ‘n’ values to represent the River Ivel study reach (Cowan, 1956). This method is comprised of a variety of components with numerical values used to describe the physical aspects of a river channel to generate numerical values (Equation 6.10). The values are then worked into the Cowan’s equation to generate an estimate of each Manning’s ‘n’ value for each cross section (Equation 6.10).

$$n = (n_0 + n_1 + n_2 + n_3 + n_4)m_5 \qquad \textbf{6.10}$$

where:

n_0 the portion of the n value that represents the channel material in a straight, uniform smooth reach

n_1 the additional value added to correct for the effect of channel surface irregularities

n_2 the additional value for variations in shape and size of the channel cross section through the reach

n_3 The additional value for obstructions

n_4 the additional value for vegetation in the channel

m_5 the correction factor for the meandering of the channel

Source: Haestad Methods et al. (2007, p. 150)

The appropriate value for each component as in Equation 6.10 were derived by applying the following methods:

- $n_{0:}$ channel material value was based on observed channel bed material as per River Ivel channel survey.
- $n_{1:}$ degree of channel irregularity value was based on observing each individual cross section shape in the ISIS 1D model.
- $n_{2:}$ variation of channel cross section value was based on observing the change between each cross section shape in the ISIS 1D model.
- $n_{3:}$ relative effect of obstructions value is based on observed channel bed material as per River Ivel channel survey and observed obstructions as result of site visits for each cross section.
- $n_{4:}$ vegetation value was based on observed channel bed material as per River Ivel channel survey.
- $m_{5:}$ degree of meandering value was based on map analysis of the River Ivel study reach.

An ISIS 1D model was created for each of the parameterisation methods and corresponding Manning's 'n' values in order to model the river stage levels. The modelled river stage for each cross section were then compared to the observed river stage from the River Ivel channel survey (Appendix C, Table C.1.1) by application of statistical and graphical model evaluation techniques.

Validation of the ISIS 1D model was conducted to substantiate that the model possesses a satisfactory accuracy range, which is consistent with its intended use. (Refsgaard and Henrikson, 2004). Only one set of independent observed river stage data was available based on the River Ivel survey (Appendix C, Table C.1.1) to validate and assess the robustness of the model. The modelled river stage from each parameterised Manning's 'n' roughness value was then compared to the observed river stage data. The Manning's 'n' roughness value which represents the optimum agreement of the modelled to observed river stage was then applied in the linked ISIS 1D-2D model as deduced from statistical and graphical model evaluation techniques.

6.4.1.6 **Model simulation**

The 1D models for each lateral connectivity scenario applied the design flood hydrographs as in Figure 6.15 as upstream boundaries in a steady state (direct method) simulation to generate the initial conditions for values of flow and stage prior to the commencement of unsteady (fixed timestep) simulations (Halcrow, 2010). The timestep of the unsteady state simulation in the 1D model was set to 10 seconds to maintain the stability of the hydraulic computations (Samuels, 1990). The unsteady state (fixed timestep) and start and finish time were set to 0 and 90 hours respectively corresponding to the design flood event hydrograph start and finish times in the upstream boundary (Figure 6.15). The downstream boundary was set to the normal depth in order to generate a flow-head relationship as the downstream stage of the River Ivel study reach was unknown (Halcrow, 2010).

A 2D model was created for each individual lateral connectivity scenario and design flood event hydrograph (Figure 6.15). The simulation length was set to 90 hours to correspond with the 1D model fixed time step finish time and design flood event hydrograph boundary (Figure 6.15). The 2D model timestep was set at 5 seconds i.e. half the 1D timestep as recommended to act as the model boundary data transfer between the 1D model (Halcrow, 2010). The 2D link boundary cells require a water level from the 1D model every double 2D timestep which will enable a stable and convergent performance between the 1D and 2D domains i.e. river and floodplain.

The ADI (Alternating Direction Implicit) solution method was selected as this scheme 2D solver provides shorter run times and suitable for modelling primarily subcritical flows as the flow regime of the 1D model presents Froude number <1 (Halcrow, 2010).

The linked ISIS 1D-2D model generates as initially mentioned in Section 3.5.1 and listed in Table 3.4. The flood hydrograph may be modified in two ways as a result of flood routing by attenuation and translation (Shaw et al., 2011). The attenuation describes the diminishing of the flood peak in magnitude downstream as a result of flood routing. The hydrograph shape flattens out with the volume of floodwater taking longer to pass on the falling limb of the hydrograph and downstream. The translation describes when the time to peak discharge of the downstream hydrograph occurring at a later time and point downstream. The 1D-2D linking was simulated in the ISIS 2D model for each scenario and respective design flood event. The discharge simulation results for each scenario were extracted from the linked ISIS 1D-2D model for the cross section IV-00052 representative of the downstream hydrograph. The discharge peak attenuation was calculated by subtracting the modelled downstream peak discharge from the upstream peak discharge for each respective design flood event in the ISIS linked 1D-2D model. The discharge peak translation was calculated by subtracting the upstream peak discharge time from the modelled downstream peak discharge time for each respective design flood event in the linked ISIS 1D-2D model.

The ISIS 2D model generates the flood inundation depth and velocity output data (Halcrow, 2010). These model outputs were extracted for the total flood inundation extent e.g. area for each scenario as the case study floodplain has a gentle slope (Figure 5.9 and 5.10) and the ground surface elevation was found to be quite homogenous with an average elevation of 19.75 mAOD (EA, 2011; OS, 2009a,b). The 2D flood calculator in ISIS Mapper was utilised to enable calculation of the flood inundation volume and wetted area i.e. inundation area for the each scenario. The 2D flood calculator was also utilised to export the flood inundation velocity and depth results in grid format. This data was then further processed using spatial analyst in ESRI ArcMap to classify the depth and velocity data into defined interval results i.e. 0.1 m depth and 0.1 m s^{-1} and their respective inundation area for the hydrograph peak and 90th hour flood event discharge time steps as appropriate.

6.4.2 **Results and Discussion**

6.4.2.1 **Sensitivity**

The Manning's 'n' roughness sensitivity results data are displayed in Appendix C.3 and C.4. Table 6.18 provides the river stage sensitivity statistical results of ±20% Manning's 'n' roughness values against the estimated global Manning's 'n' value applied in the ISIS 1D model. Figure 6.24 provides a graphical representation of river stage results for the ±20% Manning's 'n' values results against the estimated global Manning's 'n' value applied in the ISIS 1D model.

Table 6.18 ISIS 1D model river stage Manning's 'n' roughness statistical sensitivity results

Manning's 'n'			**MAE (m)**	**RMSE (m)**	**NSE**
Description	**Value**	**%Δ**			
C.b.5 Max	0.04	0			
C.b.2 Normal	0.03	-20	-0.20	0.20	0.98
C.b.6 Max	0.05	+20	-0.02	0.13	0.99

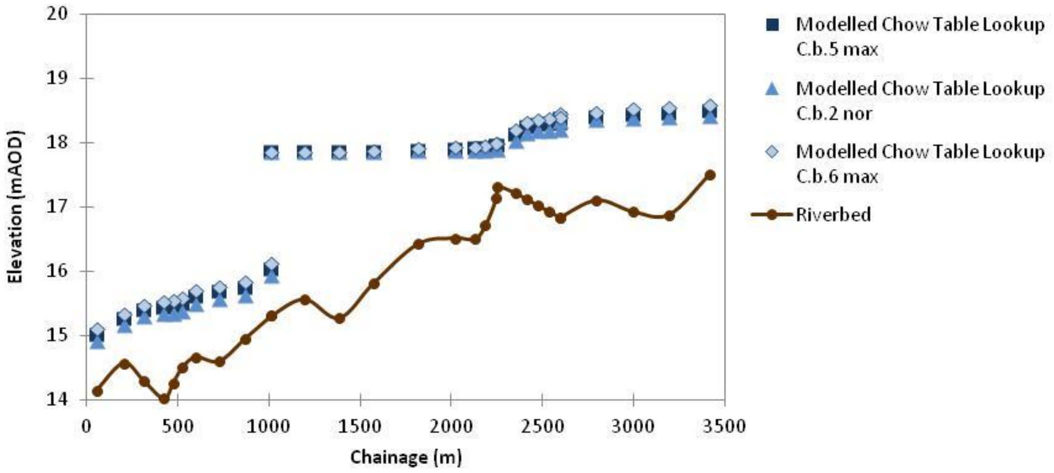

Figure 6.24 ISIS 1D model river stage Manning's 'n' roughness sensitivity test results

The river stage was marginally sensitive to lowering the Manning's 'n' channel roughness in the ISIS 1D model by -20% based on the MAE and RMSE results and also considering the immediate upstream and downstream cross sections of the River Ivel reach (Table 6.18 and Figure 6.24). The NSE results indicated a good agreement between the estimated that the Manning's 'n' global value applied to the ISIS 1D model and the ±20% Manning's 'n' roughness river stage results displaying negligible impact. The low resistance to flood flows in the river channel by lowering the Manning's 'n' roughness value especially has an impact on the river stage at the immediate upstream and downstream sections. Lowering the roughness in this instance resembles cross sections with channels and materials providing low resistance e.g. clean uniform shape sections with low or no vegetation (Chow, 1959).

Table 6.19 displays the downstream boundary sensitivity statistics results of the 1D ISIS model comparing the ±0.5 m and the existing IV-00052 cross section river bed elevation modelled values. Figure 6.25 displays the downstream boundary graphical results of the 1D ISIS model comparing the ±0.5 m and the existing IV-00052 cross section riverbed elevation modelled values.

Table 6.19 Downstream boundary ISIS 1D model river stage statistical sensitivity results

Downstream boundary	**MAE (m)**	**RMSE (m)**	**NSE**
0			
-0.5 DB	-0.04	0.11	0.99
+0.5 DB	0.09	0.16	0.99

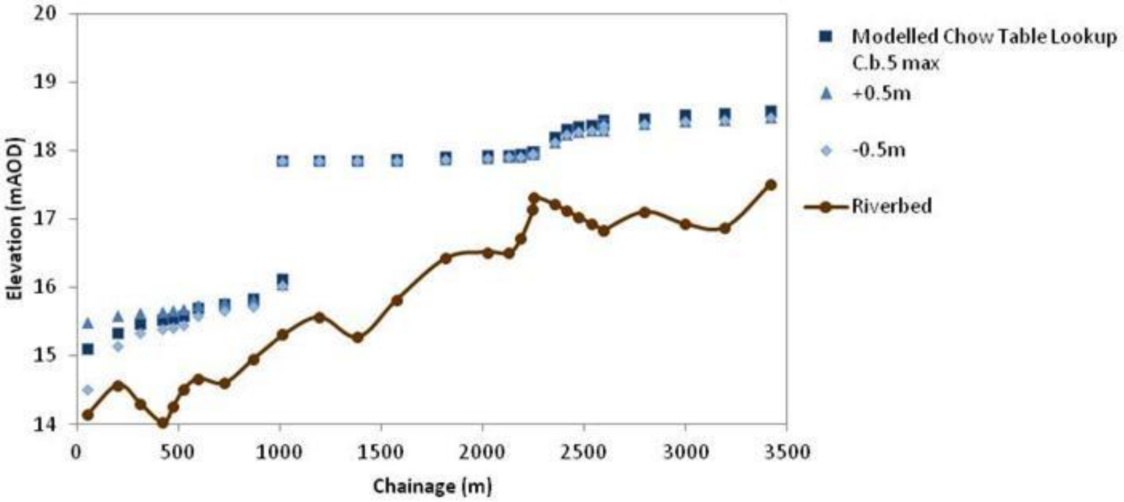

Figure 6.25 ISIS 1D model river stage downstream boundary sensitivity results

The downstream boundary displays low sensitivity to raising and lowering the riverbed elevation as indicated by Figure 6.25 and especially the RMSE results (Table 6.19). The NSE results indicate a good agreement between the river stage results for the original riverbed elevation and ±0.5 m for the downstream boundary, displaying a negligible impact. Lowering the downstream boundary was found to be marginally more sensitivity on the river water level in the model performance based on the MAE results (Table 6.19). Lowering the downstream boundary causes the river flow to become supercritical as opposed subcritical flows in the majority of the river study reach.

The sensitivity test results of the linked ISIS 1D-2D model by varying the Manning's 'n' floodplain value by ±20% on the discharge hydrograph, the floodplain inundation area and volume, depth and velocity data are displayed in Appendix C.4. Table 6.20 provides the statistical sensitivity results of the linked ISIS 1D-2D model discharge hydrograph for the defined floodplain Manning's 'n' roughness value 0.030 against ±20% Manning's 'n' values.

Table 6.20 Linked ISIS 1D-2D model discharge hydrograph floodplain Manning's 'n' roughness statistical sensitivity results

Manning's *n* value			**MAE ($m^3.s^{-1}$)**	**RMSE ($m^3.s^{-1}$)**	**NSE**
Description	**Value**	**%∆**			
D.2.a.1 Normal	0.03	0			
D.2.a.1 Minimum	0.025	-20	-0.10	0.33	1.00
D.2.a.1 Maximum	0.035	+20	0.00	0.16	1.00

The river discharge displayed minimum sensitivity to lowering or raising the Manning's 'n' value based on the MAE and RMSE results (Table 6.20). The NSE results indicate a perfect agreement confirming that the effects of increasing or decreasing floodplain roughness have no impact on the river discharge results (Table 6.20).

Table 6.21 provides the statistical sensitivity results of the linked ISIS 1D-2D model floodplain inundation area for the defined floodplain Manning's 'n' roughness value of 0.030 against ±20% Manning's 'n' roughness values.

Table 6.21 Linked 1D-2D model floodplain inundation area statistical sensitivity test results

Manning's *n* value			**MAE (m^2)**	**RMSE (m^2)**	**NSE**
Description	**Value**	**%∆**			
D.2.a.1 Normal	0.03	0			
D.2.a.1 Minimum	0.025	-20	0.00	0.00	1.00
D.2.a.1 Maximum	0.035	+20	17,648	24,758	1.00

The statistical results initially indicate that the raising the floodplain roughness by 20% has a greater impact on the inundation area results based on the MAE and RMSE results (Table 6.21). The case study floodplain has an area of 3,650,000 m^2. The percentage of MAE and RMSE results in regard to the case study floodplain area indicate <1% sensitivity of the inundation area by raising the roughness. In addition, the NSE indicates perfect agreement comparing both the modelled inundation area of the ±20% Manning's 'n' roughness values and the defined floodplain Manning's 'n' roughness value.

Table 6.22 provides the statistical sensitivity results of the linked ISIS 1D-2D model floodplain inundation volume for the selected Manning's n' value 0.030 against ±20% Manning's 'n' values.

Table 6.22 Linked ISIS 1D-2D model floodplain inundation volume statistical sensitivity test results

Manning's *n* value			**MAE (m^3)**	**RMSE (m^3)**	**NSE**
Description	**Value**	**%∆**			
D.2.a.1 Normal	0.03	0			
D.2.a.1 Minimum	0.025	-20	0.00	0.00	1.00
D.2.a.1 Maximum	0.035	+20	9424	14556	1.00

The NSE results indicate perfect agreement with comparing both the modelled inundation volume for the defined floodplain Manning's 'n' roughness value against the ±20% Manning's 'n' roughness values.

Table 6.23 provides the statistical sensitivity results of the linked ISIS 1D-2D model floodplain inundation depth for the defined floodplain Manning's n' roughness value of 0.030 against ±20% Manning's 'n' roughness values.

Table 6.23 Linked 1D-2D model floodplain inundation depth sensitivity statistics test results

Manning's *n* value			**MAE (m)**	**RMSE (m)**	**NSE**
Description	**Value**	**%∆**			
D.2.a.1 Normal	0.03	0			
D.2.a.1 Minimum	0.025	-20	-0.02	0.03	0.98
D.2.a.1 Maximum	0.035	+20	0.00	0.03	0.98

The results (Table 6.23) indicate that raising or lowering the floodplain roughness has a negligible effect on the inundation depths modelled in the linked ISIS 1D-2D model.

Table 6.24 provides the statistical sensitivity results of the linked ISIS 1D-2D model floodplain inundation velocity for the defined Manning's n' roughness value against ±20% Manning's 'n' values.

Table 6.24 Linked 1D-2D model floodplain inundation velocity sensitivity statistics test results

Manning's *n* value			**MAE ($m.s^{-1}$)**	**RMSE ($m.s^{-1}$)**	**NSE**
Description	**Value**	**%∆**			
D.2.a.1 Normal	0.03	0			
D.2.a.1 Minimum	0.025	-20	0.10	0.11	0.96
D.2.a.1 Maximum	0.035	+20	-0.004	0.22	0.85

The results indicate that the raising rather than lowering the Manning's 'n' roughness has a greater impact on the inundation velocity results as indicated by the RMSE and NSE values (Table 6.24). As both MAE and RMSE results are low and the NSE results are >0.5 and closer to 1, raising and lowering the Manning's 'n' roughness by ±20% has minimal impact on the inundation velocity.

6.4.2.2 **Validation**

The validation results for the ISIS 1D model are displayed in Appendix C.5.2. Table 6.25 provides the statistical results to measure model efficiency and performance of the ISIS 1D modelled river stage against the observed river stage data. The optimum validation results are highlighted in the green rows in Table 6.25.

Table 6.25 ISIS 1D model validation statistical test results

Manning's 'n'			MAE (m)	RMSE (m)	NSE
Description		Value			
Chow Table Lookup	C.b.5 min	0.025	-0.19	0.22	0.96
	C.b.5 normal	0.035	-0.14	0.17	0.98
	C.b.5 max	0.040	-0.11	0.14	0.98
	C.b.2 min	0.025	-0.19	0.22	0.96
	C.b.2 normal	0.03	-0.16	0.19	0.97
	C.b.2 max	0.033	-0.15	0.18	0.98
Cowan's Equation		0.039-0.068	-0.03	0.10	0.99

Figure 6.26 provides a graphical representation of the ISIS 1D model validation results displaying the modelled river stage for each Manning's 'n' roughness value and the observed river stage for the River Ivel study reach.

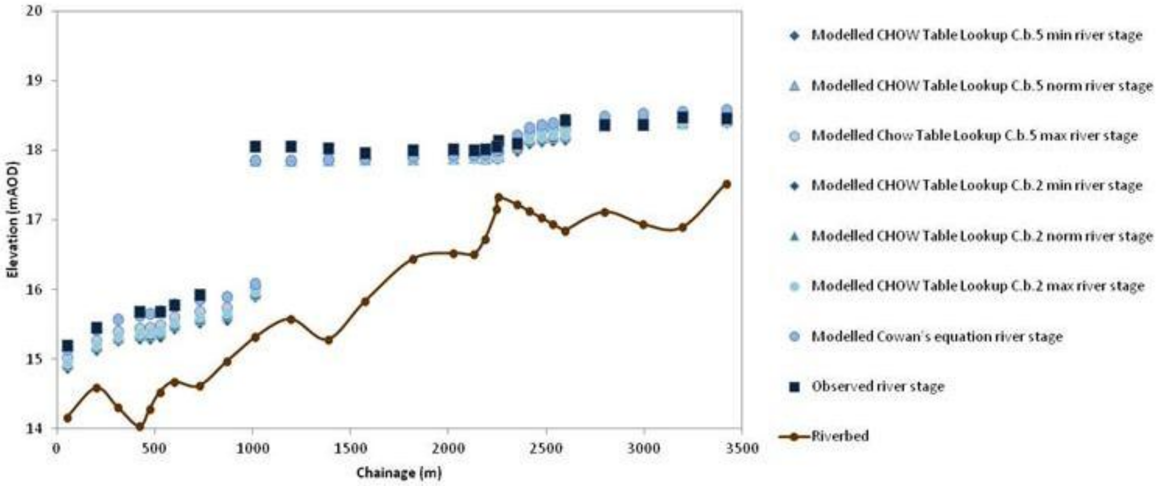

Figure 6.26 ISIS 1D modelled Manning's 'n' value methods river stage against observed river stage results

The validation results of the ISIS 1D model (Table 6.25) indicate that the Cowan's equation method Manning's 'n' roughness values were the most efficient and optimal roughness values for the model to represent the observed river flows. Figure 6.26 indicate that both the modelled Manning's 'n' Chow table lookup roughness values i.e. C.b.5 and Cowan's equation displayed a good agreement in comparison to the observed river stage for each respective cross section in the River Ivel study reach. The main differences observed between the two Manning's 'n' roughness methods were present at the immediate upstream and downstream sections of the River Ivel study reach. In the upstream section of the River Ivel, the Chow table lookup C.b.5 Manning's 'n' roughness values display an improved agreement over the Cowan's equation, which overestimated the modelled river stage. In the downstream section of the River Ivel, the Cowan’s equation Manning’s ‘n’ roughness values displayed an improved agreement over the Chow table lookup C.b.5 Manning’s ‘n’ roughness values which underestimated the modelled river stage.

It was observed during initial model runs to simulate the design flood events and lateral connectivity scenarios that applying the Cowan’s equation Manning’s ‘n’ roughness values led to model instabilities which caused model non-convergence in the linked ISIS 1D-2D model. This issue was the result of applying the local Manning’s ‘n’ roughness values for each respective cross section in the River Ivel study reach (Appendix C.5, Table C.5.3). It was recommended by Halcrow, the ISIS 1D and 2D software developer to apply a global roughness value to all cross sections on the River Ivel study reach to alleviate and remove model instabilities and model non-convergence. In this instance, the Chow table look up Manning’s ‘n’ roughness value of 0.040 i.e. C.b.5 - excavated or dredged channel, earth, winding and sluggish with stony bottom and weedy banks was applied to the model as a global roughness across all cross sections. This Manning’s ‘n’ value presented the next best model performance results to Cowan’s equation Manning’s n values with the error variation reflecting marginal insignificance between the modelled and observed river levels (Table 6.25, Figure 6.26).

6.4.2.3 **Inundation area**

Figure 6.27 displays the inundation area results for the 90th hour of each design flood event and respective lateral connectivity scenario. The inundation area linked ISIS 1D-2D model data are displayed in Appendix C.6.1.

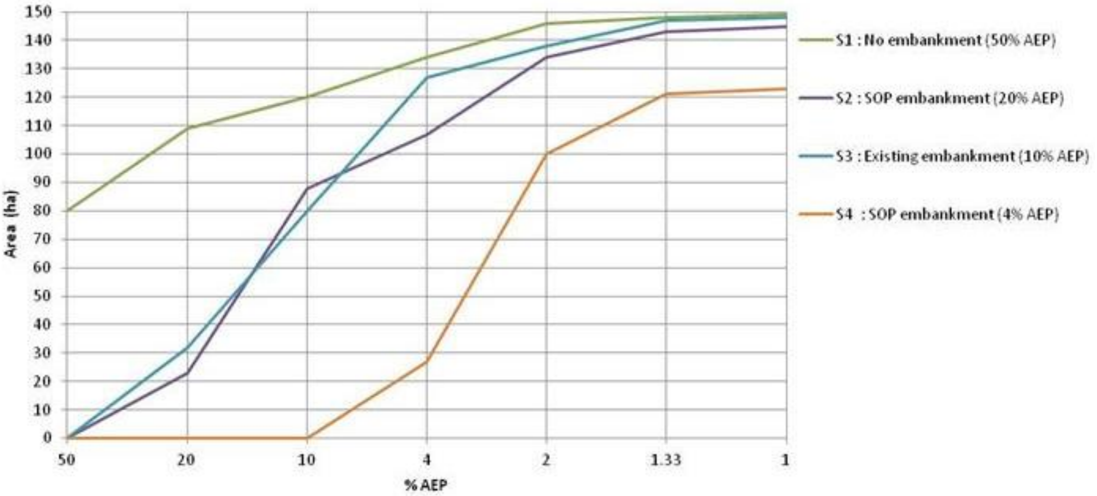

Figure 6.27 Lateral connectivity and flood event scenario inundation area (ha) results

In high frequency/low magnitude flood events the results clearly indicate that increasing connectivity by lowering embankments will cause greater spatial extent of flood water inundation in the floodplain. Scenario 4: 4% SoP inhibited flood inundation due to the embankment crest elevations along the River Ivel study reach. In low frequency/high magnitude flood events, the results indicated that the increasing connectivity by lowering embankments causes greater area of the floodplain to become inundated by floodwaters. In scenario 4, minimal flood inundation was observed from 20-10% AEP flood events. This was a result of low depression of the river channel bank elevations at cross sections IV-02595 and IV-01013 (Figure 6.22).

Several authors have assessed the impact of lateral connectivity and flood events upon the inundation area (Förster et al., 2006; Dutta et al., 2003; Alkema and Middelkoop, 2005; Kazama et al., 2009). However, these studies were limited to assessing the impact of low frequency/high magnitude flood events and single and/or dual lateral connectivity scenarios. This research demonstrates the impacts of lateral connectivity hydraulic controls for a wider range of flood events and impact to the inundation area. The understanding of these impacts are pertinent for the delivery of flood alleviation, flood damage, water supply, terrestrial habitat, freshwater fish habitat, agricultural productivity and recreation ecosystem services. The impact of the scenarios to the ecosystem services mentioned will be discussed further in Chapter 7.

6.4.2.4 **Inundation volume**

Figure 6.28 displays the inundation volume for the 90th hour of each design flood event and respective lateral connectivity scenario. The inundation volume linked ISIS 1D-2D model data are displayed in Appendix C.6.2.

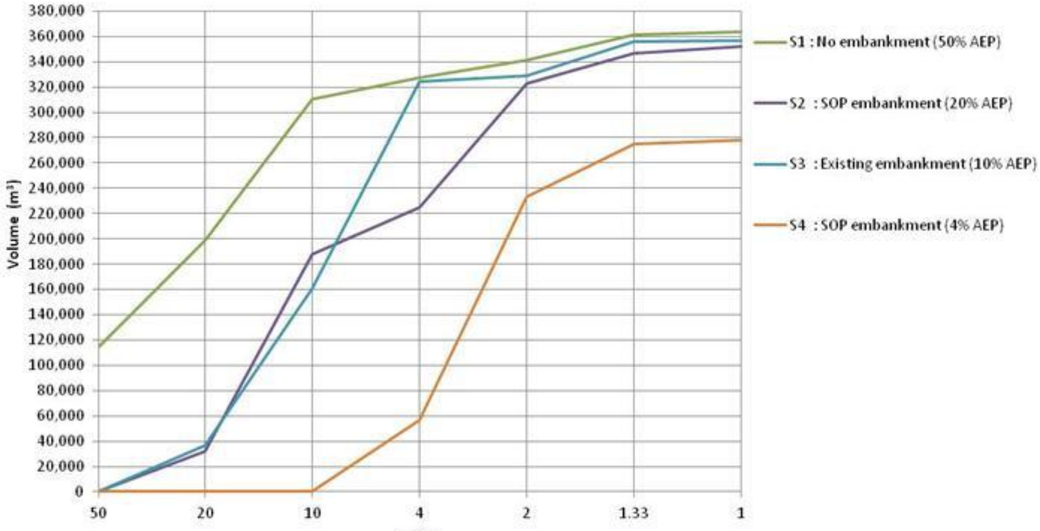

Figure 6.28 Lateral connectivity and flood event scenario inundation volume (m^3) results

In high frequency/low magnitude flood events, the inundation volume results indicate that increasing connectivity by lowering embankments provides more storage of flood waters in the floodplain. In low frequency/high magnitude flood events, the inundation volume results indicate that increasing connectivity by lowering embankments causes greater floodwater storage. This outcome is the likely response to high magnitude flood events providing greater floodwaters inundating the floodplain.

Several authors have assessed the impact of lateral connectivity and flood events upon the inundation volume (Förster et al., 2006; Dutta et al., 2003; Alkema and Middelkoop, 2005; Kazama et al., 2009). However, these studies were limited to assessing the impact of low frequency/high magnitude flood events and single and/or dual lateral connectivity scenarios. This research demonstrates the impacts of lateral connectivity hydraulic controls for a wider range of flood events and impact to the inundation volume. The understanding of these impacts is pertinent for the delivery of the flood alleviation ecosystem service. The impact of the scenarios to flood alleviation will be discussed further in Chapter 7.

6.4.2.5 **Discharge peak attenuation and translation**

Figure 6.29 displays the discharge peak attenuation results for each design flood event and respective lateral connectivity scenario. The discharge hydrographs and the model output data for the linked ISIS 1D-2D model are presented in Appendix C.6.3.

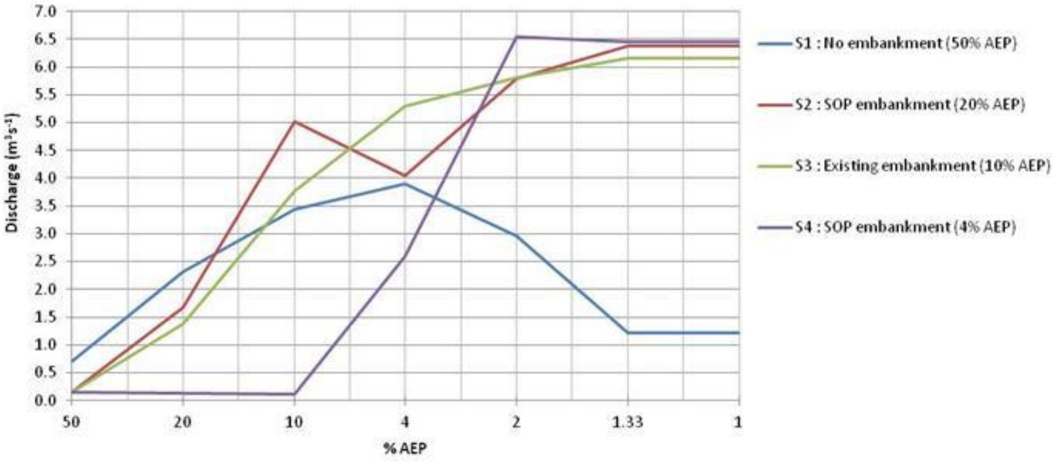

Figure 6.29 Lateral connectivity and flood event scenario discharge peak attenuation ($m^3.s^{-1}$) results

In high frequency/low magnitude flood events the results of scenarios 1-3 clearly indicate that increasing connectivity by lowering embankments provides more attenuation with greater floodwaters stored in the floodplain. In low frequency/high magnitude flood events, the attenuation is greater as a result of decreasing connectivity by raising embankments e.g. scenarios 2-4. This impact is the likely result of the attenuation of the floodwaters that haven't returned to the river and have been stored behind the flood embankments with decreasing lateral connectivity. The most interesting results were deduced from scenario 1: no embankment. In this case, the attenuation was greatest in high frequency/low magnitude flood events and then was reduced in low frequency/high magnitude flood events. Since, there is no hydraulic control for overbank flow, in low frequency/high magnitude flood events, the floodwaters were not attenuated, with the floodplain flows returning to the river with increasing flood magnitude. Minimal attenuation was observed in scenarios 3 from 50-10% and scenario 4 from 50-4% AEP due to floodwater inundation possibly occurring at a low depression of the river channel bank elevation at cross sections IV-02595 and IV-01013 (Figure 6.22). Förster et al. (2008) studied the impacts of attenuating the discharge peak but only considering time gated operations with a single raised embankment for low frequency/high magnitude flood events. This research demonstrated the impacts of lateral connectivity hydraulic controls for a wider range of flood events and impact to the discharge peak attenuation. The understanding of these impacts is pertinent for the delivery of the flood alleviation ecosystem service. The impact of the scenarios to flood alleviation will be discussed further in Chapter 7

Figure 6.30 displays the discharge peak translation results of each flood event and respective lateral connectivity scenario. The discharge hydrographs and the original modelled output data for the linked ISIS 1D-2D model are presented in Appendix C.6.3

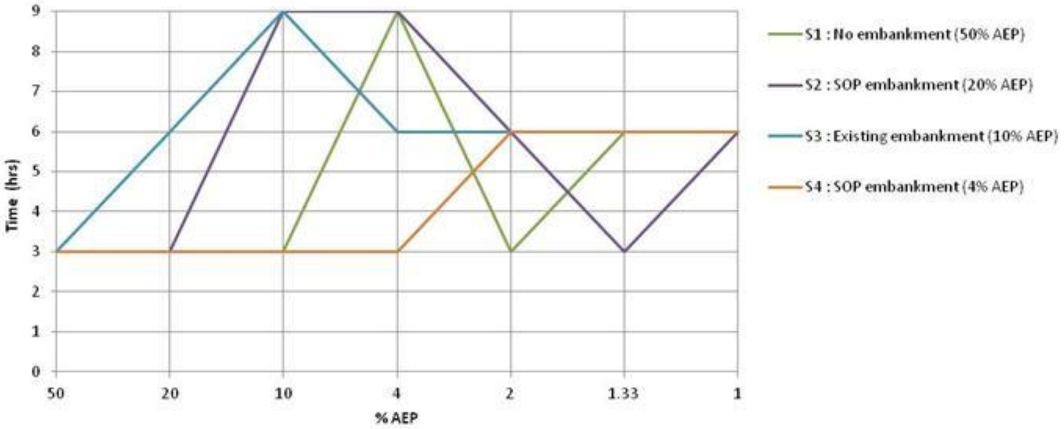

Figure 6.30 Lateral connectivity and flood event scenario discharge peak translation (hours) results

The results (Figure 6.30) displayed no clear pattern in regard to determining the benefit impact between scenarios. This outcome is the product of the results being extracted in 3 hourly translation times from the linked ISIS 1D-2D model simulations based on model run time intervals. The interpretation of the 3 hourly data was quite limited and too coarse to allow effective comparison of the scenarios. In high frequency/low magnitude flood events increasing or decreasing lateral connectivity provide a mixed pattern or benefits. However, it was observed that greater translation was more apparent in low frequency/high magnitude flood events with increasing lateral connectivity by lowering the embankments.

The research literature review indicated that no current research was available in regard to studying the effects of translation of the discharge flood peak in regard to lateral connectivity and flood events. This research provides new information to demonstrate the impacts of lateral connectivity hydraulic controls for a wide range of flood events and impact to the discharge peak translation. The translation represents an important dynamic in regard to the flood alleviation ecosystem service for the removal of river discharge and routing to the floodplain to alleviate flooding to downstream communities (Shaw et al., 2011; DCLG, 2009). The impact of the scenarios to flood alleviation will be discussed further in Chapter 7.

6.4.2.6 **Inundation depth**

Figure 6.31 displays the inundation area at the minimum inundation depth of 0.1 m at the 90th hour of each design flood event and respective lateral connectivity scenario. This particular depth was selected as an example to allow comparison between the linked ISIS 1D-2D model lateral connectivity scenarios and design flood events as the inundation depths for all scenarios ranged from 0-1.8 m (Appendix C.6.4.). The complete inundation depth and corresponding area histogram data are displayed in Appendix C.6.4.

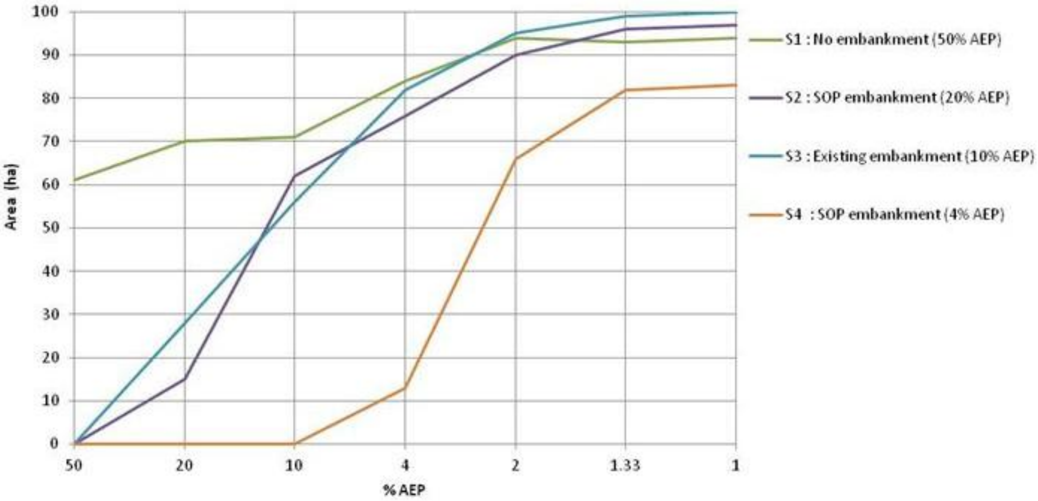

Figure 6.31 Lateral connectivity and flood event scenarios inundation area (ha) at 0.1 m depth results

The inundation depth results indicated that increasing connectivity by lowering embankments provides greater inundation depths and inundation area occupied by these depths from flood inundation.

Several authors have assessed the impacts of the inundation depth for mainly flood damage and agricultural productivity ecosystem services (Dutta et al., 2003; Alkema and Middelkoop, 2005; Kazama et al., 2009). These studies were limited to assessing the impacts of inundation depths in low frequency/high magnitude flood events and single and/or dual lateral connectivity scenarios. This research demonstrates the impacts of lateral connectivity hydraulic controls for a wider range of flood events and impact to the inundation depth. The understanding of these impacts are pertinent for the delivery of flood damage, terrestrial habitat, freshwater fish habitat, agricultural productivity and recreation ecosystem services. The impact of the scenarios to the ecosystem services mentioned will be discussed further in Chapter 7.

6.4.2.7 **Inundation velocity**

Figure 6.32 displays the area at the inundation velocity of 1 m.s^{-1} at the the 90th hour of each design flood event and respective lateral connectivity scenario. This value was applied as an example to allow comparison between the linked ISIS 1D-2D model lateral connectivity scenarios and flood events as the inundation velocities for all scenarios range from 0-1.8 m s^{-1} (Appendix C.6.5.).

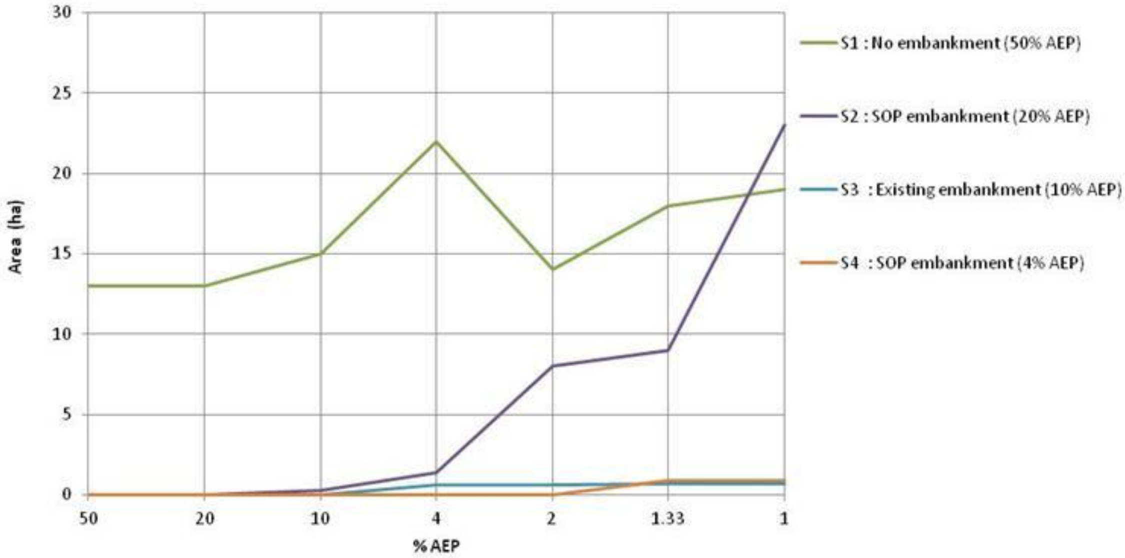

Figure 6.32 Lateral connectivity and flood event scenario inundation area (ha) at 0.1 m.s^{-1} inundation velocity results

The inundation velocity results indicate that decreasing the lateral connectivity by raising embankments reduces the area occupied by 0.1 m.s^{-1}. The highest velocities and associated area occur when increasing the lateral connectivity by lowering the embankments (Appendix C.6.5.). Raising embankments inhibits overbank flow and also contributes to a reduction in velocities from the river being disconnected from the floodplain. This research demonstrates the impacts of lateral connectivity hydraulic controls for a wide range of flood events and impact to the inundation velocity. The understanding of these impacts is pertinent for the delivery of the freshwater fish habitat ecosystem service. The impact of the scenarios to the freshwater fish habitat ecosystem service will be discussed further in Chapter 7.

6.5 Vertical connectivity modelling

6.5.1 **Methodology**

6.5.1.1 **Floodplain schematization**

This section describes the methods applied to derive the input parameters to set up the WaSim model and simulate the impacts of the seasonal year events and vertical connectivity scenarios. Figure 6.33 displays the vertical connectivity model input data sampling and measurements map at the field study site. The map describes the following information:

- Location of the automated leveloggers and dipwell points
- Surface drain location and spacing measurement
- Soil sampling strategy
- Crop type

The field study site was applied as the model boundary for the WaSim model to simulate the impacts of the seasonal year events and vertical connectivity scenarios on ecosystem services delivery. Soil, drainage, climate, crop and initial run settings information were derived as input parameters to model the seasonal year event and vertical connectivity scenarios (Counsell and Hess, 2000).

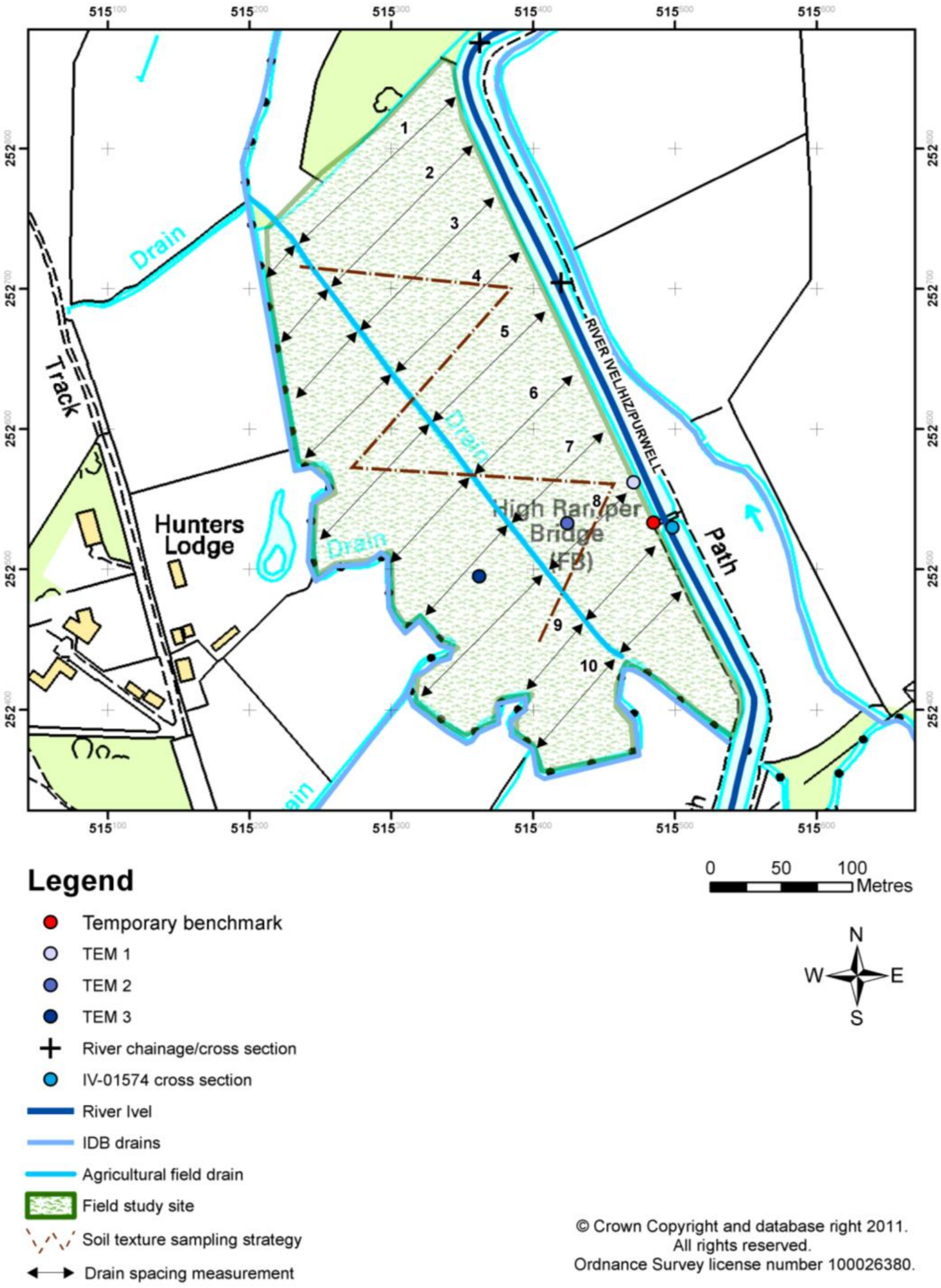

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Figure 6.33 Field study site vertical connectivity model input data sampling and measurements map

6.5.1.2 **Soil texture**

WaSim contains a database with a number of soil texture types. The WaSim model design regards a site as homogenous with no spatial horizontal or vertical variation in regard to the soil type (Counsell and Hess, 2000). The clay loam soil texture was applied to the WaSim model as derived based on field and laboratory analysis (Section 5.2.2.2)

6.5.1.3 **Drainage**

The field study site contains a number of surface drains (Figure 6.33) as described in Section 5.2.2.1. In WaSim, the drainage system was specified to include dimensions for the drain depth, spacing, diameter and the depth to the impermeable layer (Counsell and Hess, 2000). A field survey and desktop map survey (OS, 2009a,b) of the field site was conducted to assess the location and geometry of the drainage systems present at the field study site as described in Section 5.2.2.1. The IDB main drain had a 2 m width and 1 m depth and the agricultural drain had a 1m width and 1m depth. The drain spacing (Figure 6.33) of the field study site was calculated described in Section 5.2.2.1. The drain spacing between the river channel and IDB drain had a mean width of 188 m. The drain spacing between the river channel and the agricultural field drain had a mean width of 109 m. During the water table monitoring period, no drain water level was observed upon field study site visits and therefore the initial condition of the drain level was set to 0 m in the WaSim model. The depth to the impermeable layer was determined by assessing Borehole records and superficial and bedrock geology at the field site as described in Section 5.2.2.1. TL15SE21 ‘Blunham Grange’ borehole was selected as the ‘depth to the impermeable layer’ of 1.68 m as this borehole record was located proximate to the field study site with the dip-well excavations also indicating a similar depth to impermeable layer characteristics (Figure 5.9, 5.12 and Table 5.6).

6.5.1.4 **Climate**

Climate data files were generated as described in Counsell and Hess (2000) from daily rainfall and evapotranspiration data for the following:

- Calibration and validation: Rainfall and evapotranspiration data for the monitoring period as described in Section 6.2.1.1 for split sample periods.
- Seasonal year scenarios: Dry, wet and average years inclusive of a 6-month ‘lead in time’ as described in Section 6.3.2.

6.5.1.5 **Crop**

The crop type for the field study site was defined as ‘permanent grass’ based on observation from a field site visit (Figures 5.4-5.8). The associated crop data parameters for ‘permanent grass’ crop type were as per WaSim model prescribed values (Counsell and Hess, 2000)

6.5.1.6 **Vertical connectivity scenarios**

Four vertical connectivity scenarios representing a range of drainage systems by varying the drain spacing were defined and described in Table 6.26.

Table 6.26 Vertical connectivity scenarios for the WaSim model

ID	Vertical connectivity scenario	Drain Spacing (m)	Description
a	No drain	NA	Natural: 'no drainage system'
b	Agricultural standard	53	Artificial: Agricultural drainage ditch representing pasture land management based on field study site soil type, hydraulic conductivity of soil and agro-climate area
c	Existing agricultural field drain	109	Artificial: Existing agricultural field drain for pasture land management
d	Existing IDB field drain	188	Artificial: Existing IDB surface field drain for water level management for ▪ agricultural land drainage ▪ flood risk management ▪ surface water management i.e. amenity and biodiversity maintenance and conservation

Scenario b was calculated by applying drainage design methods as per Severn-Trent Water Authority (1984a,b). The calculation of the agricultural drainage design spacing was based on applying a grassland type. The depth to the impermeable layer (D_o) was derived as 1.68 m. The rainfall (q) value for grassland was extracted from Area 28: Cambridgeshire and Bedfordshire agro climatic area data sheet (Smith and Trafford, 1976). The q value was extracted as the mean heaviest rainfall expected in 5 days in 2 years as 34 mm and was recalculated as a daily rainfall value of 6.8 mm. The hydraulic conductivity of soil (K) for a clay loam soil was extracted from Table VI.A.2 (Severn-Trent Water Authority, 1984b) as 2.5 $m.d^{-1}$. The calculated q/k and D_o was then applied to Figure VI.A.1 'Drainage design for a deep permeable soil' monograph (Severn-Trent Water Authority, 1984b) and the spacing was derived as 53 m by extrapolating D_o = 1.68 m as a point between D_o =1 and D_o = 2 nomograph curves. A value of 53 m was applied based on calculation for a grassland drainage system design. Scenarios c and d were based on the surface drains present at the field study site.

6.5.1.7 **Sensitivity**

Sensitivity testing was performed on the hydraulic conductivity, seepage rate and drain spacing as these parameters were considered sensitive to changes, which may impact on the modelled position of the water table level in the WaSim model. The sensitivity testing was conducted to determine the rate of change in the model outputs for the

WaSim model with respect to the ±20% changes to the model input parameters (Moriasi et al., 2007).

The seepage rate in the WaSim model referred to seepage from the river as a constant addition to the water table (Hess et al., 2000). The addition of water from the river to the water table may contribute to an increase in water table position as a function of the seepage rate applied. The seepage rate was initially set at 2 $mm.d^{-1}$ and varied by ±20%.

The hydraulic conductivity is a function of the soil texture applied in the model and affects the flow of water transmitted in the soil with higher values indicating higher flow rates, which will contribute to an increase in the water table level (Lewis et al., 2006). The soil type at the field study site was derived as a ‘clay loam’ with hydraulic conductivity range values of 0.02-0.2 $m.d^{-1}$ and 0.5-2 $m.d^{-1}$ (Smedema et al., 2004). The hydraulic conductivity was initially set at 1.3 $m.d^{-1}$ and varied by ±20%.

The drain spacing influences water table control and the water table position through varying the distance between the drains (Young’s, 1992). The drain spacing was initially set at 50 m and varied the distance between drains by ±20%. The statistical and graphical model evaluation techniques as described in Section 6.4.2.1 were applied to evaluate the changes in sensitivity to the water table position for the model parameters.

6.5.1.8 **Calibration and Validation**

Calibration and validation was required in order to test the agreement of the model simulated water table level results against the observed water table level values at the field study site (Ewen, 2011; McCuen et al., 2006). The same statistical and graphical techniques as described in Section 6.4.2.1 were applied to evaluate the model performance for the assessment of the models ability to simulate reality (Legates and McCabe Jr, 1999). The calibration and validation of the model applied a split time series of independent observed data (Beven, 2001). The hydraulic conductivity, seepage rate and drain spacing were calibrated in order to establish confidence in the model data outputs. TEM 1 dipwell observed water table level data was utilised for the model calibration and validation as this dipwell was located proximate to the River Ivel study reach. Table 6.27 displays the calibration periods and parameters calibrated and the validation period.

Table 6.27 WaSim model calibration parameters and validation time series

	Parameter	Event Period	Date/Year
Calibration	Seepage rate	1 (summer 1)	April – October 2011
	Hydraulic conductivity	2 (winter 1)	November 2011 – February 2012
	Drain spacing		
Validation	NA	3 (summer 2)	March – July 2012

The split time series was chosen based of the net rainfall seasonal pattern of results (Section 6.2.2.1, Figure 6.7). Calibration of the seepage rate was applied by estimating a priori involving trial and error in adjusting this parameter to get a better fit between the modelled and observed water table levels for event period 1 (Beven, 2001). The calibration of the seepage rate was chosen for period 1 as it was established that the evapotranspiration was greater than the rainfall in the field study site over this period. Adjusting this parameter may cause a rise in the water table level in the WaSim model in order to enable the best fit between the modelled to observed data. The seepage rate was calibrated for event period 1 by adjusting the parameter by increments of 1 mm.d^{-1} ranging from 0-10 mm.d^{-1}. The maximum allowable constant seepage rate that can be applied in the WaSim model was 10 mm.d^{-1}. The hydraulic conductivity (K) was set at 1.0 m.d^{-1}. The calibrated seepage rate was applied as a fixed parameter in event period 2 where the hydraulic conductivity and drain spacing will be calibrated by estimating a priori through trial and error of adjusting the parameter values until the best fit between the modelled and observed water tables has been achieved.

The hydraulic conductivity and the drain spacing parameters were calibrated for event period 2. These specific parameters were selected since it was established that the rainfall was greater than the evapotranspiration in the field study site over this period. Adjusting these parameters may cause lowering of the water table level in the WaSim model to enable a best fit between the modelled to observed data. The hydraulic conductivity and drain spacing were calibrated for event period 2 by the following:

- Hydraulic conductivity: parameter adjustment by 0.1 m.d^{-1} increments from a range of 1.0-1.5 m.d^{-1}
- Drain spacing: parameter adjustment by 10 m increments from a range of 10-100 m.

The WaSim model was then validated for event period 3 using the calibrated parameter values for the hydraulic conductivity, seepage rate and drain spacing from calibration event periods 1 and 2. The modelled and observed water table levels were then compared to substantiate that the model possesses a satisfactory accuracy range, which is consistent with its intended use (Refsgaard and Henrikson, 2004). The 'initial water table depth' was set as the observed water table level on the first day of each event period for the calibration and validation time series.

6.5.1.9 **Model simulation**

A model was created for each seasonal year event i.e. average, wet and dry years (Section 6.3.2) for each vertical connectivity scenario (Section 6.3.3) and was simulated to generate a water table position for each scenario. Each model was run for the appropriate rainfall event hydrological year with a 6 month lead in time. The results were summarised annually at 30 September to represent results of a hydrological year. The 'initial water content in the unsaturated zone' was defined at field capacity. The 'initial water table depth' was set to 0.51 m (depth below surface) based on the average manual dip level of all 3 dip-wells at the field study site on 31/03/2011 i.e. start of water table monitoring period.

6.5.2 **Results and Discussion**

6.5.2.1 **Sensitivity**

The seepage rate sensitivity statistical results are displayed in Table 6.28.

Table 6.28 WaSim model seepage rate sensitivity statistical results

Seepage rate (mm/d)		**MAE (mbgl)**	**RMSE (mbgl)**	**NSE**
2.0	**0**	0.00	0.00	0.00
1.6	**-20%**	0.00	0.00	1.00
2.4	**+20%**	0.00	0.00	1.00

Modelling the seepage rate water table level at ±20% has no impact on the water table levels when compared to the initial modelled water table level for a seepage rate of 2 $mm.d^{-1}$ (Table 6.28).

The sensitivity test results of the hydraulic conductivity are displayed in Figure 6.34 and Table 6.29. A black dotted line indicates the modelled water table level of the initial hydraulic conductivity value while the blue coloured lines indicate the modelled water table level for ±20% hydraulic conductivity values.

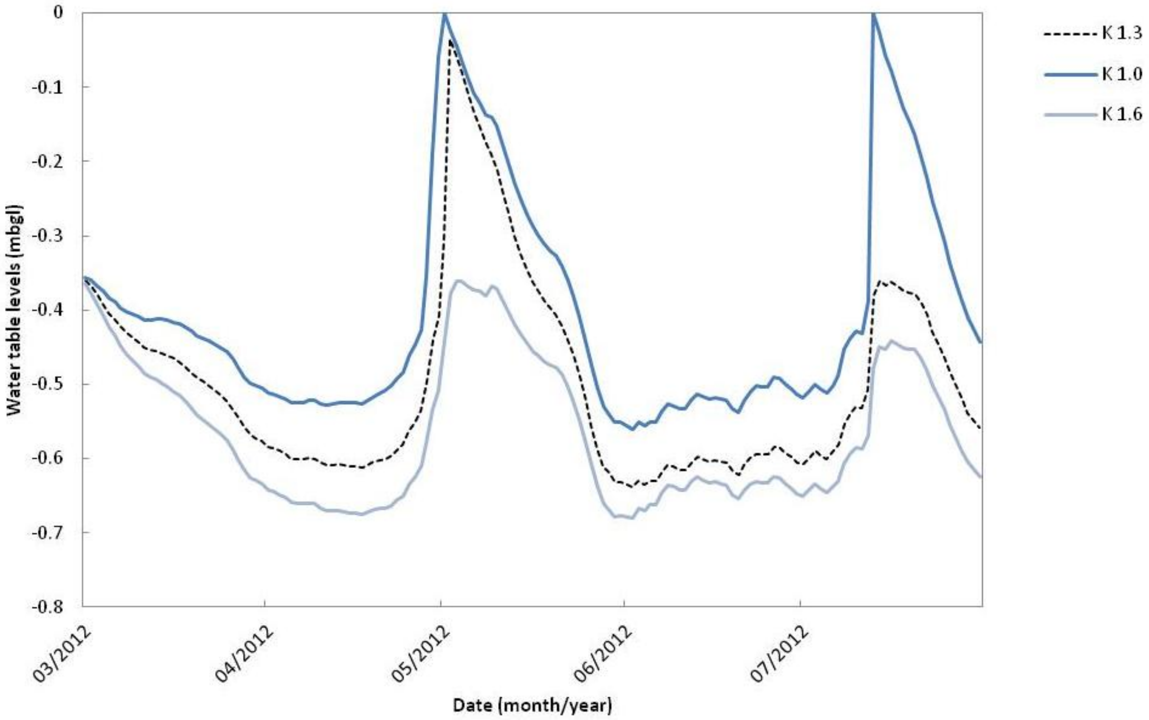

Figure 6.34 WaSim model water table level hydraulic conductivity sensitivity results

Table 6.29 WaSim model hydraulic conductivity sensitivity statistical results

Hydraulic conductivity ($m.d^{-1}$)		**MAE (mbgl)**	**RMSE (mbgl)**	**NSE**
1.3				
1.0	-20%	0.09	0.11	0.27
1.6	+20%	-0.07	0.08	0.60

Figure 6.34 indicates that both raising and lowering the hydraulic conductivity values impact on the water table level position. The statistical tests (Table 6.29) indicate the lowering the hydraulic conductivity has a more pronounced affect based on the MAE and RMSE results. The NSE results of <0.5 indicate a poor agreement between the -20% hydraulic conductivity of 1.0 m d^{-1} and the initial modelled hydraulic conductivity of 1.3 $m.d^{-1}$ value. Hydraulic conductivity is a critical parameter to enable the accurate modelling of the water table at the field study site. Raising the hydraulic conductivity increases the transmission of water through the soil which should impact on raising the water table level and vice versa yet in this instance the opposite effect has occurred. It is possible that excess water removed from the system through the surface drains occurred when raising the hydraulic conductivity thus lowering the water table position.

The sensitivity test results of the drain spacing are displayed in Figure 6.35 and Table 6.30. A black dotted line indicates the observed water table level for the initial drain spacing with the blue coloured lines indicate the modelled water table level for the ±20% drain spacing values.

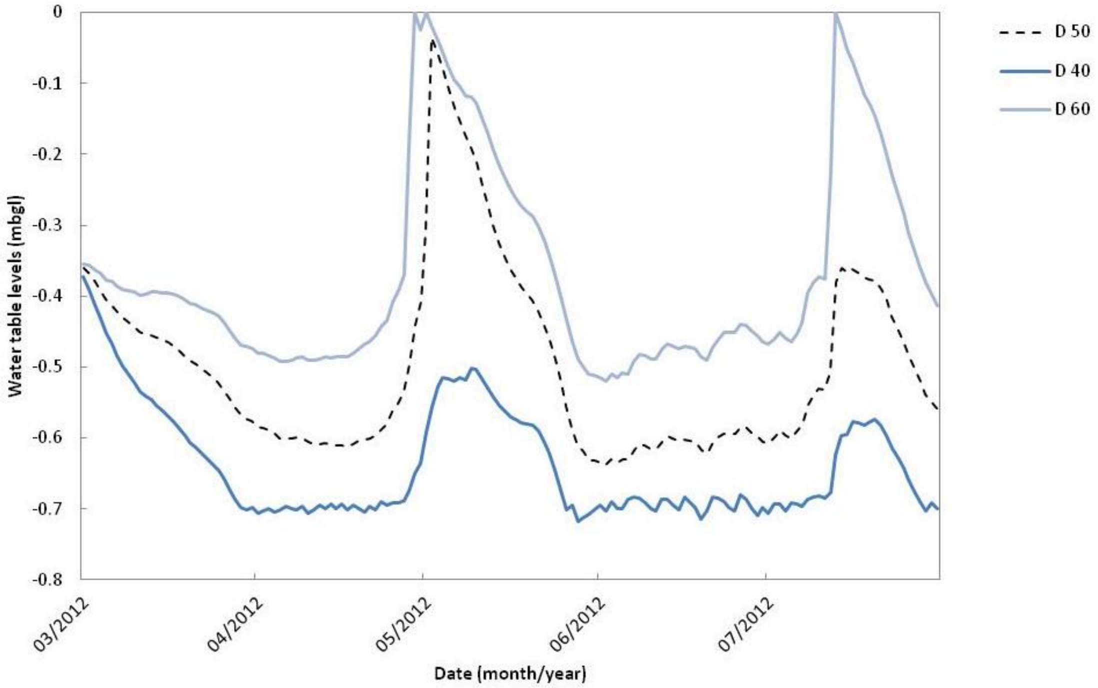

Figure 6.35 WaSim model water table level drain spacing sensitivity results

Table 6.30 WaSim model drain spacing sensitivity statistical results

Drain spacing (m)		**MAE (mbgl)**	**RMSE (mbgl)**	**NSE**
50				
40	-20%	-0.14	0.16	-0.50
60	+20%	0.13	0.15	-0.23

The effects of raising and lowering the drain spacing had the same pattern of impact on the water table level as the hydraulic conductivity paramters although decreasing the drain spacing e.g. 40 m lowers the water table level and increasing the drain spacing e.g. 60 m raises the water table level. The statistical tests (Table 6.30) indicate that both decreasing and increasing the drain spacing has a pronounced effect based on the MAE and RMSE results. The NSE results of <0.5 indicate a poor agreement between the ±20% drain spacing and the initial modelled drain spacing of 50 m value.

6.5.2.2 **Calibration**

Figure 6.36 displays the modelled and observed water table level for each seepage rate (S) for a fixed hydraulic conductivity (K) of 1.0 m.d^{-1}. A black dotted line indicates the observed water table level. The blue coloured lines indicate the modelled water table level for the range of seepage rate values.

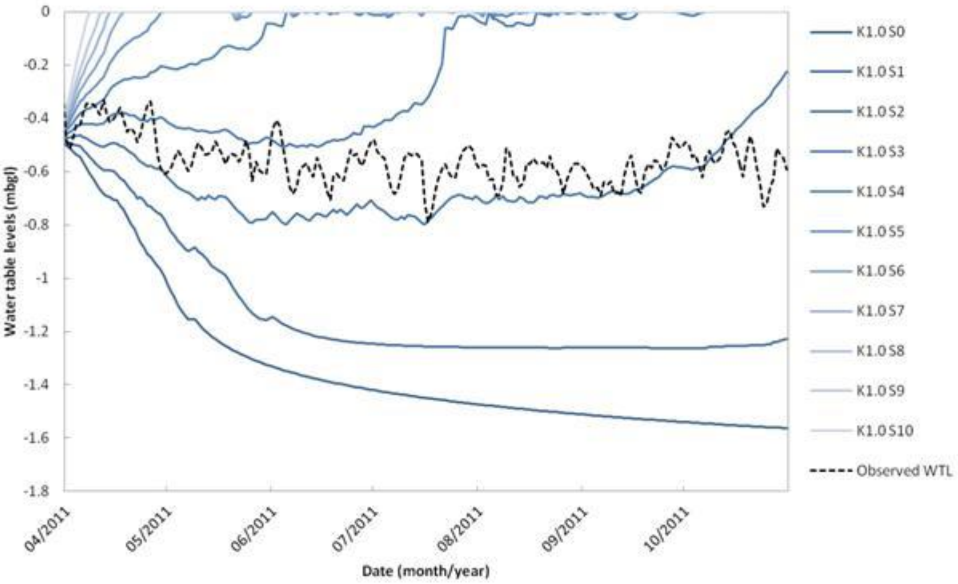

Figure 6.36 WaSim model seepage rate calibration for event period 1 modelled and observed water table level results

It is was observed in Figure 6.36 that a seepage rate of 2 mm.d^{-1} represents the better fit between the modelled and observed water table data for event period 1. Table 6.31 displays the statistical analysis results of the seepage rate calibration in event period 1.

Table 6.31 Seepage rate calibration for event period 1 statistical analysis results

Scenario	MAE (mm.d^{-1})	RMSE (mm.d^{-1})	NSE
K1.0 S0	-0.78	0.81	-87.08
K1.0 S1	-0.56	0.59	-46.25
K1.0 S2	0.00	0.15	-2.15
K1.0 S3	0.32	0.41	-21.46
K1.0 S4	0.49	0.52	-35.21
K1.0 S5	0.53	0.55	-39.13
K1.0 S6	0.54	0.55	-39.95
K1.0 S7	0.54	0.56	-40.24
K1.0 S8	0.54	0.56	-40.44
K1.0 S9	0.54	0.56	-40.44
K1.0 S10	0.55	0.56	-40.67

The statistical results in Table 6.31 indicate a poor agreement between the modelled and observed water table levels. However, a seepage rate of 2 mm.d^{-1} provided an improved agreement based on the NSE results.

Figures 6.37 - 6.42 display graphs and Tables 6.32 -6.37 display the statistical analysis tables of the modelled and observed water table levels to calibrate the hydraulic conductivity and seepage rate in event period 2 for the WaSim model.

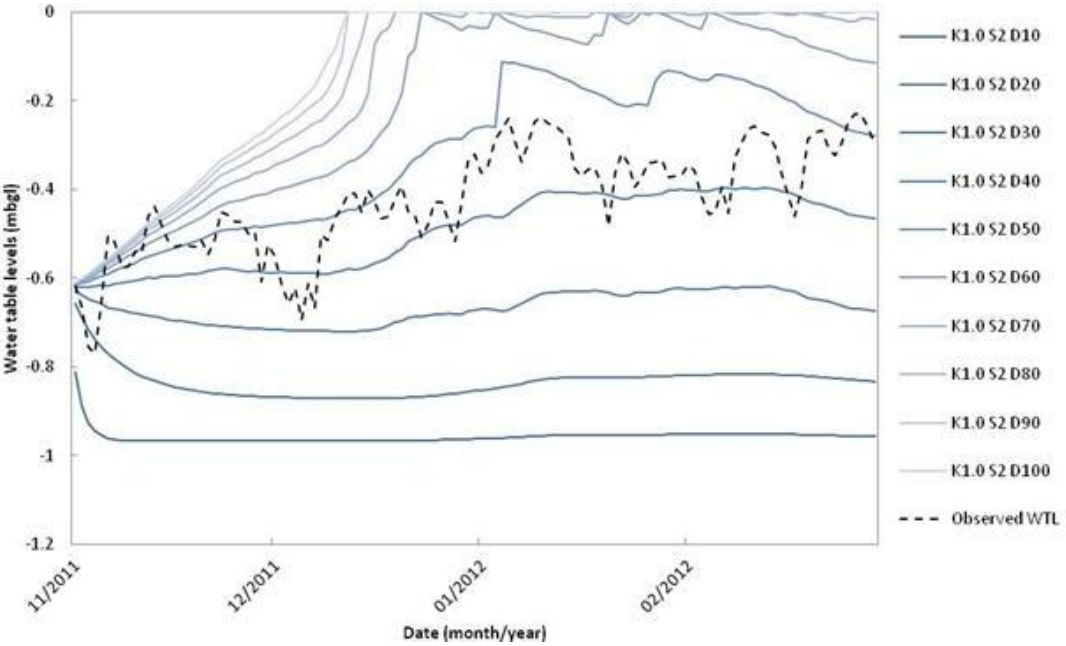

Figure 6.37 WaSim model drain spacing calibration (Hydraulic conductivity = 1.0 m.d^{-1}) for event period 2 modelled and observed water table level results

Table 6.32 WaSim model drain spacing calibration (Hydraulic conductivity = 1.0 m.d^{-1}) for event period 2 statistical analysis results

Simulation	**MAE (mm.d^{-1})**	**RMSE (mm.d^{-1})**	**NSE**
K1.0 S2 D10	-0.54	0.55	-19.58
K1.0 S2 D20	-0.67	0.43	-11.72
K1.0 S2 D30	-0.25	0.27	-3.91
K1.0 S2 D40	-0.07	0.11	0.22
K1.0 S2 D50	0.10	0.14	-0.27
K1.0 S2 D60	0.22	0.26	-3.51
K1.0 S2 D70	0.26	0.30	-5.03
K1.0 S2 D80	0.28	0.31	-5.68
K1.0 S2 D90	0.29	0.32	-6.07
K1.0 S2 D100	0.30	0.33	-6.31

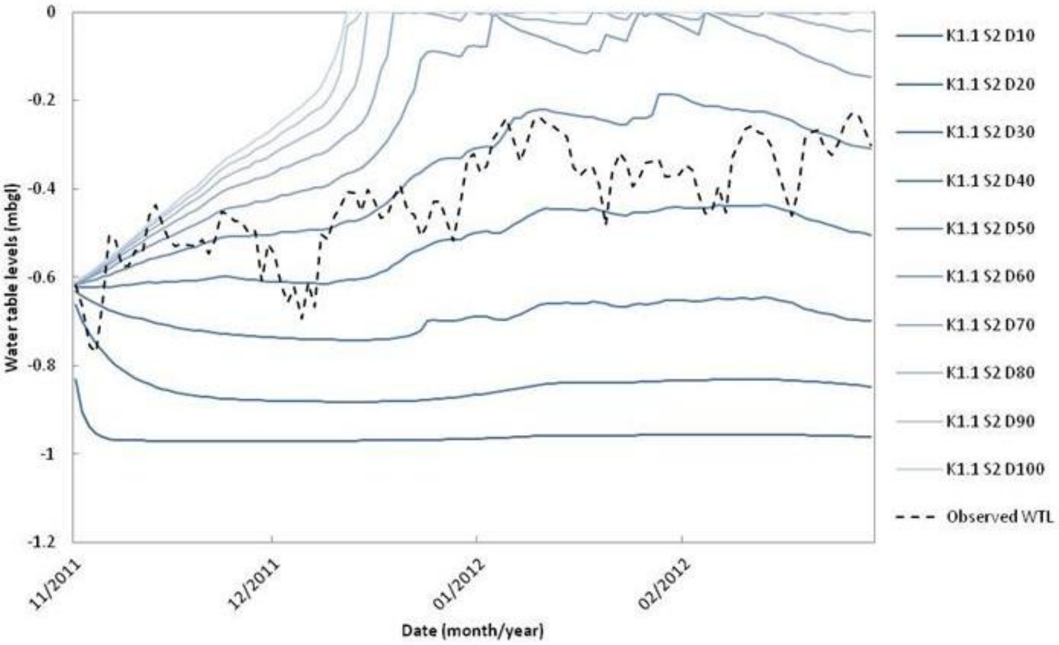

Figure 6.38 WaSim model drain spacing calibration (Hydraulic conductivity = 1.1 m.d^{-1}) for event period 2 modelled and observed water table level results

Table 6.33 WaSim model drain spacing calibration (Hydraulic conductivity = 1.1 m.d^{-1}) for event period 2 statistical analysis results

Simulation	**MAE (mm.d^{-1})**	**RMSE (mm.d^{-1})**	**MAE (mm.d^{-1})**
K1.1 S2 D10	-0.53	0.55	-15.50
K1.1 S2 D20	-0.42	0.55	-9.60
K1.1 S2 D30	-0.26	0.44	-3.50
K1.1 S2 D40	-0.09	0.29	-0.01
K1.1 S2 D50	0.07	0.14	0.13
K1.1 S2 D60	0.20	0.26	-2.71
K1.1 S2 D70	0.26	0.32	-4.47
K1.1 S2 D80	0.29	0.34	-5.36
K1.1 S2 D90	0.30	0.35	-5.78
K1.1 S2 D100	0.31	0.36	-5.99

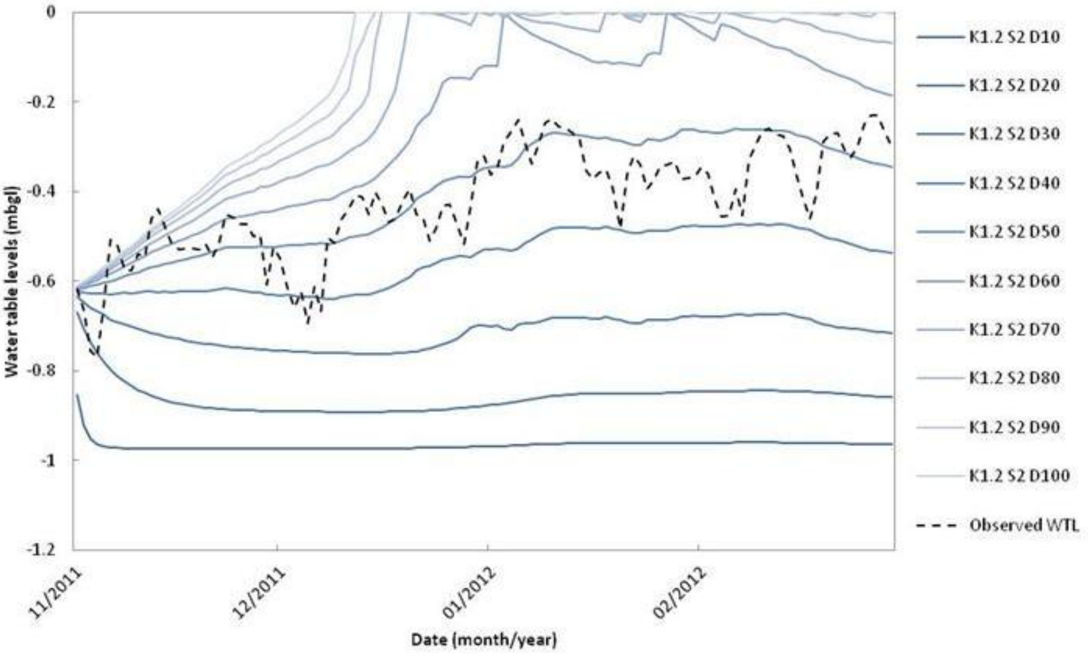

Figure 6.39 WaSim model drain spacing calibration (Hydraulic conductivity = 1.2 m.d^{-1}) for event period 2 modelled and observed water table level time series graph

Table 6.34 WaSim model drain spacing calibration (Hydraulic conductivity = 1.2 m.d^{-1}) for event period 2 statistical analysis results

Simulation	**MAE (mm.d^{-1})**	**RMSE (mm.d^{-1})**	**MAE (mm.d^{-1})**
K1.2 S2 D10	-0.54	0.56	-20.09
K1.2 S2 D20	-0.43	0.46	-13.17
K1.2 S2 D30	-0.29	0.31	-5.57
K1.2 S2 D40	-0.13	0.16	-0.65
K1.2 S2 D50	0.023	0.08	0.55
K1.2 S2 D60	0.17	0.21	-1.99
K1.2 S2 D70	0.24	0.28	-4.29
K1.2 S2 D80	0.27	0.31	-5.35
K1.2 S2 D90	0.28	0.32	-5.79
K1.2 S2 D100	0.29	0.32	-6.11

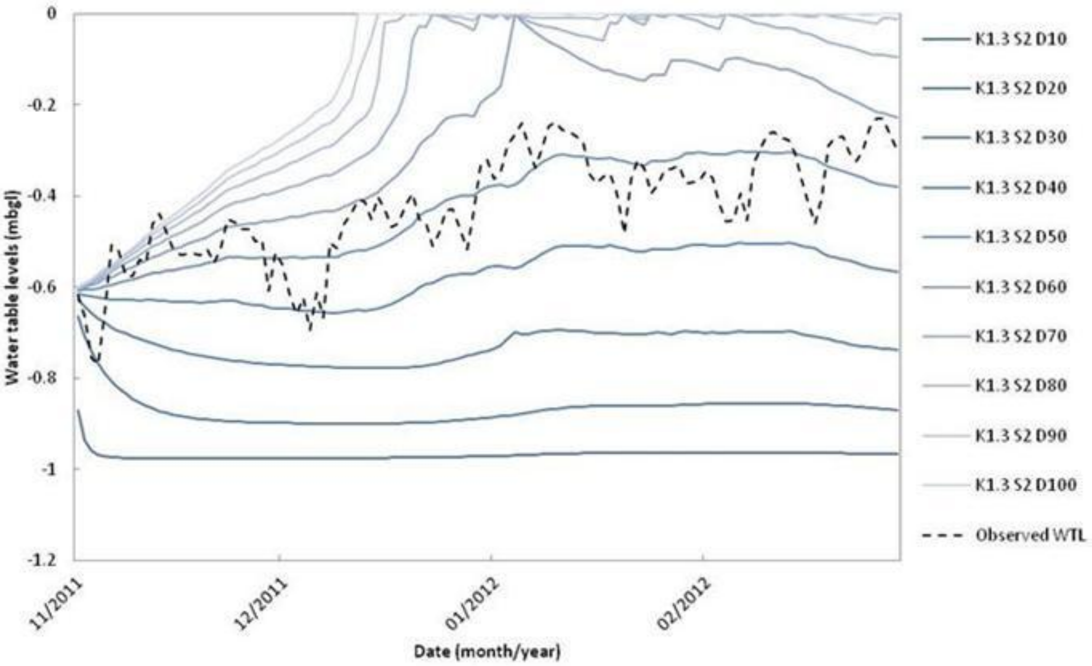

Figure 6.40 WaSim model drain spacing calibration (Hydraulic conductivity = 1.3 m.d^{-1}) for event period 2 modelled and observed water table level results

Table 6.35 WaSim model drain spacing calibration (Hydraulic conductivity = 1.3 m.d^{-1}) for event period 2 statistical analysis results

Simulation	**MAE (mm.d^{-1})**	**RMSE (mm.d^{-1})**	**MAE (mm.d^{-1})**
K1.3 S2 D10	-0.55	0.56	-20.29
K1.3 S2 D20	-0.45	0.47	-13.76
K1.3 S2 D30	-0.31	0.33	-6.28
K1.3 S2 D40	-0.15	0.18	-1.14
K1.3 S2 D50	**-0.003**	**0.07**	**0.62**
K1.3 S2 D60	0.14	0.18	-1.16
K1.3 S2 D70	0.23	0.27	-3.94
K1.3 S2 D80	0.27	0.30	-5.16
K1.3 S2 D90	0.28	0.31	-5.73
K1.3 S2 D100	0.29	0.32	-6.10

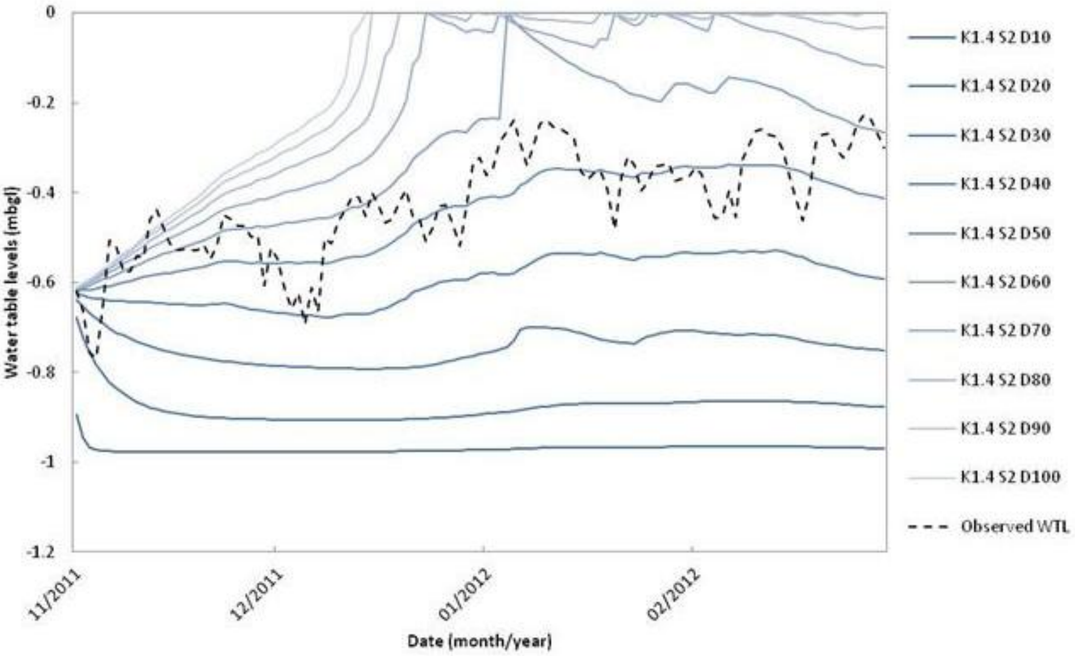

Figure 6.41 WaSim model drain spacing calibration (Hydraulic conductivity = 1.4 m.d^{-1}) for event period 2 modelled and observed water table level results

Table 6.36 WaSim model drain spacing calibration (Hydraulic conductivity = 1.4 m.d^{-1}) for event period 2 statistical analysis results

Simulation	**MAE (mm.d^{-1})**	**RMSE (mm.d^{-1})**	**MAE (mm.d^{-1})**
K1.4 S2 D10	-0.55	0.56	-20.47
K1.4 S2 D20	-0.46	0.47	-14.29
K1.4 S2 D30	-0.32	0.34	-7.01
K1.4 S2 D40	-0.18	0.20	-1.68
K1.4 S2 D50	-0.03	0.08	0.56
K1.4 S2 D60	0.11	0.15	-0.52
K1.4 S2 D70	0.21	0.26	-3.43
K1.4 S2 D80	0.26	0.29	-4.79
K1.4 S2 D90	0.28	0.31	-5.54
K1.4 S2 D100	0.29	0.32	-5.91

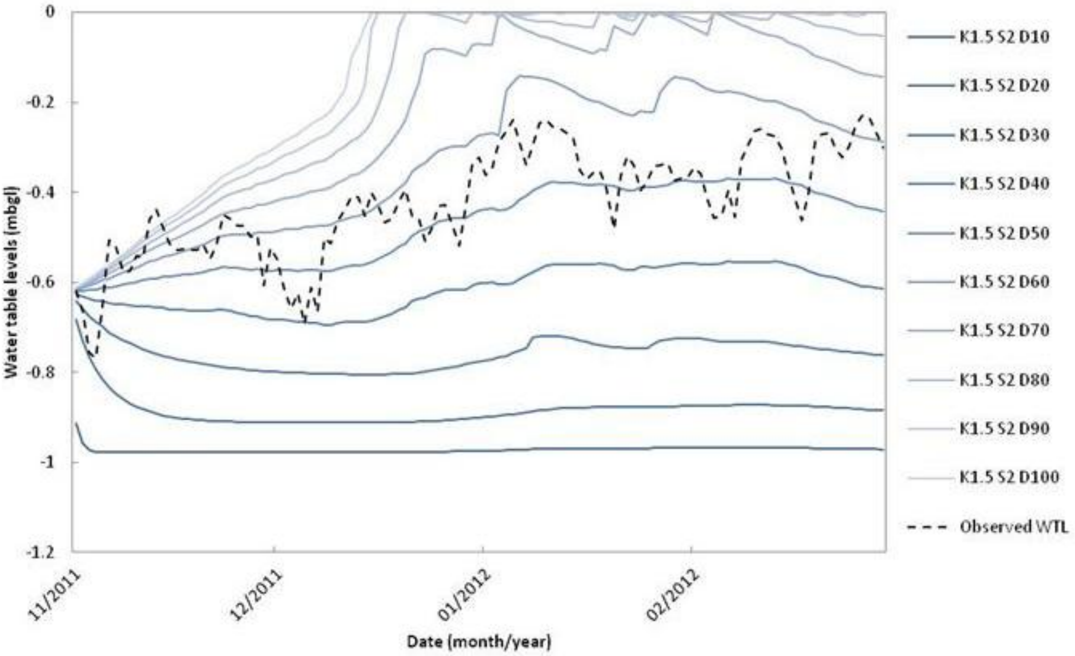

Figure 6.42 WaSim model drain spacing calibration (Hydraulic conductivity = 1.5 m.d^{-1}) for event period 2 modelled and observed water table level results

Table 6.37 WaSim model drain spacing calibration (Hydraulic conductivity = 1.5 m.d^{-1}) for event period 2 modelled statistical analysis results

Simulation	**MAE (m)**	**RMSE**	**NSE**
K1.5 S2 D10	-0.55	0.56	-20.62
K1.5 S2 D20	-0.46	0.48	-14.76
K1.5 S2 D30	-0.34	0.36	-7.68
K1.5 S2 D40	-0.19	0.22	-2.20
K1.5 S2 D50	-0.05	0.09	0.41
K1.5 S2 D60	0.08	0.12	-0.05
K1.5 S2 D70	0.20	0.24	-2.85
K1.5 S2 D80	0.25	0.28	-4.52
K1.5 S2 D90	0.27	0.31	-5.40
K1.5 S2 D100	0.29	0.32	-5.78

The calibration results (Figures 6.37 - 6.42 and Tables 6.32 -6.37) indicate that when the drain spacing is less than 50 m, the modelled water table is below the observed water table level and vice versa. When the hydraulic conductivity increases from 1.0-1.5 m.d^{-1}, this causes a rise in the modelled to observed water table position. A hydraulic conductivity of 1.3 m.d^{-1} and drain spacing of 50 m provided the best fit of the modelled to the observed water table level (Figure 6.40 and Table 6.35). The NSE results were 0.62 indicating a good agreement between the modelled and observed water table levels (Table 6.35).

6.5.2.3 **Validation**

The seepage rate of 2 mm.d^{-1}, hydraulic conductivity of 1.3 m.d^{-1} and drain spacing of 50 m was utilised for validation using event period 3. Figure 6.43 displays the modelled to observed water table level validation results and Table 6.38 displays the statistical analysis results.

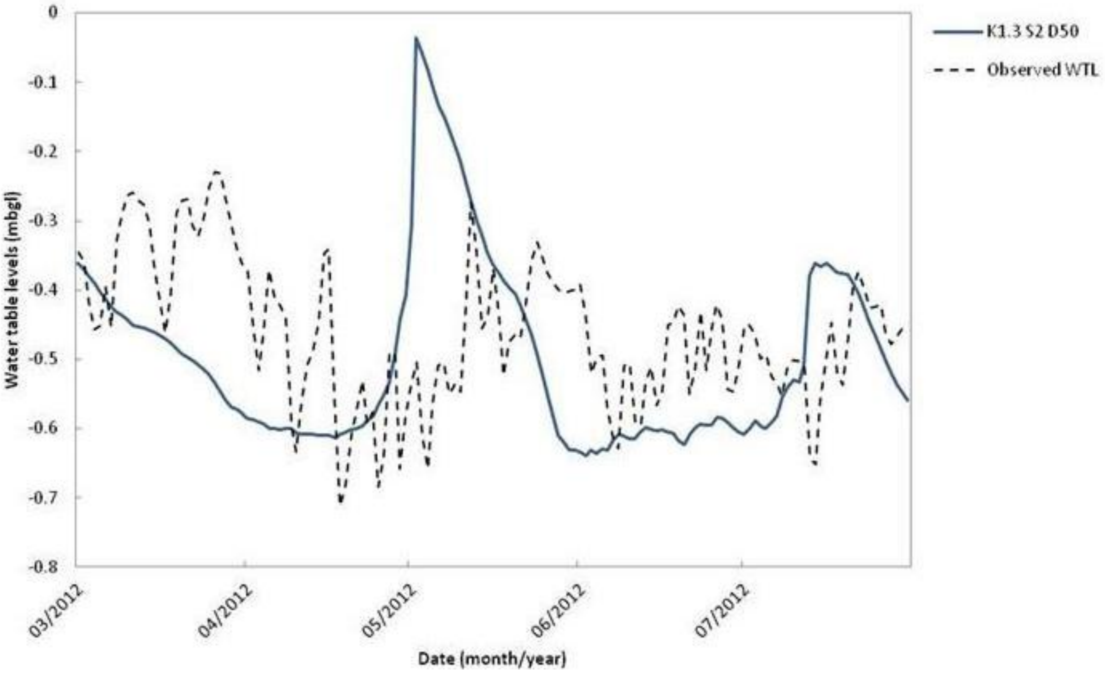

Figure 6.43 WaSim model validation for event period 3 modelled and observed water table level results

Table 6.38 WaSim model validation statistical analysis results

	MAE	**RMSE**	**NSE**
K1.3 S2 D50	-0.04	0.19	-1.74

Figure 6.43 quite clearly indicates that there is large variation in comparing the modelled to the observed water table levels. The overall bias of the model as measured by the MAE (Table 6.38) is negative indicating that the model underestimates the observed water table levels as reinforced by the results in Figure 6.43. The model performance using the NSE displayed results <0 which indicates that using the mean of the observed values is better than the model predictions (Legates and McCabe, 1999). The sensitivity, calibration and validation results generally indicate

that the modelled water table levels were underestimated in comparison to the observed water table levels at the site.

In this instance, it was deduced that potentially groundwater seepage from the aquifer is contributing to the position of the water table level at the field study site. The hydrogeological analysis (Section 5.2.2.2) of the field study site indicated that the field site had an unconfined aquifer. The main flows were identified as net rainfall, infiltration, groundwater recharge and lateral and vertical seepage from the river channel and surface drains with the potential to affect the position of the water table. It was discussed in Section 5.2.2.2 that a clay loam top soil was present with a depth of 1 - 1.47 mbgl from west to east for the field study site (Figure 5.9). More importantly, river terrace gravels are present below the clay loam ranging in thickness from 0.8-1.7 m (Figure 5.9). The confining layer of the field study site was identified as an Oxford Clay Formation (Mudstone) at 1.68 mbgl. The river terrace gravels are also potentially connected to the river channel (Figure 5.9) and it is possible that seepage from the river channel is recharging the water table. It can be also be hypothesised that potentially other hydrological flows e.g. lateral and vertical seepage from outside of the field study site from the regional aquifer are also affecting the position of the water table. The WaSim model was capable of simulating the hydrological flows as conceptualised for the field study site yet simulating seepage from the aquifer is not possible. The data collected to characterise the subsurface system provided and incomplete picture of the hydrological flows introducing substantial uncertainty to the conceptual model. Based on the model calibration and validation results, WaSim was not suitable for its intended use in this research, therefore the mean of the observed values was utilised as a single vertical connectivity ‘no drain’ scenario in this research.

6.6 Integrated modelling system

The following section describes the intended integrated modelling system scenarios, results and discussion.

6.6.1 Integrated model scenarios

The floodplain connectivity scenarios for the integrated modelling system are described in Table 6.39. Initially the linked ISIS 1D-2D model was used to simulate the lateral connectivity scenarios for each design flood event. It was intended that the modelled inundation depth output from the linked ISIS 1D-2D model would be integrated with the

WaSim model to simulate the impact of the flooded depth under each seasonal year event and vertical connectivity scenario.

Table 6.39 Floodplain connectivity scenarios for the integrated model system

Scenario	Description	Connectivity	Model
1.	No embankment (50% AEP), (50, 20, 10, 4, 2, 1.33 and 1% AEP)	Lateral	Linked ISIS 1D-2D
a	No drain (WET, AVE, DRY)	Vertical	WaSim
b	Agricultural standard (WET, AVE, DRY)		
c	Existing agricultural field drain (WET, AVE, DRY)		
d	Existing IDB field drain (WET, AVE, DRY)		
2.	SOP Embankment (20% AEP), (50, 20, 10, 4, 2, 1.33 and 1% AEP)	Lateral	Linked ISIS 1D-2D
a	No drain (WET, AVE, DRY)	Vertical	WaSim
b	Agricultural standard (WET, AVE, DRY)		
c	Existing agricultural field drain (WET, AVE, DRY)		
d	Existing IDB field drain (WET, AVE, DRY)		
3.	Existing Embankment (10% AEP), (50, 20, 10, 4, 2, 1.33 and 1% AEP)	Lateral	Linked ISIS 1D-2D
a	No drain (WET, AVE, DRY)	Vertical	WaSim
b	Agricultural standard (WET, AVE, DRY)		
c	Existing agricultural field drain (WET, AVE, DRY)		
d	Existing IDB field drain (WET, AVE, DRY)		
4.	SOP Embankment (4% AEP), (50, 20, 10, 4, 2, 1.33 and 1%A EP)	Lateral	Linked ISIS 1D-2D
a	No drain (WET, AVE, DRY)	Vertical	WaSim
b	Agricultural standard (WET, AVE, DRY)		
c	Existing agricultural field drain (WET, AVE, DRY)		
d	Existing IDB field drain (WET, AVE, DRY)		

The coupled full integration of the linked ISIS 1D and 2D model was successful in creating the exchange of river and floodplain flows creating the river discharge in the ISIS 1D model and the inundation area, volume, depth and velocity results. The sequential integration of the linked ISIS 1D and 2D model and the WaSim model could not be completed in this research as the WaSim model displayed poor validation results as described in Section 6.5.2.3. Therefore modelling the seasonal year event scenarios for each vertical connectivity scenario would be invalid and prone to bias.

To demonstrate the impacts of the floodplain connectivity on the ecosystem services delivery, the design flood event and lateral connectivity scenarios was applied using a single vertical connectivity scenario which was based on the average observed water table level of 0.53 mbgl representing the ‘no drain’ i.e. scenario a. The hydrological season average water table level was calculated based on the monitored water table levels at the field study site (Table 6.40). A sensitivity test was applied to assess the difference between the average and seasonal water table levels using a MAE statistical test (Moriasi et al., 2007).

Table 6.40 Hydrological season water table levels at the field study site

Hydrological season	**Observed water table level period**	**Water table level (mbgl)**	**MAE (mbgl)**
Average	1st April 2011 – 31st July 2012	0.53	
Summer 2010	1st April – 30th September 2011	0.56	0.03
Winter 2011	1st October 2011 – 30th March 2012	0.47	-0.06

The seasonal impacts of the water table level were excluded in preference to the application of the average observed water table level, as the seasonal difference was negligible (Table 6.40).

The impacts of the design flood event and lateral connectivity scenarios upon the water table position were then estimated by applying a mathematical empirical formula to calculate the rise in the water table level utilising the inundation depth from the linked ISIS 1D-2D model and the average water table level. The method applied is as follows:

1. The inundation depths for the 90th hour of each downstream flood event hydrograph and lateral connectivity scenario were extracted from the linked ISIS 1D-2D model results. These results represent the inundation depth in the floodplain after the flood event has subsided.
2. The inundation depth considering the loss of water through evapotranspiration and infiltration into the soil zone was calculated as follows:
    a. Subtraction of the LTA evapotranspiration i.e. 1.73 mm as calculated for the case study site over the monitoring period i.e. 31/03/2011 – 31/07/2012 from the modelled inundation depths for each scenario. The LTA evapotranspiration value represents 1 day based on the remaining inundated floodwaters at the 90th hour of the flood hydrograph.
    b. Subtraction of the potential infiltrated depth (Equation 6.11) from the modelled inundation depths for each scenario. The drainable porosity for a clay loam soil (Rawls et al., 1982) = 0.143 $cm^3.cm^{-3}$. The average water table position at the field site was derived as 0.53 mbgl over the monitoring period i.e. 31/03/2011 – 31/07/2012.

$$Potential\ infiltrated\ depth(m) = D.P.x\ W.T \qquad \textbf{6.11}$$

where:

D.P. = drainable porosity of clay loam soil ($cm^3.cm^{-3}$)

W.T. = water table position of field study site (mbgl)

The potential infiltrated depth was calculated as 0.076 m and was rounded up to 0.1 m. This value was also based on the minimum data value that can be extracted for the inundation depth from the linked ISIS 1D-2D model results.

c. The average inundation depth for each scenario was then calculated.

3. Where the average inundation depth scenario results were ≤0.1 m, Equation 6.12 was applied to calculate the water table position.

$$Water\ table\ position\ (mbgl) = \left(\frac{I}{D.P.}\right) - W.T \quad (6.12)$$

where

I = Inundation depth (m)

$D.P.$= drainable porosity of clay loam soil ($cm^3.cm^{-3}$)

$W.T.$ = water table position of field study site (mbgl)

4. Where the average inundation depth scenario results were >0.1 m; the soil zone has completed infiltrated with floodwater and the water table is at ground level e.g. 0 magl. In this instance, the average inundation depth (mabgl) was applied.
5. Where no flooding of the lateral connectivity scenarios occurred, the average observed water table position of 0.53 mbgl was applied.

6.6.2 **Results and discussion**

The linked ISIS 1D-2D model results for the discharge hydrograph, inundation area, volume, depth and velocity for each design flood event and lateral connectivity scenario are displayed in Appendix C.6 and were also displayed and discussed in Section 6.4.2. The impact of the design flood event and lateral connectivity scenarios for a ‘no drain’ vertical connectivity scenario upon the water table position are displayed in Table 6.41. These results (Table 6.41) display the negative values to indicate the water table position; (mbgl) and the positive values indicate the surface water level in the floodplain (magl).

Table 6.41 Design flood event and lateral connectivity scenarios for a ‘no drain’ vertical connectivity scenario water table position (mbgl) and surface water level (magl) results

Scenario		**Flood event (%AEP)**						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	+0.55	+0.55	+0.70	+0.79	+0.70	+0.70	+0.70
S2a	SOP embankment (20%AEP), no drain	-0.53	+0.40	+0.65	+0.79	0.70	+0.70	+0.70
S3a	Existing embankment (10%AEP) , no drain	-0.53	+0.50	+0.70	+0.75	+0.75	+0.75	+0.70
S4a	SOP embankment (4%AEP) , no drain	-0.53	-0.53	-0.53	+0.55	+0.81	+0.85	+0.85

In high frequency/low magnitude flood events, decreasing the floodplain connectivity limits flood inundation to inhibit raising the water table level position. In low frequency/high magnitude flood events, decreasing connectivity has a limited impact on reducing flood inundation as the magnitude of the flood event is so greater and the embankment crests are high. Floodwaters are trapped behind the embankments leading to infiltration and groundwater recharge to raise the water table levels and maintaining high surface water levels. The impact of controlling lateral connectivity is critical for flood damage, terrestrial habitat, agricultural productivity and recreation ecosystem services delivery. The impact of the scenarios to ecosystem services mentioned will be discussed further in Chapter 7.

7 ECOSYSTEM SERVICES ASSESSMENT

7.1 Introduction

The following chapter describes the methods applied to assess the impact of the design flood events and floodplain connectivity scenarios on the delivery of floodplain ecosystem services, synergies and trade-offs. Finally, the ecosystem service assessment results for each floodplain connectivity scenario are displayed and discussed.

7.2 Methodology

7.2.1 **Hydrological indicators**

Each ecosystem function was subdivided into ecosystem services and defined as a benefit or disbenefit based on the impact of their associated hydrological physical processes (De Groot, 2006; Wheeler et al., 2004; Morris et al., 2004 and Penning-Rowsell et al., 2005). The indicators were derived from the hydrological attributes for each hydrological physical process (Brauman et al., 2007). The attributes describe the state i.e. condition of the ecosystem service in consideration of flood event and floodplain connectivity (Scholes et al., 2010). The indicators were also based on the linked ISIS 1D-2D model outputs and derived from the field study site observed hydrological outputs and standard hydrological values based on the site characteristics. The indicators chosen also met the criteria to assess the state of ecosystem services (Scholes et al., 2010 and DCLG, 2009) as follows:

- Quantitative: as a single variable with a logical connection to the process or object of concern i.e. hydrological processes and attributes.
- Composite indices: individual indices are related to separate and distinguishable components and when combined provide a single impacts result. The combination of indices increases reliability and ease of communication to assess ecosystem services impacts.
- Policy relevant, scientifically sound, simple to calculate, easy to understand and practical and affordable.
- Suitable for aggregation.
- Sources of indicator information include peer-reviewed literature, maps, computer models, indigenous technical and traditional knowledge.
- Ecosystem services may be assessed in temporal and spatial scales.

Table 7.1 provides a summary of the ecosystem functions and services based on floodplain hydrological processes (Posthumus et al., 2010). The impact types e.g. benefit or disbenefit, are defined for each ecosystem service. The hydrological processes that define the impact type and their attributes and indicators are listed. These individual hydrological indices while related to separate, distinguishable components when combined provide a single composite impact performance score to provide a more robust, and reliable assessment of the impacts of design flood events and floodplain connectivity on ecosystem services delivery.

Table 7.1 Ecosystem function and services impact type and hydrological physical processes, attributes and indicators

Ecosystem		**Impact type**	**Hydrological**		
Function	**Services**		**Process**	**Attribute**	**Indicator**
Regulation	Flood alleviation	Benefit	Flood attenuation	Quantity	▪ Inundation volume ▪ Discharge peak attenuation
				Timing	▪ Discharge peak translation
	Flood damage	Disbenefit	Flood inundation	Quantity	▪ Inundation area ▪ Inundation depth ▪ Flooded buildings count
	Water storage	Benefit	Groundwater recharge	Quantity	▪ Infiltrated volume - Infiltrated area based on the potential infiltrated depth
Habitat	Terrestrial	Benefit	Water regime dynamics	Quantity	▪ Inundation area ▪ Water table position
				Timing	▪ Ponding duration
	Freshwater fish	Benefit		Quantity	▪ Inundation depth and velocity area
Production	Agricultural productivity	Disbenefit	Flood inundation	Quantity	▪ Inundation area ▪ Water table position ▪ Ponding duration
				Timing	▪ Ponding duration
Information	Recreation	Disbenefit	Flood inundation	Quantity	▪ Inundation area ▪ Inundation depth
				Timing	▪ Ponding duration

Source: after Posthumus et al. (2010); Brauman et al. (2007); De Groot (2006); MA (2005); Wheeler et al. (2004); Morris et al. (2004): Penning-Rowsell et al. (2005)

The linked ISIS 1D-2D model output data applied and methods to calculate each hydrological indicator are described as follows:

1. The inundation area (ha) and the inundation volume (m^3) for the 90th hour of each downstream flood event hydrograph were extracted from the linked ISIS 1D-2D model for each scenario. These results represent the area and volume of water retained in the floodplain and removed from the river channel after the flood event has subsided.
2. The discharge peak attenuation was calculated using Equation 7.1 as follows:

$$A = U/S - D/S \tag{7.1}$$

where:

A = Discharge peak attenuation ($m^3.s^{-1}$)
U/S = upstream boundary of river: hydrograph peak for a flood event ($m^3.s^{-1}$)
D/S = downstream boundary of river: hydrograph peak for the flood event of each floodplain connectivity scenario ($m^3.s^{-1}$)

3. The discharge peak translation was calculated using Equation 7.2 as follows:

$$T = D/S - U/S \tag{7.2}$$

where:

T = Discharge peak translation (hrs)
U/S = upstream boundary of river: hydrograph peak time for a flood event (hrs)
D/S = downstream boundary of river: hydrograph peak time for a flood event of each floodplain connectivity scenario (hrs)

4. The inundation depth (mabgl) was calculated as follows:
   (a) The inundation depths for the 90th hour of each downstream flood event hydrograph and lateral connectivity scenario were extracted from the linked ISIS 1D-2D model results. These results represent the inundation depth in the floodplain after the flood event has subsided.
   (b) The inundation depth considering the loss of water through evapotranspiration and infiltration into the soil zone was calculated as follows:
      i. Subtraction of the LTA evapotranspiration i.e. 1.73 mm as calculated for the case study site over the monitoring period i.e. 31/03/2011 – 31/07/2012 from the modelled inundation depths for each scenario. The LTA evapotranspiration value represents 1 day based on the remaining inundated floodwaters at the 90th hour of the flood hydrograph.
      ii. Subtraction of the potential infiltrated depth (Equation 7.3) from the modelled inundation depths for each scenario. The drainable porosity for a clay loam soil (Rawls et al., 1982) = 0.143 $cm^3.cm^{-3}$. The average water

table position at the field site was derived as 0.53 mbgl over the monitoring period i.e. 31/03/2011-31/07/2012.

$$Potential\ infiltrated\ depth(m) = D.P.x\ W.T \qquad (7.3)$$

where

D.P. = drainable porosity of clay loam soil ($cm^3.cm^{-3}$)

W.T. = water table position of field study site (mbgl)

The potential infiltrated depth was calculated as 0.076 m and was rounded up to 0.1 m. This value was also based on the minimum data value that can be extracted for the inundation depth from the linked ISIS 1D-2D model results.

iii. The average inundation depth for each scenario was calculated.

5. The inundation velocity ($m.s^{-1}$) for the 90th hour of the downstream flood event hydrograph was extracted from the linked ISIS 1D-2D model for each scenario. These results represent the inundation depth in the floodplain after the flood event has subsided.
6. The inundation depth and velocity area (ha) for the 90th hour of each downstream hydrograph were extracted from the linked ISIS 1D-2D model for each scenario. The inundation depth, velocity and corresponding area were assessed against the specific freshwater fish species depth and velocity requirements (Table D.1). The average of the inundation depth and velocity area for all fish species in each scenario was calculated.
7. The water table position (mbgl) post flood inundation was calculated by the following steps:
    - (a) The inundation depths (m) for the 90th hour of the downstream flood event hydrograph were extracted from the linked ISIS 1D-2D model results for each scenario. These results represent the inundation depth in the floodplain after the flood event has subsided.
    - (b) The inundation depth considering the loss of water through evapotranspiration and infiltration into the soil zone was calculated as follows:
        - i. Subtraction of the LTA evapotranspiration i.e. 1.73 mm as calculated for the case study site over the monitoring period i.e. 31/03/2011-31/07/2012 from the modelled inundation depths for each scenario. The LTA evapotranspiration value represents 1 day based on the remaining inundated floodwaters at the 90th hour of the flood hydrograph.

ii. Subtraction of the potential infiltrated depth of 0.1 m (Equation 7.3) representing the maximum amount of water that can be infiltrated into the soil zone from each scenario.
iii. The average inundation depth for each scenario was calculated.

(c) Where the average inundation depth scenario results were ≤0.1 m, Equation 7.4 was applied to calculate the water table position

$$Water\ table\ position\ (mbgl) = \left(\frac{I}{D.P.}\right) - W.T \qquad \textbf{7.4}$$

where
I = Inundation depth (m)
$D.P.$= drainable porosity of clay loam soil ($cm^3.cm^{-3}$)
$W.T.$ = water table position of field study site (mbgl)

(d) Where the average inundation depth scenario results were >0.1 m; the soil zone has completed infiltrated with floodwater and the water table is at ground level e.g. 0 magl. In this instance, the average inundation depth (mabgl) was applied.

(e) Where no flooding of the lateral connectivity scenarios occurred, the average observed water table position of 0.53 mbgl was applied.

8. The ponding duration (days) was calculated as follows:

(a) The inundation depths for the 90th hour of the downstream flood event hydrograph were extracted from the linked ISIS 1D-2D model results for each scenario. These results represent the ponded depth in the floodplain after the flood event has subsided.

(b) Subtraction of the LTA evapotranspiration i.e. 1.73 mm as calculated for the case study site over the monitoring period i.e. 31/03/2011–31/07/2012 from the modelled inundation depths of each scenario to account for loss of water through evapotranspiration. The LTA evapotranspiration value represents 1 day based on the remaining inundated floodwaters at the 90th hour of the flood hydrograph.

(c) The average inundation depth was calculated for each scenario.

(d) Subtraction of the potential infiltrated depth of 0.1 m (Equation 7.3) representing the maximum amount of water that can be infiltrated into the soil zone from each scenario.

(e) Where the average inundation depth scenario results were ≤0.1 m, the ponded duration was calculated by dividing the infiltration rate for clay loam soil type i.e. 0.01 $m.hr^{-1}$ (Brouwer, 1998) by each average inundation scenario result.

    (f) Where the average inundation depth is > 0.1 m, no ponding duration can be calculated as the soil has reached its storage capacity and the remaining inundation depths after evapotranspiration and infiltration may only be removed by drainage to the surface drains and eventually the river channel.

9. The infiltrated volume (m^3) was calculated by utilising the floodwater inundation area hydrological indicator results from the linked ISIS 1D-2D model and the drainable porosity of a clay loam soil with Equation 7.5 after Hamil (2001).

$$V = D\,x\,A \tag{7.5}$$

where:
V = infiltrated volume (m^3)
D = Potential infiltrated depth (m)
A = Inundated area of the potential infiltrated depth (m^2)

    (a) The potential infiltrated depth of 0.1 m (Equation 7.3) representing the maximum amount of water that can be infiltrated into the soil zone from each scenario.
    (b) The LTA evapotranspiration i.e. 1.73 mm as calculated for the case study site over the monitoring period i.e. 31/03/2011 – 31/07/2012 was subtracted from the from calculated potential infiltrated depth to account for loss of water through evapotranspiration at the field study site. The LTA evapotranspiration value represents 1 day based on the remaining inundated floodwaters at the 90th hour of the flood hydrograph.
    (c) The inundation area for the 90th hour of the downstream flood hydrograph representing the maximum flooded area were extracted for 0.1 m inundation depths for each scenario simulation from the linked ISIS 1D-2D model results. This inundation area represents the area of water at 0.1 m potential infiltration depth that can infiltrate the soil zone for water storage.
    (d) The infiltrated volume was then calculated as in Equation 7.5 for all scenarios.
10. The flooded buildings count (No.) was calculated by the sum of the number of buildings located within the inundation area from the linked ISIS 1D-2D model results for each scenario.

A further description of the impact of each hydrological indicator for each specific ecosystem service is provided in Sections 7.2.6-7.2.12.

7.2.2 **Scoring and normalisation**

A non-monetary performance scoring system based on Multi-Criteria Analysis (MCA) techniques was applied in order to compare and capture the wide range of impacts related to assessing multiple ecosystem services (RPA, 2004; DCLG, 2009; Alkema and Middelkoop, 2005).

This research applied a similar approach by Alkema and Middelkoop (2005) to further develop and apply a more elaborate impact assessment method based on sets of hydrological indicators for individual ecosystem services. A simple non-monetary MCA approach was applied to allow comparison of scenarios and the capture of the impact value to enable greater transparency, communication and interpretation of ecosystem service synergies and trade-offs under each design flood event and floodplain connectivity scenario (RPA, 2004; Alkema and Middelkoop, 2005).

Figure 7.1 displays a flow diagram of the ecosystem services assessment system methodology and processes applied in this research.

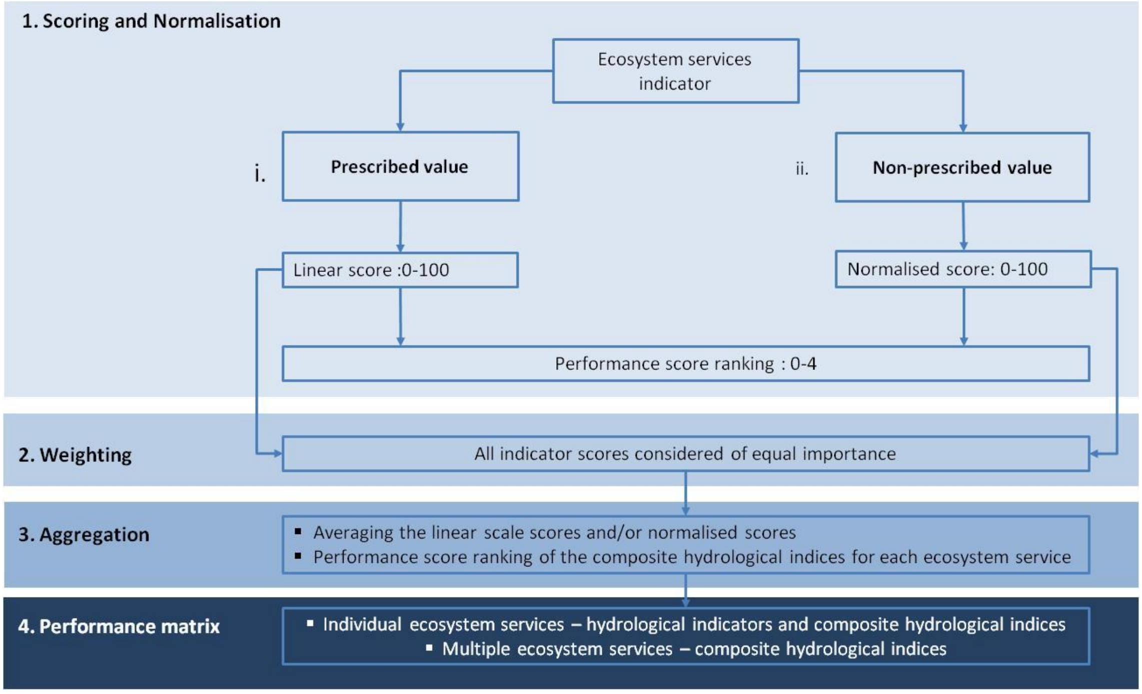

Figure 7.1 Ecosystem services assessment system methodology

Each ecosystem service hydrological indicator was described by either prescribed or non-prescribed impact values in this research and defined as follows:

- Prescribed: Hydrological values and range of values pertaining to the impact on ecosystem services based on past research.

- Non-prescribed: Hydrological values with a logical connection to the processes and attributes that impact on ecosystem services delivery based on past research with no previous defined values or range of values. Hydrological results are generated from the modelling of the design flood event and floodplain connectivity scenarios.

The scoring and normalisation of the prescribed and non-prescribed impact values were based on simple non-monetary MCA methods (RPA, 1998). Performance score ranking was then performed for the following:

- Assessment of the benefit or disbenefit impact of each hydrological indicator for each ecosystem.
- Assessment of the benefit and disbenefit impact of the composite hydrological indices for each ecosystem service.

Scoring and normalization of the prescribed impact values were based on applying a simple non-monetary MCA method with a linear scale scoring system (RPA, 1998). A linear scale was applied for defined cut-off points in the scaling system based on hydrological values from past research and will be further described in subsequent sections. The model results generated were proportional based on the flood event and floodplain connectivity scenario with the respective linear scale score signifying the impact and therefore no normalization was necessary. The impact values of each scenario were then scored in a scale of 0-100 for each respective hydrological indicator. The scenarios were then ranked from 0-4, where 0 represents no impact and 1 represents the maximum impact. Subsequent rank scores 1-3 represent lower benefit or disbenefit impacts for a given hydrological indicator. For example, considering the flood damage ecosystem service, the linear scale, cut-off points and scores were based on the depth of flooding for standard depth/damage information (Penning-Rowsell et al., 2005) and defined in Table 7.2.

Table 7.2 Prescribed linear scale scoring system example

Depth(m)	**Description**	**Linear scale score**
0	No flooding	0
0.01-0.09	Ground floor level to include damage to floors	25
0.10-0.19	To include damage to carpets and floor coverings	50
0.20-0.29	To include superficial damage to both internal building fabric and inventory items	75
0.30-3.0	To include superficial damage to both internal building fabric and inventory items with progressively more items of damage	100

For example, the linear scale score and the impact performance rank score results for the 20% AEP flood event and floodplain connectivity scenarios for the inundation depth indicator as part of flood damage ecosystem services are displayed in Table 7.3.

Table 7.3 Prescribed normalised and impact performance rank score example

Scenario		**Average Inundation depth (m)**	**Linear scale score**	**Impact performance rank score**
ID	**Description**			
S1a	No embankment (50% AEP), no drain	0.57	100	1
S2a	SOP embankment (20% AEP), no drain	0.42	100	1
S3a	Existing embankment (10% AEP), no drain	0.52	100	1
S4a	SOP embankment (4% AEP), no drain	0.00	0	0

Scoring and normalization of the non-prescribed values were based on applying a simple non-monetary MCA method of normalisation (RPA, 2004). The impact values of each scenario are normalised to a scale of 0-100 scale for each hydrological indicator with scenario 1: no embankment floodplain connectivity representing the maximum hydrological impact and assigned a score of 100. This will ensure the proportionality between the hydrological indicators in order to assess the impact of subsequent decreasing connectivity i.e. raising embankments against the no embankment i.e. increasing connectivity scenario. The scenarios were then ranked from 0-4, where 0 represents no impact and 1 represents the maximum impact. The scenarios were then ranked from 0-4, where 0 represents no impact and 1 represents the maximum impact. Subsequent rank scores 1-3 represent lower benefit or disbenefit impacts for a given hydrological indicator. For example, the normalised score and the impact performance rank score results for the 20% AEP flood event and floodplain connectivity scenarios for the inundation volume indicator as part of flood alleviation ecosystem service are displayed in Table 7.4.

Table 7.4 Non-prescribed normalised and impact performance rank score example

Scenario		**Inundation volume (m^3)**	**Normalised score**		**Impact performance rank score**
ID	**Description**				
S1a	No embankment (50% AEP), no drain	198,778	100	100	1
S2a	SOP embankment (20% AEP), no drain	31,586	S2a/S1a x 100	15	3
S3a	Existing embankment (10% AEP), no drain	36,337	S3a/S1a x 100	18	2
S4a	SOP embankment (4% AEP), no drain	0	S3a/S1a x 100	0	0

In some instances, the individual scores may have the same score (Table 7.3) indicating that the specific scenarios performed no different to each other. Table 7.5 summarises a description of the ecosystem services, hydrological indicators, scoring and normalisation methods applied in this research.

Table 7.5 Ecosystem function and services, hydrological indicator, impact value, scoring methods

Ecosystem		Hydrological indicator	Scoring and normalisation method	
Function	**Services**			
Regulation	Flood alleviation	1. Inundation volume	Non-prescribed	Normalised score
		2. Hydrograph peak attenuation		
		3. Hydrograph peak translation		
	Flood defence	1. Inundation area	Non-prescribed	Normalised score
		2. Inundation depth	Prescribed	Linear scale score
		3. Ponding duration		
		4. Flood buildings count	Non-prescribed	Normalised score
	Water storage	1. Inundation area, depth and drainable porosity	Non-prescribed	Normalised score
Habitat	Terrestrial	1. Inundation area	Non-prescribed	Normalised score
		2. Water table position	Prescribed	Linear scale score
	Aquatic-fisheries	1. Ponding duration	Non-prescribed	Normalised score
		2. Inundation depth	Prescribed	Linear scale score
		3. Inundation velocity		
Production	Agriculture	1. Inundation area	Non-prescribed	Normalised score
		2. Water table position	Prescribed	Linear scale score
		3. Ponding duration		
Information	Recreation	1. Inundation area	Non-prescribed	Normalised score
		2. Inundation depth		
		3. Ponding duration		

7.2.3 **Weighting**

No weighting was applied to assess the benefit and disbenefit impacts of the hydrological indicators for each ecosystem service as each hydrological indicator impact performance score was considered of equal importance (Posthumus et al., 2010).

7.2.4 **Aggregation**

The hydrological indices for each ecosystem service were then aggregated by averaging the sum of the linear scale scores and/or the normalised scale scores were applicable. This score was then ranked to produce a single composite ecosystem service impact performance score for each scenario.

7.2.5 **Performance matrix**

The impact performance score from each scenario was then integrated into a performance matrix as described in DCLG (2009). This is a standard feature of a MCA were each row describes an option e.g. floodplain connectivity and each column describes the score of the option e.g. impact type and level of impact as described by the linear scale, normalisation and impact performance ranking scores to include colour coding (Table 7.6). 0 represents ‘no impact’ while 1 represents the maximum impact and all subsequent scores reflecting progressively lower benefit or disbenefit impacts. The colour code is described by white as having ‘no impact’, the benefit impact is displayed in green and the disbenefit impact is displayed in red with higher to lower colour intensities coinciding with the impact scores.

Table 7.6 Ecosystem services assessment performance matrix system

Benefit impact	**Disbenefit impact**	**Description**
0	0	None
1	1	Maximum
2	2	⇩
3	3	
4	4	Minimum

Two performance matrices were designed to assess ecosystem services delivery as follows:

1. Individual ecosystem services:
   Assessment of the design flood events and floodplain connectivity scenarios e.g. decreasing lateral connectivity for a single vertical connectivity scenario for each ecosystem service. The impact performance of each scenario was assessed for each individual hydrological indicator and the composite hydrological indices.
2. Multiple ecosystem services:
   Assessment of the multiple ecosystems for potential synergy and trade-offs. The ecosystem services were described as a benefit or disbenefit impact type based on their preferred hydrological process (Table 7.1) to describe their initial potential for synergy and trade-offs. A performance matrix was applied for each flood event scenario in decreasing frequency/increasing magnitude e.g. 50-1% AEP. In each performance matrix, the composite hydrological indices results of each ecosystem service were displayed for each floodplain connectivity scenario in order of decreasing lateral connectivity ranging from 50%-4% AEP with a single fixed vertical

connectivity representing a ‘no drain’ scenario with the average water table level of 0.53 mbgl .

The performance matrix conveys the final product of this research to enable the assessment of the impact of design flood events and floodplain connectivity upon ecosystem services delivery (DCLG, 2009). It also enables for ease of communication, speed and efficiency in assessing the impacts for decision-making to policy makers and planners to manage floodplain connectivity to enable synergies and reduce trade-offs to maximise sustainable use of a floodplain.

7.2.6 **Flood alleviation**

Flood alleviation was defined as a benefit impact as the storage, attenuation and translation of floodwaters in the floodplain adjacent to the river reduce the impact of flood loss and damage to communities downstream of the immediate floodplain (Förster et al., 2008; Alkema & Middelkoop, 2005; DCLG, 2009). The inundation volume, discharge peak attenuation and translation hydrological indicators were applied to assess the impacts of design flood events and floodplain connectivity upon ecosystem services delivery.

7.2.6.1 **Inundation volume**

The inundation volume refers to the volume of water stored and retained in the immediate floodplain with greater storage and retention having the potential to alleviate flood inundation to communities further downstream of the immediate floodplain (Förster et al., 2008; DCLG, 2009). No prescribed impact value or ranges of values were available for this hydrological indicator with the premise that greater benefit is gained through higher storage and retention of the inundation volume of floodwaters. The inundation volume (Section 7.2.1) was calculated for each scenario applying the scoring and normalization method as described in Section 7.2.2 for a non-prescribed value.

7.2.6.2 **Discharge peak attenuation**

The discharge peak attenuation refers to the reduction in flood peak discharge through flood routing at downstream points (Shaw et al., 2011). The floodwater in temporary storage attenuates the flood peak levels, which reduce the effects of excess river flow discharge on downstream communities alleviating flood inundation risk. Förster et al., (2008) and Alkema & Middelkoop (2005) described the benefit of attenuation as reducing the river discharge through floodwater inundation at the immediate floodplain thereby reducing river discharge and the potential for flood inundation to communities further downstream. The discharge peak attenuation (Section 7.2.1) was calculated for each scenario and the scoring and normalization method was then applied as described in Section 7.2.2 for a non-prescribed value.

7.2.6.3 **Discharge peak translation**

The flood peak translation refers to the change in time of the flood peak flow as a function of floodwater routing (Shaw et al., 2011). The flood peak translation time is critical in terms of safe water release to allow for adequate warning times where water levels in a river have diminished post flood discharge peak (Förster et al., 2008; Penning-Rowsell et al., 2005). The hydrograph peak translation (Section 7.2.1) was calculated for each scenario and the scoring and normalization method was then applied as described in Section 7.2.2 for a non-prescribed value.

7.2.6.4 **Composite indices performance score**

The hydrological indicators were then aggregated as described in Section 7.2.4 and 7.2.5 to provide the final composite impact performance score.

7.2.7 **Flood damage**

Flood damage was defined as a disbenefit impact since the frequency and magnitude of flood events may lead to flood inundation with the potential to cause damage to properties and vulnerability to people within the floodplain (DCLG, 2009). The inundation area, depth and ponding duration were applied to assess the impacts of the design flood events and floodplain connectivity scenarios for this ecosystem service (DCLG, 2009: Penning-Rowsell et al., 2005; Dutta et al., 2003; Alkema and Middelkoop, 2005).

7.2.7.1 **Inundation area**

The inundation area in a floodplain adjacent to the river refers to the spatial hazard, vulnerability, future planning and development potential as a consequence of flooding (DCLG, 2009; EA, 2009). No prescribed impact value or ranges of values are available for this hydrological indicator with the premise that greater disbenefit is gained through greater area of floodwater inundation. The inundation area (Section 7.2.1) was calculated for each scenario applying the scoring and normalization method as described in Section 7.2.2 for a non-prescribed value.

7.2.7.2 **Inundation depth**

Flood damage and loss to the structural building integrity, inventory components and vulnerability to life is a function of the ground surface depth (Penning-Rowsell et al., 2005). Prescribed values were available to assess the impacts based on inundation depth/damage information (Penning-Rowsell et al., 2005). The impacts were described in 15 depths for above and below the ground floor level in regard to damage to areas, internal building fabric and inventory items (Table 7.7). Examples of building fabric include garage, shed, plumbing and heating, power and gas supply, boundary walls, gates and fences. Examples of inventory items include domestic appliances, heating and electrical equipment, furniture and soft furnishings and personal effects.

Table 7.7 Depth of flooding for standard depth/damage information

Range	Depths (m)	Description
1	-0.3	To include damage to sub-floor areas
2	0.0	Ground floor level to include damage to floors
3	0.05	To include damage to carpets and floor coverings
4	0.1	To include superficial damage to both internal fabric and inventory items
5-6	0.2 & 0.3	To include superficial damage to both internal building fabric and inventory items
7-15	0.6 to 3.0	In incremental steps of 0.3 m to include progressively more items or damage

Source: after Penning-Rowsell et al. (2005)

This research applied four surface water depth ranges to assess the impacts of the design flood event and floodplain connectivity scenarios upon flood damage ecosystem services delivery (Table 7.8).

Table 7.8 Inundation depth hydrological indicator scoring system

Depths (m)	Score	Description
0	0	No inundation
0.01-0.09	25	Ground floor level to include damage to floors, carpets and floor coverings
0.10-0.19	50	To include superficial damage to both internal fabric and inventory items
0.20-0.29	75	To include superficial damage to both internal building fabric and inventory items
0.30-3.0	100	Progressively more damage to inventory items

Depths below 0 m i.e. ground level and above 3.0 m ground level were not considered as the inundation depth results of the linked ISIS 1D-2D model were greater than 0 with a maximum depth recorded at 1.82 m (Appendix C.6.4). The linear scores reflect the level of impact for the inundation depth range (Table 7.8) with a score of 0 representing ‘non inundation’ and a score of 100 representing the maximum impact. The inundation depth (Section 7.2.1) was calculated for each scenario and applying the scoring system (Table 7.8) to assess the impact of inundation depths for the flood damage ecosystem service.

7.2.7.3 **Flooded buildings count**

The flooded buildings count indicator represents the number of buildings affected within the flood inundation area extent of each scenario as simulated in the linked ISIS 1D-2D model. No prescribed impact value or range of values are available for this hydrological indicator with the premise that greater disbenefit is gained through the higher count of buildings located within the flood inundation area extent. The flooded buildings count (Section 7.2.1) was calculated for each scenario and applying the scoring and normalization method as described in Section 7.2.2 for a non-prescribed value.

7.2.7.4 **Composite indices performance score**

The hydrological indicators were then aggregated as described in Section 7.2.4 and 7.2.5 to provide the final composite impact performance score.

7.2.8 **Water Storage**

The water supply ecosystem service was defined as a benefit impact with flood inundation providing storage of floodwaters in the soil zone, which may contribute to groundwater recharge. The field study site was defined as having an unconfined aquifer (Section 5.2.2.2) indicating the flooded water has the potential to be stored in the soil zone, which may contribute to groundwater recharge. This stored water may be utilised for extractive or in situ services e.g. agricultural, commercial, industrial, and municipal uses and reducing the inundation depth after a flood event has occurred (Brauman et al., 2007; Kazama et al., 2007). No prescribed impact value or ranges of values were available for this hydrological indicator with the premise that greater benefit is gained through an increase in the infiltrated volume in the soil zone upon flood inundation. The infiltrated volume (Section 7.2.1) was calculated for each scenario and applying the scoring and normalization method as described in Section 7.2.2 for a non-prescribed value.

7.2.9 **Terrestrial habitat**

The terrestrial habitat was defined as a disbenefit impact based on flood inundation as one of many physical causes of waterlogging which can affect the water table position leading to a change in the species community composition (Toogood and Joyce, 2009 and 2008; Wheeler et al., 2003). The terrestrial habitat of the case study field site was identified as a floodplain grazing marsh (DEFRA, 2012; Bedford and Luton BRMC, 2008). This habitat is of particular importance for conservation as it is a priority habitat in the UK under the Biodiversity Action Plan (Natural England, 2012b; Bedford and Luton BRMC, 2008). More specifically, the habitat was identified as a mesotrophic grassland community i.e. MG6 (Lolium perenne-Cynosurus cristatus grassland) floristic composition (Environment Agency, Per Coms, 12 March 2012). This ecosystem service was assessed by applying the inundation area and depth, ponding duration and the water table position.

7.2.9.1 **Inundation area**

Inundation area of the floodplain adjacent to river refers to the spatial extent that may be subjected to change in the grassland community composition as a consequence of flood inundation (Baptist et al., 2004; Duranel et al., 2007). Both these studies discussed the spatial extent of flood inundation for their respective study sites to highlight the potential area of impact from flood inundation for grassland community conservation/restoration. No prescribed impact value or ranges of values were available for this hydrological indicator with the premise that greater disbenefit is gained through greater area of floodwater inundation. The inundation area (Section 7.2.1) was calculated for each scenario and applying the scoring and normalization method as described in Section 7.2.2 for a non-prescribed value.

7.2.9.2 **Ponding duration**

The ponding duration indicator was selected based on Baptist et al. (2006), Wheeler et al. (2004) and Vervuren et al. (2003) describing the duration of waterlogging as one of many critical indicators for the potential to cause ecological succession. As the field study site was identified as an MG6 grassland community, waterlogging would potential cause a disbenefit impact for the conservation and maintenance of the existing habitat.

Two prominent hydrological conditions described by Wheeler et al. (2004) can affect the change in floristic composition of a grassland community as follows:

- Extensive soil drying e.g. decreasing lateral connectivity by raising embankments and/or less frequent flood events of low magnitude may lead to less or no flood inundation to cause a further reduction in species richness and less productive meadow.

- Prolonged waterlogging in the growing season e.g. increasing lateral connectivity by lowering embankments and/or frequent flooding and/or of high flood event magnitudes to increase flood inundation may cause a change to a wetter grassland community or mire/swamp habitat.

The MG6 grassland community while common in the UK is species poor and of limited ecological interest hence limited information is available on its hydrological requirements. This grassland community would be susceptible to grass kill if it were submerged by flooding for more than a few days especially during the growing season (Professor Gowing, Per Coms, 12 March 2012). Based on the hydrological conditions for an MG6 habitat as previously described, this research applied the following scoring system in Table 7.9

Table 7.9 Ponding duration indicator scoring system

Duration (days)	Score	Description
0	0	No inundation
0-1	4	⇧ Tolerable
1-2	3	
2-3	2	
3-4	1	Not tolerable: susceptible to grass kill

The scores reflect the level of impact for the ponding duration range (Table 7.9) with a score of 0 representing ‘no inundation’ and a score of 1 representing the maximum impact and defined as 3-4 days based on hydrological conditions as described above. The ponding duration ranges (Table 7.9) also describe the level of tolerance to inhibit conservation and maintenance of an MG6 grassland community. The ponding duration (Section 7.2.1) was calculated for each scenario and applying the prescribed scoring system (Table 7.9) to assess the impact of ponding duration for the terrestrial habitat ecosystem service.

7.2.9.3 **Water table position**

Toogood and Joyce (2008, 2009) discussed that over a long-term period, inundation from flood events can raise water table levels leading to a change in plant species composition thus altering the habitat type. Wheeler et al. (2004) described a range of target and tolerable water table positions for seasons in regard to the conservation of grassland communities. Where the tolerance water table positions are breached within a year, a change in floristic composition and hence habitat community is likely to be experienced. The water table position for an MG6 grassland needs to be less than 0.5 m from the ground surface to maintain and conserve the existing habitat at the field study site (Professor Gowing, Pers Coms, 23 January 2012). In this case, a prescribed scoring system was defined for this hydrological indicator in Table 7.10.

Table 7.10 Water table position scoring system

Water table position (mbgl)	Score	Description
0.01-0.50	100	High impact for potential to change the floristic composition of species
0.50-1	0	Low impact to change in the species composition

The water table position (Section 7.2.1) was calculated for each scenario and applying the scoring system (Table 7.10) to assess the impact of water table position for the terrestrial habitat ecosystem service.

7.2.9.4 **Composite indices performance score**

The hydrological indicators were then aggregated as described in Section 7.2.4 and 7.2.5 to provide the final composite impact performance score.

7.2.10 **Freshwater fish habitat**

The freshwater fish habitat ecosystem service was defined as a benefit impact in that increasing floodplain connectivity can lead to rehabilitation of fish populations and increase fish species diversity as fish utilise the floodplain for spawning, nursery, refuge and feeding (EA, 2008; Bolland et al., 2008; Peirson et al., 2008). Grift et al. (2003) and Cowx et al. (2004) described that flow velocity and depth are the most important factors for habitat utilisation of fish species. These habitat characteristics were based on water depth and flow requirements in rivers, which are essential for the fish to migrate to floodplains for spawning, nursery, refuge from predators and shelter during their life cycle stages (Welcomme and Halls, 2001).

7.2.10.1 **Inundation depth and velocity area**

Prescribed information for habitat characteristics requirements for the different life stages of UK coarse freshwater fish species in rivers are available as a result of several research papers conducted (Cowx et al., 2004) and displayed in Appendix D, Table D.1.1. Twenty five UK coarse freshwater fish species across various stages in their life cycle i.e. Larvae, spawning, 0+, fry, juvenile and adult in 10 family classification were identified as present in the River Ivel (Environment Agency, Per Coms, 12 March 2012). The inundation area that represents the inundation depths and velocity requirements of the fish species (Table D.1.1) were calculated (Section 7.2.1). The premise is that greater inundation area that meets the inundation depths and velocity requirements is reflective of greater benefits to the fish species under consideration. The scoring and normalization method as described in Section 7.2.2 was then applied for a prescribed value.

7.2.10.2 **Composite indices performance score**

The hydrological indicators where then aggregated as described in Section 7.2.4 and 7.2.5 to provide the final composite impact performance score.

7.2.11 **Agricultural productivity**

The agriculture ecosystem service was defined as a disbenefit impact based on flood inundation having the potential to cause damages through waterlogging affecting crops and livestock leading to a loss of agricultural productivity (Penning-Rowsell et al., 2005; Smedema et al., 2004). The hydrological indicators applied to assess the impact of flood inundation upon agricultural ecosystem service delivery included the inundation area, water table position and ponding duration. The impacts of waterlogging to agricultural productivity (Morris and Wheater, 2007; Castle et al., 1984; Smedema and Rycroft, 1983) are described as follows:

- Crop growth inhibition e.g. root development
- Crop damage e.g. effects on quality and condition
- Livestock mortality
- Field access restriction-machines and livestock
- Limitation of crop and livestock yield and activities

The agriculture ecosystem service in this research was defined by arable cereal farming and beef/dairy farming based on the agricultural land use and types found in the case study floodplain from field observation.

7.2.11.1 **Inundation area**

The inundation area refers to the land inundated with floodwaters adjacent to river and represents the spatial impacts to agricultural productivity (Dunderdale and Morris, 1997). Kazama et al. (2009) assessed the impacts of flood events and floodplain connectivity to cause a disbenefit to agricultural productivity using flood inundation models. The outcome of the study confirmed that the control of floodplain connectivity was crucial to limit the disbenefit impacts of flood inundation in order to increase agricultural productivity. No prescribed impact value or ranges of values were available for this hydrological indicator with the premise that greater disbenefit is gained through greater area of floodwater inundation. The inundation area (Section 7.2.1) was calculated for each scenario and applying the scoring and normalization method as described in Section 7.2.2 for a non-prescribed value.

7.2.11.2 **Water table position**

The water table position describes the impacts of flood inundation to cause a rise in water table position as a result of infiltration and groundwater recharge. The water table position is a critical hydrological indicator that may influence crop yield for arable crops, field access for the grazing of livestock, constraints to land access and impaired field operations (Smedema et al., 2004). Prescribed values to describe the field water table levels and drainage conditions that impact on agricultural productivity were available and displayed in Table 7.11 (Penning-Rowsell et al., 2005; Dunderdale and Morris, 1997)

Table 7.11 Agricultural productivity drainage condition and field water table levels

Agricultural drainage condition	**Agricultural productivity class**	**Depth to water table from surface (mbgl)**
Good:'rarely wet'	Normal, no impediment imposed by drainage	≥0.5
Bad:'occassionaly wet'	Low, reduced yields, reduced field access and grazing season	0.3-0.49
Very Bad: 'commonly or permenantly wet'	Very low, severe constraints on land use, much reduced field access and grazing season: mainly wet grassland	<0.3

This research applied a linear scale score for each water table level to described the disbenefit impact to agricultural productivity based on water table positions and agricultural productivity class as per Penning-Rowsell et al. (2005) and Dunderdale and Morris (1997).

Table 7.12 Agricultural productivity water table position hydrological indicator scoring system

Water table position (mbgl)	Score	Agricultural drainage condition	Agricultural productivity class
<0.3	100	Very Bad: 'commonly or permanently wet'	Very low, severe constraints on land use, much reduced field access and grazing season: mainly wet grassland
0.3-0.49	66.6	Bad:'occassionaly wet'	Low, reduced yields, reduced field access and grazing season
≥0.5	33.3	Good:'rarely wet'	Normal, no impediment imposed by drainage

The water table position (Section 7.2.1) was calculated for each scenario and applying the scoring system (Table 7.12) to assess the impact of water table position for the agricultural productivity ecosystem service.

7.2.11.3 **Ponding duration**

The ponding duration is a critical hydrological indicator to describe the crop yield loss as a result of the duration of waterlogging on the land surface. This hydrological indicator applies the ponding duration in full days (Smedema et al., 2004). The crop yield of this hydrological indicator refers to fodder crop, winter/summer grains, maize, sunflower, sugar beets and potatoes. In general, Smedema et al. (2004) described that the percentage crop yield losses are due to surface ponding in 3, 7, 11 and 15 days of full ponding. While greater yield losses were observed in summer rather than winter seasons for most crops. This research applied a ponding duration scoring system by using surface ponding day bands as per Smedema et al., (2004) with a linear scale score. The linear scale scores reflect the level of impact for the ponding duration range (Table 7.13) with a score of 0 representing 'no inundation' and a score of 100 representing the maximum impact interpreted and defined as ≥ 15 days to describe level of crop yield loss.

Table 7.13 Agricultural productivity ponding duration hydrological indicator scoring system

Duration (days)	Score	Description
0	0	No inundation
>0<3	25	⇧ Level of crop yield loss
>3<11	50	
>11<15	75	
≥15	100	Maximum crop yield loss

The ponding duration (Section 7.2.1) was calculated for each scenario and applying the scoring system (Table 7.13) to assess the impact of ponding duration for the agricultural productivity ecosystem service.

7.2.11.4 **Composite indices performance score**

The hydrological indicators where then aggregated as described in Section 7.2.4 and 7.2.5 to provide the final composite impact performance score.

7.2.12 **Recreation**

The recreation ecosystem service was defined as a disbenefit impact as the main attribute to affect recreational activity is land access as described by Haines-Young et al. (2006). In the context of this research, the recreation ecosystem service shall be defined as dry land based activities with examples described in Table 7.14 for the case study floodplain.

Table 7.14 Dry land based recreation activities in the case study floodplain

Activities	**Site Access Types**	**No. and name of villages /urban centres**	**Examples**
▪ Walking ▪ Jogging and running ▪ Cycling ▪ Nature and wildlife watching ▪ Greens/multi-use space e.g. playing fields ▪ Angling ▪ Historic sites ▪ Picnics ▪ Festivals /events	▪ Bridleway ▪ Public rights of way ▪ Village Streets	2 villages ▪ Tempsford ▪ Blunham	▪ Kingfisher way – River Ivel nature walk ▪ Playing fields – Tempsford village ▪ Green space/parks at Blunham ▪ Gannock Castle – Tempsford ▪ River Ivel - Angling

Source: Let's Go (2013); EA (2010b); CLG (2008); EA (2006); OS (2009a,b)

In this instance, flood inundation and waterlogging reduce the ability to engage in dryland based recreational activities in the floodplain (Alkema and Middelkoop, 2005). The hydrological indicators to assess the impact of flood inundation on recreation ecosystem service include the inundation area, depth and ponding duration.

7.2.12.1 **Inundation area**

The inundation area adjacent to river refers to the spatial impact of inundation that restricts land access to permit dry land recreational activities as described in Table 7.14. No prescribed impact value or ranges of values were available for this hydrological indicator with the premise that greater disbenefit is gained through greater areal extent of floodwater inundation. The inundation area (Section 7.2.1) was calculated for each scenario and applying the scoring and normalization method as described in Section 7.2.2 for a non-prescribed value.

7.2.12.2 **Inundation depth**

The inundation depth adjacent to river refers to the impact of waterlogging that restricts land access to permit dry land recreational activities as described in Table 7.14. The inundation depth (Section 7.2.1) was calculated for each scenario and applying the scoring and normalization method as described in Section 7.2.2 for a non-prescribed value.

7.2.12.3 **Ponding duration**

The ponding duration of floodwaters adjacent to river refers to the impact of waterlogging that restricts land access to permit dry land recreational activities as described in Table 7.14. The ponding duration (Section 7.2.1) was calculated for each scenario and applying the scoring and normalization method as described in Section 7.2.2 for a non-prescribed value.

7.2.12.4 **Composite indices performance score**

The hydrological indicators where then aggregated as described in Section 7.2.4 and 7.2.5 to provide the final composite impact performance score.

7.3 Results and Discussion

The following sections present the ecosystem services assessment results and discussion to study the impacts of design flood events and floodplain connectivity on ecosystem services delivery. Sections 7.3.1 – 7.3.7 provide the impacts for the individual ecosystem services to include the impact for each hydrological indicator and the composite hydrological indices. Section 7.3.8 provides the impacts for multiple ecosystem services in regard to synergy and trade-offs.

7.3.1 **Flood alleviation**

The flood alleviation inundation volume hydrological indicator results for each scenario to include the model results, normalised and ranking impact performance scores are displayed in Tables 7.15-7.17.

Table 7.15 Inundation volume (m^3) hydrological indicator scenario results

Scenario		Flood event (%AEP)						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	114,163	198,779	310,508	327,680	341,430	361,104	363,514
S2a	SOP embankment (20%AEP), no drain	0	31,586	188,165	224,794	322,559	346,506	352,164
S3a	Existing embankment (10%AEP) , no drain	0	36,337	161,047	324,165	329,335	356,149	356,855
S4a	SOP embankment (4%AEP) , no drain	0	0	0	56,659	233,179	274,592	278,322

Table 7.16 Inundation volume hydrological indicator normalised score scenario results

Scenario		Flood event (%AEP)						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	100	100	100	100	100	100	100
S2a	SOP embankment (20%AEP), no drain	0	16	61	69	94	96	97
S3a	Existing embankment (10%AEP) , no drain	0	18	52	99	96	99	98
S4a	SOP embankment (4%AEP) , no drain	0	0	0	17	68	76	77

Table 7.17 Inundation volume hydrological indicator impact performance rank score scenario results

Scenario		Flood event (%AEP)						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	1	3	3	4	4	4	4
S2a	SOP embankment (20%AEP), no drain	0	1	2	2	2	2	2
S3a	Existing embankment (10%AEP) , no drain	0	2	1	3	3	3	3
S4a	SOP embankment (4%AEP) , no drain	0	0	0	1	1	1	1

The results (Table 7.17) clearly indicate that flood alleviation benefits increase with decreasing lateral connectivity from high frequency/low magnitude to low frequency/high magnitude flood events. This observation is a product of greater floodwaters stored with decreasing connectivity, as floodwater is held behind the embankments preventing the return of some floodwaters back to the river channel at the immediate floodplain. It would be expected that the order of benefit impact between scenario 2a and 3a would increase yet the opposite was evident. This is a direct response to the type of connectivity of the two scenarios, as scenario 3a: existing embankment has irregular bank elevations along the length of the River Ivel study reach as displayed in Figure 6.21. This allows floodwater to inundate the floodplain from the low elevations in the longitudinal bank profile in comparison to scenario 2a which has uniform bank elevations along the length of the River Ivel study reach (Figure 6.22).

The flood alleviation discharge peak attenuation hydrological indicator results for each scenario to include the model results, normalised and ranking impact performance scores are displayed in Tables 7.18-7.20.

Table 7.18 Discharge peak attenuation ($m^3.s^{-1}$) hydrological indicator scenario results

Scenario		Flood event (%AEP)						
ID	Description	50	20	10	4	2	1.33	1
S1a	No embankment (50%AEP), no drain	0.71	2.32	3.43	3.89	2.96	1.22	1.83
S2a	SOP embankment (20%AEP), no drain	0.15	1.67	5.02	4.05	5.79	6.38	6.75
S3a	Existing embankment (10%AEP) , no drain	0.15	1.38	3.77	5.30	5.80	6.15	5.27
S4a	SOP embankment (4%AEP) , no drain	0.15	0.14	0.12	2.59	6.54	6.45	6.35

Table 7.19 Discharge peak attenuation hydrological indicator normalised score scenario results

Scenario		Flood event (%AEP)						
ID	Description	50	20	10	4	2	1.33	1
S1a	No embankment (50%AEP), no drain	100	100	100	100	100	100	100
S2a	SOP embankment (20%AEP), no drain	21	72	147	104	195	524	368
S3a	Existing embankment (10%AEP) , no drain	21	60	110	136	196	505	288
S4a	SOP embankment (4%AEP) , no drain	21	6	3	67	221	529	347

Table 7.20 Discharge peak attenuation hydrological indicator impact performance rank score scenario results

Scenario		Flood event (%AEP)						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	1	1	3	3	4	4	4
S2a	SOP embankment (20%AEP), no drain	2	2	1	2	3	2	1
S3a	Existing embankment (10%AEP) , no drain	2	3	2	1	2	3	3
S4a	SOP embankment (4%AEP) , no drain	2	4	4	4	1	1	2

The results (Table 7.20) provided a more dynamic response and in general, the discharge attenuation increases with decreasing lateral connectivity from high frequency/low magnitude to low frequency/high magnitude flood events. Increasing lateral connectivity allows floodwater to inundate the floodplain thereby reducing the flood discharge and increasing the benefit impact. In low frequency/low magnitude flood events, decreasing lateral connectivity is preferable to increase attenuation benefits as the floodwater from the high magnitude flood events are held behind the embankments. The 50% AEP flood event results had the same impact score with decreasing connectivity for scenarios 2 – 4 as they shared the same attenuation results (Table 7.18). In this case, attenuation was most likely reduced due to decreasing lateral connectivity for this particular %AEP flood event.

The flood alleviation discharge peak translation hydrological indicator results for each scenario to include the model results, normalised and ranking impact performance scores are displayed in Tables 7.21-7.23.

Table 7.21 Discharge peak translation (hrs) hydrological indicator scenario results

Scenario		Flood event (%AEP)						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	3	3	3	9	3	6	6
S2a	SOP embankment (20%AEP), no drain	3	3	9	9	6	3	6
S3a	Existing embankment (10%AEP) , no drain	3	6	9	6	6	6	6
S4a	SOP embankment (4%AEP) , no drain	3	3	3	3	6	6	6

Table 7.22 Discharge peak translation hydrological indicator normalised score scenario results

Scenario		**Flood event (%AEP)**						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	100	100	100	300	50	100	100
S2a	SOP embankment (20%AEP), no drain	100	100	300	300	100	50	100
S3a	Existing embankment (10%AEP) , no drain	100	200	300	200	100	100	100
S4a	SOP embankment (4%AEP) , no drain	100	100	100	100	100	100	100

Table 7.23 Discharge peak translation hydrological indicator impact performance rank score scenario results

Scenario		**Flood event (%AEP)**						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	1	2	2	1	2	1	1
S2a	SOP embankment (20%AEP), no drain	1	2	1	1	1	2	1
S3a	Existing embankment (10%AEP) , no drain	1	1	1	2	1	1	1
S4a	SOP embankment (4%AEP) , no drain	1	2	2	3	1	1	1

The results (Table 7.23) displayed no clear pattern in regard to determining the benefit impact between scenarios. This outcome is the product of the results being extracted in 3 hourly translation times from the linked ISIS 1D-2D model simulations based on model run time intervals. The interpretation of the 3 hourly data was quite limited and too coarse to allow effective comparison of the scenarios. In high frequency/low magnitude flood events increasing or decreasing lateral connectivity provide a mixed pattern or benefits. However, it was observed that greater translation was more apparent in low frequency/high magnitude flood events with increasing lateral connectivity. The flood alleviation composite hydrological indices normalised and impact performance rank score for flood alleviation ecosystem service are displayed in Tables 7.24 and 7.25.

Table 7.24 Flood alleviation composite hydrological indices scenario results

Scenario		Flood event (%AEP)						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	100.0	100.0	100.0	166.7	83.3	100.0	100.0
S2a	SOP embankment (20%AEP), no drain	40.4	62.6	169.1	157.6	129.9	223.3	188.3
S3a	Existing embankment (10%AEP) , no drain	40.2	92.6	154.0	145.1	130.8	234.4	161.9
S4a	SOP embankment (4%AEP) , no drain	40.4	35.3	34.5	61.3	129.7	235.1	174.4

Table 7.25 Flood alleviation composite hydrological indices impact performance rank score scenario results

Scenario		Flood event (%AEP)						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	1	1	3	1	4	4	4
S2a	SOP embankment (20%AEP), no drain	2	3	1	2	2	3	1
S3a	Existing embankment (10%AEP) , no drain	3	2	2	3	1	2	3
S4a	SOP embankment (4%AEP) , no drain	2	4	4	4	3	1	2

The results (Table 7.25) display a dynamic pattern of benefits largely as a direct result of the inclusion of the discharge hydrograph peak translation hydrological indicator scores. This pattern is also a product of the differences in types of floodplain connectivity between scenarios 2a and 3a embankment elevations as described earlier. It can be deduced from the results (Table 7.25) that increasing lateral connectivity is more beneficial in high frequency/low magnitude flood events as lowering embankments allow greater storage, attenuation and translation of floodwaters in the floodplain. However, in low frequency/high magnitude flood events, decreasing lateral connectivity allows greater storage, attenuation and translation of floodwaters as the embankments act to prevent the return of floodwaters from the floodplain to the river channel.

Förster et al. (2008) discussed the benefits to flood alleviation through modelling a single embankment in terms of floodplain connectivity yet only considering the attenuation of the discharge flood hydrograph on two low frequency/high magnitude flood events i.e. 1 and 0.5% AEP flood events. Although the benefits of flood attenuation were specific to gated and timed operations for flood alleviation. The benefit of this research is that it provides a more comprehensive insight through the utilization of composite hydrological indices with the extra inclusion of inundation volume and discharge peak hydrograph translation to understand the impacts of floodplain connectivity through a range of flood events. The impact of managing the floodplain connectivity as observed from the results will not provide benefits to the immediate floodplain of where flooding occurs but rather provide benefits to the communities further downstream by reduction of flood volume and discharge from the river thereby reducing flood loss and damage (DCLG, 2009; Alkema & Middelkoop, 2005)

7.3.2 **Flood damage**

The flood damage inundation area hydrological indicator results for each scenario and flood event to include the model results, normalised scores and impact performance ranking scores are displayed in Tables 7.26-7.28.

Table 7.26 Inundation area (ha) hydrological indicator results

Scenario		**Flood event (%AEP)**						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	80	109	120	134	146	148	149
S2a	SOP embankment (20%AEP), no drain	0	23	88	107	134	143	145
S3a	Existing embankment (10%AEP) , no drain	0	32	80	127	138	147	148
S4a	SOP embankment (4%AEP) , no drain	0	0	0	10	68	107	125

Table 7.27 Inundation area hydrological indicator normalised score scenario results

Scenario		**Flood event (%AEP)**						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	100.0	100.0	100.0	100.0	100.0	100.0	100.0
S2a	SOP embankment (20%AEP), no drain	0.0	21.4	73.7	79.6	91.5	97.1	97.3
S3a	Existing embankment (10%AEP) , no drain	0.0	29.2	66.9	94.8	94.3	99.6	99.5
S4a	SOP embankment (4%AEP) , no drain	0.0	0.0	0.0	20.0	68.3	81.6	82.3

Table 7.28 Inundation area hydrological indicator impact performance rank score scenario results

Scenario		Flood event (%AEP)						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	1	1	1	1	1	1	1
S2a	SOP embankment (20%AEP), no drain	0	3	2	3	3	3	3
S3a	Existing embankment (10%AEP) , no drain	0	2	3	2	2	2	2
S4a	SOP embankment (4%AEP) , no drain	0	0	0	4	4	4	4

The results (Table 7.28) clearly indicate that flood damage disbenefit impacts are far greater with increasing lateral connectivity from high frequency/low magnitude to low frequency/high magnitude flood events. Increasing lateral connectivity causes greater areal extent of floodwater inundation. The same pattern in regard to the order of disbenefit impact between scenario 2a and 3a was observed as described in Section 7.3.1.

The inundation area as a hydrological indicator of flood damage has seldom been applied in research to described the disbenefit impact of flood damage. Alkema and Middelkoop (2005) and EA (2014b,c) have previously assessed the impact of areal flood extent based on flood hazard mapping in low frequency/high magnitude flood events in particular to 0.08% AEP; 1 and 0.1% AEP flood events respectively. In regard to floodplain connectivity, Alkema and Middelkoop (2005) considered scenarios with only past and present embankments limiting the understanding of the impact of increasing or decreasing lateral connectivity on the areal extent of floodwater inundation. This research develops upon EA (2014b,c) and Alkema and Middelkoop (2005) by assessing the spatial hazard of the flood inundation area by studying the impact of multiple decreasing lateral connectivity and high frequency/low magnitude to low frequency/high magnitude flood events. This research highlights the importance of understanding the disbenefit impacts in multiple flood events and floodplain connectivity as this indicator is critical for the spatial hazard, vulnerability, future planning and development potential as a consequence of flooding (DCLG, 2009; EA, 2009).

The flood damage inundation depth hydrological indicator results for each scenario and flood event to include the model results, normalised and ranking impact performance scores are displayed in Tables 7.29-7.31.

Table 7.29 Inundation depth (mabgl) hydrological indicator scenario results

Scenario		**Flood event (%AEP)**						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	0.55	0.55	0.70	0.66	0.70	0.70	0.70
S2a	SOP embankment (20%AEP), no drain	0.00	0.40	0.65	0.70	0.70	0.70	0.70
S3a	Existing embankment (10%AEP) , no drain	0.00	0.50	0.70	0.75	0.75	0.75	0.75
S4a	SOP embankment (4%AEP) , no drain	0.00	0.00	0.00	0.46	0.81	0.85	0.85

Table 7.30 Flood damage inundation depth hydrological indicator score scenario results

Scenario		**Flood event (%AEP)**						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	100	100	100	100	100	100	100
S2a	SOP embankment (20%AEP), no drain	0	100	100	100	100	100	100
S3a	Existing embankment (10%AEP) , no drain	0	100	100	100	100	100	100
S4a	SOP embankment (4%AEP) , no drain	0	0	0	100	100	100	100

Table 7.31 Flood damage inundation depth hydrological indicator impact performance rank score scenario results

Scenario		**Flood event (%AEP)**						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	1	1	1	1	1	1	1
S2a	SOP embankment (20%AEP), no drain	0	1	1	1	1	1	1
S3a	Existing embankment (10%AEP) , no drain	0	1	1	1	1	1	1
S4a	SOP embankment (4%AEP) , no drain	0	0	0	1	1	1	1

The results (Table 7.29) indicate that increasing lateral connectivity in high frequency/low magnitude flood events causes greater disbenefit impacts as greater flood inundation occurs from lower embankment crests causing a rise in the inundation depth in the floodplain. However, decreasing lateral connectivity in low frequency/high magnitude flood events causes greater disbenefit impacts as the crest of the embankments impedes overbank flow returning to the river and causes some floodwater to remain trapped behind the embankments leading to an increase in the inundation depths in the floodplain (Table 7.29). The results (Table 7.29 and 7.31) conclude that damage will occur to floors, carpets and floor coverings, superficial damage to both the internal building fabric and many inventory items comparing the results to the flood damage hydrological indicator scores (Table 7.8). It would normally be expected that flood inundation occurring in scenario 4a for a 4% flood event should not occur, as the embankment crest elevation should inhibit flood inundation. This observation is likely to be a result of inundation occurring at a low embankment elevation (Figure 6.22) based on the creation of scenario 4a embankment elevations through simulating a 4% flood event.

The flooded buildings count hydrological indicator results display the flood inundation areal extent, inundation depth and flooded buildings for all scenarios displayed in Figures 7.2-7.24. The flood buildings count values, normalised and impact performance ranking scores are displayed in Tables 7.32-7.34.

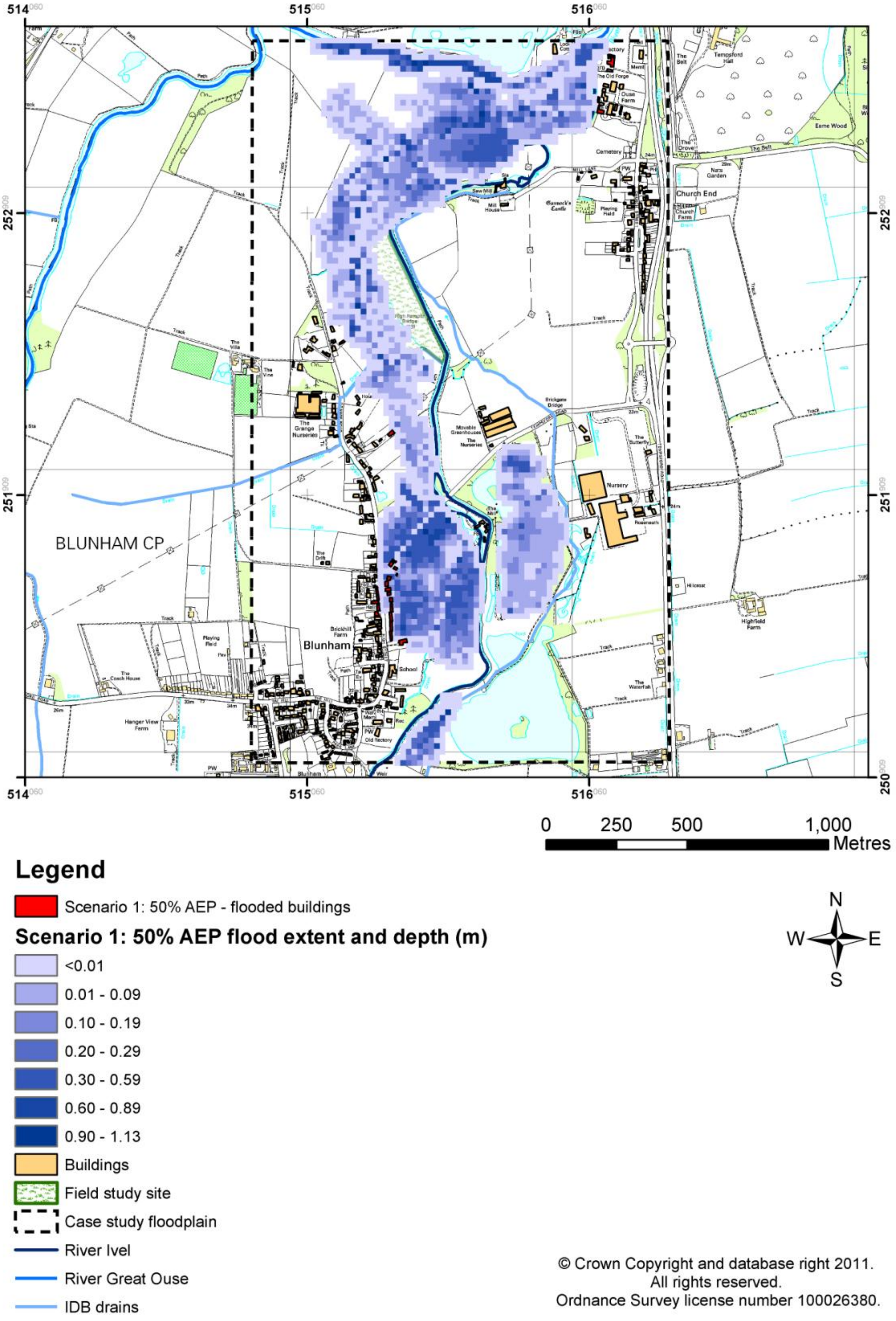

Figure 7.2 Scenario 1: 50% AEP flood extent and depth (m) with flooded buildings

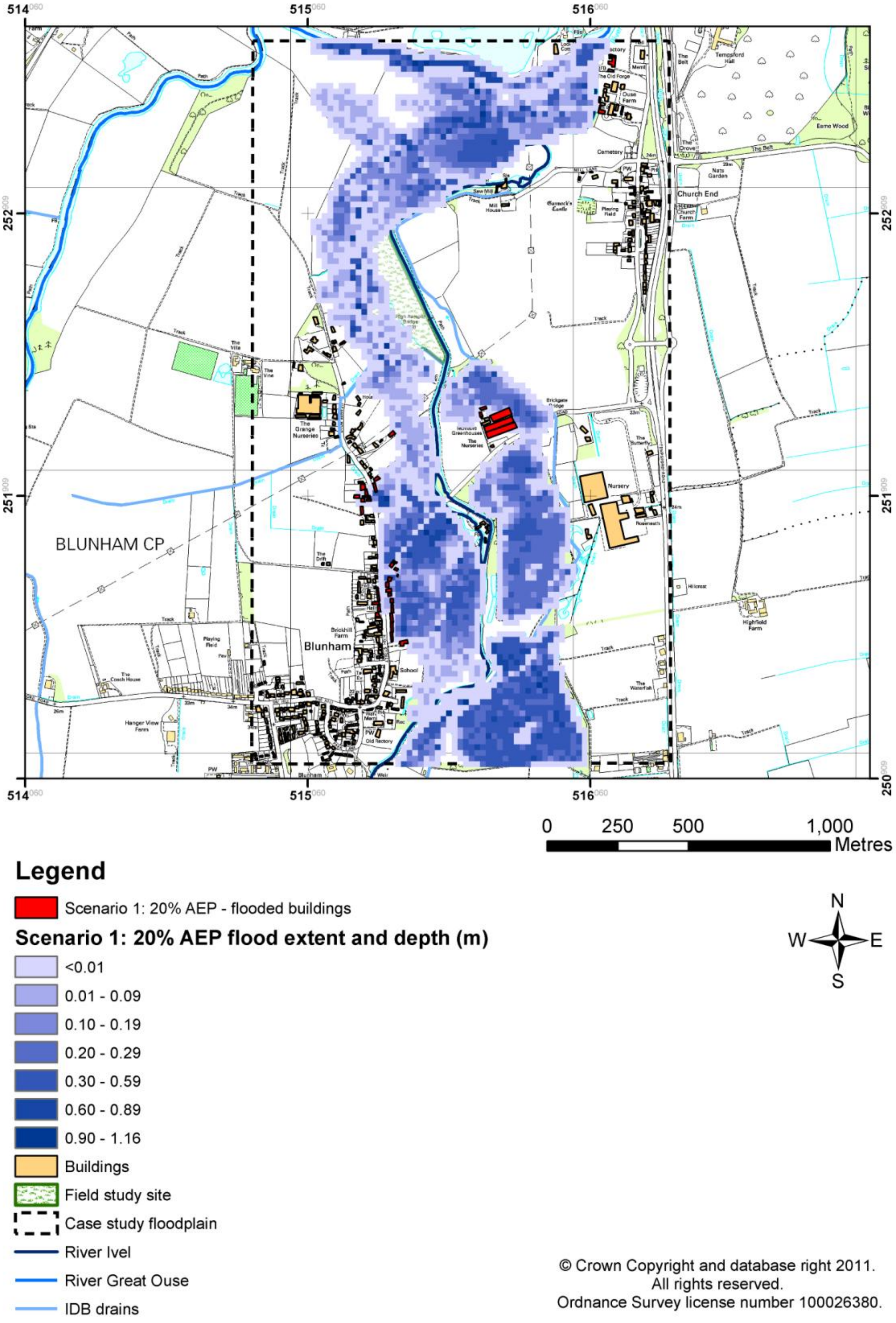

Figure 7.3 Scenario 1: 20% AEP flood extent and depth (m) with flooded buildings

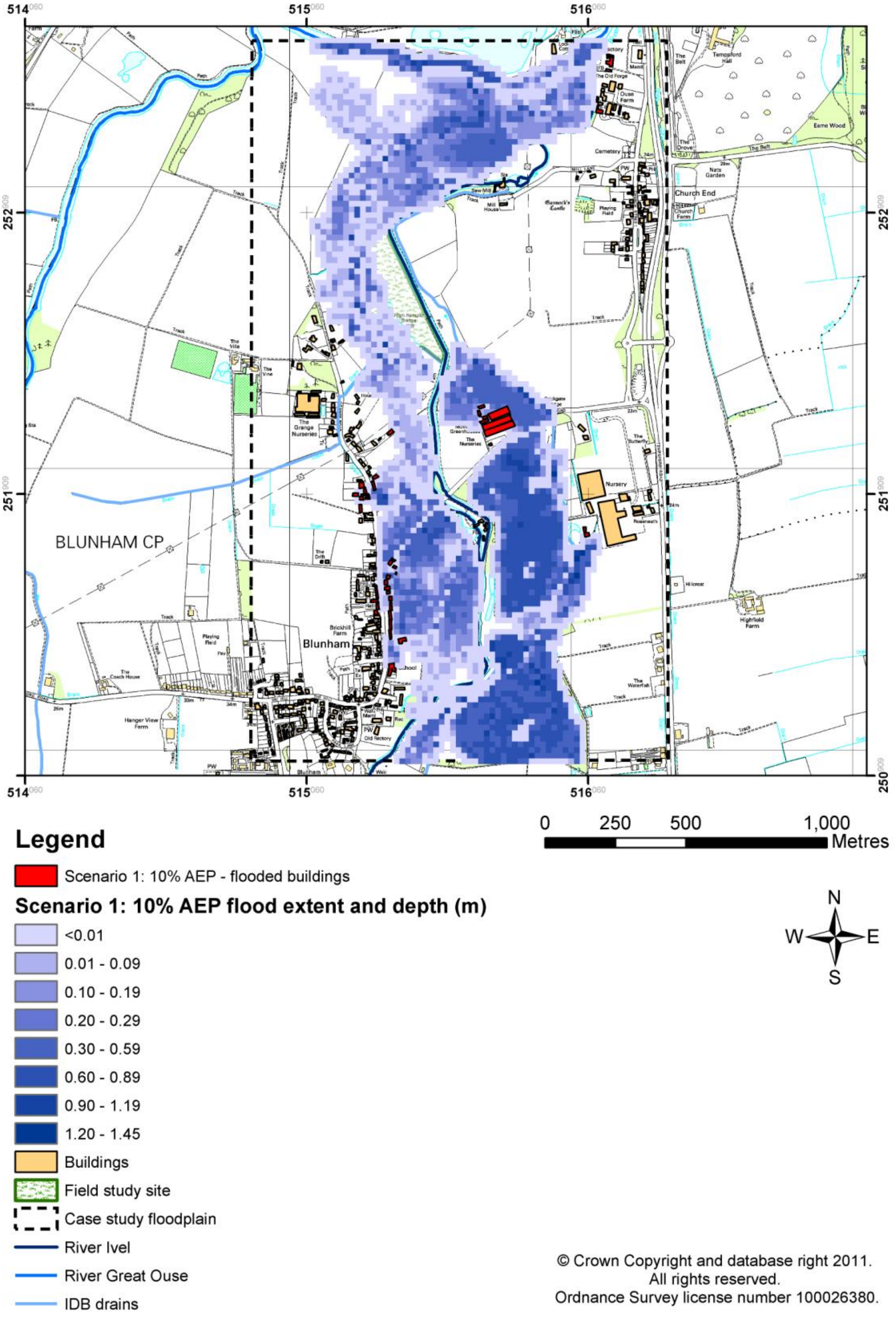

Figure 7.4 Scenario 1: 10% AEP flood extent and depth (m) with flooded buildings

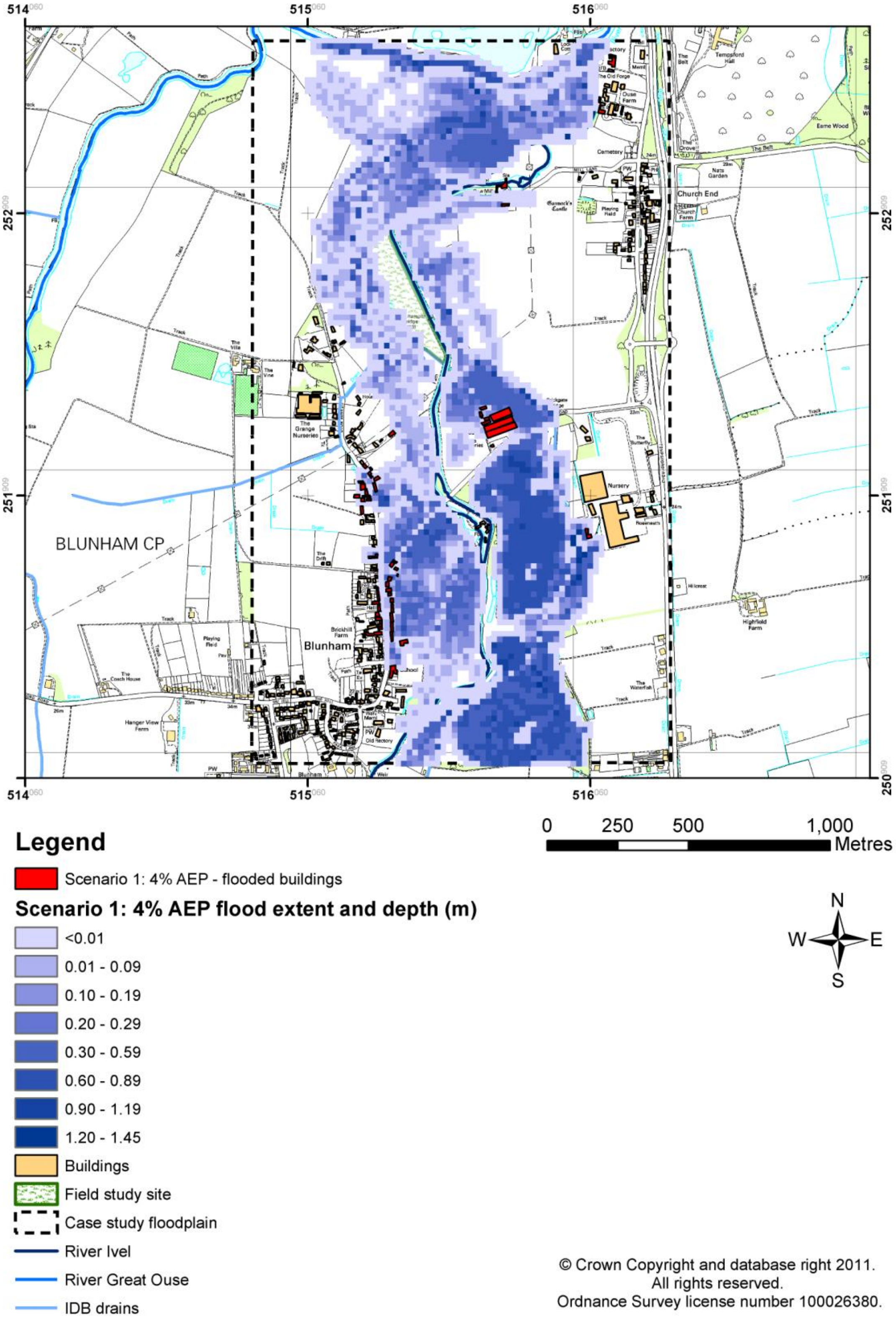

Figure 7.5 Scenario 1: 4% AEP flood extent and depth (m) with flooded buildings

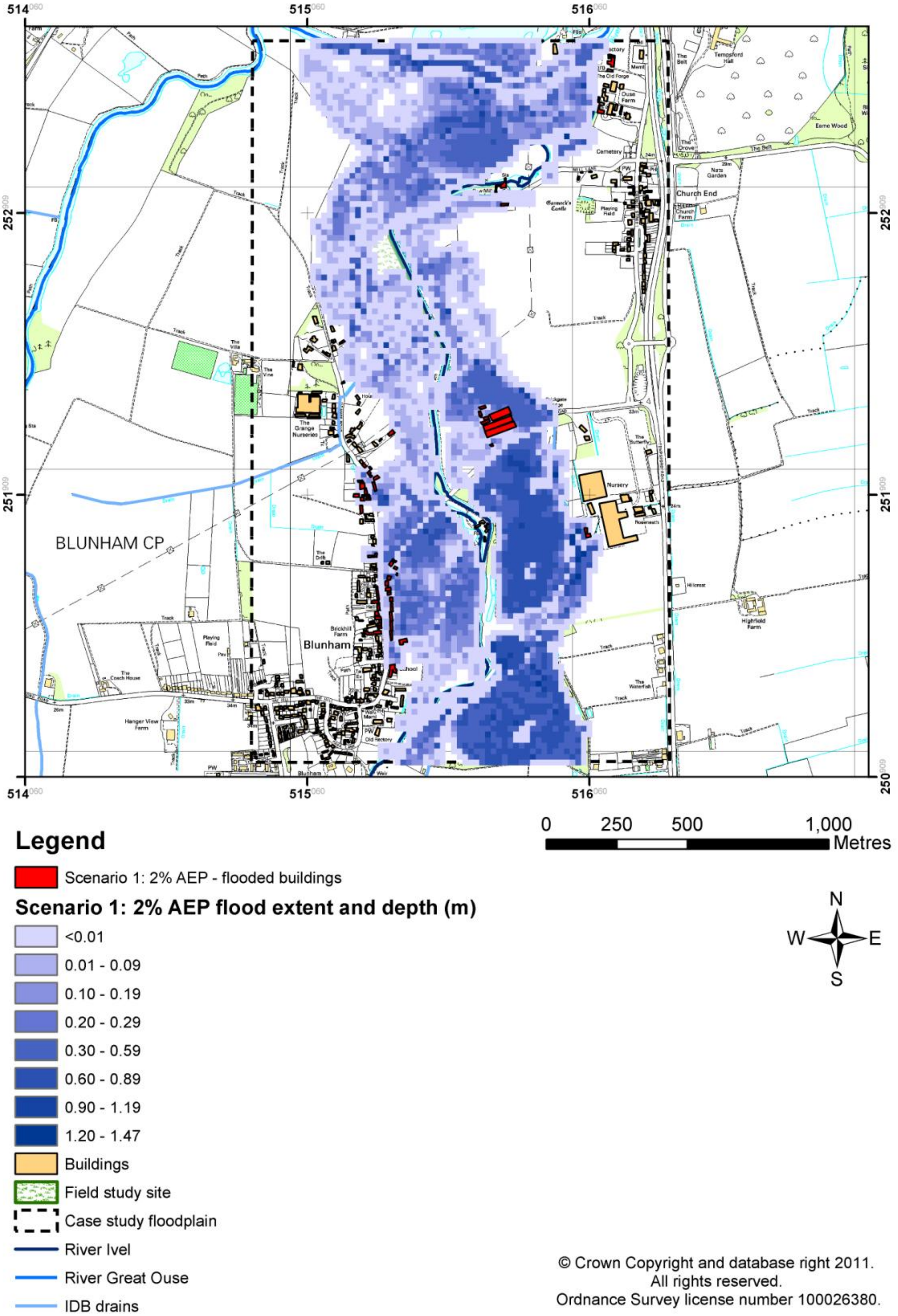

Figure 7.6 Scenario 1: 2% AEP flood extent and depth (m) with flooded buildings

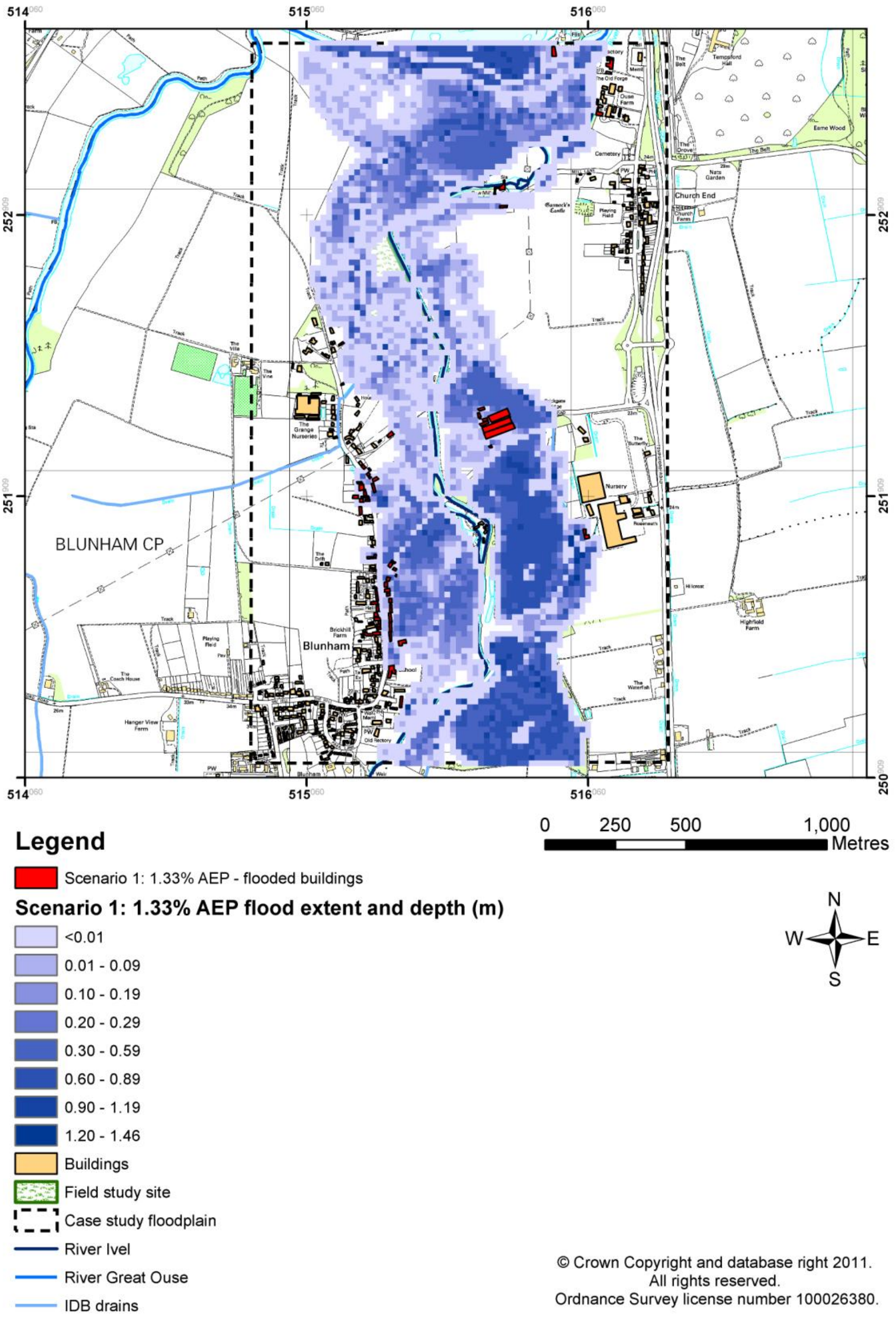

Figure 7.7 Scenario 1: 1.33% AEP flood extent and depth (m) with flooded buildings

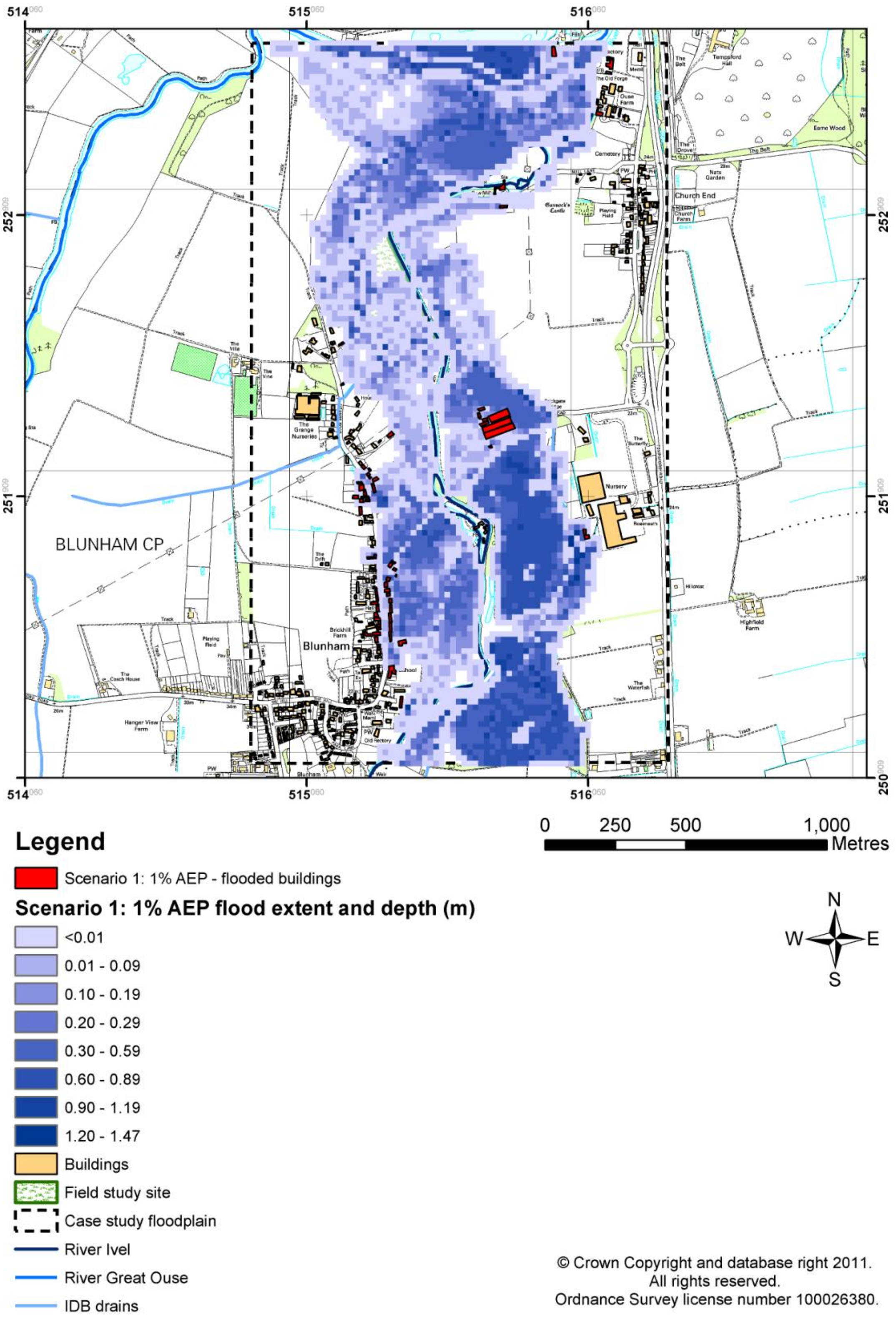

Figure 7.8 Scenario 1: 1% AEP flood extent and depth (m) with flooded buildings

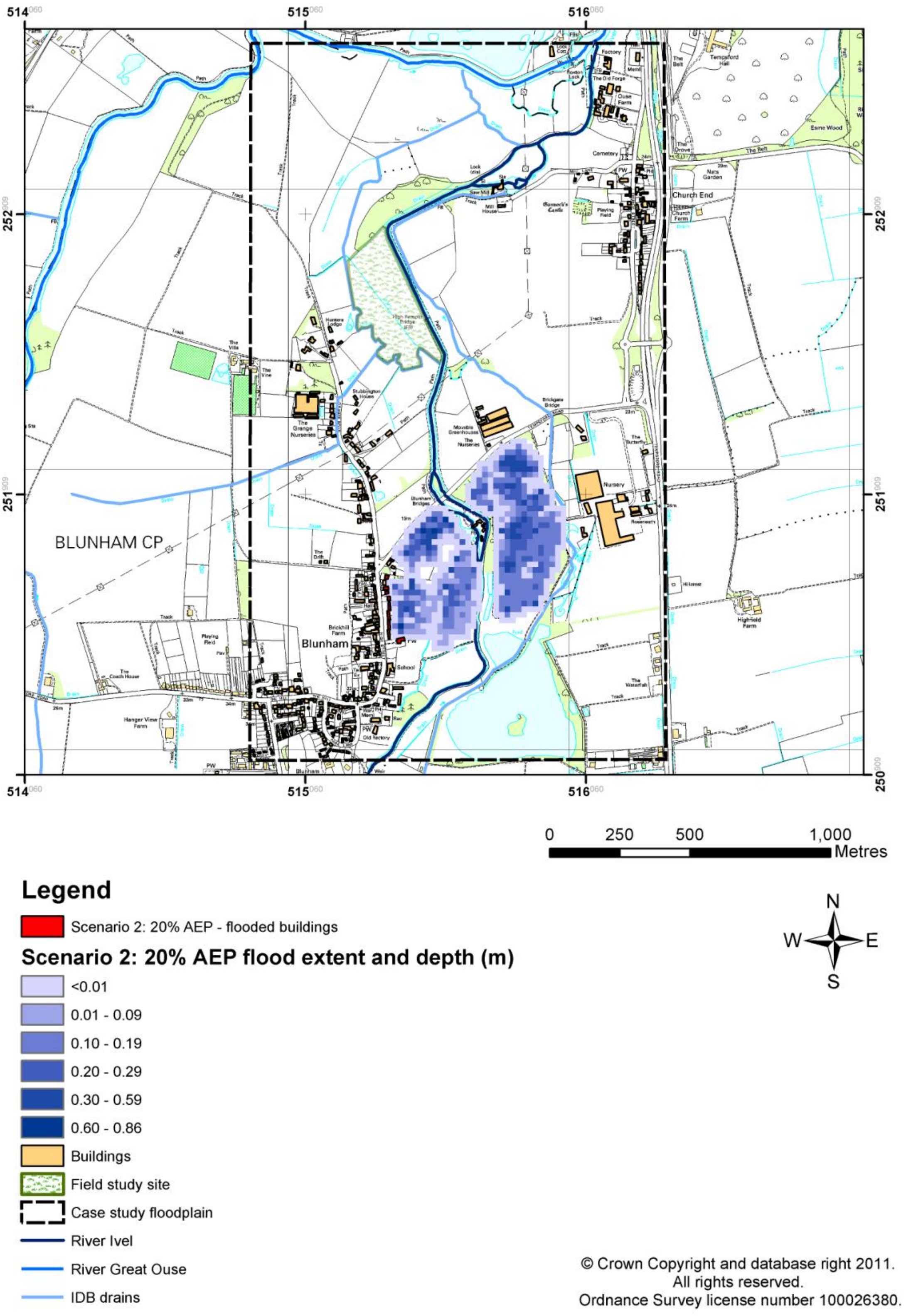

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Figure 7.9 Scenario 2: 20% AEP flood extent and depth (m) with flooded buildings

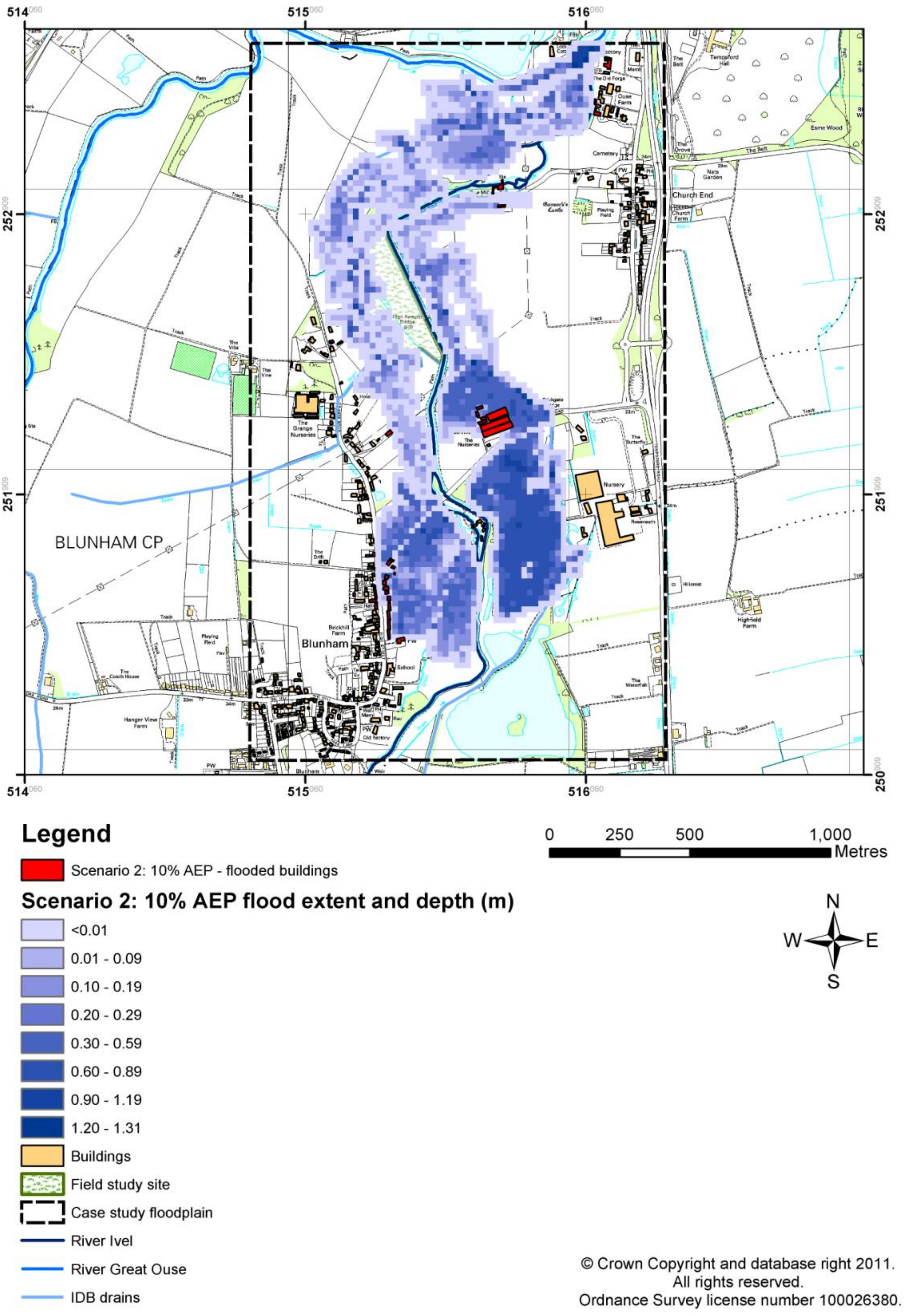

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Figure 7.10 Scenario 2: 10% AEP flood extent and depth (m) with flooded buildings

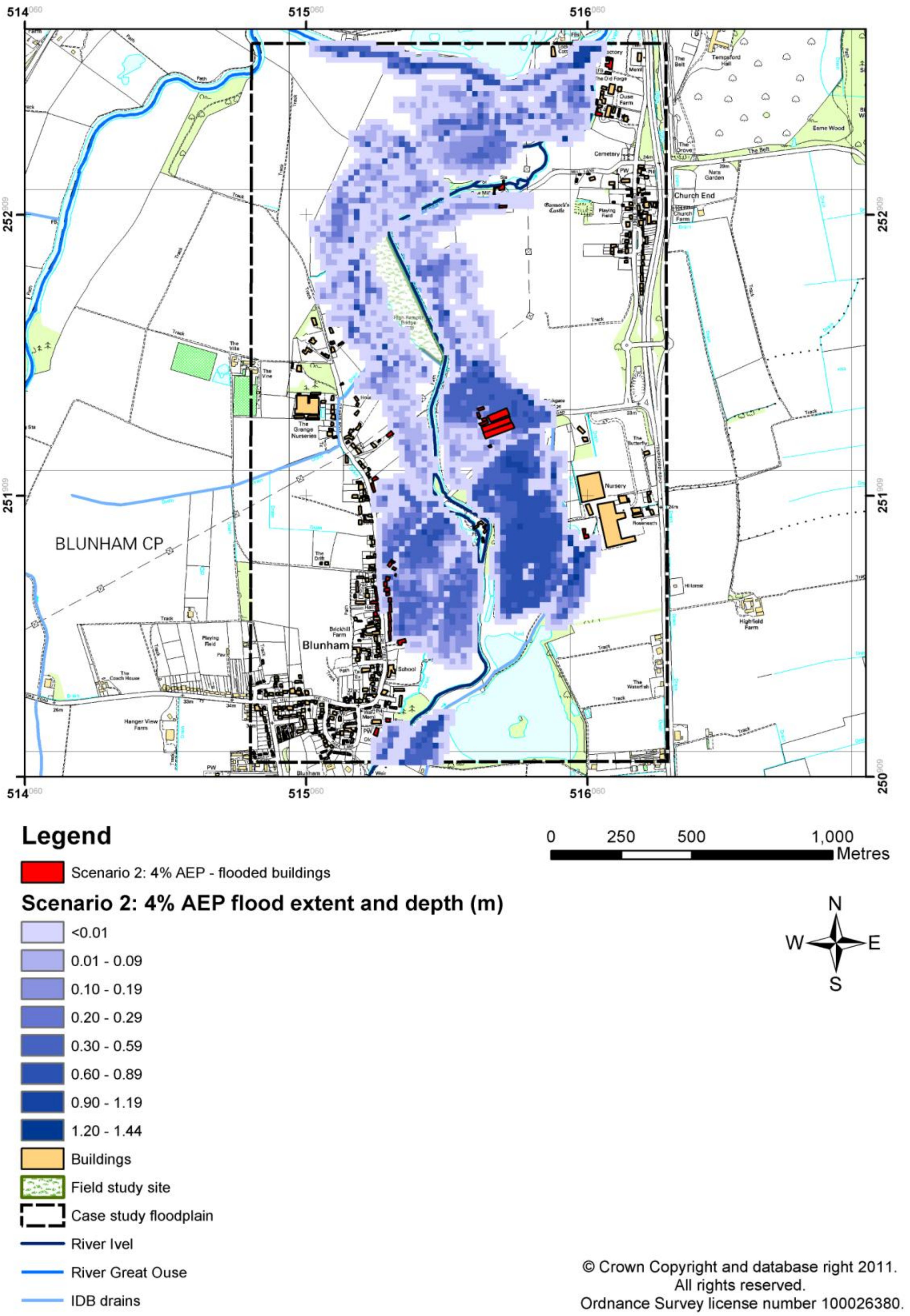

Figure 7.11 Scenario 2: 4% AEP flood extent and depth (m) with flooded buildings

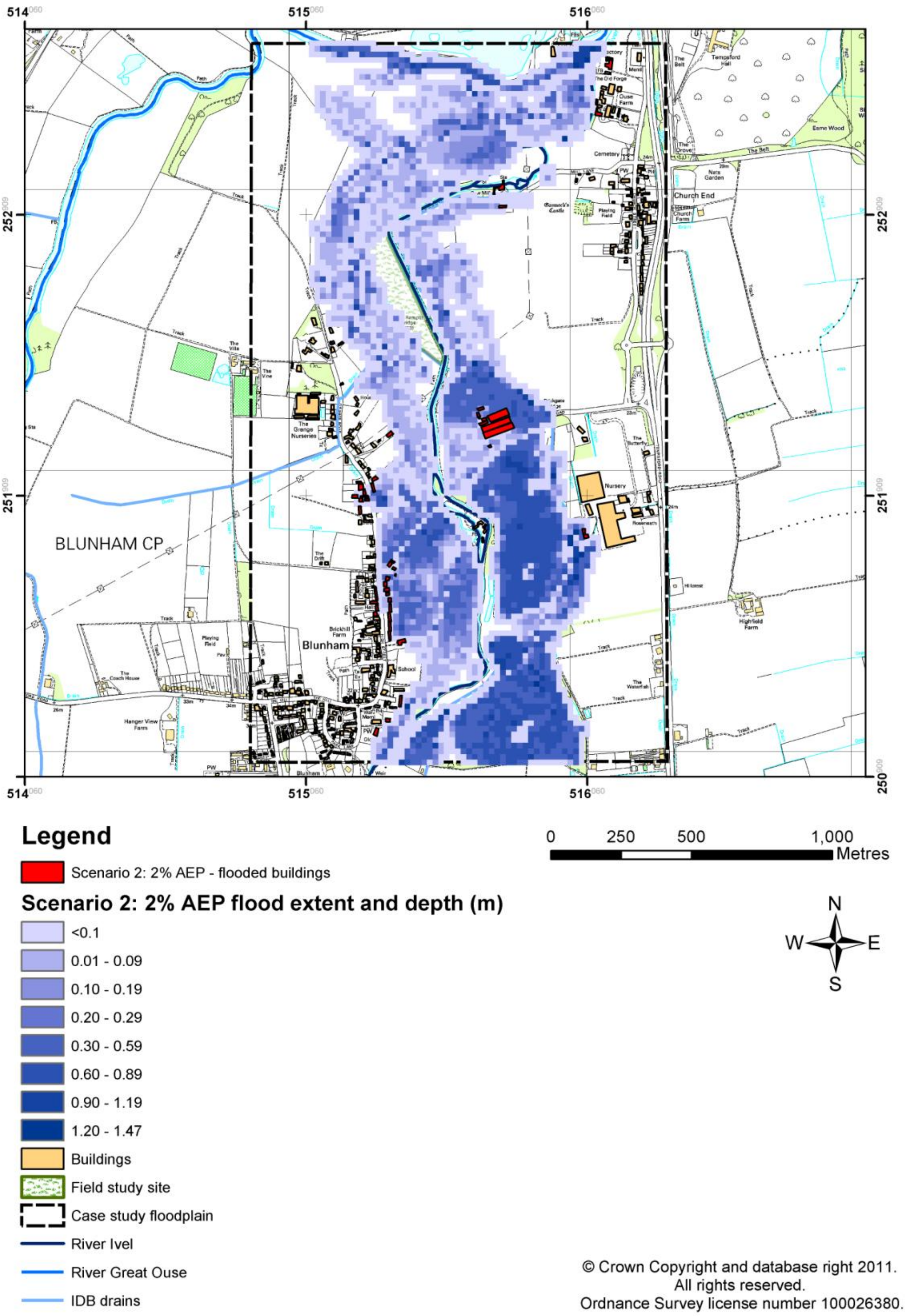

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Figure 7.12 Scenario 2: 2% AEP flood extent and depth (m) with flooded buildings

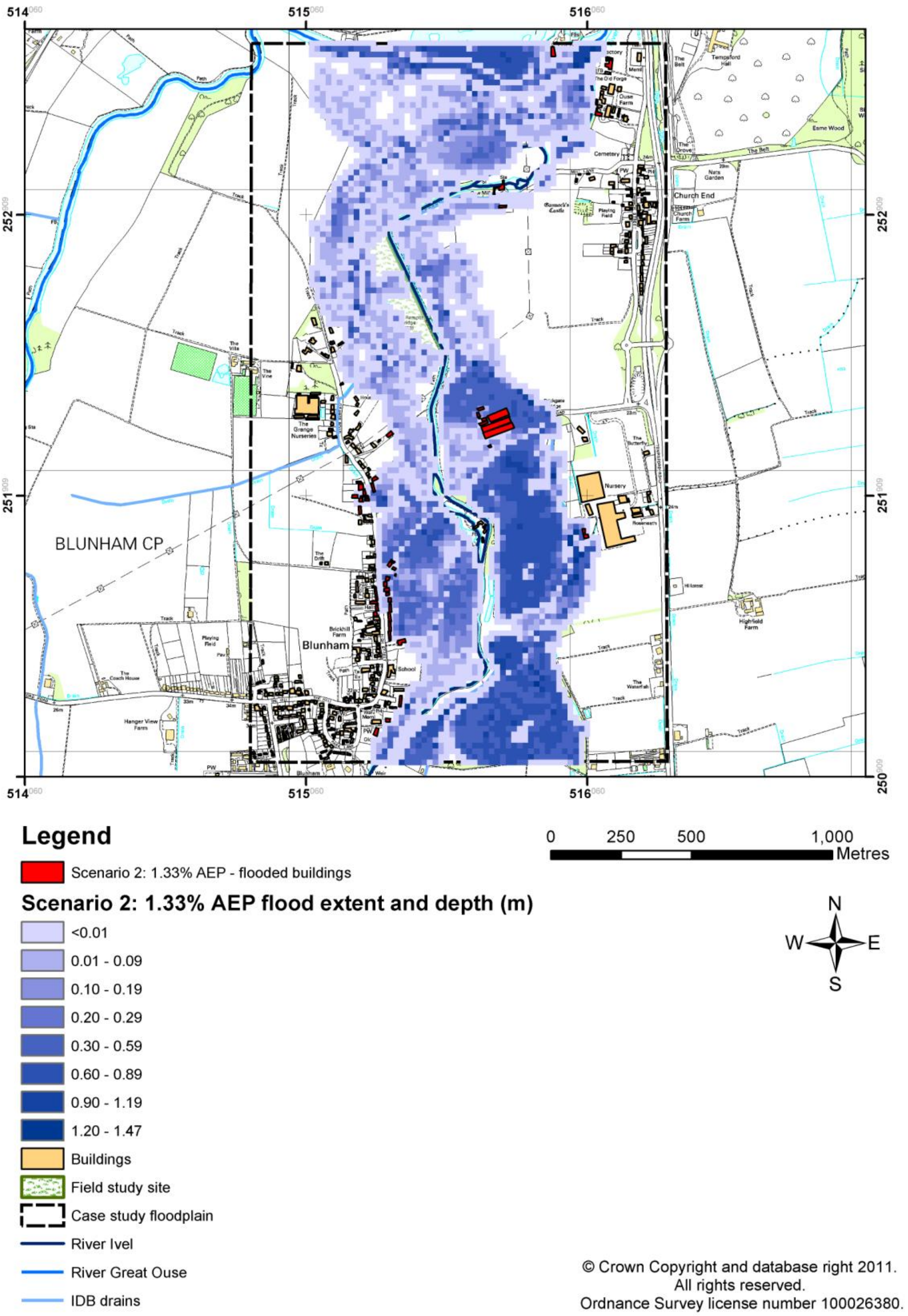

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Figure 7.13 Scenario 2: 1.33% AEP flood extent and depth (m) with flooded buildings

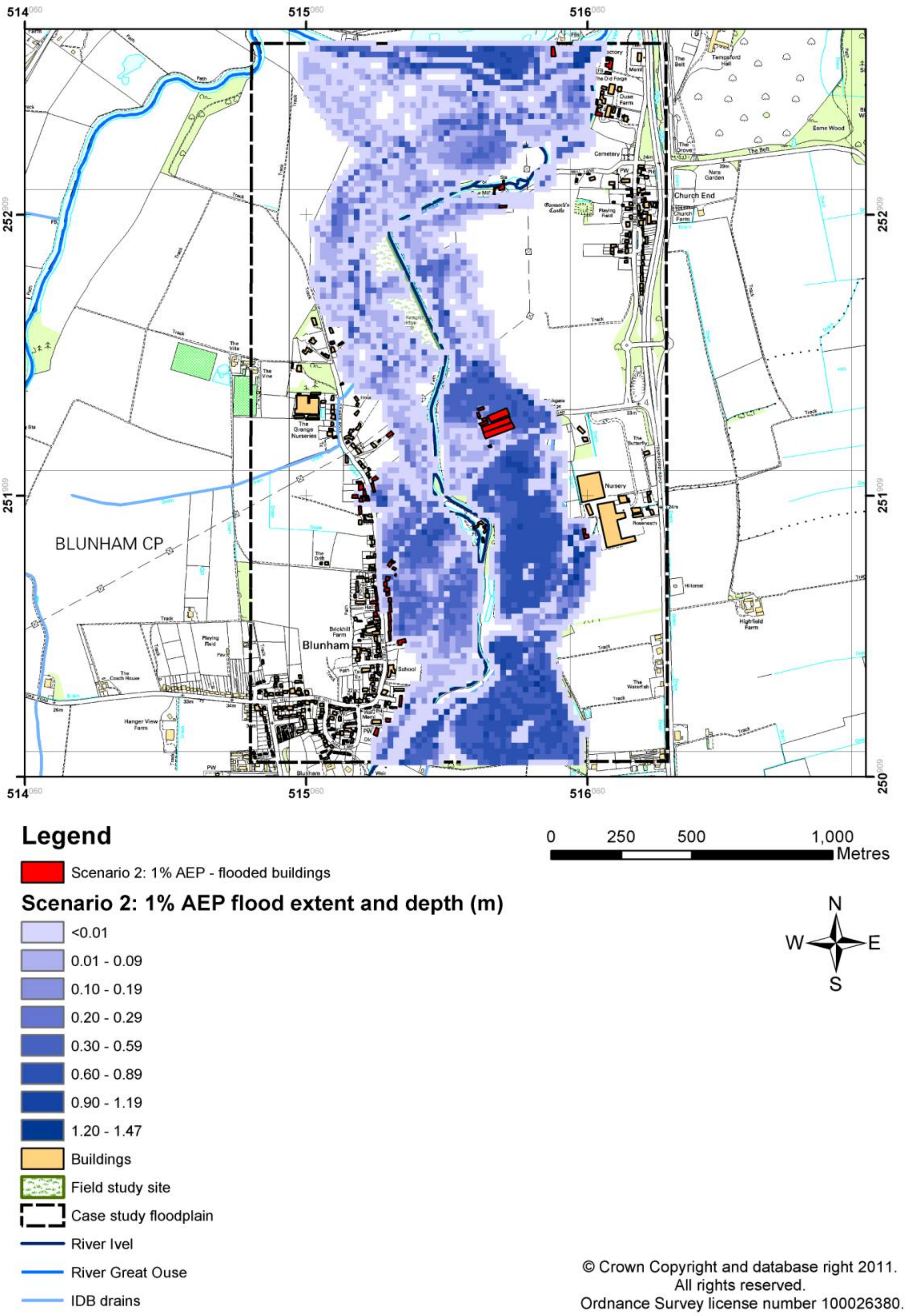

Figure 7.14 Scenario 2: 1% AEP flood extent and depth (m) with flooded buildings

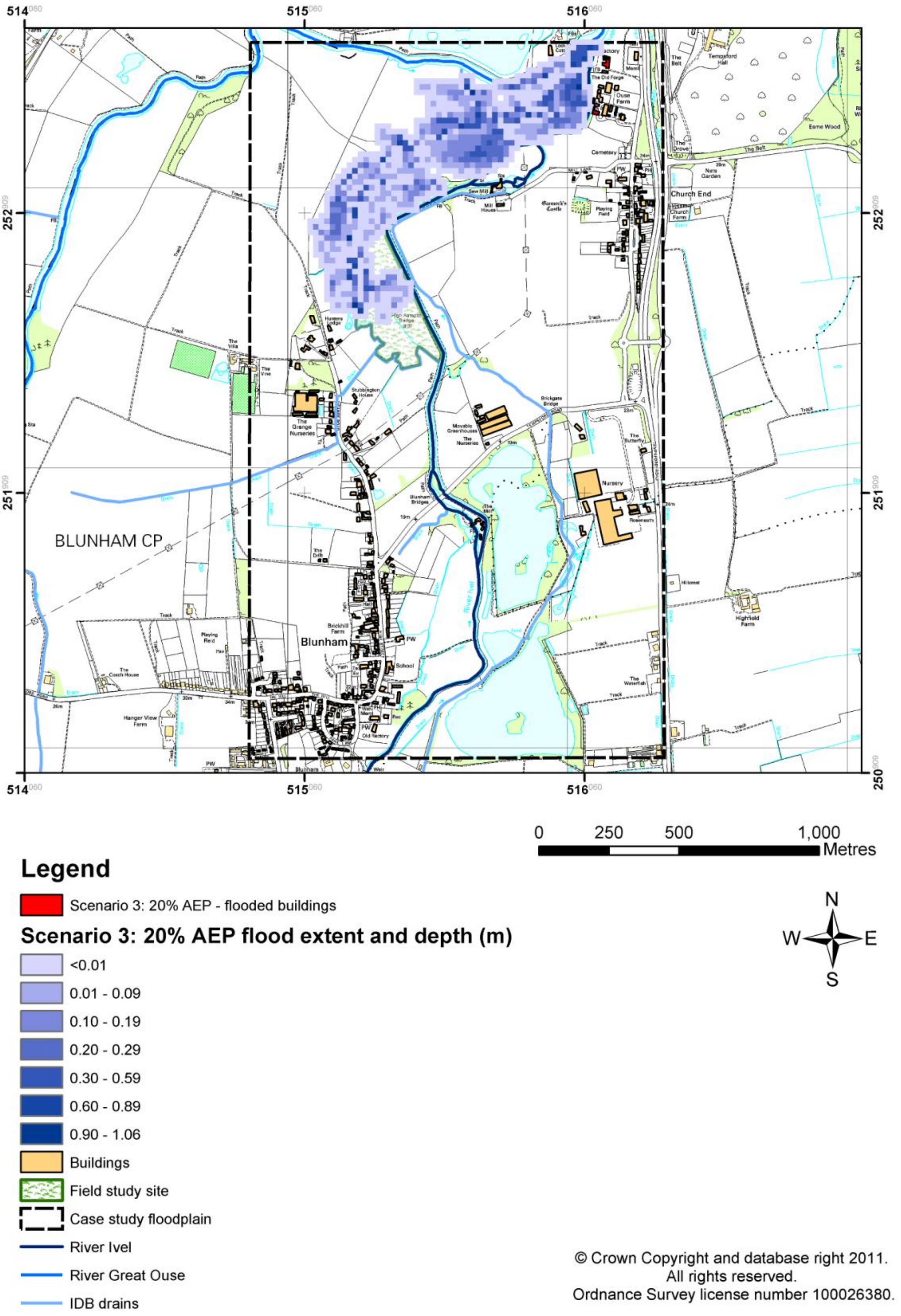

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Figure 7.15 Scenario 3: 20% AEP flood extent and depth (m) with flooded buildings

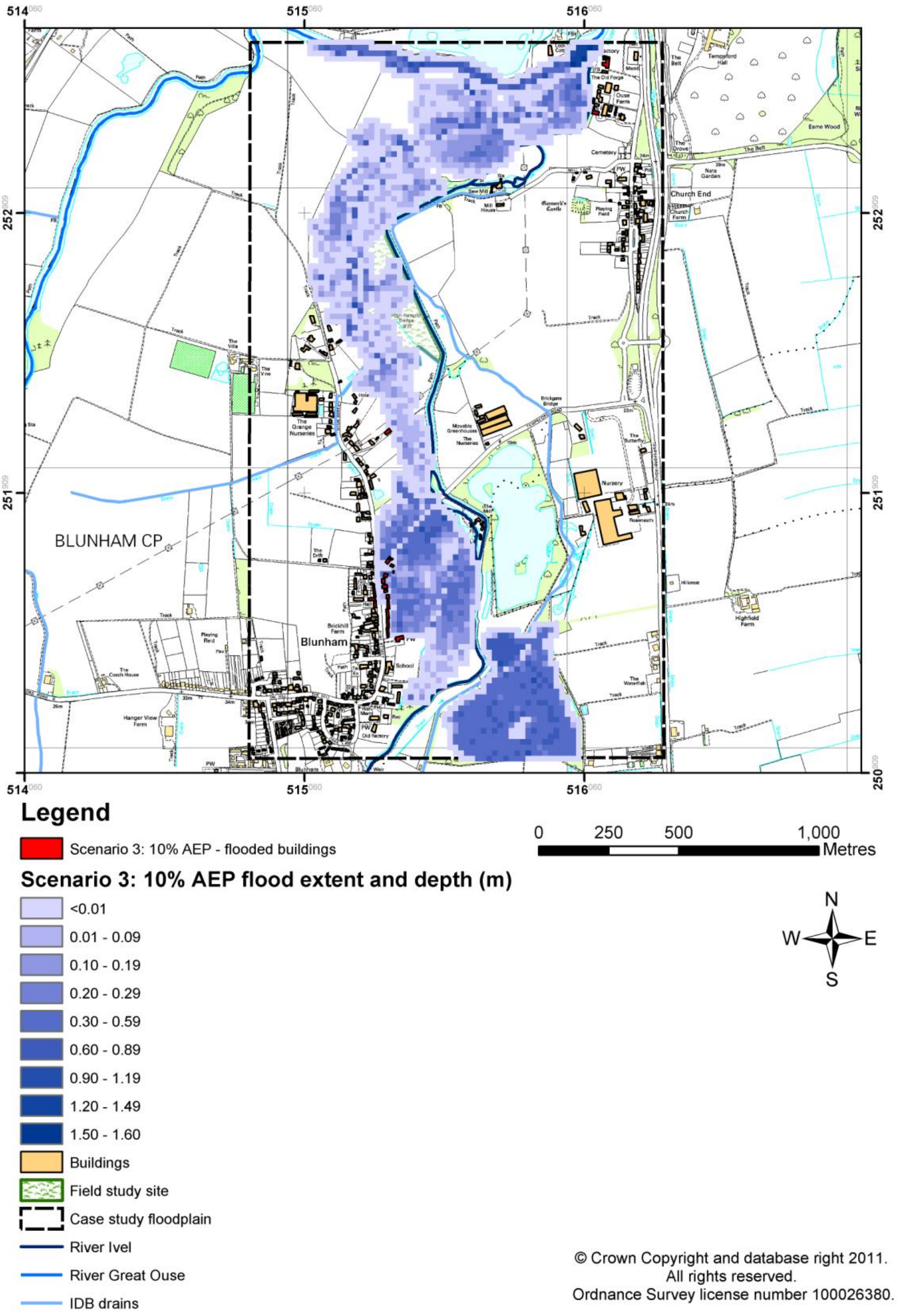

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Figure 7.16 Scenario 3: 10% AEP flood extent and depth (m) with flooded buildings

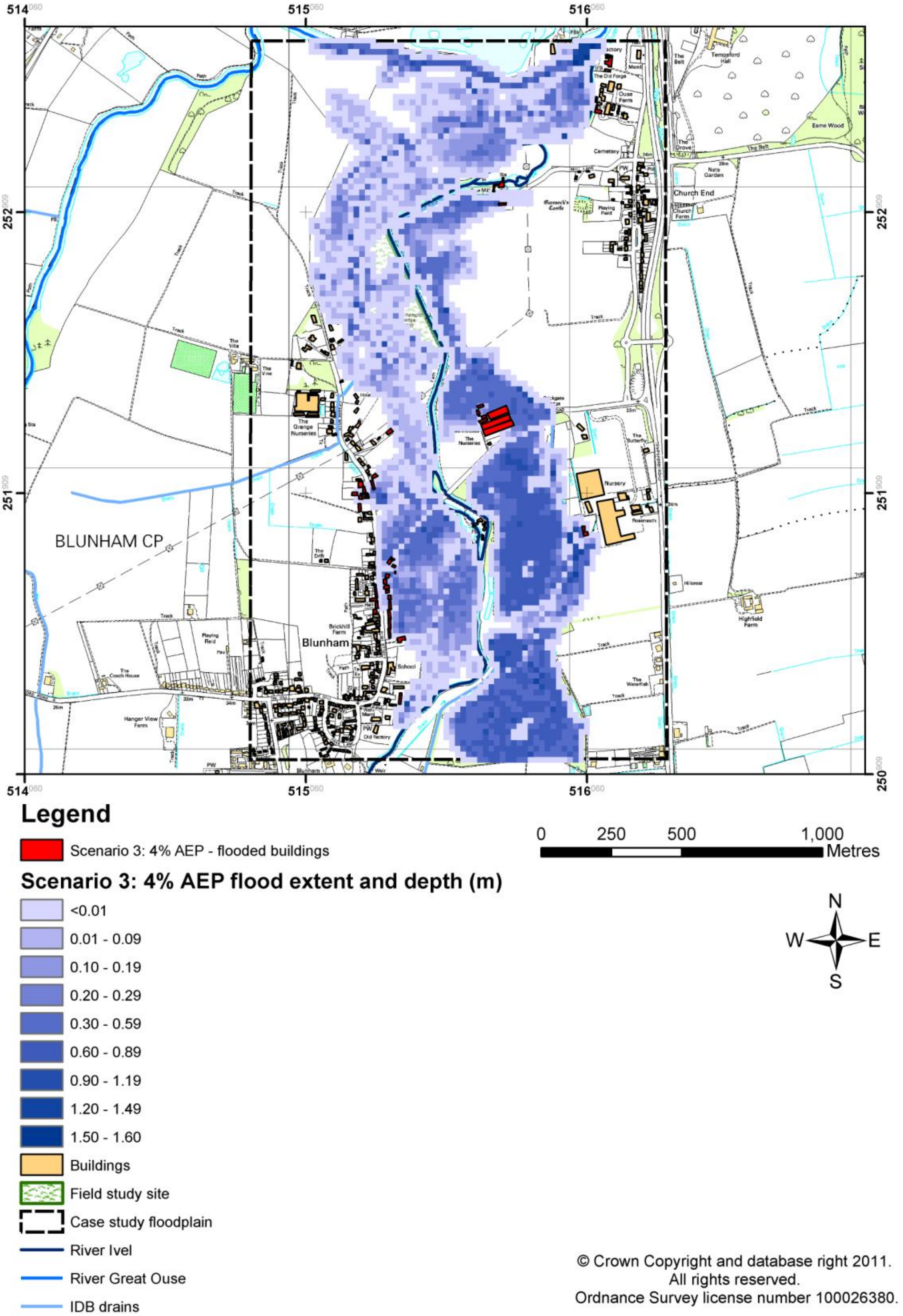

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Figure 7.17 Scenario 3: 4% AEP flood extent and depth (m) with flooded buildings

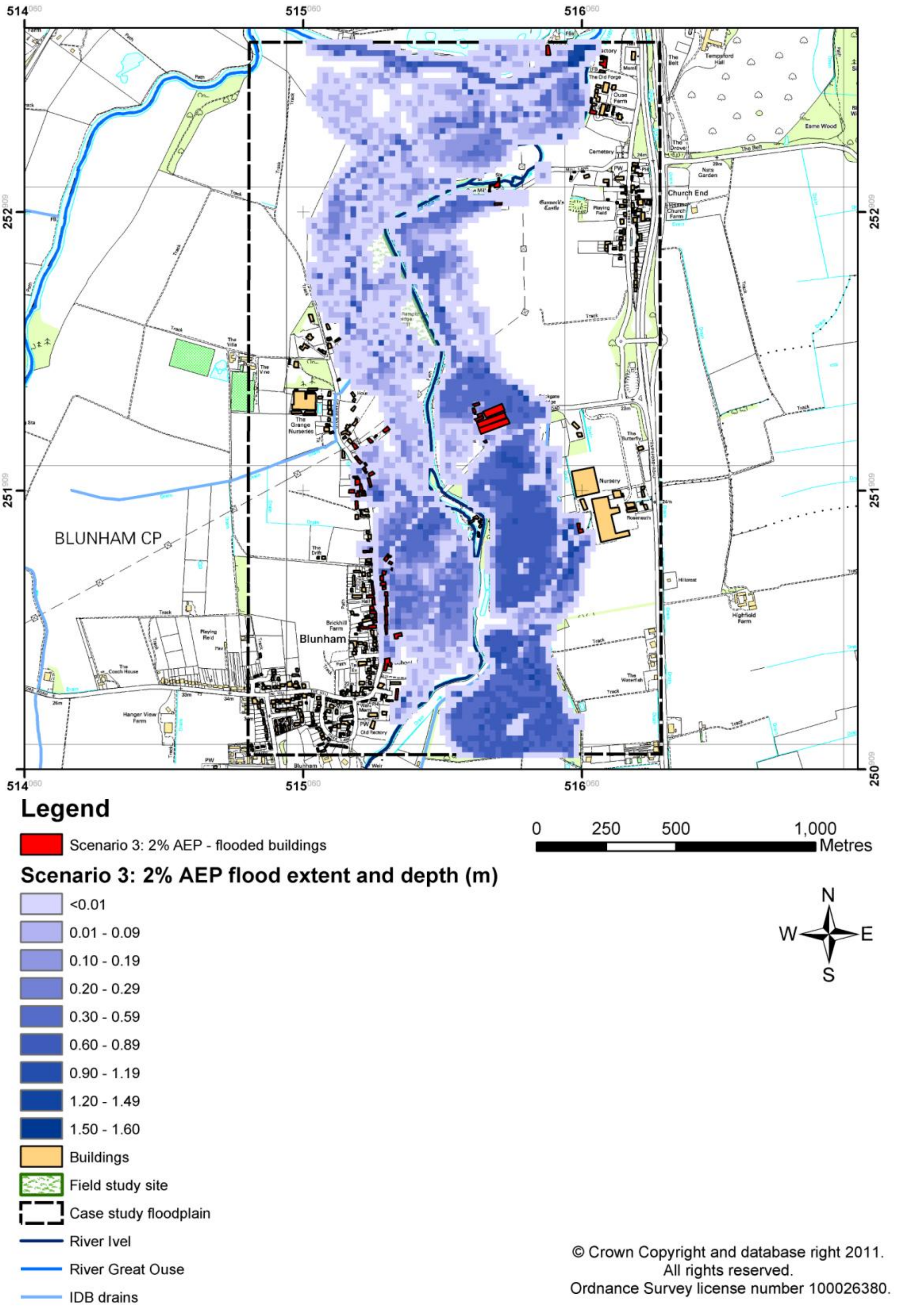

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Figure 7.18 Scenario 3: 2% AEP flood extent and depth (m) with flooded buildings

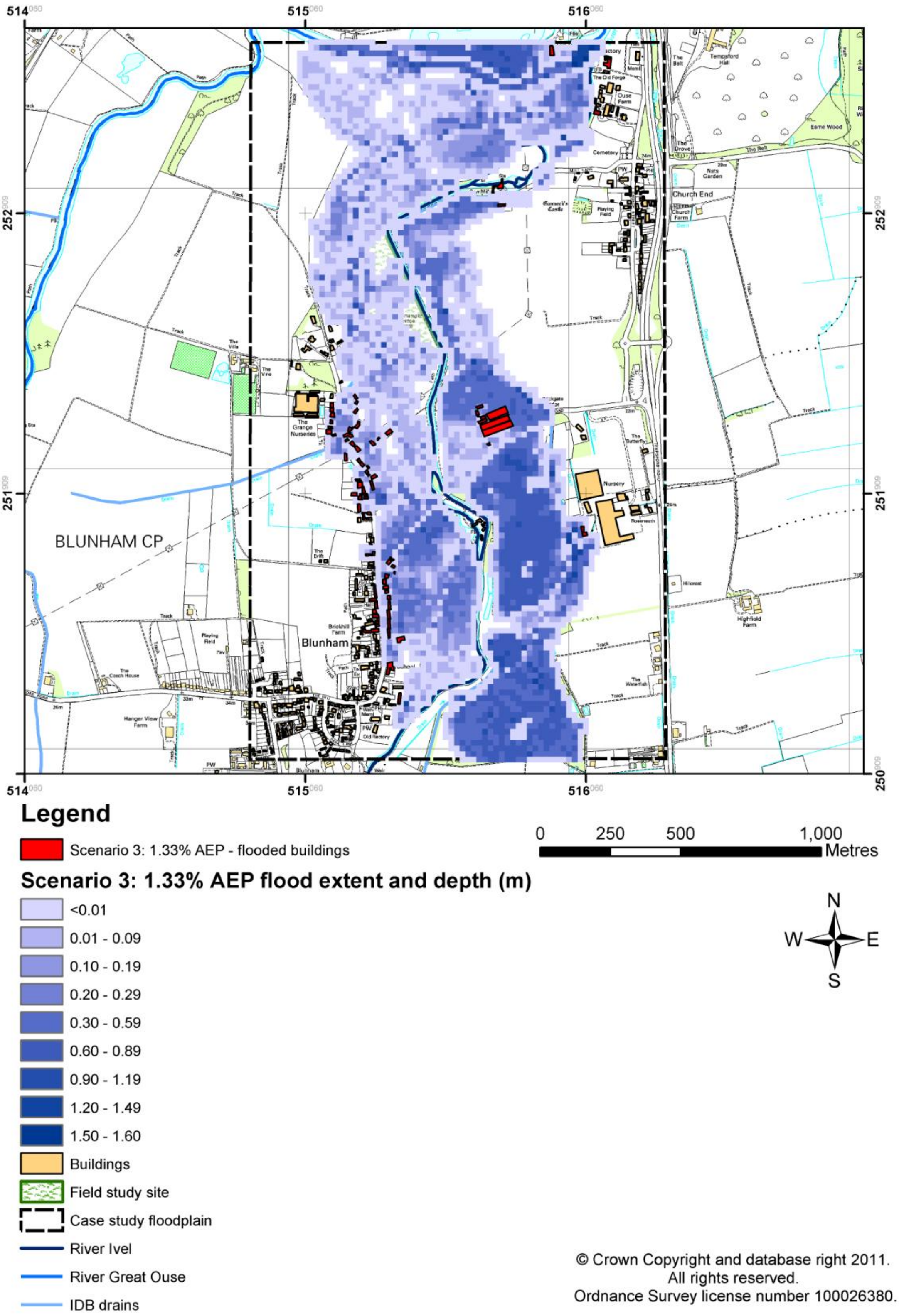

Figure 7.19 Scenario 3: 1.33% AEP flood extent and depth (m) with flooded buildings

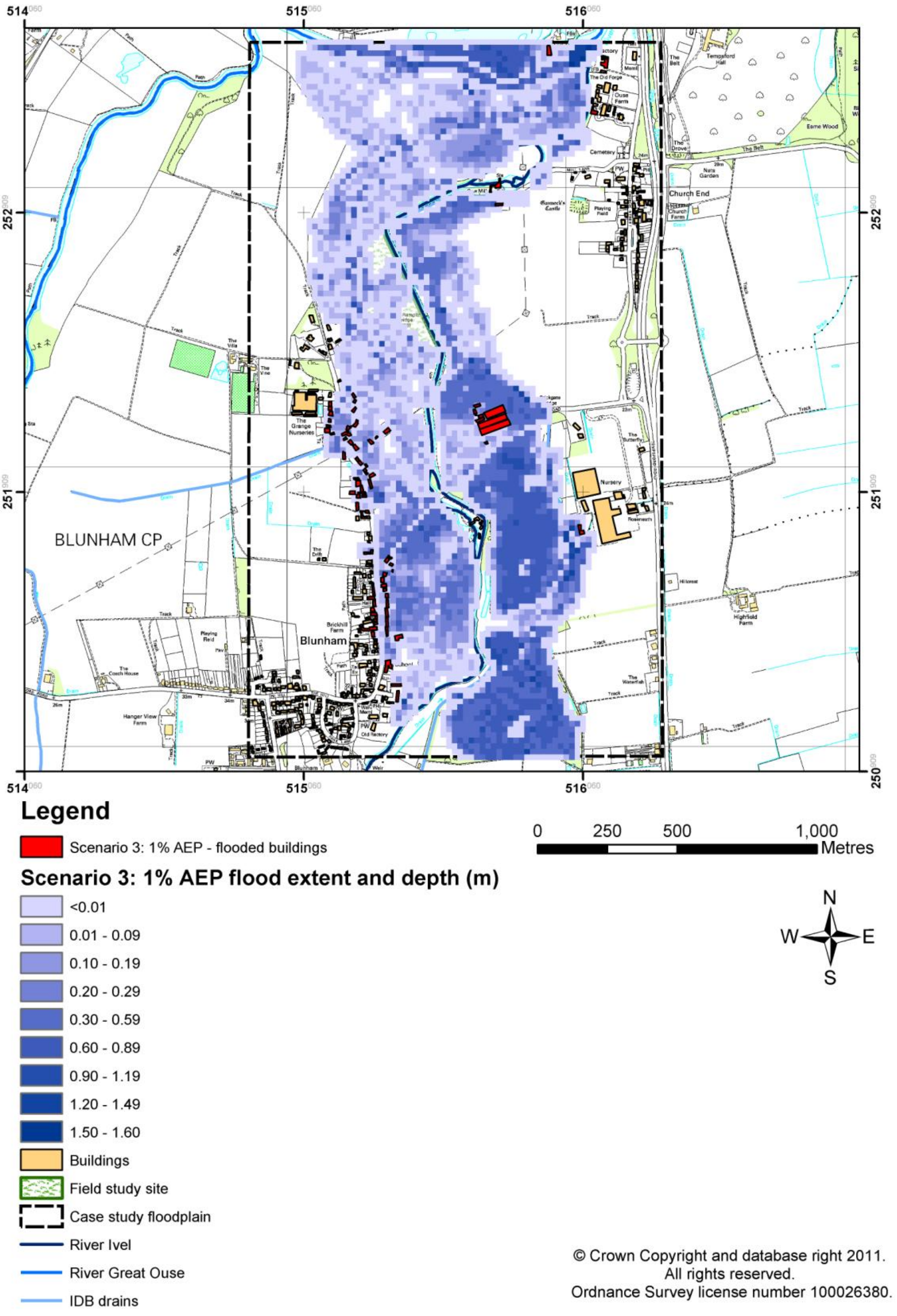

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Figure 7.20 Scenario 3: 1% AEP flood extent and depth (m) with flooded buildings

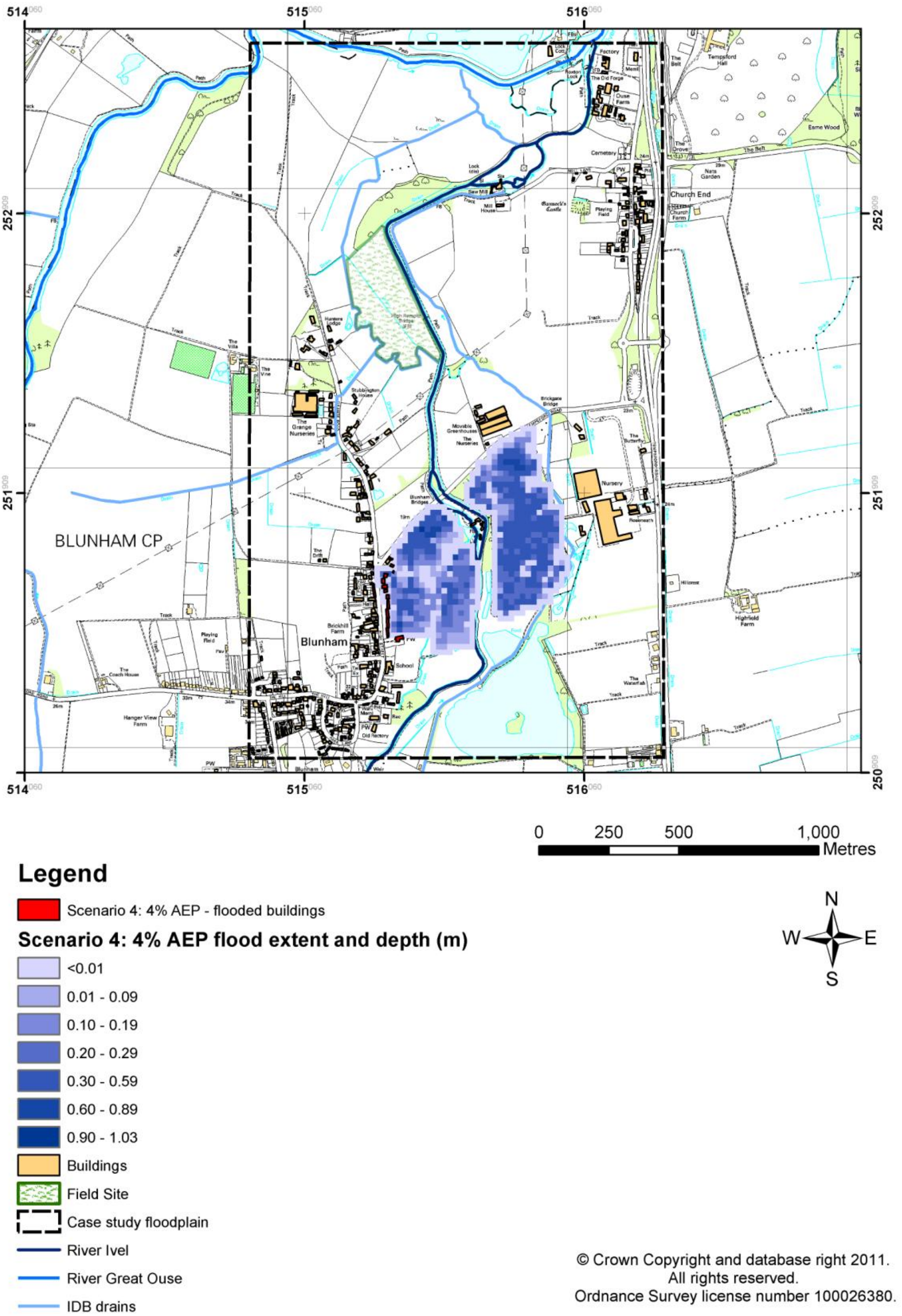

Figure 7.21 Scenario 4: 4% AEP flood extent and depth (m) with flooded buildings

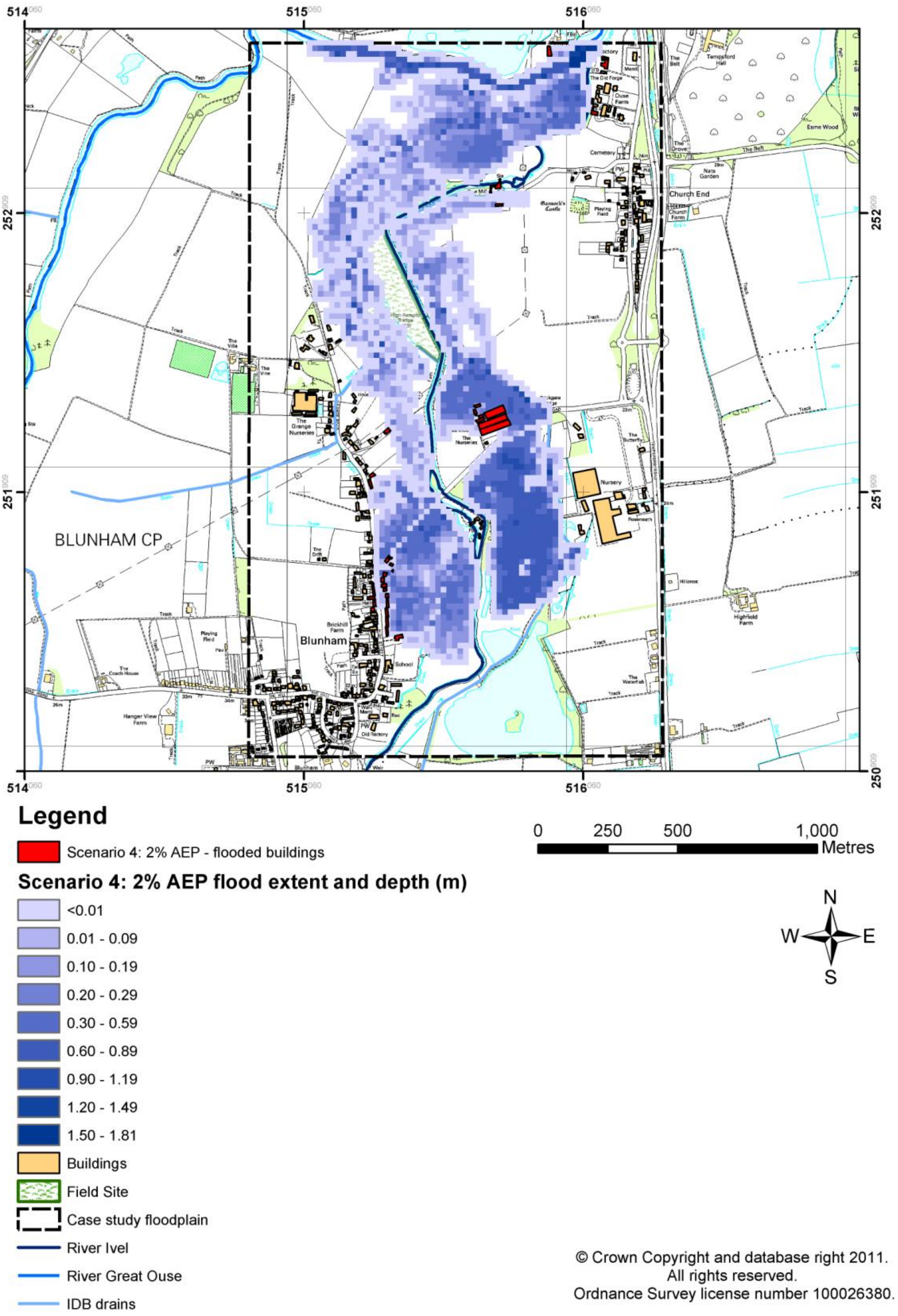

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Figure 7.22 Scenario 4: 2% AEP flood extent and depth (m) with flooded buildings

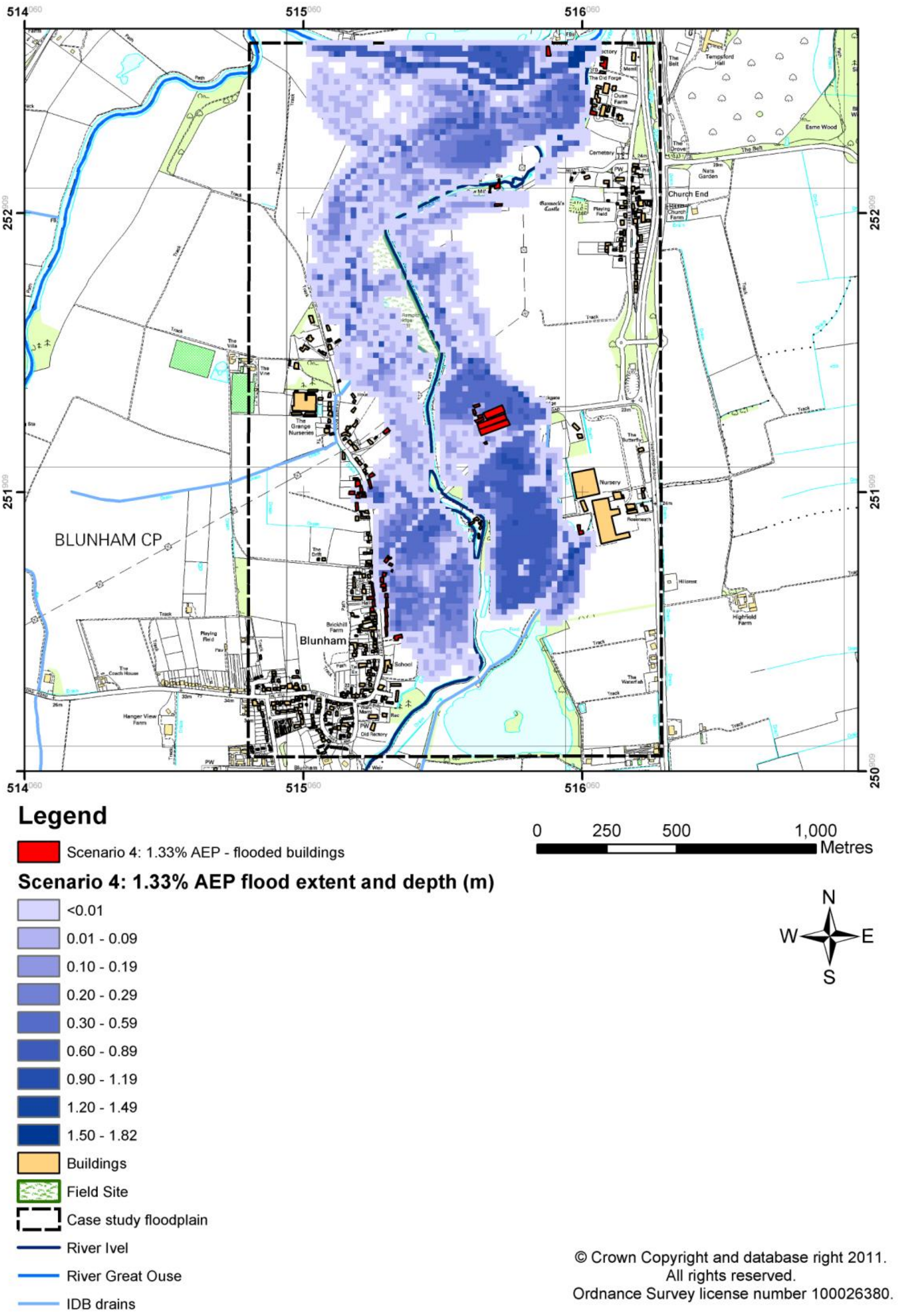

Figure 7.23 Scenario 4: 1.33% AEP flood extent and depth (m) with flooded buildings

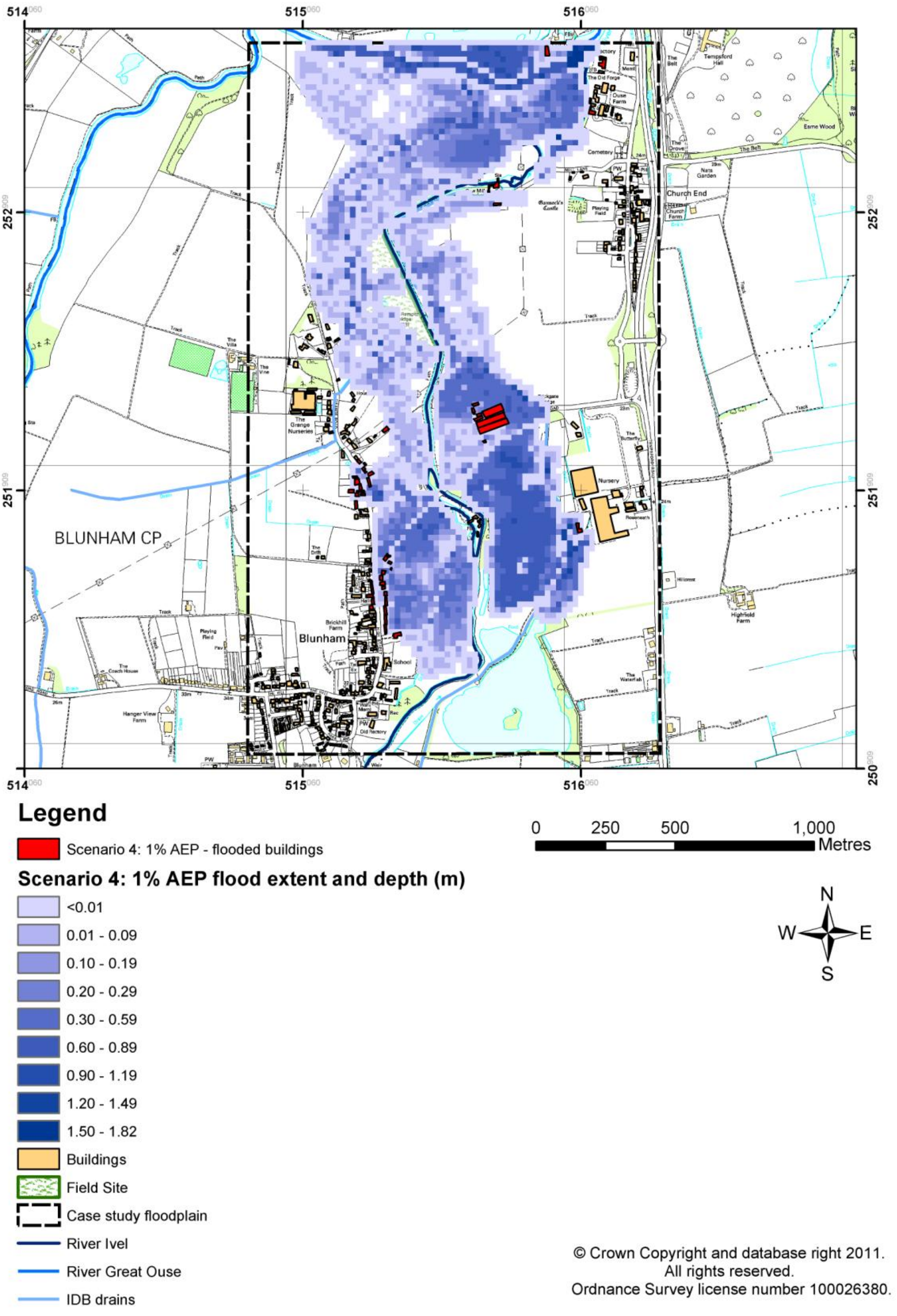

Figure 7.24 Scenario 4: 1% AEP flood extent and depth (m) with flooded buildings

Table 7.32 Flooded buildings count hydrological indicator scenario results

Scenario		Flood event (%AEP)						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	23	37	42	57	59	61	64
S2a	SOP embankment (20%AEP), no drain	0	9	32	39	47	49	49
S3a	Existing embankment (10%AEP) , no drain	0	0	0	14	36	46	51
S4a	SOP embankment (4%AEP) , no drain	0	0	0	14	36	46	51

Table 7.33 Flooded buildings hydrological indicator normalised score scenario results

Scenario		Flood event (%AEP)						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	100.0	100.0	100.0	100.0	100.0	100.0	100.0
S2a	SOP embankment (20%AEP), no drain	0.0	24.3	76.2	68.4	79.7	80.3	76.6
S3a	Existing embankment (10%AEP) , no drain	0.0	0.0	0.0	24.6	61.0	75.4	79.7
S4a	SOP embankment (4%AEP) , no drain	0.0	0.0	0.0	24.6	61.0	75.4	79.7

Table 7.34 Flooded buildings hydrological indicator impact performance rank score scenario results

Scenario		Flood event (%AEP)						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	1	1	1	1	1	1	1
S2a	SOP embankment (20%AEP), no drain	0	2	2	2	2	2	3
S3a	Existing embankment (10%AEP) , no drain	0	0	0	3	3	3	2
S4a	SOP embankment (4%AEP) , no drain	0	0	0	3	3	3	2

The flood damage flood buildings hydrological indicator results (Table 7.34) presented a similar pattern of disbenefit impacts to the inundation area results (Table 7.28). Flood damage disbenefit impacts increase with increasing lateral connectivity especially in low frequency/high magnitude flood events causing more buildings to become flooded in the case study floodplain. The same pattern in regard to the order of disbenefit impact between Scenario 2a and 3a was observed as described in Section 7.3.1. The flood buildings count is a critical site-specific hydrological indicator in regard to assessing flood damage disbenefits as it provides an actual impact of the flooded buildings as a result of flood inundation. This hydrological indicator is seldom applied in research. However, it is quite commonly applied as part of methods for strategic, pre-feasibility and full feasibility studies concerning planning and development based on implementing policies as set out in HM Treasury 'Green Book' and Defra Flood and Coastal Management project appraisal guidance (Penning-Rowsell et al., 2005). The outcome of assessing this hydrological indicator confirms its status to understand the impacts of flood events and levels of lateral connectivity hydraulic controls for hazard and vulnerability, future planning and development as a potential consequence of flooding (DCLG, 2009; EA, 2009).

The final performance composite hydrological indices normalised and impact performance scores for flood damage ecosystem service are displayed in Tables 7.35 and 7.36.

Table 7.35 Flood damage composite hydrological indices normalised score scenario results

Scenario		**Flood event (%AEP)**						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	100.0	100.0	100.0	100.0	100.0	100.0	100.0
S2a	SOP embankment (20%AEP), no drain	0.0	48.6	83.3	82.7	90.4	92.5	91.3
S3a	Existing embankment (10%AEP) , no drain	0.0	43.1	55.6	73.1	85.1	91.7	93.1
S4a	SOP embankment (4%AEP) , no drain	0.0	0.0	0.0	48.2	76.4	85.7	87.3

Table 7.36 Flood damage composite hydrological indices impact performance rank score scenario results

Scenario		**Flood event (%AEP)**						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	1	1	1	1	1	1	1
S2a	SOP embankment (20%AEP), no drain	0	2	2	2	2	2	3
S3a	Existing embankment (10%AEP) , no drain	0	3	3	3	3	3	2
S4a	SOP embankment (4%AEP) , no drain	0	0	0	4	4	4	4

The results of the flood damage composite hydrological indices impact performance scores (Table 7.36) clearly indicate that flood damage disbenefit impacts are exacerbated by increasing lateral connectivity from high frequency/low magnitude to low frequency/high magnitude flood events. The same pattern in regard to the order of disbenefit impact between Scenario 2a and 3a was observed as described in Section 7.3.1.

Dutta et al. (2003), Alkema and Middlekoop (2005) and Kazama et al. (2009) assessed the impacts flood damage as function of flood events and lateral connectivity. These studies were limited to low frequency/high magnitude flood events and two lateral connectivity strategies i.e. embankment/no embankment or breach. These studies focused heavily on assessing the impacts of flood damage in terms of stage/damage curves applying inundation depths to derive a monetary valuation of damages. Although, Kazama et al. (2009) applied the inundation area as a critical indicator of flood defence disbenefits from flood inundation. The application of multiple hydrological indicators allows for a wider interpretation of the consequences of flood inundation on flood damage disbenefits. The assessment of a wider range of flood event and floodplain connectivity scenarios allows for a greater understanding of the flood damage disbenefit in terms of the impacts of flood events floodplain connectivity.

7.3.3 **Water storage**

The water storage infiltrated volume hydrological indicator results for each scenario to include the model results, normalised values and final impact performance scores are displayed in Tables 7.37-7.40.

Table 7.37 Infiltrated area (ha) at 0.1 m scenario results

Scenario		**Flood event (%AEP)**						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	60.6	69.6	70.8	83.8	93.6	93.3	94.0
S2a	SOP embankment (20%AEP), no drain	0.0	15.0	62.4	76.4	89.7	96.2	96.9
S3a	Existing embankment (10%AEP) , no drain	0.0	27.8	56.0	81.8	94.6	99.4	100.4
S4a	SOP embankment (4%AEP) , no drain	0.0	0.0	0.0	13.2	65.7	81.6	83.2

Table 7.38 Infiltrated volume (m^3) hydrological indicator scenario results

Scenario		Flood event (%AEP)						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	6.1	7.0	7.1	8.4	9.4	9.3	9.4
S2a	SOP embankment (20%AEP), no drain	0.0	1.5	6.2	7.6	9.0	9.6	9.7
S3a	Existing embankment (10%AEP) , no drain	0.0	2.8	5.6	8.2	9.5	9.9	10.0
S4a	SOP embankment (4%AEP) , no drain	0.0	0.0	0.0	1.3	6.6	8.2	8.3

Table 7.39 Water storage infiltrated volume hydrological indicator normalised score scenario results

Scenario		Flood event (%AEP)						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	100.0	100.0	100.0	100.0	100.0	100.0	100.0
S2a	SOP embankment (20%AEP), no drain	0.0	21.5	88.1	91.1	95.8	103.1	103.1
S3a	Existing embankment (10%AEP) , no drain	0.0	39.9	79.1	97.6	101.0	106.5	106.9
S4a	SOP embankment (4%AEP) , no drain	0.0	0.0	0.0	15.7	70.1	87.5	88.5

Table 7.40 Water storage infiltrated volume hydrological indicator impact performance score scenario results

Scenario		Flood event (%AEP)						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	1	1	1	1	2	3	3
S2a	SOP embankment (20%AEP), no drain	0	3	2	3	3	2	2
S3a	Existing embankment (10%AEP) , no drain	0	2	3	2	1	1	1
S4a	SOP embankment (4%AEP) , no drain	0	0	0	4	4	4	4

The results (Table 7.38) indicate that low volumes of infiltration occur by increasing lateral connectivity. The results (Table 7.40) clearly indicate that water supply benefit impacts are greater with increasing lateral connectivity from high frequency/low magnitude to low frequency/high magnitude flood events. Increasing the lateral connectivity allows for greater flood inundation thereby promoting a greater volume of water to become available for groundwater recharge. The same pattern in regard to the order of disbenefit impact between Scenario 2a and 3a was observed as described in Section 7.3.1.

Kazama et al. (2007) discussed the importance of floodplain connectivity by simulating a single embankment lateral connectivity configuration and three observed flood events ranging in flood magnitude scenarios. The study discussed that the functioning of groundwater recharge is dependent on inundation area and inundation depth parameters and that flood control activities i.e. floodplain connectivity needs to be carefully planned to consider the negative impacts upon groundwater resources. This research compliments Kazama et al. (2007) by assessing the impacts of water storage to contribute towards groundwater recharge from a range of floodplain connectivity and flood event scenarios. This research outcome infers that floodplain connectivity is an important consideration for the management of delivering water supply ecosystem services. Consideration must be made in the design of floodplain connectivity controls i.e. lateral connectivity and also flood frequency and magnitude to maximise water supply ecosystem service delivery and/or balance the needs for other indirect ecosystem services e.g. extractive or in situ services for agricultural, commercial, industrial, and municipal uses (Brauman et al., 2007; Kazama et al., 2007).

7.3.4 **Terrestrial habitat**

The terrestrial habitat inundation area hydrological indicator results for each scenario to include the model results, normalised and impact performance ranking scores are displayed in Tables 7.41-7.43.

Table 7.41 Inundation area (ha) hydrological indicator scenario results

Scenario		**Flood event (%AEP)**						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	80	109	120	134	146	148	149
S2a	SOP embankment (20%AEP), no drain	0	23	88	107	134	143	145
S3a	Existing embankment (10%AEP) , no drain	0	32	80	127	138	147	148
S4a	SOP embankment (4%AEP) , no drain	0	0	0	27	100	121	123

Table 7.42 Inundation area hydrological indicator normalised score scenario results

Scenario		Flood event (%AEP)						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	100.0	100.0	100.0	100.0	100.0	100.0	100.0
S2a	SOP embankment (20%AEP), no drain	0.0	21.4	73.7	79.6	91.5	97.1	97.3
S3a	Existing embankment (10%AEP) , no drain	0.0	29.2	66.9	94.8	94.3	99.6	99.5
S4a	SOP embankment (4%AEP) , no drain	0.0	0.0	0.0	20.0	68.3	81.6	82.3

Table 7.43 Inundation area hydrological indicator impact performance rank score scenario results

Scenario		Flood event (%AEP)						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	1	1	1	1	1	1	1
S2a	SOP embankment (20%AEP), no drain	0	3	2	3	3	3	3
S3a	Existing embankment (10%AEP) , no drain	0	2	3	2	2	2	2
S4a	SOP embankment (4%AEP) , no drain	0	0	0	4	4	4	4

The results (Table 7.43) clearly indicate that terrestrial habitat disbenefit impacts are greater with increasing lateral connectivity from high frequency/low magnitude to low frequency/high magnitude flood events. Increasing lateral connectivity causes a greater area to be affected by flood inundation with the potential to cause a change in grassland community composition. The same pattern in regard to the order of disbenefit impact between scenario 2a and 3a was observed as described in Section 7.3.1.

Duranel et al. (2007) and Baptist et al. (2004) investigated the impacts of the flood inundation area for restoration/rejuvenation of grassland species at their respective study sites yet specific to high frequency/low magnitude and low frequency/high magnitude flood events and considering the existing single floodplain connectivity configuration and control. This research expands upon Duranel et al. (2007) and Baptist et al. (2004) by including the assessment of the impacts to decreasing lateral connectivity for grassland habitat conservation/restoration or rejuvenation. In this case, it was clear that increasing lateral connectivity has a negative impact through the occurrence of greater area of flood inundation. However, the water table position and ponding duration hydrological indicators will provide a more critical indication of ecological succession that can affect the conservation and maintenance of grassland communities as a result of flood inundation (Baptist et al., 2006; Wheeler et al., 2004; Vervuren et al., 2003). The terrestrial habitat ponding duration hydrological indicator results for each scenario are displayed in Table 7.44.

Table 7.44 Ponding duration (days) hydrological indicator scenario results

Scenario		**Flood event (%AEP)**						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	0.42	0.42	0.42	0.42	0.42	0.42	0.42
S2a	SOP embankment (20%AEP), no drain	0.00	0.42	0.42	0.42	0.42	0.42	0.42
S3a	Existing embankment (10%AEP) , no drain	0.00	0.42	0.42	0.42	0.42	0.42	0.42
S4a	SOP embankment (4%AEP) , no drain	0.00	0.00	0.42	0.42	0.42	0.42	0.42

The ponding duration can affect the conservation and maintenance of the MG6 grassland community at the field study site. The results (Table 7.44) where flood inundation has occurred display the same result of 0.42 days based on the potential infiltration depth of 0.1 m and the infiltration rate of 0.01 m.hr^{-1} that can infiltrate the soil based on the soil type and the existing water table position. The inundation depth results were > 0.1 m and floodwaters remain on the floodplain (Table 7.29). The effective ponding duration at the field study site cannot be calculated for the case study site as the drainage rate encompassing the surface drains for the removal of water at the floodplain is unknown and more information is required to effectively calculate the ponding duration based on the inundation depths.

The terrestrial habitat water table position hydrological indicator results for each scenario to include the model results, normalised and impact performance ranking scores are displayed in Tables 7.45-7.47. The results (Table 7.45) display the negative values to indicate the water table position; (mbgl) and the positive values indicate the surface water level in the floodplain (magl).

Table 7.45 Water table position (mbgl) and (magl) hydrological indicator scenario results

Scenario		Flood event (%AEP)						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	+0.55	+0.55	+0.70	+0.79	+0.70	+0.70	+0.70
S2a	SOP embankment (20%AEP), no drain	-0.53	+0.40	+0.65	+0.79	0.70	+0.70	+0.70
S3a	Existing embankment (10%AEP) , no drain	-0.53	+0.50	+0.70	+0.75	+0.75	+0.75	+0.75
S4a	SOP embankment (4%AEP) , no drain	-0.53	-0.53	-0.53	+0.55	+0.81	+0.85	+0.85

Table 7.46 Terrestrial habitat water table position hydrological indicator normalised score scenario results

Scenario		Flood event (%AEP)						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	100	100	100	100	100	100	100
S2a	SOP embankment (20%AEP), no drain	0	100	100	100	100	100	100
S3a	Existing embankment (10%AEP) , no drain	0	100	100	100	100	100	100
S4a	SOP embankment (4%AEP) , no drain	0	0	0	100	100	100	100

Table 7.47 Terrestrial habitat water table position hydrological indicator impact performance rank score scenario results

Scenario		Flood event (%AEP)						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	1	1	1	1	1	1	1
S2a	SOP embankment (20%AEP), no drain	0	1	1	1	1	1	1
S3a	Existing embankment (10%AEP) , no drain	0	1	1	1	1	1	1
S4a	SOP embankment (4%AEP) , no drain	0	0	0	1	1	1	1

The results (Table 7.47) clearly indicate that terrestrial habitat disbenefit impacts are greater with increasing lateral connectivity from high frequency/low magnitude to low frequency/high magnitude flood events. In low frequency/high magnitude flood events, there is no control from lateral connectivity due to the magnitude of flood events causing greater disbenefit impacts. Increasing the lateral connectivity causes greater floodwater inundation, which has the potential to infiltrate the soil and recharge the water table. The water table results (Table 7.45) clearly display that the water table is above ground level through increasing lateral connectivity especially in low frequency/high magnitude flood events. The same pattern in regard to the order of disbenefit impact between Scenario 2a and 3a was observed as described in Section 7.3.1.

Toogood and Joyce (2009, 2008) observed that flood events occurring over long-term periods raised water table levels causing a change in plant species composition thus altering the habitat type as a result of floodwater inundation. The existing field study site is an MG6 grassland and described as common and species poor and therefore of limited ecological interest with limited research being conducted to determine its habitat requirements. This particular grassland community prefers a well-drained profile and is commonly grazed throughout much of the year. Wheeler et al. (2004) described a range of target and tolerable water table positions for seasons in regard to the conservation of grassland communities. Increasing lateral connectivity will cause greater flood inundation leading to infiltration and groundwater recharge to cause the grassland community to change in floristic composition towards a wetland grassland community, mire or swamp. However, increasing floodplain connectivity could prove beneficial in providing a more species rich floristic composition of ecological interest e.g. MG 8, MG13 based on trajectories of community change in response to water regimes (Wheeler et al., 2004). The composite hydrological indices normalised and impact performance rank scores for terrestrial habitat ecosystem service are displayed in Tables 7.48 and 7.49.

Table 7.48 Terrestrial habitat composite hydrological indices normalised score scenario results

Scenario		**Flood event (%AEP)**						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50% AEP), no drain	100.0	100.0	100.0	100.0	100.0	100.0	100.0
S2a	SOP embankment (20% AEP), no drain	0.0	60.7	86.9	89.8	95.8	98.6	98.7
S3a	Existing embankment (10% AEP) , no drain	0.0	64.6	83.4	97.4	97.2	99.8	99.7
S4a	SOP embankment (4% AEP) , no drain	0.0	0.0	0.0	60.0	84.1	90.8	91.2

Table 7.49 Terrestrial habitat composite hydrological indices impact performance rank score scenario results

Scenario		Flood event (%AEP)						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50% AEP), no drain	1	1	1	1	1	1	1
S2a	SOP embankment (20% AEP), no drain	0	3	2	3	3	3	3
S3a	Existing embankment (10% AEP) , no drain	0	2	3	2	2	2	2
S4a	SOP embankment (4% AEP) , no drain	0	0	0	4	4	4	4

The results (Table 7.49) clearly indicate that terrestrial habitat disbenefit impacts are greater with increasing connectivity from high frequency/low magnitude to low frequency/high magnitude flood events. Increasing the lateral connectivity allows for greater flood inundation thereby leading to groundwater recharge. The same pattern in regard to the order of disbenefit impact between Scenario 2a and 3a was observed as described in Section 7.3.1.

Extensive research has been performed to assess the terrestrial habitat benefits by managing the hydrological regime through water table management and in response to flood inundation (Duranel et al., 2007; Baptist et al, 2004; Thompson et al., 2004; Zsuffa and Bogardi, 1995). Hydrological/hydraulic and groundwater modelling can effectively represent complex floodplain hydrology to inform on the establishment and maintenance of habitat types (Baptist et al., 2004; Thompson et al., 2004; Karim et al., 2011). The common aspect of these studies involved assessing the impacts from the existing floodplain connectivity and water table position.

This research expands upon past research by assessing the impacts of terrestrial habitat through a wide range of flood event frequencies and magnitudes and by decreasing lateral connectivity. Past research relied on assessing the impacts of habitats based on water table positions and ponding durations only as a result of flood inundation (Duranel et al., 2007; Baptist et al., 2004; Zsuffa and Bogardi, 1995). The application of composite hydrological indices provides a more comprehensive assessment and greater understanding of the influence of hydrological indices to assess ecosystem services delivery.

7.3.5 **Freshwater fish habitat**

The composite hydrological indices normalised and impact performance rank scores for each scenario are displayed in Tables 7.50-7.51.

Table 7.50 Freshwater fish habitat composite inundation area (ha) for inundation depth and velocity hydrological indicator range normalised score scenario results

Scenario		**Flood event (%AEP)**						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	131.6	131.6	131.6	131.6	131.6	131.6	131.6
S2a	SOP embankment (20%AEP), no drain	0.0	17.1	63.6	79.4	136.3	126.3	186.9
S3a	Existing embankment (10%AEP) , no drain	0.0	23.5	56.5	87.5	84.6	89.7	88.3
S4a	SOP embankment (4%AEP) , no drain	0.0	1.3	0.0	16.0	57.1	71.0	72.4

Table 7.51 Freshwater fish habitat composite hydrological indicator performance rank score scenario results

Scenario		**Flood event (%AEP)**						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	1	1	1	1	2	1	2
S2a	SOP embankment (20%AEP), no drain	0	3	2	3	1	2	1
S3a	Existing embankment (10%AEP) , no drain	0	2	3	2	3	3	3
S4a	SOP embankment (4%AEP) , no drain	0	4	0	4	4	4	4

The results (Table 7.51) clearly indicate that benefit impacts are greater with increasing lateral connectivity in high frequency/low magnitude flood events. However, in low frequency/high magnitude flood events, a more varied pattern emerges although greater benefits are derived through increasing lateral connectivity. Lowering of embankments to allow for flood inundation creates the necessary water depth and velocity lifecycle requirements in the floodplain for freshwater fish (Table D.1).

The frequency of flood events is crucial during a fish species lifecycle to enable fish species to migrate to floodplains for spawning, nursery, refuge from predators and shelter (Cowx et al., 2004). In this instance, the results (Table 7.51) clearly indicate that increasing connectivity i.e. lowering of embankments is necessary in order to provide the necessary hydrological requirements to enhance fish population and increasing species diversity. The same pattern in regard to the order of benefit impacts between scenario 2 and 3 was observed as described in Section 7.3.1. Seasonal flooding especially in spring/summer months would be essential for spawning and feeding requirements respectively to boost fish populations and diversity (Cowx et al., 2004, Appendix D, Table D.1).

Previous research has investigated the impacts of flood inundation and floodplain connectivity on the conservation and enhancement of fish populations in floodplains (Grift et al., 2003; Nunn et al., 2007; Henning et al., 2007). However, these studies only observed fish behaviour through field sampling by electrofishing during flood events. Van de Wolfsaar et al. (2010) described the application of hydrodynamic models to estimate the spawning habitat availability as a result of flood inundation. Water depth and velocity were amongst the most significant modelled outputs that affect habitat suitability and utilization. This particular study confirmed the robustness of 2D hydrodynamic modelling to estimate habitat suitability yet only in 3 coarse freshwater fish species utilising spatial inundation depth and velocity model results. The outcome of the study discussed that lateral connectivity between the river and floodplain can influence the variability of fish population dynamics. Previous studies were also limited to assessing active floodplains with frequent flooding and existing floodplain connectivity present on the floodplains. This research further expands upon Grift et al. (2003), Nunn et al. (2007), Henning et al. (2007) and Van de Wolfshaar et al. (2010) by assessing the impacts of a range of lateral connectivity scenarios and flood events for freshwater fish habitat suitability. This research also considered 25 coarse fish species across various stages in life cycle i.e. Larvae, spawning, 0+, fry, juvenile and adult in 10 family classifications were assessed. Previous studies were restricted to 3-4 coarse fish species on average primarily focussed on 0+ lifecycle of fish and specific spawning seasons. This research provides a more comprehensive assessment of habitat suitability for coarse freshwater fish species at various stages in life cycle i.e. Larvae, spawning, 0+, fry, juvenile and adult over a range hydrological connectivity and flood events.

7.3.6 **Agricultural productivity**

The agricultural productivity hydrological indicator results to include the model results, normalised and impact performance rank scores are displayed in Tables 7.52-7.54.

Table 7.52 Inundation area (ha) hydrological indicator scenario results

Scenario		Flood event (%AEP)						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	80	109	120	134	146	148	149
S2a	SOP embankment (20%AEP), no drain	0	23	88	107	134	143	145
S3a	Existing embankment (10%AEP) , no drain	0	32	80	127	138	147	148
S4a	SOP embankment (4%AEP) , no drain	0	0	0	27	100	121	123

Table 7.53 Inundation area hydrological indicator normalised score scenario results

Scenario		Flood event (%AEP)						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	100.0	100.0	100.0	100.0	100.0	100.0	100.0
S2a	SOP embankment (20%AEP), no drain	0.0	21.4	73.7	79.6	91.5	97.1	97.3
S3a	Existing embankment (10%AEP) , no drain	0.0	29.2	66.9	94.8	94.3	99.6	99.5
S4a	SOP embankment (4%AEP) , no drain	0.0	0.0	0.0	20.0	68.3	81.6	82.3

Table 7.54 Inundation area hydrological indicator impact performance rank scores scenario results

Scenario		Flood event (%AEP)						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	1	1	1	1	1	1	1
S2a	SOP embankment (20%AEP), no drain	0	3	2	3	3	3	3
S3a	Existing embankment (10%AEP) , no drain	0	2	3	2	2	2	2
S4a	SOP embankment (4%AEP) , no drain	0	0	0	4	4	4	4

The results (Table 7.54) clearly indicate that agricultural productivity disbenefit impacts are greater with increasing lateral connectivity from high frequency/low magnitude to low frequency/high magnitude flood events. Increasing lateral connectivity causes greater areal extent of floodwater inundation. The same pattern in regard to the order of disbenefit impact between scenario 2a and 3a was observed as described in Section 7.3.1. Kazama et al. (2009) assessed the impacts of flood events and lateral connectivity as a disbenefit to agricultural productivity indicating the controlling the lateral connectivity was crucial to limiting the impacts of flood inundation to increase agricultural productivity using flood inundation models. The study only assessed the impacts in regard to low frequency/high magnitude observed flood events with the existing floodplain connectivity e.g. embankments. This research expands upon Kazama et al. (2009) by assessing the impacts of a wider range of flood events i.e. high frequency/low magnitude to low frequency/high magnitude to include a range of decreasing lateral connectivity.

The agricultural water table position hydrological indicator results for each scenario to include the model results, normalised and impact performance rank scores are displayed in Tables 7.55-7.57. The results (Table 7.55) display the negative values to indicate the water table position; (mbgl) and the positive values indicate the surface water level in the floodplain (magl).

Table 7.55 Water table position (mbgl) and (magl) hydrological indicator scenario results

Scenario		Flood event (%AEP)						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	+0.55	+0.55	+0.70	+0.79	+0.70	+0.70	+0.70
S2a	SOP embankment (20%AEP), no drain	-0.53	+0.40	+0.65	+0.79	0.70	+0.70	+0.70
S3a	Existing embankment (10%AEP) , no drain	-0.53	+0.50	+0.70	+0.75	+0.75	+0.75	+0.70
S4a	SOP embankment (4%AEP) , no drain	-0.53	-0.53	-0.53	+0.55	+0.81	+0.85	+0.85

Table 7.56 Water table position hydrological indicator normalised score scenario results

Scenario		Flood event (%AEP)						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	100.0	100.0	100.0	100.0	100.0	100.0	100.0
S2a	SOP embankment (20%AEP), no drain	33.3	100.0	100.0	100.0	100.0	100.0	100.0
S3a	Existing embankment (10%AEP) , no drain	33.3	100.0	100.0	100.0	100.0	100.0	100.0
S4a	SOP embankment (4%AEP) , no drain	33.3	33.3	33.3	100.0	100.0	100.0	100.0

Table 7.57 Water table position hydrological indicator performance rank score scenario results

Scenario		**Flood event (%AEP)**						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	1	1	1	1	1	1	1
S2a	SOP embankment (20%AEP), no drain	3	1	1	1	1	1	1
S3a	Existing embankment (10%AEP) , no drain	3	1	1	1	1	1	1
S4a	SOP embankment (4%AEP) , no drain	3	3	3	1	1	1	1

The results (Table 7.57) clearly indicate that agricultural productivity disbenefit impacts are greater with increasing lateral connectivity from high frequency/low magnitude to low frequency/high magnitude flood events. In low frequency/high magnitude flood events, there is no hydraulic control for the lateral connectivity due to the magnitude of the flood events causing greater disbenefit impacts. Increasing the lateral connectivity causes greater floodwater inundation, which has the potential to infiltrate the soil and recharge the water table thus limiting agricultural productivity. The results (Table 7.55) indicate the potential for constraints on land use, field access, grazing and reduced crop yield.

Dunderdale and Morris (1997) previously applied a non-steady state water table model to assess the impacts of river maintenance and flood frequency on changes to the river and ditchwater levels and the water table level in a floodplain. A flood return period curve was applied to assess the impact of flood frequency and magnitude on river maintenance. This study was more focused on the impact of river maintenance e.g. weed cutting and removal, desilting, tree/bush cutting and removal in channel rather than lateral connectivity e.g. manipulating embankment elevation to increase or decrease connectivity. This research expands upon Dunderdale and Morris (1997) by modelling the overbank flows using flood inundation models to assess the impact of a range of flood events and manipulating the floodplain connectivity to assess the impact to agricultural productivity. The seasonal impacts of controlling floodplain connectivity are also critical in summer months in terms of field access for machinery, grazing of livestock and the crop growing season (Smedema et al., 2004). Flood inundation can impact on the waterlogging of the land and the ponding duration which affects trafficability of the land and crop yield (Smedema et al., 2004). The results in this instance are more applicable to trafficability and crop yield of winter cereals. The agricultural productivity ponding duration hydrological indicator model results for each scenario are displayed in Table 7.58.

Table 7.58 Ponding duration (days) hydrological indicator scenario results

Scenario		**Flood event (%AEP)**						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	0.42	0.42	0.42	0.42	0.42	0.42	0.42
S2a	SOP embankment (20%AEP), no drain	0.00	0.42	0.42	0.42	0.42	0.42	0.42
S3a	Existing embankment (10%AEP) , no drain	0.00	0.42	0.42	0.42	0.42	0.42	0.42
S4a	SOP embankment (4%AEP) , no drain	0.00	0.00	0.42	0.42	0.42	0.42	0.42

The ponding duration of floodwaters is a critical hydrological indicator in regard the potential for crop yield loss (Table 7.13). The results (Table 7.58) where flood inundation has occurred display the same result of 0.42 days based on the potential infiltration depth of 0.1 m and the infiltration rate of 0.01 m.hr^{-1} that can infiltrate the soil based on the soil type and the existing water table position. The inundation depth results are > 0.1 m and floodwaters remain on the floodplain (Table 7.29). The effective ponding duration at the field study site cannot be calculated for the case study site as the drainage rate encompassing the surface drains for the removal of water at the floodplain is unknown and more information is required to effectively calculate the ponding duration based on the inundation depths.

The final composite hydrological indices impact performance rank score for agricultural productivity ecosystem service inclusive of the inundation area and water table position only are displayed in Tables 7.59 and 7.60.

Table 7.59 Agricultural productivity composite hydrological indices aggregated score scenario results

Scenario		**Flood event (%AEP)**						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	100.0	100.0	100.0	100.0	100.0	100.0	100.0
S2a	SOP embankment (20%AEP), no drain	16.7	60.7	86.9	89.8	95.8	98.6	98.7
S3a	Existing embankment (10%AEP) , no drain	16.7	64.6	83.4	97.4	97.2	99.8	99.7
S4a	SOP embankment (4%AEP) , no drain	16.7	16.7	16.7	60.0	84.1	90.8	91.2

Table 7.60 Agricultural productivity composite hydrological indices performance rank score scenario results

Scenario		**Flood event (%AEP)**						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	1	1	1	1	1	1	1
S2a	SOP embankment (20%AEP), no drain	2	3	2	3	3	2	2
S3a	Existing embankment (10%AEP) , no drain	2	2	3	2	2	1	1
S4a	SOP embankment (4%AEP) , no drain	2	4	4	4	4	3	3

The results (Table 7.60) clearly indicate that disbenefit impacts are greater with increasing lateral connectivity in high frequency/low magnitude and low frequency/high magnitude flood events. However, in high frequency/low magnitude flood events, the disbenefit impact is less pronounced as decreasing connectivity helps to limit the impact of flood inundation on agricultural productivity.

The literature review discussed that assessing the impact of flood events and floodplain connectivity on agricultural productivity had previously been conducted by applying hydrological/hydraulic models (Dutta et al., 2006; Alkema and Middelkoop, 2005). Both studies had assessed the impacts by applying a single hydrological indicator e.g. inundation depth as a stage damage function with increasing water depth in floodplain increasing the damage factor and hazard to agricultural productivity. In both studies, only the impacts of low frequency/high magnitude flood events were considered. In regard to lateral connectivity, Alkema and Middelkoop (2005) considered the impacts to agricultural productivity for scenarios with only past and present embankments while Dutta et al. (2006) considered three structural measures to include an increase in embankment elevations, smoothing of the river bed and construction of retarding basins. This research improves upon Alkema and Middelkoop (2005) and Dutta et al. (2006) by assessing the impact of decreasing lateral connectivity and high frequency/low magnitude flood events. The application of the composite hydrological indices provides a more comprehensive and robust ecosystem services assessment system and allows greater understanding of the impacts of flood events and floodplain connectivity.

7.3.7 **Recreation**

The recreation inundation area hydrological indicator results for each scenario and flood event to include the model results, normalised and performance rank scores are displayed in Tables 7.61-7.63.

Table 7.61 Inundation area (ha) hydrological indicator scenario results

Scenario		**Flood event (%AEP)**						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	80	109	120	134	146	148	149
S2a	SOP embankment (20%AEP), no drain	0	23	88	107	134	143	145
S3a	Existing embankment (10%AEP) , no drain	0	32	80	127	138	147	148
S4a	SOP embankment (4%AEP) , no drain	0	0	0	27	100	121	123

Table 7.62 Inundation area hydrological indicator normalised score scenario results

Scenario		**Flood event (%AEP)**						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	100.0	100.0	100.0	100.0	100.0	100.0	100.0
S2a	SOP embankment (20%AEP), no drain	0.0	21.4	73.7	79.6	91.5	97.1	97.3
S3a	Existing embankment (10%AEP) , no drain	0.0	29.2	66.9	94.8	94.3	99.6	99.5
S4a	SOP embankment (4%AEP) , no drain	0.0	0.0	0.0	20.0	68.3	81.6	82.3

Table 7.63 Inundation area hydrological indicator performance scores scenario results

Scenario		**Flood event (%AEP)**						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	1	1	1	1	1	1	1
S2a	SOP embankment (20%AEP), no drain	0	3	2	3	3	3	3
S3a	Existing embankment (10%AEP) , no drain	0	2	3	2	2	2	2
S4a	SOP embankment (4%AEP) , no drain	0	0	0	4	4	4	4

The results (Table 7.63) clearly indicate that recreation disbenefit impacts are greater with increasing connectivity from high frequency/low magnitude to low frequency/high magnitude flood events. Increasing lateral connectivity causes areal extent of floodwater inundation thus potential to impact on dryland recreation activities as described in Table 7.14. The same pattern in regard to the order of disbenefit impact between Scenario 2a and 3a was observed as described in Section 7.3.1. The literature review found no research in regard to the spatial impact of flood inundation. The application of the linked ISIS 1D-2D model provides beneficial information in regard to assessing the impacts of areal floodwater inundation from a range of flood events and a range of decreasing lateral connectivity configurations.

The recreation inundation depth hydrological indicator results for each scenario and flood event to include the model results, normalised and impact performance rank scores are displayed in Tables 7.64-7.66.

Table 7.64 Inundation depth (mabgl) hydrological indicator scenario results

Scenario		**Flood event (%AEP)**						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	0.55	0.55	0.70	0.70	0.70	0.70	0.70
S2a	SOP embankment (20%AEP), no drain	0.00	0.40	0.65	0.70	0.70	0.70	0.70
S3a	Existing embankment (10%AEP) , no drain	0.00	0.50	0.70	0.75	0.75	0.75	0.75
S4a	SOP embankment (4%AEP) , no drain	0.00	0.00	0.00	0.50	0.81	0.85	0.85

Table 7.65 Inundation depth hydrological indicator normalised score scenario results

Scenario		**Flood event (%AEP)**						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	100.0	100.0	100.0	100.0	100.0	100.0	100.0
S2a	SOP embankment (20%AEP), no drain	0.0	72.8	92.9	100.0	100.0	100.0	100.0
S3a	Existing embankment (10%AEP) , no drain	0.0	90.9	100.0	107.1	107.1	107.1	107.1
S4a	SOP embankment (4%AEP) , no drain	0.0	0.0	0.0	71.5	115.9	121.4	121.4

Table 7.66 Inundation depth hydrological indicator impact performance rank score scenario results

Scenario		Flood event (%AEP)						
ID	Description	50	20	10	4	2	1.33	1
S1a	No embankment (50%AEP), no drain	1	1	1	2	3	3	3
S2a	SOP embankment (20%AEP), no drain	0	3	2	2	3	3	3
S3a	Existing embankment (10%AEP) , no drain	0	2	1	1	2	2	2
S4a	SOP embankment (4%AEP) , no drain	0	0	0	3	1	1	1

The results (Table 7.66) indicated that greater disbenefit impact occurs with increasing lateral connectivity in high frequency/low magnitude flood events as greater flood inundation generates larger inundation depths limiting access for dryland recreation activities as described in Table 7.14. In low frequency/high magnitude flood events, decreasing lateral connectivity reduces disbenefit impacts as the crest elevations of the embankments impede overbank flow and floodwater inundation.

The literature review described Alkema and Middelkoop (2005) utilising a floodplain inundation model with a single hydrological indicator e.g. inundation depth to assess the impacts of observed low frequency/high magnitude flood events and past and present embankments lateral connectivity scenario on recreation ecosystem service delivery. The inundation depth was applied as a stage/damage function with increasing water depth in the floodplain increasing the damage factor and hazard to recreation. This research expands upon Alkema and Middelkoop (2005) by applying a wider range of flood events and lateral connectivity scenarios to assess the impact of the flood inundation depth on the recreation ecosystem service. The ponding duration hydrological indicator modelled results for each scenario are displayed in Table 7.67.

Table 7.67 Ponding duration (days) hydrological indicator scenario results

Scenario		Flood event (%AEP)						
ID	Description	50	20	10	4	2	1.33	1
S1a	No embankment (50%AEP), no drain	0.42	0.42	0.42	0.42	0.42	0.42	0.42
S2a	SOP embankment (20%AEP), no drain	0.00	0.42	0.42	0.42	0.42	0.42	0.42
S3a	Existing embankment (10%AEP) , no drain	0.00	0.42	0.42	0.42	0.42	0.42	0.42
S4a	SOP embankment (4%AEP) , no drain	0.00	0.00	0.42	0.42	0.42	0.42	0.42

The ponding duration of floodwaters is a critical hydrological indicator in regard to access for dryland recreational activities (Table 7.14). The ponding duration results in Table 7.67 where flood inundation has occurred display the same result of 0.42 days based on the potential infiltration depth of 0.1 m and the infiltration rate of 0.01 m.hr^{-1} that can infiltrate the soil based on the soil type and the existing water table position. The inundation depth results are > 0.1 m and floodwaters remain on the floodplain (Table 7.29). The effective ponding duration at the field study site cannot be calculated for the case study site as the drainage rate encompassing the surface drains for the removal of water at the floodplain is unknown and more information is required to effectively calculate the ponding duration based on the inundation depths.

The final composite hydrological indices impact performance rank score for recreation ecosystem service inclusive of the inundation area and depth are displayed in Tables 7.68 and 7.69.

Table 7.68 Recreation composite hydrological indices normalised score scenario results

Scenario		**Flood event (%AEP)**						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	100.0	100.0	100.0	100.0	100.0	100.0	100.0
S2a	SOP embankment (20%AEP), no drain	0.0	47.1	83.3	89.8	95.8	98.6	98.7
S3a	Existing embankment (10%AEP) , no drain	0.0	60.1	83.4	101.0	100.7	103.3	103.3
S4a	SOP embankment (4%AEP) , no drain	0.0	0.0	0.0	45.8	92.1	101.5	101.9

Table 7.69 Recreation composite hydrological indices performance rank score scenario results

Scenario		**Flood event (%AEP)**						
ID	**Description**	**50**	**20**	**10**	**4**	**2**	**1.33**	**1**
S1a	No embankment (50%AEP), no drain	1	1	1	2	2	3	3
S2a	SOP embankment (20%AEP), no drain	0	3	3	3	3	4	4
S3a	Existing embankment (10%AEP) , no drain	0	2	2	1	1	1	1
S4a	SOP embankment (4%AEP) , no drain	0	0	0	4	4	2	2

The results (Table 7.69) clearly indicate that disbenefit impacts are greater with increasing connectivity in high frequency/low magnitude and low frequency/high magnitude flood events. Increasing lateral connectivity allows greater flood inundation causing the land to become less accessible for dryland recreation activities with an increase in spatial area affected and higher inundation depths. In low frequency/high magnitude flood events, decreasing lateral connectivity reduces disbenefit impacts as the crest elevations of the embankments impede overbank flow and floodwater inundation.

This research expands upon Alkema and Middelkoop (2005) by utilising composite hydrological indices and assessing the impacts of recreation across a range of flood events and floodplain connectivity scenarios. This provides a greater understanding in regard to the influence that the hydrological indices have on recreation ecosystem service delivery and the control of lateral connectivity necessary to limit recreation disbenefits from flood inundation.

7.3.8 **Synergy and Trade-off**

The results for ecosystem services synergy and trade-off assessment for all scenarios are displayed in Tables 7.70-7.76.

Table 7.70 50% AEP flood event ecosystem services synergy and trade-off performance matrix for floodplain connectivity scenarios

Scenario		Ecosystem service						
No.	**Description**	**Flood alleviation**	**Flood damage**	**Water Storage**	**Freshwater fish habitat**	**Terrestrial habitat**	**Agricultural productivity**	**Recreation**
S1a	No embankment (50 %AEP), no drain	1	1	1	1	1	1	1
S2a	SOP embankment (20% AEP), no drain	2	0	0	0	0	2	0
S3a	Existing embankment (10% AEP) , no drain	3	0	0	0	0	2	0
S4a	SOP embankment (4% AEP) , no drain	2	0	0	0	0	2	0

Table 7.71 20% AEP flood event ecosystem services synergy and trade-off performance matrix for floodplain connectivity scenarios

Scenario		Ecosystem service						
No.	**Description**	**Flood alleviation**	**Flood damage**	**Water Storage**	**Freshwater fish habitat**	**Terrestrial habitat**	**Agricultural productivity**	**Recreation**
S1a	No embankment (50% AEP), no drain	1	1	1	1	1	1	1
S2a	SOP embankment (20% AEP), no drain	3	2	3	3	3	3	3
S3a	Existing embankment (10% AEP) , no drain	2	3	2	2	2	2	2
S4a	SOP embankment (4% AEP) , no drain	4	0	0	4	0	4	0

Table 7.72 10% AEP flood event ecosystem services synergy and trade-off performance matrix for floodplain connectivity scenarios

Scenario		Ecosystem service						
No.	**Description**	**Flood alleviation**	**Flood damage**	**Water Storage**	**Freshwater fish habitat**	**Terrestrial habitat**	**Agricultural productivity**	**Recreation**
S1a	No embankment (50% AEP), no drain	3	1	1	1	1	1	1
S2a	SOP embankment (20% AEP), no drain	1	2	2	2	2	2	3
S3a	Existing embankment (10% AEP) , no drain	2	3	3	3	3	3	2
S4a	SOP embankment (4% AEP) , no drain	4	0	0	0	0	4	0

Table 7.73 4% AEP flood event ecosystem services synergy and trade-off performance matrix for floodplain connectivity scenarios

Scenario		Ecosystem service						
No.	**Description**	**Flood alleviation**	**Flood damage**	**Water Storage**	**Freshwater fish habitat**	**Terrestrial habitat**	**Agricultural productivity**	**Recreation**
S1a	No embankment (50% AEP), no drain	1	1	1	1	1	1	2
S2a	SOP embankment (20% AEP), no drain	2	2	3	3	3	3	3
S3a	Existing embankment (10% AEP) , no drain	3	3	2	2	2	2	1
S4a	SOP embankment (4% AEP) , no drain	4	4	4	4	4	4	4

Table 7.74 2% AEP flood event ecosystem services synergy and trade-off performance matrix for floodplain connectivity scenarios

Scenario		Ecosystem service						
No.	**Description**	**Flood alleviation**	**Flood damage**	**Water Storage**	**Freshwater fish habitat**	**Terrestrial habitat**	**Agricultural productivity**	**Recreation**
S1a	No embankment (50% AEP), no drain	4	1	2	2	1	1	2
S2a	SOP embankment (20% AEP), no drain	2	2	3	1	3	3	3
S3a	Existing embankment (10% AEP) , no drain	1	3	1	3	2	2	1
S4a	SOP embankment (4% AEP) , no drain	3	4	4	4	4	4	4

Table 7.75 1.33% AEP flood event ecosystem services synergy and trade-off performance matrix for floodplain connectivity scenarios

Scenario		Ecosystem service						
No.	**Description**	**Flood alleviation**	**Flood damage**	**Water Storage**	**Freshwater fish habitat**	**Terrestrial habitat**	**Agricultural productivity**	**Recreation**
S1a	No embankment (50% AEP), no drain	4	1	3	1	1	1	3
S2a	SOP embankment (20% AEP), no drain	3	2	2	2	3	2	4
S3a	Existing embankment (10% AEP) , no drain	2	3	1	3	2	1	1
S4a	SOP embankment (4% AEP) , no drain	1	4	4	4	4	3	2

Table 7.76 1% AEP flood event ecosystem services synergy and trade-off performance matrix for all hydrological connectivity scenarios

Scenario		**Ecosystem service**						
No.	**Description**	**Flood alleviation**	**Flood damage**	**Water Storage**	**Freshwater fish habitat**	**Terrestrial habitat**	**Agricultural productivity**	**Recreation**
S1a	No embankment (50% AEP), no drain	4	1	3	2	1	1	3
S2a	SOP embankment (20% AEP), no drain	1	3	2	1	3	2	4
S3a	Existing embankment (10% AEP) , no drain	3	2	1	3	2	1	1
S4a	SOP embankment (4% AEP) , no drain	2	4	4	4	4	3	2

Flood alleviation, water supply and freshwater fish habitat ecosystem services were defined in this research as synergy ecosystem services as flood inundation and typically, increasing lateral connectivity is necessary to provide benefits as described in Sections 7.2.6, 7.2.8 and 7.2.10. While, flood damage, terrestrial habitat, agricultural productivity and recreation ecosystem services were defined in this research as trade-off ecosystem services as flood inundation and typically increasing lateral connectivity causes disbenefits as a result of flood inundation as described in Sections 7.2.7, 7.2.9, 7.2.11 and 7.2.12.

In high frequency/low magnitude flood events (Tables 7.70-7.71), decreasing the lateral connectivity provides lower benefits and disbenefits amongst all ecosystem services. In a 50% AEP flood event, decreasing lateral connectivity provides no synergy between ecosystem services and rather trade-offs between flood alleviation and agricultural productivity. Flood inundation is beneficial in the storage of floodwaters for flood alleviation yet is not beneficial to agricultural productivity due to waterlogging. No benefit or disbenefit impacts were observed for flood damage, water supply, freshwater fish habitat, terrestrial habitat and recreation ecosystem services by decreasing the lateral connectivity since no flood inundation had occurred. Increasing lateral connectivity provided clear benefits and disbenefits with more apparent synergy and trade-off amongst ecosystem services e.g. Scenario 1a. In a 20% AEP flood event, decreasing lateral connectivity provided lower benefits and disbenefits with synergy occurring between flood alleviation, water supply and freshwater habitat and trade-offs occurring with flood damage, terrestrial habitat, agricultural productivity and recreation ecosystem services. In Scenario 4a, decreasing the lateral connectivity provides mainly no inundation/impact as flood inundation was reduced displaying trade-offs with low benefits/disbenefits observed between flood alleviation and agricultural productivity.

In mid frequency/magnitude flood events (Tables 7.72-7.73), increasing lateral connectivity displayed the same impact, synergy and trade-offs as with low frequency/high magnitude flood events. The main difference being in Scenario 4a, the embankment is raised and for a 10% AEP flood event (Table 7.72) provides synergy and low benefits between flood alleviation and agricultural productivity and no impact to flood damage, water supply, freshwater fish habitat, terrestrial habitat and recreation ecosystem services. Decreasing lateral connectivity reduces flood inundation promoting less benefits and synergy amongst ecosystem services in a 10% AEP flood event. While decreasing the lateral connectivity for Scenario 4a in the 4% AEP flood event provided greater synergy with low benefits and low disbenefits as a result of limited flood inundation.

In low frequency/high magnitude flood events (Tables 7.74-7.76), ecosystem service synergies and trade-offs are readily apparent due to high magnitude flood events causing greater flood inundation amongst all floodplain connectivity scenarios. Increasing lateral connectivity provides greater benefits and synergy between flood alleviation, water supply and freshwater fish habitat ecosystem services. While greater disbenefits and trade-offs occurred for flood damage, terrestrial habitat, agricultural productivity and recreation ecosystem services as increasing the lateral connectivity enabled greater flood inundation. Decreasing the lateral connectivity provided generally lower benefits and synergy for flood alleviation, water supply and freshwater fish habitat. While higher disbenefits and trade-offs for flood damage, terrestrial habitat, agricultural productivity and recreation ecosystem services were observed with decreasing lateral connectivity.

Considering all the flood events and floodplain connectivity scenario results, the greatest benefits and disbenefits, synergy and trade-offs are readily apparent when increasing lateral connectivity. However, decreasing lateral connectivity while still providing clear synergy and trade-offs provides lower benefits and disbenefits impacts to the ecosystem services assessed e.g. Scenario 2a and 3a in 20-4% AEP flood events. In this case, the 20 and 10% AEP SOP embankments respectively have greater potential to provide more benefits for flood alleviation, water supply, and freshwater fish habitat and less disbenefit in flood damage, terrestrial habitat, agricultural productivity and recreation ecosystem services.

8 CONCLUSIONS

The final chapter provides a summary of the research through revisiting the objectives and drawing conclusions. The structure of the chapter follows the objectives as set out in Chapter 1 discussing the fulfilment of each individual objective. Limitations of the research along with recommendations for further work as a product of the research findings are discussed.

8.1 Objectives

8.1.1 **Introduction**

The aim of this research was to develop a method to assess the delivery of ecosystem services in response to changes in floodplain connectivity and evaluate the performance. The further development of methods to estimate hydrological indicators will improve understanding of the implications of controlling the floodplain connectivity and will take the ecosystems approach forward. The product of the research will enhance decision making for policy makers and planners embracing the complete hydrological system to provide sustainable benefits to multiple stakeholders. A number of objectives were deployed as outlined in this section to meet the research aim.

8.1.2 **Case study floodplain and field study site**

A case study site was selected at Tempsford (TL15523 51624) in the UK. The case study site was defined in two ways as the case study floodplain forming the model boundary for the linked ISIS 1D-2D hydrodynamic model and the field study site forming the model boundary for the WaSim 1D water balance model. The case study site was chosen as it represented good examples of existing natural and artificial flood embankments and an extensive surface drain network as a basis for modelling floodplain connectivity. It also represented an area relying on multifunctional land use by stakeholders.

The site was characterised by a 3.4 km stretch of the River Ivel with a floodplain area of 365 ha. The dominant hydrological transfer flows were identified in order to generate a conceptual model to understand the implications of the hydrological flows at the case study site and to select an appropriate modelling system to study the impacts of floodplain connectivity on ecosystem services delivery. The case study site had natural and structural earth embankments of 10% AEP standard of protection present to include an extensive surface drain network. The hydrogeology of the site indicated an unconfined aquifer with a shallow superficial deposits layer consisting of a clay loam soil and gravels. The main ecosystem services present at the case study site were derived as flood damage e.g. protection of settlements, agricultural productivity (winter cereals and grazing of livestock) and terrestrial habitat (MG6 floodplain grazing marsh habitat).

Hydrological analysis of the field study site confirmed that the water table levels were constant. The hydraulic gradient of the water table displayed a flow moving from the dipwells away from the river. However, the hydraulic gradient between the dipwell proximate to the river was found to be potentially equal for most of the monitoring period based on the derived river stage data being within a margin of error and, as the river stage was not directly measured. For a brief period of four months, the rainfall was greater than evapotranspiration leading to infiltration and groundwater recharge where the hydraulic gradient indicated that the groundwater was flowing towards the river. The estimated seepage rate between the river and groundwater was found to be quite low with the river potentially feeding the groundwater to maintain the constant water table levels.

8.1.3 **Hydrological events and flood connectivity scenarios**

A range of hydrological events encompassing design flood events and seasonal years events were defined to study the impacts of floodplain connectivity controls on ecosystem services delivery. These events also formed the basis for boundary conditions for the respective modelling system applied. Design % AEP flood events describing high frequency/low magnitude – low frequency/high magnitude discharge hydrographs were defined from 50, 20, 10, 4, 2, 1.33 and 1% AEP representing natural to extreme events. Seasonal years representing dry, wet and average rainfall hydrological years were also selected based on the impact to the seasonal water table levels. These hydrological events were also chosen as they represented a wide range of hydrological events that may impact upon ecosystem services delivery. A range of floodplain connectivity scenarios were defined to study the impacts of hydraulic controls on ecosystem service delivery. Lateral connectivity scenarios were described by decreasing lateral connectivity e.g. raising embankments for a 50, 20, 10 and 4% AEP standard of protection and embankment crest elevations. Vertical connectivity scenarios were defined by drain spacing for a no drain, agricultural drain design (53 m), and existing surface drains (109 and 188 m) representing a range increasing hydraulic control e.g. increasing drain spacing thereby reducing water table level control.

8.1.4 **Integrated modelling system**

A sequential integrated modelling system was selected using a linked ISIS 1D-2D hydrodynamic model and WaSim: a 1D soil water balance model to represent the dominant hydrological transfer flows of the river and floodplain. This type of integrated modelling system was chosen based on the concept of parsimony where the use of the models needed to be no more complex than necessary to make sufficiently useful and accurate predictions. The linked ISIS 1D-2D model represented state of the art techniques and was independently benchmarked for model performance simulate lateral connectivity. The WaSim model was widely demonstrated as a valuable research tool for hydrological and water management studies.

The sequential integration of the model components followed a stepwise process. Initially, the design flood events and lateral connectivity scenarios were simulated in the linked ISIS 1D-2D model. The inundation depth results from the linked ISIS 1D-2D model scenario simulations were then to be integrated to the WaSim model as ponded depth. The WaSim model would then applied to simulate the seasonal and vertical connectivity scenarios. This model integration would enable the study of multiple hydrological events and floodplain connectivity scenarios to assess the impact of ecosystem services.

The linked ISIS 1D-2D model was successfully applied to simulate the design flood events and lateral connectivity scenarios. Sensitivity tests to study the impacts of raising or lowering the channel roughness and downstream boundary on critical hydrological modelled outputs indicated good model agreement. The model was parameterized as the channel roughness was surveyed and then validated against the observed river stage levels. A global channel roughness value was applied to all cross sections for the River Ivel study reach providing a perfect agreement for the modelled to observed river stage results. The model simulations generated discharge hydrographs, inundation area, volume, depth and velocity results. These results were then assessed to understand the implications of the design flood events and lateral connectivity hydraulic controls upon the hydrological regime. In high frequency/low magnitude flood events, decreasing lateral connectivity reduces flood inundation hence, lower discharge peak attenuation and translation, reduced areal flood inundation extent, lower floodwater storage, inundation depths and velocities.

However, in low frequency/high magnitude flood events, decreasing connectivity causes lower areal extent of floodwater inundation and storage, higher discharge peak attenuation and translation and lower inundation depth and velocities. Past research have modelled the impacts of either high frequency/low magnitude or low frequency/high magnitude flood events and generally single or dual lateral connectivity scenarios e.g. existing, raised or lowered embankments on flood inundation. These studies only assessed the impacts of the aforementioned flood events and hydraulic controls using a discrete and limited set of hydrological outputs. This research contributes an improved understanding of the impacts to a wider range of flood events and lateral connectivity controls upon flood inundation. Utilising multiple hydrological model outputs provides greater knowledge in order to assess the impacts of these flood events and lateral connectivity controls. The generation and utilisation of these multiple modelled outputs are also pertinent to develop hydrological indicators to assess hydrological based ecosystem services delivery.

The application of the WaSim model to simulate the seasonal year and vertical connectivity scenarios was unsuccessful due to poor calibration and validation model performance. Initially, sensitivity tests to study the impact of raising or lowering the hydraulic conductivity and drain spacing indicated poor model agreement resulting in a in lower or higher modelled water table from the initial water table levels based on standard values applied in the simulation. The seepage rate, hydraulic conductivity and drain spacing parameters were calibrated to optimize the parameters to improve the agreement of the modelled water table level to the observed water table level. Calibration and validation of these parameters were poor and were observed to underestimate the modelled to observed water table levels with the NSE results indicating that applying the mean of the observed water table values would be better than the model predictions. As a result, no seasonal year and vertical connectivity scenario were simulated.

The hydrogeological analysis of the field study site indicated that an unconfined aquifer was present. Further hydrological analysis and conceptualisation of the hydrological flows identified net rainfall, infiltration, groundwater recharge and seepage from the river channel to potentially influence the water table position. The selection of the WaSim model was considered suitable based on the hydrological data collected and the conceptualisation of the hydrological flows. It could only be hypothesised that seepage from outside of the field study site and possibly from the regional aquifer is potentially affecting the position of the water table. In this case, the sequential integration of the linked ISIS 1D-2D model and the WaSim model could not be completed.

In order to demonstrate the impacts of the design flood events and lateral connectivity scenarios upon ecosystem services delivery, a single vertical connectivity scenario was applied utilising the average observed water table level e.g. 0.53 mbgl representing a ‘no drain’ scenario. The hydrological season water table position for winter and summer were calculated and compared to the average water table position with the difference found to be negligible. The impacts of the design flood event and floodplain connectivity scenarios on the water table position were calculated by applying empirical generated mathematical equation to calculate the water table position utilising the inundation depth from the linked ISIS 1D-2D model and the average water table level.

The results indicated that in high frequency/low magnitude flood events, decreasing the lateral connectivity limits flood inundation hence impact on raising the water table level. In low frequency/high magnitude flood events, decreasing connectivity has a limited impact on reducing flood inundation, as the magnitude of the flood event is so great and the embankment crest is high, floodwaters are trapped behind the embankments leading to increased inundation depth leading to infiltration and groundwater recharge to raise the water table level.

8.1.5 **Ecosystem services assessment**

A simple, comprehensive and transparent non-monetary multi-criteria assessment method was developed considering a range of hydrological indices to provide a single composite impact performance score for each ecosystem service. This new method was based on peer-reviewed research and scientifically sound information to assess the impacts of alternative floodplain connectivity options upon ecosystem services delivery. The hydrological indicators were defined as benefit or disbenefit impacts for each ecosystem services based on peer reviewed literature. In some instances, prescribed hydrological indicator values were utilised based on peer-reviewed literature involving scoring with no normalisation as proportionality was inherent with each scenario impact,. In many cases, non-prescribed hydrological indicators were developed based on the hydrological processes and attributes with scientifically sound understanding sourced from peer-reviewed literature. These indicators were scored and normalized to Scenario 1: No Embankment floodplain connectivity as a reference for the other scenarios, which decrease in floodplain connectivity. The hydrological indicators were also based on the linked ISIS 1D-2D model outputs and derived from the field study site observed hydrological outputs and standard hydrological values based on site characteristics. The prescribed or non-prescribed hydrological indicators were individually ranked as an impact performance score for each ecosystem service. The composite hydrological indices for all ecosystem services had no weighting applied as each hydrological indicator was considered of equal importance. In addition, the composite hydrological indicators were aggregated by averaging the linear scale scores of the prescribed values and/or the normalized scores of the non-prescribed values as appropriate. Two performance matrices were designed to assess impacts of the design flood event and floodplain connectivity scenarios. A performance matrix was utilised to describe the impacts of the scenarios for each individual hydrological indicator and composite hydrological indices of an ecosystem service. Another performance matrix was utilised to describe the impacts of the scenarios upon multiple ecosystem services using the composite indices impact performance scores to assess synergy and trade-offs.

This method provided an improved understanding of the hydrological processes by which the values are formed including the necessary data required to assess alternative floodplain connectivity options to support decision making for stakeholders, policy makers and planners to support floodplain management. This method also enables greater opportunity for interpretation and transparency to communicate the impacts of floodplain connectivity on ecosystem services delivery, synergies and trade-offs.

8.1.6 **Floodplain connectivity impacts on ecosystem service delivery**

The flood alleviation results indicated that control of floodplain connectivity is crucial to enhance flood alleviation by increasing connectivity to allow greater discharge peak attenuation, translation and storage of floodwaters especially in high frequency/low magnitude flood events. Previous studies were limited to assessing the impact of flood inundation from extreme flood events and single lateral connectivity scenarios and considering single hydrological indicators. Assessing multiple flood events and lateral connectivity controls in conjunction with composite hydrological indices provides a more robust and comprehensive measure to assess the impacts of lateral connectivity to of performance to assess the impacts of flood alleviation ecosystem service.

The flood damage results indicated that increasing lateral connectivity causes greater disbenefits through greater area of flood inundation and higher flooded depths with more properties becoming flooded. Previous research was limited to the assessment of the impacts from low frequency/high magnitude flood events and either single existing or raised embankments. The use of composite hydrological indices as opposed to use of a single hydrological indicator i.e. inundation depth as applied in past research improves upon understanding to include added dimensions of impacts to the area affected and number of buildings flooded by increasing lateral connectivity. Assessing the impacts of decreasing lateral connectivity controls enhances information on the importance of the level hydraulic control required to reduce flood damage disbenefit especially considering high frequency/low magnitude flood events, which are less commonly assessed.

The water supply ecosystem service results indicated that increasing the floodplain connectivity provides a greater infiltrated volume for contribution to groundwater recharge making water available for extractive and in-situ services. Previous studies have discussed the implications of controlling the floodplain connectivity on groundwater recharge yet were limited to high and low flood event magnitudes and considering only a single existing lateral connectivity scenario. This research expands upon past research by further exploring the impacts of decreasing lateral connectivity across a wider range of flood event magnitudes. The results concluded that increasing lateral connectivity is paramount especially in high frequency/low magnitude events to improve water supply ecosystem services benefits.

The terrestrial habitat ecosystem service results indicated that increasing floodplain connectivity would cause greater disbenefits considering the existing MG6 grassland habitat present in the case study floodplain. This particular habitat prefers a drier well-drained grassland. Increasing connectivity enables greater area of inundation and raising the water table to the surface with greater inundation depths to create a wetter hydrological regime. In this instance, it is likely that grass kill and/or a change in the floristic composition may occur to form a wetter grassland habitat e.g. MG8 and MG13. Past studies have modelled the impacts of a limited range of flood events with embanked and non-embanked lateral connectivity scenarios concluding that managing the floodplain connectivity was critical to enhancing habitat conservation and restoration of terrestrial grassland habitats. This research builds upon previous studies through assessing a range of hydraulic controls of floodplain connectivity across a wider range of flood events to assess terrestrial habitat ecosystem services delivery. This foundation provides an improved basis to manage the hydrological regime to reduce terrestrial habitat loss and enhance terrestrial habitat conservation and restoration. Previous studies have also assessed the impact of flood inundation applying only the inundation depth or water table position or inundation area. The application of composite hydrological indices provides a more robust and comprehensive assessment to study the impacts of floodplain connectivity on terrestrial habitat ecosystem service delivery.

The freshwater fish habitat ecosystem service results indicated that increasing lateral connectivity provided greater benefits allowing greater flood inundation for 25 coarse fish species to migrate to the floodplain for spawning, nursery, refuge and shelter from predators as part of their lifecycle requirements. Past studies have heavily focused on observed flood events in single embanked scenarios assessing the impacts for up to 4 coarse fish species and mainly 0+ fish lifecycle stage in terms of spawning. This research reinforced that the inundation depth and velocity and their associated inundation area were amongst the most significant modelled outputs that affect habitat suitability and utilization for the coarse fish species assessed. This research also assessed the impact of decreasing lateral connectivity for the various stages of each coarse fish species lifecycle i.e. larvae, spawning, 0+, fry, juvenile and adult. The outcome of this research enhances the knowledge through modelling that increasing lateral connectivity and the level of hydraulic control is paramount especially in high frequency/low magnitude flood events to encourage fish migration to the floodplain in order to improve fish species diversity and population in river systems.

The agricultural productivity ecosystem service indicated that increasing connectivity caused greater disbenefits through greater area of flood inundation, increased flooded depths leading to a rise in the water table position. This will cause the agricultural condition to worsen for crop yield and field access for grazing and machinery use based on the drainage condition. Past studies were limited to assessing the impact of low or high magnitude flood events and an existing or a single raised embankment lateral connectivity scenario. Modelling a wide range of design flood events with decreasing lateral connectivity generates new information on the level of hydraulic control required as a result of the design flood events to reduce agricultural productivity disbenefits. Managing lateral connectivity is especially important considering high frequency/low magnitude flood events. Past research has commonly assessed the impacts of flood events and lateral connectivity using either inundation depth or the water table position independently. The application of composite hydrological indices to include both the inundation depth, water table potion and the inundation area provides a more robust measurement of the impacts of flood events and lateral connectivity to enable agricultural productivity ecosystem service delivery.

The recreation ecosystem services results indicated that increasing lateral connectivity causes more disbenefits by reducing land access for dry land based recreation activities. The disbenefit was the result of greater areal extent of floodwater inundation and an increase in flooded depths. Past studies have considered only the inundation depth as an indicator for recreation ecosystem service delivery for extreme flood events and existing embanked scenarios. The addition of the inundation area as part of the composite hydrological indices provides an added dimension to form a more robust assessment of design flood events and lateral connectivity on recreation ecosystem service delivery. Assessing the impacts of decreasing lateral connectivity presents new knowledge on the level hydraulic control required to reduce recreation ecosystem service disbenefits especially considering high frequency/low magnitude flood events.

8.1.7 **Synergy and trade-offs**

The ecosystem services were assessed for their potential for synergy or trade-offs under the design flood event and lateral connectivity scenarios. A performance matrix was applied for each design flood event to include decreasing lateral connectivity and include the fixed vertical connectivity scenario to assess the impact performance of each scenario for each ecosystem service. The ecosystem services were described as a benefit or disbenefit impact type based on their preferred hydrological process to describe their initial potential for synergy and trade-offs. Flood alleviation, water supply and freshwater fish habitat were defined as benefit and synergy ecosystem services as they require flood inundation and increasing floodplain connectivity by lowering embankments. Flood damage, terrestrial habitat, agricultural productivity and recreation were defined as disbenefit and trade-off ecosystem services as flood inundation and increasing the floodplain connectivity would have a negative impact on these services.

In general, increasing lateral connectivity provides more disbenefits and trade-offs for all the ecosystem services assessed. However, decreasing lateral connectivity indicated clear synergies between flood alleviation, water supply and freshwater fish habitat and trade-offs between flood damage, terrestrial habitat, agricultural productivity and recreation ecosystem services provided. Although, lower benefits and disbenefits impacts were observed with decreasing lateral connectivity for Scenarios 2a and 3a in 20 and 4% AEP flood events. It was deduced that the 20 and 10% AEP SoP embankments of Scenarios 2a and 3a respectively have greater potential to provide more benefits for flood alleviation, water supply, and freshwater fish habitat and less disbenefit in flood damage, terrestrial habitat, agricultural productivity and recreation ecosystem services.

8.1.8 **Concluding remarks**

Several studies have discussed the impacts of floodplain connectivity on ecosystem services delivery as identified. There was considerable scope to improve the understanding of the hydrological processes and further develop hydrological indicators to estimate the impact of floodplain connectivity upon ecosystem services delivery.

Previous studies and this research have demonstrated the potential of integrated modelling as a useful tool to provide safe and reliable information to enable decision making across a wide variety of stakeholders. The application of integrated models has still yet to be fully harnessed as research has heavily relied on individual model components rather than integrated models to represent the hydrosystem and pertinent hydrological flows and feedback mechanisms. This research developed a method to apply an integrated modelling system to generate the hydrological data sets to develop hydrological based ecosystem service indicators. While the sequential integration was unsuccessful, this research demonstrated the application of the fully integrated linked ISIS 1D-2D model and an empirical method to simulate a number of hydrological outputs e.g. discharge peak attenuation and translation; inundation area, volume, depth and velocity; and the water table position. The generation of these hydrological outputs are essential in order to provide a complete understanding of the impact of natural to extreme flood events and decreasing floodplain connectivity hydraulic controls upon the hydrological regime in a floodplain. The methods described were pertinent in order to assess the impacts of floodplain connectivity on ecosystem services delivery.

The common theme of past research mainly treated the assessment of ecosystem services independently which is not consistent with the ecosystems approach considering the concept of multifunctionality to provide a more resilient and sustainable use of floodplains (UKNEA, 2011). Assessing the impacts to ecosystem services by applying hydrological based indicators were largely associated with production and regulation ecosystem functions from the development of well-established methods and data sets (Posthumus et al., 2010). While assessment of hydrological indicators for habitat and information ecosystem functions has proved more challenging and suffered from limited understanding of the processes and limited research.

The development of a simple non-monetary MCA method utilising composite hydrological indices provides a more robust and comprehensive platform to assess the impact of floodplain connectivity on ecosystem services delivery. It also improves understanding of the hydrological processes, attributes and indicators that may have an impact on ecosystem service delivery. The application of a performance matrix provided an efficient, clear and easy way of assessing and communicating the impacts of floodplain connectivity.

Kazama et al. (2007) discussed that floodplain connectivity must be carefully planned in order to deliver the desired level of ecosystem services benefits and synergies as required by policy, legislation and stakeholders. The outcome of this research provides a clear understanding of the implications of increasing or decreasing floodplain connectivity on ecosystem services delivery. Synergy and trade-offs will always be present due to the opposing benefits and disbenefits of flood inundation for each specific ecosystem service. Although, managing and controlling the level of connectivity is critical to providing a higher level of benefits and lower level of disbenefits to enable more sustainable use of the floodplain while promoting multi-functional land use. Developing methods to model floodplain connectivity controls alongside new estimates for hydrological based ecosystem service indicators and assessment has taken the ecosystem approach forward to support decision making for policy makers, planners and stakeholders.

8.2 Limitations

The following section discusses the limitations of the research in regard to the application of the integrated modelling system applied, the model results and the ecosystem services assessment.

The assessment of levelogger drift could not be effectively conducted in order to establish a positive, negative or random trend due to the limited spot manual measurements taken throughout the monitoring period. The assessment of the levelogger accuracy revealed that the readings were outside of operating limits when comparing manual measurements. The difference in the water levels and the range of variation was likely to be a product of the non-steady variation in atmospheric pressure recorded. The mean absolute error of the observed water table level was calculated as ± 0.1 m. Further assessment of this error concluded marginally impacts to raising or lowering the benefit or disbenefit impacts specific 50 and 20% AEP design flood events in terms of increasing lateral connectivity. This impact would affect flood damage, water storage terrestrial habitat, agricultural productivity and recreation ecosystem services which utilise the water table position hydrological output as part of inundation depth, infiltrated volume and water table position hydrological indicators. There was no impact for this error observed in regard to the application of the composite hydrological indices ecosystem services results.

The calibration and validation of the WaSim model was poor during with the results indicating that the modelled water table levels were underestimated in comparison to the observed water table levels. It was hypothesized that potentially seepage from outside of the field study site and possibly from the regional aquifer is affecting the water table position. The selection of the WaSim model was considered suitable based on the hydrological data collected and the conceptualisation of the hydrological flows. However, WaSim cannot account for groundwater discharge in the aquifer as it is a 1D soil water balance model only capable of modelling groundwater recharge from precipitation, lateral seepage and drain flow. As a result, the impacts of the hydrological seasonal year events and vertical connectivity scenarios could not be simulated. Therefore a range of decreasing lateral connectivity scenarios and a single ‘no drain’ vertical connectivity scenario was applied to demonstrate the impact to ecosystem services delivery, synergy and trade-offs.

Based on past research, vertical connectivity control in terms of seasonal water table positions is an important dynamic for water storage, agricultural productivity, terrestrial and freshwater fisheries habitat ecosystem services. In terms of water storage, floodplain connectivity to control flood inundation is critical during the dry season that may impact on groundwater storage and recharge to provide water as a resource to fulfil consumption requirements (Kazama et al., 2007). Seasonal impacts of controlling floodplain connectivity are critical in the dry season for field access for machinery, grazing of livestock and the crop-growing season (Smedema et al., 2004). Managing floodplain connectivity in the growing season for grassland terrestrial habitats is critical considering the water table position and the ponding duration as flood inundation may cause waterlogging. This may lead to grass kill or change in floristic species community, which is detrimental to the existing grassland at the case study floodplain but may be more beneficial to wetter grassland habitats (Wheeler et al., 2004). Understanding the impacts of floodplain connectivity in the dry season is especially important in regard to spawning and feeding respectively to boost fish populations and diversity (Cowx et al., 2004, Table D.1).

It was not possible to effectively calculate the ponding duration for the terrestrial habitat, agricultural productivity and recreation ecosystem services based on the existing field site characteristics. The field study site had a clay loam soil with low drainable porosity, low infiltration rate and a high water table level (0.53 mbgl). In this case, the potential infiltrated depth of inundated floodwaters was 0.1 m with a ponding duration of 0.42 days. For all scenarios the inundation depth was >0.1 m remaining on the floodplain were flooding occurred through increasing lateral connectivity. Further information on the drainage rate of the ponded water off the site through surface drains for example would be required. In this case the ponding duration was not included as part of composite hydrological indicator score for the terrestrial habitat, agricultural productivity and recreation ecosystem services.

The linked ISIS 1D-2D model results were extracted and processed for the total flood inundation extent for each scenario as the topography was considered homogenous based on the elevation and slope of the case study floodplain. Floodwater inundation maps were generated to display the inundation depths as per flooded areal extent for each lateral connectivity scenario. It was observed from the results that specific areas within the case study floodplain are subject to greater inundation depths. The results of the lateral connectivity scenarios indicated that inundation depths can reach up to 1.8 m in specific areas of low depression across the case study floodplain. To assess the impacts of floodplain connectivity scenarios on ecosystem services delivery, the average inundation depth was calculated over the total inundation area/extent for each scenario. Utilizing the average inundation depth masks the level of benefit or disbenefit impact to specific areas in the case study floodplain. Where greater inundation depths occurred, it is hypothesized that flood damage, terrestrial habitat, agricultural productivity and recreation ecosystem services would be subject to an increase or decrease in the level of benefits or disbenefits impacts.

The inundation depth and inundation velocity results were extracted for the inundation area of each floodplain connectivity scenario independently. The performance of each hydrological indicator for freshwater fish lifecycle hydrological requirements were based on the inundation area falling under each independent inundation depth and velocity range. It is not possible to extract the inundation velocity for each inundation depth which is essential to describe the impact of floodplain connectivity on freshwater fish ecosystem service. The results in this instance are indicative of the impact of floodplain connectivity but subject to uncertainty.

8.3 Further work

The following section provides recommendations for future work as a result of conducting this research.

8.3.1 **Water table measurement accuracy**

To establish the trend of instrument drift over time would involve taking a higher frequency of manual measurements at a case study site. Where a positive or negative trend of instrument drift can be established, appropriate measures can be taken to calibrate leveloggers at key times during a monitoring period to ensure accurate readings of the water table level. The accuracy of water table measurements is critical not only for application to integrated models but also for the assessment of ecosystem services delivery, synergy and trade-offs.

8.3.2 **Integrated models**

Further research would benefit from the integration of a vertical connectivity model to simulate the seasonal year events and vertical connectivity scenarios in combination with design flood events and lateral connectivity scenarios. This will improve the assessment of the impact of floodplain connectivity on ecosystem services delivery especially in regard to connectivity control strategies and combinations. This will also enable decision makers, planners and stakeholders to consider multiple floodplain connectivity options to manage multiple ecosystem services delivery as required.

A sequential integrated modelling system could be applied utilising a fully integrated linked 1D-2D hydrodynamic model to simulate a range of design flood events and lateral connectivity scenarios. The integration of the vertical connectivity model could be applied as described in this research. The impacts of the seasonal year and vertical connectivity scenarios could be simulated using agrohydrological models. For example, WaSim could be applied in the instance where vertical seepage from the aquifer is not a required flow or DRAINMOD could be applied were vertical seepage from the aquifer is a required flow as derived through conceptualising the hydrological transfer flows in the floodplain. The integration of both models would improve understanding for the impacts of the hydrological events and floodplain connectivity hydraulic controls o the hydrological regime. This would provide a more comprehensive assessment to study the impacts upon ecosystem services delivery, synergy and trade-offs.

Another option for further study would be to model the hydrological events and floodplain connectivity scenarios as described in this research using a full integrated model. The model would provide a single interface and could effectively model a wider array of crucial hydrological water transfer, exchange and feedback flows in the surface and subsurface hydrological systems e.g. MIKE SHE.

The impact of controlling floodplain connectivity upon terrestrial habitat and agricultural productivity ecosystem services can be variable over time. The water table position is a key indicator in this context as it is normally subject to diurnal, monthly or seasonal variation in response to climate and site characteristics. It is recommended that further studies to assess the impact of floodplain connectivity should simulate continuous events for the vertical connectivity models based on the seasonal years as originally intended for application by this research. This research applied a fixed water table position of 0.53 mbgl for a single 'no drain' vertical connectivity scenario. It was concluded through hydrological analysis that this water table level was quite constant with no seasonal variation for the field study site. It is possible that in other case study sites that the water table level may be dynamic. Utilizing a long duration event to encompass days and months and seasons to assess the response of flood inundation upon the water table position may yield higher or lower benefits in particular to habitat and agricultural productivity ecosystem services. The duration of the water table position is a critical component for the delivery of these services especially over longer periods. In regard to agricultural productivity, the water table position over time is critical for crop yield especially during the growing season, and land use for the grazing season and field access for machinery (Smedena et al., 2004). In regard to terrestrial habitat, the water table position over time is critical considering water table regime requirements especially with regard to seasons for habitat conservation. Where the water table position is outside of tolerable limits over longer periods of time, the existing grassland community may be subject to ecological succession to form a drier or wetter grassland community (Wheeler et al., 2004). The impact of floodplain connectivity is critical especially for the conservation of floodplain habitats considering the current trends (UKNEA, 2011).

8.3.3 **Flood inundation extent and depth application for ecosystem services assessment**

It was observed from the flood inundation extent and depth results that specific areas in the case study floodplain may be subjected to greater inundation depths with the potential to impact on ecosystem services delivery. This research recommends to compartmentalise the linked ISIS 1D-2D model results for specific areas of the flood inundation extent based on inundation depths. This research hypothesises that compartmentalisation of the linked ISIS 1D-2D model results will enable an improved assessment for specifically flood damage, terrestrial habitat, agricultural productivity and recreation ecosystem services. In regard to flood damage, specific areas may be critical to assess impacts to flood damage to existing properties/ infrastructure and inventory items and to assess planning and development options. It could also highlight areas in the floodplain that may have reduced potential for agricultural productivity e.g. crop of pasture types of farming. This may give the landowner opportunity to landscape the land as appropriate to reduce depressions in the land to reduce ponding and improve runoff and drainage. It may enhance the conservation and restoration of managed grasslands through identifying areas for example are that subject to waterlogging with potential to cause an unwanted change to the grassland community composition. Compartmentalisation of the model results could prove critical to enhance the use of the floodplain by freshwater fish. This will not only to identify specific areas that will provide the optimum hydrological lifecycle requirements for each or multiple fish species but also to identify and locate drainage paths where the fish will migrate to the floodplain and return to the rivers. The lack of drainage paths or low depressions in the floodplain and embankments may lead to loss of fish species due to isolation in pools on the floodplain after the floodwater has receded and predation from piscivores.

8.3.4 **Site characteristics**

This research considered local scale hydrological conditions and physical site characteristics to demonstrate a method to assess the delivery of ecosystem services in response to changes in floodplain connectivity and evaluate their performance. In addition, this research was presented in consideration of floodplain connectivity at local scale to enable decision support for local stakeholders. The research outcome elicited that certain physical site characteristics can influence the impact of ecosystem services delivery.

It was hypothesized that the results may vary according to other local conditions and sites due to the complex interrelationships of hydrological conditions and physical site characteristics. The influence of hydrological flows and their impact on ecosystem service delivery can occur through a number of site characteristics e.g. climate and spatial variation, floodplain shape and topography, soil type and hydrogeology, connectivity, material cover and land use, geographic position within catchment and spatial scale (Gilvear, 2012; Mulligan, 2004). It is recommended that the application of the integrated model design should be applied to contrasting case study floodplains with different physical site characteristics to assess the impacts of floodplain connectivity on ecosystem services delivery synergy and trade-off.

The climate characteristics e.g. precipitation and evapotranspiration will determine the spatial distribution of these contributions in a catchment and from areas within a catchment. At the field study site, the hydrological analysis of the net rainfall observed in general that the evapotranspiration was greater than the rainfall. While fluctuations in rainfall and evapotranspiration were present, the field study site was characteristic of drier climate lending a low influence to infiltration from rainfall, seepage from the river for groundwater recharge to influence the water table position. The presence, absence and intensity of rainfall can have an impact on pluvial, fluvial and groundwater flooding thus influencing ecosystem services delivery. These dynamics can impact on the hydrological regime with the potential to cause a higher level of disbenefits for flood damage, agricultural productivity, terrestrial habitat and recreation ecosystem services. The absence of rainfall or the increase in evapotranspiration could lead to drier conditions thus lowering the water table causing disbenefits to terrestrial habitat and agricultural productivity. The lack of rainfall would limit the potential for flooding thus inhibiting overbank flow and lateral migration of fish species for spawning, nursery, refuge and feeding as part of lifecycle requirements.

The shape and topography of the floodplain can have an impact on multiple ecosystem services and their associated hydrological processes. The case study floodplain topography was quite homogenous with a slight concave shape. In general, this caused flood inundation to spread across a wider area in the floodplain with generally shallower flood depths. It was observed in some instances that higher flooded depths were encountered across the case study floodplain due to the presence of lakes or areas of low depression. The shallow concave shape did promote greater flood storage and increased inundation depths in these areas. It is hypothesised that a heterogeneous topography may cause a change in the level of benefit and disbenefit in particular to flood damage, agricultural productivity, terrestrial habitat and recreation ecosystem service delivery largely due to the inundation area and depth in specific areas of the floodplain.

The soil type and hydrogeology of a site may influence the infiltration and groundwater recharge hence position of the water table due to the hydraulic conductivity and permeability of the materials present in the ground surface, unsaturated and saturated zones. The soil type is pertinent in regard to infiltration rates thus affecting the ponding duration. The field study site had a clay loam soil with a lower infiltration rate. The hydrogeology of the field study site identified in general as river alluvium superficial deposits and a shallow confining layer of Oxford Clay (mudstone). The hydrological transfer flows based on the materials indicate slow infiltration of water due to the depth of clay loam and of high permeability due to the presence of gravels mainly from seepage from the river. A high water table was observed due to these site characteristics and hydrological analysis. Materials of higher permeability may promote greater infiltration and groundwater recharge of the water table reducing the inundation depth, removing water from the floodplain and encouraging land access. This may increase benefits for flood alleviation, water storage, agricultural productivity, terrestrial habitat and recreation and reduce disbenefits for flood damage ecosystem services. The level of disbenefit would increase for freshwater fish habitat as the inundation depth would be reduced possibly affecting a number of fish species in terms of water depth requirements. While these materials may also increase the potential for groundwater flooding thus raising the water table and increasing the ponding duration this causing a greater level of disbenefit to agricultural productivity, terrestrial habitat and recreation ecosystem services.

Lateral and vertical connectivity types and geometry can impact on the delivery of ecosystem services and alter the dynamics of synergy and trade-offs amongst ecosystem services. In this research, the lateral connectivity was altered by varying the embankment crest levels to decrease connectivity between the river and floodplain by raising the embankment from floodplain level from 50% to 4% AEP SoP. It is plausible to continue to decrease connectivity by modelling the impact of raising the embankment for 2 and 1 % AEP SoP. MAFF (1999) indicates that these particular standards of protection would be pertinent specifically for the following ecosystem services:

1. Flood damage: typically intensively urban areas at risk from flooding.
2. Agricultural productivity: Some high grade agricultural land requiring protection.
3. Terrestrial habitat: some environmental assets of international importance requiring protection.

Modelling lateral connectivity with a 2 and 1% AEP embankment crest levels will provide synergy for flood damage, agricultural productivity and recreation ecosystem services. While, trade-offs for flood alleviation, water storage and terrestrial habitat, freshwater fish habitat may be more apparent.

This research applied specific types of hydraulic control, which can be described by Morris et al. (2004) as follows:

- Uncontrolled inflow and uncontrolled gravity return flow e.g. Scenario 1 as the river embankment as at the same level of the floodplain.
- Fixed controlled inflow and fixed controlled gravity return flow e.g. Scenario 2 – 4 as the river embankment is engineered to a design flood event threshold stage. Overtopping of floodwater only occurs when the design stage has been exceeded and the return flow is either retained by embankments or remaining water may find another route to the river channel downstream at lower points in the embankment.

Another option for further study would be to explore the concept of time gated operations and variable controlled inflow and outflow and as discussed in Förster et al. (2008) and Morris et al. (2004). The will involve the application of a single or series of time gate control structure(s) in the lateral connectivity model and include the modelling of controlled gate operation timing strategies. Förster et al. (2008) studied the application of controlled gate operation and strategies in regard to flood alleviation and found that in large floods, controlled gate operations can significantly reduce peak discharges although the magnitude of flood attenuation is dependent on the hydrograph shape and well time gated operation control strategies.

Morris et al. (2004) classified how water can flow into and out of a washland i.e. floodplains and generating a hydraulic matrix with nine levels of hydraulic control with the potential for multiple combinations. A number of English and European washland case studies were reported based on this hydraulic matrix and variations in the degree of hydraulic control. The common ecosystem services assessed and delivered in these studies were specific to flood alleviation, flood defence, terrestrial habitat and agricultural productivity. Further study would benefit from applying this hydraulic matrix and different combinations of flow controls to the integrated model not only to assess the impact of each individual ecosystem service as described in this study but also to study the impact on synergy and trade-offs between these ecosystem services.

In this research, only a single vertical connectivity scenario i.e. Scenario a: no drain was applied. Although, three other scenarios were defined for integrated modelling based on the removal of water from the land surface and water table control for land management practises. The modelling of these configurations for surface drainage could be addressed through use of an alternative model.

Van der Molen et al. (2007) described two surface drains characteristics involving their shape and cross section mainly based on the potential impact to agricultural productivity. The width of the surface drain may impact on the capacity to transport drainage water off site thus reducing floodwater inundation depth and may also temporarily store floodwater to diminish peak outflows from the floodplain. While the design of surface drains are usually trapezoidal, V-shaped drains usually small may also be present and applied at sites. The shape and dimension of surface drains are design based for the expected runoff, open water storage requirements, machinery access, risk of bank erosion and maintenance considerations. Further work could involve modelling the impact of surface drains considering their cross section and shape to study the impact on individual ecosystem services and synergy and trade-offs.

The field study site had surface drains present mainly to control runoff for flood defence, agricultural productivity and terrestrial habitat ecosystem services. Further work could include the modelling of subsurface drainage, which may be the potential drainage and choice of system applied in floodplains. Although, these drains are applied specifically to control the water table position by removal of water from a field through water movement within the soil profile to underground drainage network or an open ditch (Morris et al., 2005). Modelling drainage systems in either mode will further investigate the impacts upon ecosystem services delivery, synergy and trade-offs in regard to the level of water table control. The soil properties e.g. hydraulic conductivity and drainage spacing will continue to act as key parameters of water table control (Youngs et al., 1989).

The material cover e.g. trees and/or concrete and land-use type with their associated spatial variation will have multiple influences on the hydrological flows in the floodplain. They can also impact on the infiltration from rainfall or inundated floodwater thus increasing or decreasing the floodwater inundation depth or contributing to groundwater recharge hence a rise or drop in the water table. These hydrological flows may impact on flood damage, water storage, terrestrial habitat, agricultural productivity and recreation ecosystem services. The material cover may lead to a reduction or increase in floodwater inundation velocity and the spatial variation in the areas of floodwater inundation respectively. In terms of velocity, this may impact on freshwater fish habitat thus enhancing or reducing benefits based on freshwater fish species lifecycle water depth and velocity requirements (Cowx et al., 2004). The change of spatial variation from floodwater inundation as a result of changes to inundation velocity will more prominently impact on terrestrial habitat e.g. wetter and drier habitat mosaics and flood damage e.g. spatial location of properties affecting by flooding and their level of damage.

The case study floodplain was located in the lowland area of the Lower Bedford Ouse sub-catchment within the Great River Ouse Catchment. This geographic position within the catchment i.e. lowland is generally representative of slower and prolonged or subdued water level change and smaller flood peaks due to the stable morphology of the river channel and flatter topography hence lower runoff rates. Further analysis of the river slope of the River Ivel study reach also confirmed a low slope hence lower runoff and discharge rates. In contrast, upland areas of a catchment are generally steep with dynamic river morphology and subjected to rapid rates of runoff hence water level change and flashy flood peaks. Further work would benefit from applying an integrated model in upland areas to investigate the impact of hydrological connectivity on ecosystem services delivery in these areas to test the robustness of the methodology applied.

Ecosystem services delivery is dependent on a number of hydrological processes, which can take place over a range of spatial scales (Hein et al., 2006). This research was performed over a reach scale to demonstrate the performance of the methodology considering a case study site representing opportunities to study the existing and alternative floodplain connectivity options for floodplain management to enhance ecosystem service delivery. Hein et al. (2006) inferred that stakeholders at different spatial scales present very different interests for ecosystem service delivery. There is a need to analyse spatial heterogeneity and its consequence on ecosystem service delivery, synergy and trade-offs. To meet stakeholder needs, European directives, and national policies and legislation; Defra and the Environment Agency draw up long term strategic Catchment Flood Management Plans. It is recommended to apply an integrated model to catchment scale. This could function to assist in identifying potential sites for ecosystem service delivery and search for synergy amongst ecosystem services recognising that different sites may have the potential to serve different stakeholder needs (Morris et al., 2005). Initially, a pilot catchment could be modelled and assessed with the eventual further study of catchments of contrasting site characteristics e.g. drainage area, drainage density (river, tributaries and surface drain network), catchment length and slope, soil and hydrogeology and hydrological connectivity which will influence the hydrological regime and thus ecosystem services delivery.

8.3.5 **Flood event hydrograph**

One of the primary objectives of this research was to simulate the impacts of the hydrological regime under hydrological events. The UK’s rural landscape has undergone continuous land use change in response to climatic and socioeconomic factors (O’Connell et al., 2011). Water supply to rivers and floodplains can vary with time and space throughout the catchment based on channel and floodplain morphology and daily and seasonal climatic variations (Bridge, 2002). Hall and Penning-Rowsell (2011) discussed that there has been a growing concern on the impact of climate change on flood frequency and magnitude.

This research investigated the impact of a range of single flood peak hypothetical design flood events of specific flood magnitudes with a standard instantaneous unit hydrograph shape generated using ReFH methods. Further study to simulate a range of hydrograph shapes and multiple discharge peaks would enhance the understanding of the impacts to multiple ecosystem services delivery. The site characteristics of the River Ivel based on the longitudinal profile and slope indicated that the hydrograph shape had a slower prolonged response in terms of river discharge. Gordon et al. (2004) and Bridge (2002) described that the shape of a hydrograph in general can be either sharp-peaked or broad. This shape is a function of rainfall intensity over time and based on the relative quantity of overland and groundwater flow as determined by land use, drainage density, floodplain slope, vegetation, soil type, geology and antecedent conditions. O'Connell et al. (2011) discussed that multiple hydrograph peaks and the magnitude of the peaks will largely be in response two main factors as follows:

1. The volume, timing and runoff in regard to the landscape elements delivered into the channel networks to include surface drains and the river
2. The extent of the timings of the peaks for tributary hydrographs and surface drains and their outlet will phase in or out with the river hydrograph or with each other

These hydrological dynamics may influence the surface and groundwater hydrological regime causing benefits and/or disbenefits, synergies or tradeoffs in ecosystem services delivery.

Förster et al. (2008) had applied a range of hydrograph scenarios based on actual discharge records for extreme flood event incorporating wide and steep hydrographs representative of steep of flashy e.g. rapid response and wide e.g. slow prolonged response discharge. Two or multiple peaked hydrographs were applied based on discharge records for extreme flood events. The research was limited to time gate operations to control floodplain connectivity mainly for attenuation and storage of the flood hydrograph i.e. flood alleviation. The outcome confirmed that the magnitude of attenuation will depend on the steepness of a flood hydrograph and as a function of the applied floodplain connectivity strategy and time gate operation. The study serves as a perfect example to consider further studies to assess the impacts of various hydrograph shapes and two or multiple peak flood events in conjunction with decreasing floodplain connectivity scenarios upon multiple ecosystem services, synergies and tradeoffs.

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APPENDICES

Appendix A Temporary benchmark

Table B.1.1 Level surveying booking readings for the temporary benchmark at the field study site

Back sight (m)	Intermediate (m)	Foresight (m)	Rise (m)	Fall (m)	Reduced Level (mAOD)	Remarks
1.096					19.534	Local Temporary Benchmark
	2.318			1.222	**18.312**	TEM 1
	2.887			1.791	**17.743**	TEM 2
		2.388		1.292	18.242	
1.592						
		1.708		0.116	18.126	
1.349						
		1.566		0.217	**17.909**	TEM 3

Table B.1.2 Level surveying reduced readings for the temporary benchmark at the field study site

Back sight (m)	Intermediate (m)	Foresight (m)	Rise (m)	Fall (m)	Reduced Level (mAOD)	Remarks
1.566					17.909	TEM 3
		1.182	0.324		18.293	
1.429						
		0.839	0.59		18.883	
1.697						
		1.044	0.653		19.536	Local Temporary Benchmark

Appendix B Hydrological events

B.1 FEH CD-ROM 3 catchment descriptors

Table B.1.1 Catchment descriptors

Revitalised FSR/FEH rainfall runoff method

Spreadsheet application version 1.3

Catchment sheet

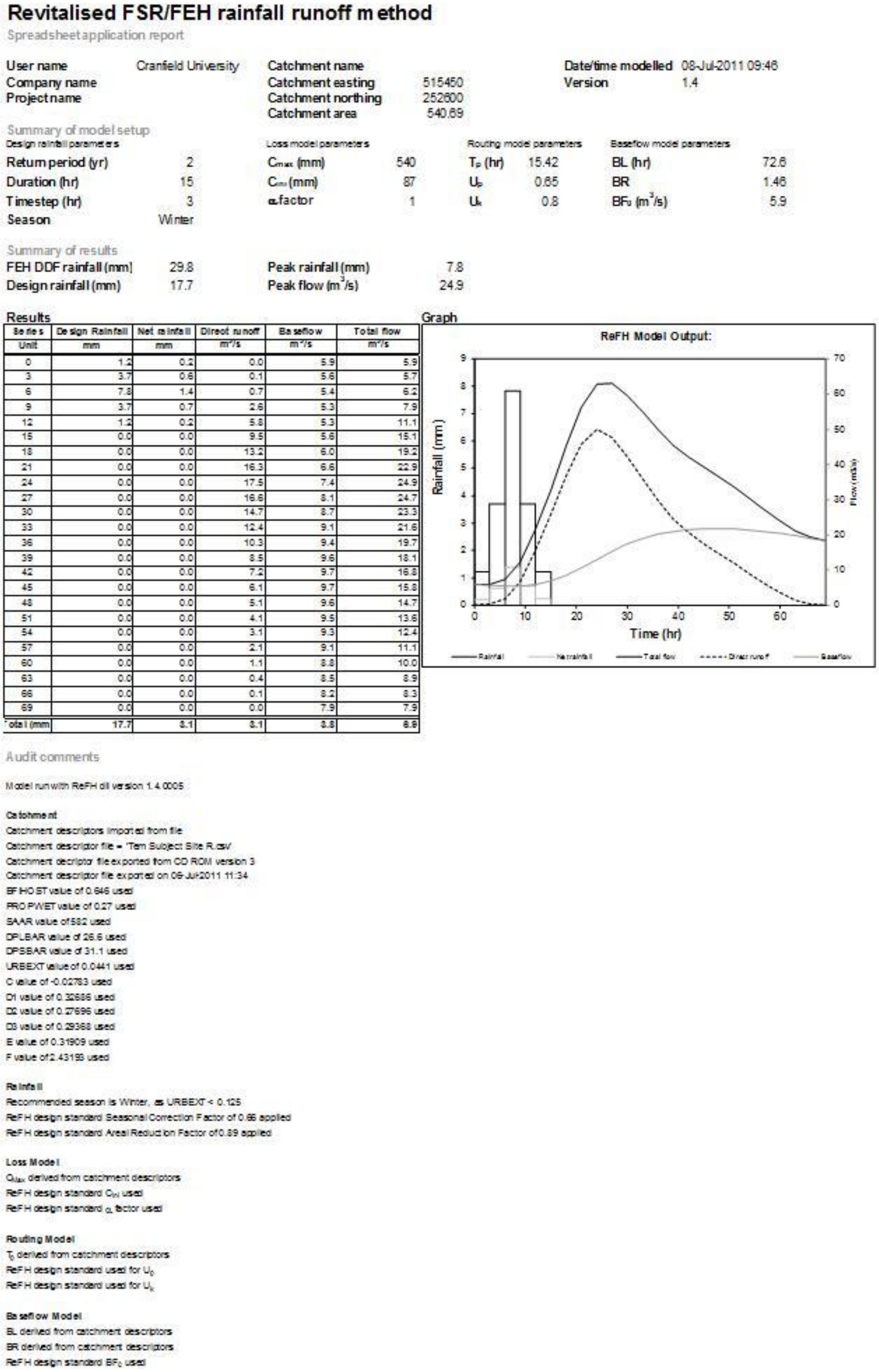
Catchment name: Tempsford

Catchment Descriptors (Descriptors in bold are used within model)

FEH CD ROM version	3	Exported on	06-Jul-2011 11:34
Easting	515450	Northing	252600
Area	540.69		
FARL	0.98	RMED-1H	10.6
PROPWET	0.27	RMED-1D	29.9
ALTBAR	73	RMED-2D	36.9
ASPBAR	22	**SAAR**	582
ASPVAR	0.15	SAAR4170	586
BFIHOST	0.646	SPRHOST	30.21
DPLBAR	26.6	URBCONC	0
DPSBAR	31.1	**URBEXT1990**	0.0441
LDP	45.04	URBLOC	0
C	-0.0278	C(1km)	-0.024
D1	0.3269	D1(1km)	0.32
D2	0.277	D2(1km)	0.217
D3	0.2937	D3(1km)	0.239
E	0.3191	E(1km)	0.306
F	2.4319	F(1km)	2.514

B.2 ReFH Model flood event summary setup and results

Table B.2.1 ReFH model, 50% AEP model run parameters and results



Revitalised FSR/FEH rainfall runoff method

Spreadsheet application report

User name	Cranfield University	Catchment name		Date/time modelled	08-Jul-2011 09:46
Company name		Catchment easting	515450	Version	1.4
Project name		Catchment northing	252600		
		Catchment area	540.69		

Summary of model setup

Design rainfall parameters		Loss model parameters		Routing model parameters		Baseflow model parameters	
Return period (yr)	2	C_{max} (mm)	540	T_p (hr)	15.42	BL (hr)	72.6
Duration (hr)	15	C_{ini} (mm)	87	U_p	0.65	BR	1.46
Timestep (hr)	3	α factor	1	U_k	0.8	BF_0 (m^3/s)	5.9
Season	Winter						

Summary of results

FEH DDF rainfall (mm)	29.8	Peak rainfall (mm)	7.8
Design rainfall (mm)	17.7	Peak flow (m^3/s)	24.9

Results

Series	Design Rainfall	Net rainfall	Direct runoff	Baseflow	Total flow
Unit	mm	mm	m^3/s	m^3/s	m^3/s
0	1.2	0.2	0.0	5.9	5.9
3	3.7	0.6	0.1	5.6	5.7
6	7.8	1.4	0.7	5.4	6.2
9	3.7	0.7	2.6	5.3	7.9
12	1.2	0.2	5.8	5.3	11.1
15	0.0	0.0	9.5	5.6	15.1
18	0.0	0.0	13.2	6.0	19.2
21	0.0	0.0	16.3	6.6	22.9
24	0.0	0.0	17.5	7.4	24.9
27	0.0	0.0	16.6	8.1	24.7
30	0.0	0.0	14.7	8.7	23.3
33	0.0	0.0	12.4	9.1	21.6
36	0.0	0.0	10.3	9.4	19.7
39	0.0	0.0	8.5	9.6	18.1
42	0.0	0.0	7.2	9.7	16.8
45	0.0	0.0	6.1	9.7	15.8
48	0.0	0.0	5.1	9.6	14.7
51	0.0	0.0	4.1	9.5	13.6
54	0.0	0.0	3.1	9.3	12.4
57	0.0	0.0	2.1	9.1	11.1
60	0.0	0.0	1.1	8.8	10.0
63	0.0	0.0	0.4	8.5	8.9
66	0.0	0.0	0.1	8.2	8.3
69	0.0	0.0	0.0	7.9	7.9
otal (mm	17.7	8.1	8.1	3.8	8.8

Graph

Audit comments

Model run with ReFH dll version 1.4.0005

Catchment

Catchment descriptors imported from file

Catchment descriptor file = 'Tem Subject Site R.csv'

Catchment decriptor file exported from CD ROM version 3

Catchment descriptor file exported on 06-Jul-2011 11:34

BFIHOST value of 0.646 used

PROPWET value of 0.27 used

SAAR value of 582 used

DPLBAR value of 26.6 used

DPSBAR value of 31.1 used

URBEXT value of 0.0441 used

C value of -0.02783 used

D1 value of 0.32686 used

D2 value of 0.27696 used

D3 value of 0.29368 used

E value of 0.31909 used

F value of 2.43193 used

Rainfall

Recommended season is Winter, as URBEXT < 0.125

ReFH design standard Seasonal Correction Factor of 0.66 applied

ReFH design standard Areal Reduction Factor of 0.89 applied

Loss Model

C_{Max} derived from catchment descriptors

ReFH design standard C_{ini} used

ReFH design standard α factor used

Routing Model

T_p derived from catchment descriptors

ReFH design standard used for U_p

ReFH design standard used for U_k

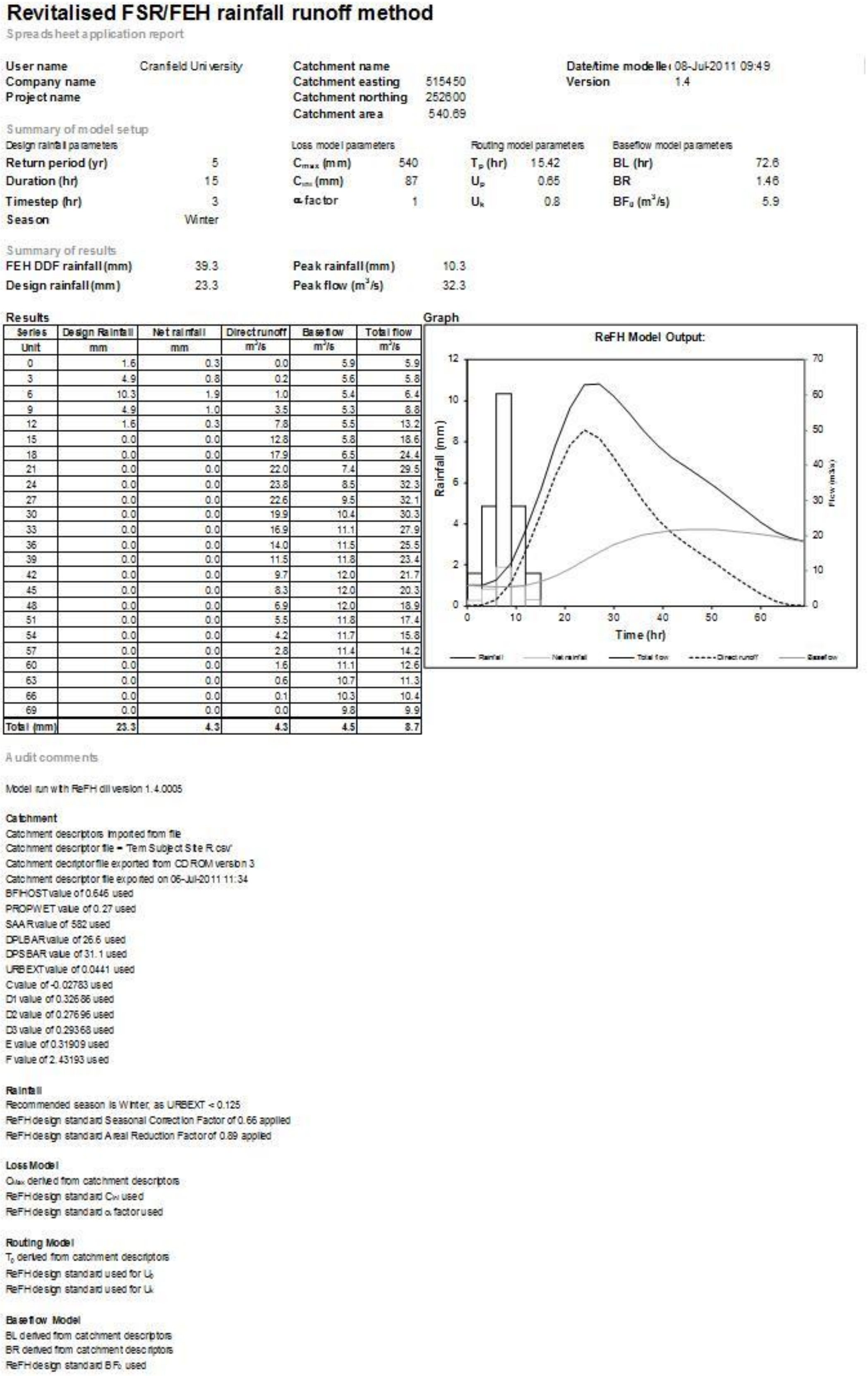
Baseflow Model

BL derived from catchment descriptors

BR derived from catchment descriptors

ReFH design standard BF_0 used

Table B.2.2 ReFH model, 20% AEP model run parameters and results



Revitalised FSR/FEH rainfall runoff method

Spreadsheet application report

User name	Cranfield University	**Catchment name**		**Date/time modelle**	08-Jul-2011 09:49
Company name		**Catchment easting**	515450	**Version**	1.4
Project name		**Catchment northing**	252600		
		Catchment area	540.69		

Summary of model setup

Design rainfall parameters		Loss model parameters		Routing model parameters		Baseflow model parameters	
Return period (yr)	5	C_{max} (mm)	540	T_p (hr)	15.42	BL (hr)	72.6
Duration (hr)	15	C_{ini} (mm)	87	U_p	0.65	BR	1.46
Timestep (hr)	3	α factor	1	U_k	0.8	BF_0 (m^3/s)	5.9
Season	Winter						

Summary of results

FEH DDF rainfall (mm)	39.3	**Peak rainfall (mm)**	10.3
Design rainfall (mm)	23.3	**Peak flow (m^3/s)**	32.3

Results

Series	Design Rainfall	Net rainfall	Direct runoff	Baseflow	Total flow
Unit	mm	mm	m^3/s	m^3/s	m^3/s
0	1.6	0.3	0.0	5.9	5.9
3	4.9	0.8	0.2	5.6	5.8
6	10.3	1.9	1.0	5.4	6.4
9	4.9	1.0	3.5	5.3	8.8
12	1.6	0.3	7.8	5.5	13.2
15	0.0	0.0	12.8	5.8	18.6
18	0.0	0.0	17.9	6.5	24.4
21	0.0	0.0	22.0	7.4	29.5
24	0.0	0.0	23.8	8.5	32.3
27	0.0	0.0	22.6	9.5	32.1
30	0.0	0.0	19.9	10.4	30.3
33	0.0	0.0	16.9	11.1	27.9
36	0.0	0.0	14.0	11.5	25.5
39	0.0	0.0	11.5	11.8	23.4
42	0.0	0.0	9.7	12.0	21.7
45	0.0	0.0	8.3	12.0	20.3
48	0.0	0.0	6.9	12.0	18.9
51	0.0	0.0	5.5	11.8	17.4
54	0.0	0.0	4.2	11.7	15.8
57	0.0	0.0	2.8	11.4	14.2
60	0.0	0.0	1.6	11.1	12.6
63	0.0	0.0	0.6	10.7	11.3
66	0.0	0.0	0.1	10.3	10.4
69	0.0	0.0	0.0	9.8	9.9
Total (mm)	23.3	4.3	4.3	4.5	8.7

Graph

Audit comments

Model run with ReFH dll version 1.4.0005

Catchment
Catchment descriptors imported from file
Catchment descriptor file = 'Tem Subject Site R.csv'
Catchment decriptor file exported from CD ROM version 3
Catchment descriptor file exported on 06-Jul-2011 11:34
BFIHOST value of 0.646 used
PROPWET value of 0.27 used
SAAR value of 582 used
DPLBAR value of 26.6 used
DPSBAR value of 31.1 used
URBEXT value of 0.0441 used
C value of -0.02783 used
D1 value of 0.32686 used
D2 value of 0.27696 used
D3 value of 0.29368 used
E value of 0.31909 used
F value of 2.43193 used

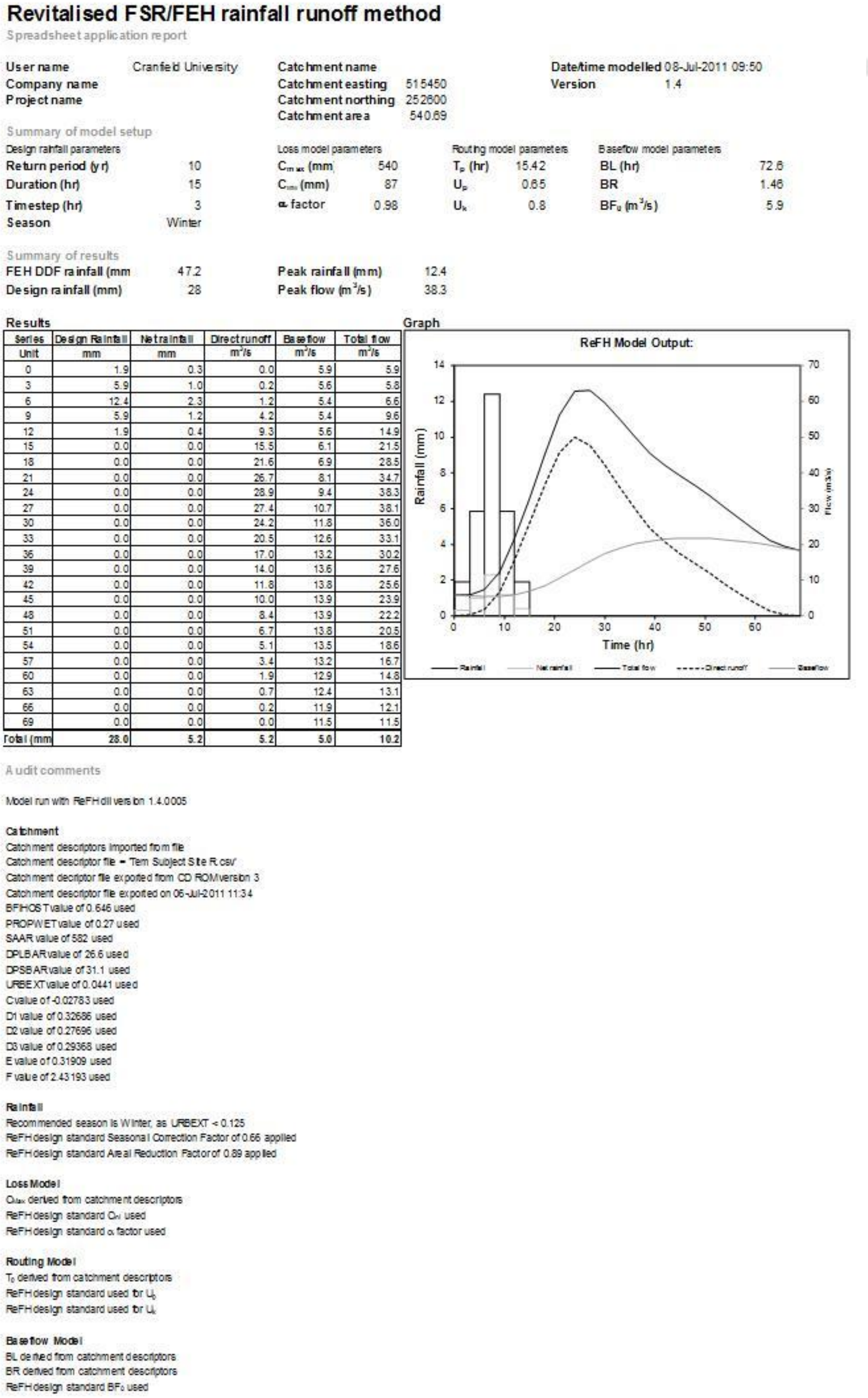
Rainfall
Recommended season is Winter, as URBEXT < 0.125
ReFH design standard Seasonal Correction Factor of 0.66 applied
ReFH design standard Areal Reduction Factor of 0.89 applied

Loss Model
C_{max} derived from catchment descriptors
ReFH design standard C_{ini} used
ReFH design standard α factor used

Routing Model
T_p derived from catchment descriptors
ReFH design standard used for U_p
ReFH design standard used for U_k

Baseflow Model
BL derived from catchment descriptors
BR derived from catchment descriptors
ReFH design standard BF_0 used

Table B.2.3 ReFH model, 10% AEP model run parameters and results



Revitalised FSR/FEH rainfall runoff method

Spreadsheet application report

User name	Cranfield University	**Catchment name**		**Date/time modelled**	08-Jul-2011 09:50
Company name		**Catchment easting**	515450	**Version**	1.4
Project name		**Catchment northing**	252600		
		Catchment area	540.69		

Summary of model setup

Design rainfall parameters		Loss model parameters		Routing model parameters		Baseflow model parameters	
Return period (yr)	10	C_{max} **(mm**	540	T_p **(hr)**	15.42	**BL (hr)**	72.6
Duration (hr)	15	C_{ini} **(mm)**	87	U_p	0.65	**BR**	1.46
Timestep (hr)	3	**α factor**	0.98	U_k	0.8	BF_0 **(m³/s)**	5.9
Season	Winter						

Summary of results

FEH DDF rainfall (mm	47.2	**Peak rainfall (mm)**	12.4
Design rainfall (mm)	28	**Peak flow (m³/s)**	38.3

Results

Series	Design Rainfall	Net rainfall	Direct runoff	Baseflow	Total flow
Unit	mm	mm	m³/s	m³/s	m³/s
0	1.9	0.3	0.0	5.9	5.9
3	5.9	1.0	0.2	5.6	5.8
6	12.4	2.3	1.2	5.4	6.6
9	5.9	1.2	4.2	5.4	9.6
12	1.9	0.4	9.3	5.6	14.9
15	0.0	0.0	15.5	6.1	21.5
18	0.0	0.0	21.6	6.9	28.5
21	0.0	0.0	26.7	8.1	34.7
24	0.0	0.0	28.9	9.4	38.3
27	0.0	0.0	27.4	10.7	38.1
30	0.0	0.0	24.2	11.8	36.0
33	0.0	0.0	20.5	12.6	33.1
36	0.0	0.0	17.0	13.2	30.2
39	0.0	0.0	14.0	13.6	27.6
42	0.0	0.0	11.8	13.8	25.6
45	0.0	0.0	10.0	13.9	23.9
48	0.0	0.0	8.4	13.9	22.2
51	0.0	0.0	6.7	13.8	20.5
54	0.0	0.0	5.1	13.5	18.6
57	0.0	0.0	3.4	13.2	16.7
60	0.0	0.0	1.9	12.9	14.8
63	0.0	0.0	0.7	12.4	13.1
66	0.0	0.0	0.2	11.9	12.1
69	0.0	0.0	0.0	11.5	11.5
Total (mm	**28.0**	**5.2**	**5.2**	**5.0**	**10.2**

Graph

Audit comments

Model run with ReFHdll version 1.4.0005

Catchment
Catchment descriptors imported from file
Catchment descriptor file = 'Tem Subject Site R.csv'
Catchment decriptor file exported from CD ROM version 3
Catchment descriptor file exported on 06-Jul-2011 11:34
BFIHOST value of 0.646 used
PROPWET value of 0.27 used
SAAR value of 582 used
DPLBAR value of 26.6 used
DPSBAR value of 31.1 used
URBEXT value of 0.0441 used
C value of -0.02783 used
D1 value of 0.32686 used
D2 value of 0.27696 used
D3 value of 0.29368 used
E value of 0.31909 used
F value of 2.43193 used

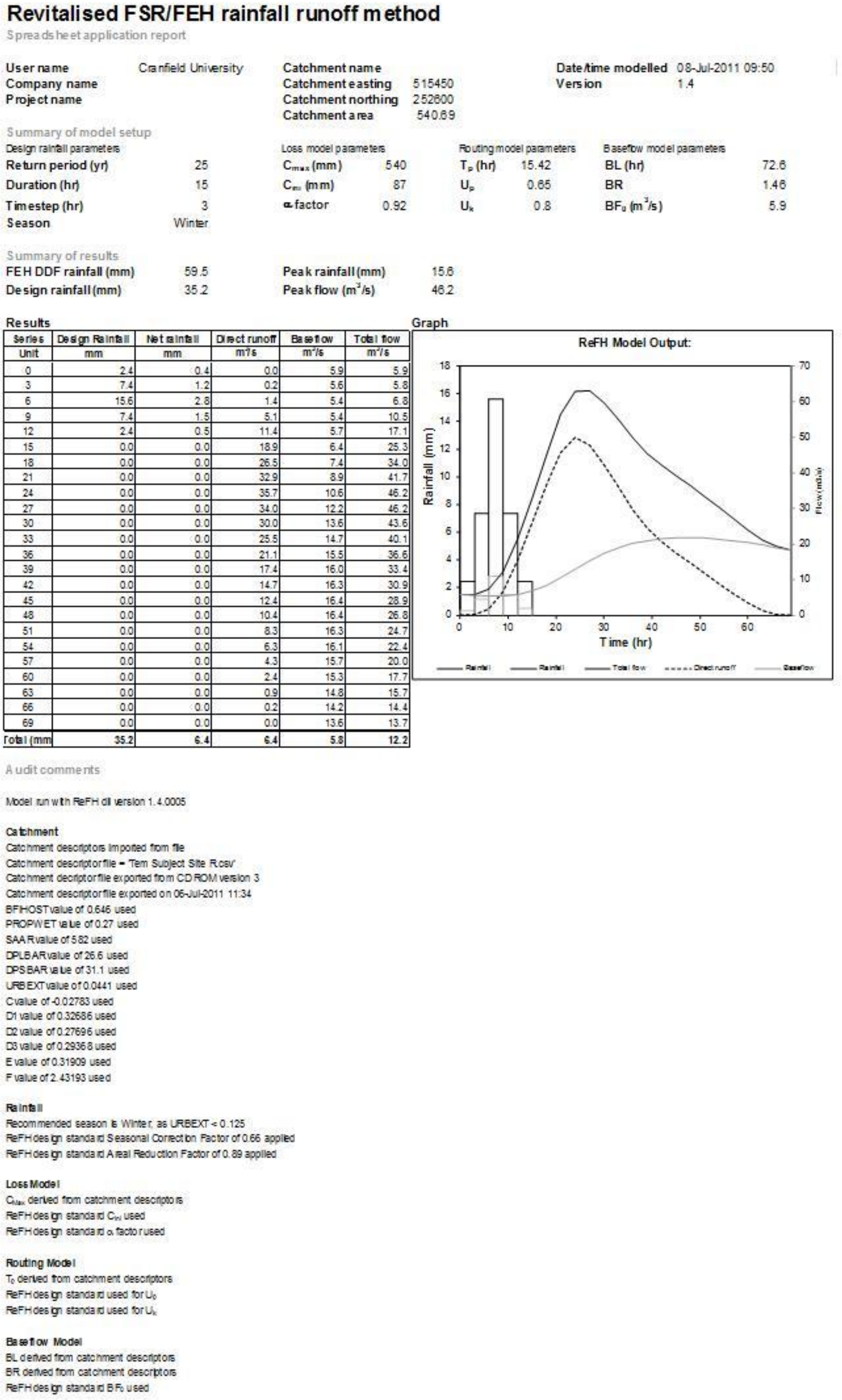
Rainfall
Recommended season is Winter, as URBEXT < 0.125
ReFH design standard Seasonal Correction Factor of 0.66 applied
ReFH design standard Areal Reduction Factor of 0.89 applied

Loss Model
C_{Max} derived from catchment descriptors
ReFH design standard C_{ini} used
ReFH design standard α factor used

Routing Model
T_p derived from catchment descriptors
ReFH design standard used for U_p
ReFH design standard used for U_k

Baseflow Model
BL derived from catchment descriptors
BR derived from catchment descriptors
ReFH design standard BF_0 used

Table B.2.4 ReFH model, 4% AEP model run parameters and results



Revitalised FSR/FEH rainfall runoff method

Spreadsheet application report

User name	Cranfield University	**Catchment name**		**Date/time modelled**	08-Jul-2011 09:50
Company name		**Catchment easting**	515450	**Version**	1.4
Project name		**Catchment northing**	252600		
		Catchment area	540.69		

Summary of model setup

Design rainfall parameters		Loss model parameters		Routing model parameters		Baseflow model parameters	
Return period (yr)	25	**C_{max} (mm)**	540	**T_p (hr)**	15.42	**BL (hr)**	72.6
Duration (hr)	15	**C_{ini} (mm)**	87	**U_p**	0.65	**BR**	1.46
Timestep (hr)	3	**α factor**	0.92	**U_k**	0.8	**BF_0 (m^3/s)**	5.9
Season	Winter						

Summary of results

FEH DDF rainfall (mm)	59.5	**Peak rainfall (mm)**	15.6
Design rainfall (mm)	35.2	**Peak flow (m^3/s)**	46.2

Results

Series Unit	Design Rainfall mm	Net rainfall mm	Direct runoff m^3/s	Baseflow m^3/s	Total flow m^3/s
0	2.4	0.4	0.0	5.9	5.9
3	7.4	1.2	0.2	5.6	5.8
6	15.6	2.8	1.4	5.4	6.8
9	7.4	1.5	5.1	5.4	10.5
12	2.4	0.5	11.4	5.7	17.1
15	0.0	0.0	18.9	6.4	25.3
18	0.0	0.0	26.5	7.4	34.0
21	0.0	0.0	32.9	8.9	41.7
24	0.0	0.0	35.7	10.6	46.2
27	0.0	0.0	34.0	12.2	46.2
30	0.0	0.0	30.0	13.6	43.6
33	0.0	0.0	25.5	14.7	40.1
36	0.0	0.0	21.1	15.5	36.6
39	0.0	0.0	17.4	16.0	33.4
42	0.0	0.0	14.7	16.3	30.9
45	0.0	0.0	12.4	16.4	28.9
48	0.0	0.0	10.4	16.4	26.8
51	0.0	0.0	8.3	16.3	24.7
54	0.0	0.0	6.3	16.1	22.4
57	0.0	0.0	4.3	15.7	20.0
60	0.0	0.0	2.4	15.3	17.7
63	0.0	0.0	0.9	14.8	15.7
66	0.0	0.0	0.2	14.2	14.4
69	0.0	0.0	0.0	13.6	13.7
Total (mm	35.2	6.4	6.4	5.8	12.2

Graph

Audit comments

Model run with ReFH dll version 1.4.0005

Catchment
Catchment descriptors imported from file
Catchment descriptor file = 'Tem Subject Site R.csv'
Catchment decriptor file exported from CD ROM version 3
Catchment descriptor file exported on 06-Jul-2011 11:34
BFIHOST value of 0.646 used
PROPWET value of 0.27 used
SAAR value of 582 used
DPLBAR value of 26.6 used
DPSBAR value of 31.1 used
URBEXT value of 0.0441 used
C value of -0.02783 used
D1 value of 0.32686 used
D2 value of 0.27696 used
D3 value of 0.29368 used
E value of 0.31909 used
F value of 2.43193 used

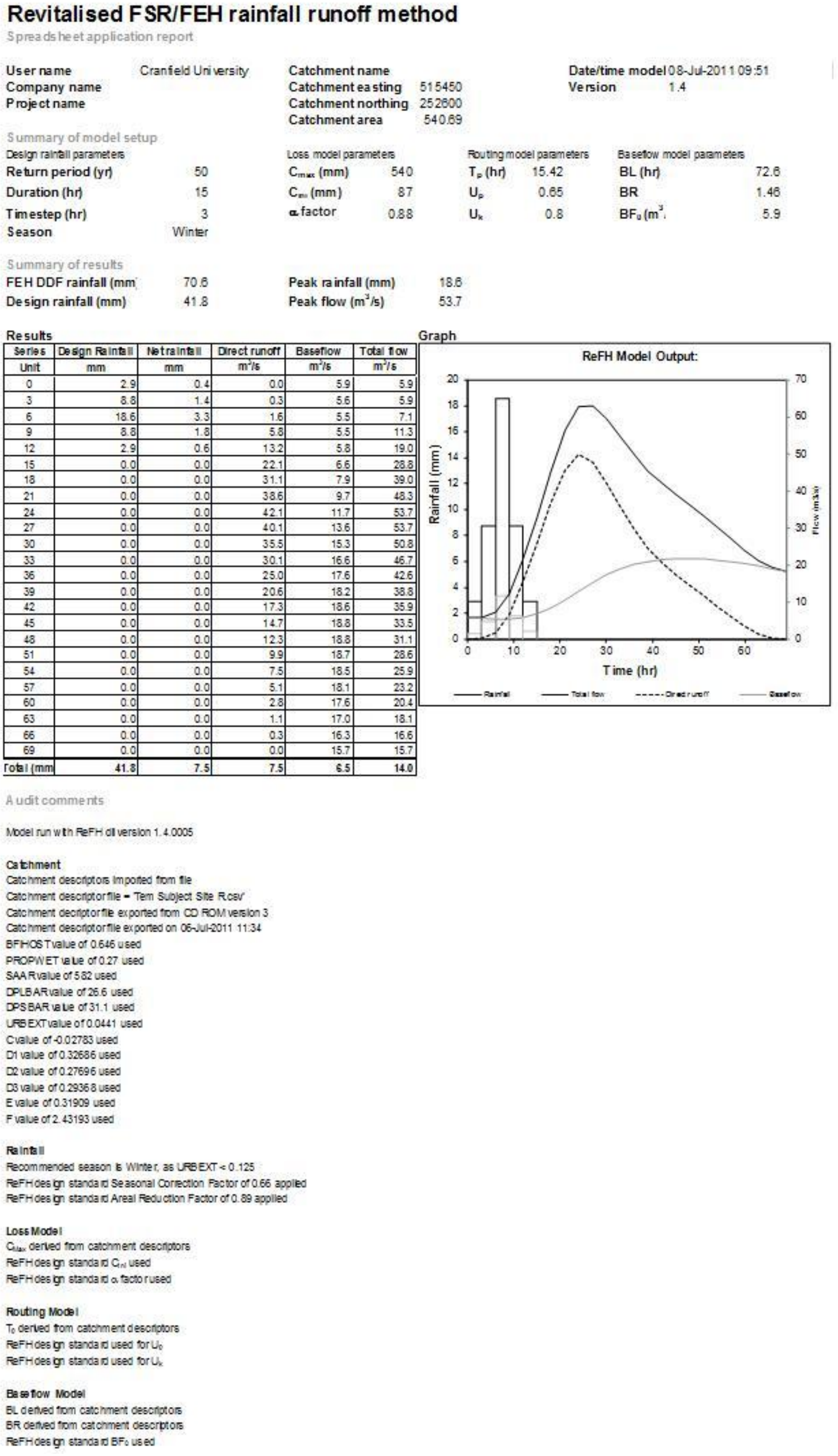
Rainfall
Recommended season is Winter, as URBEXT < 0.125
ReFH design standard Seasonal Correction Factor of 0.66 applied
ReFH design standard Areal Reduction Factor of 0.89 applied

Loss Model
C_{Max} derived from catchment descriptors
ReFH design standard C_{ini} used
ReFH design standard α factor used

Routing Model
T_p derived from catchment descriptors
ReFH design standard used for U_p
ReFH design standard used for U_k

Baseflow Model
BL derived from catchment descriptors
BR derived from catchment descriptors
ReFH design standard BF_0 used

Table B.2.5 ReFH model, 2% AEP model run parameters and results



Revitalised FSR/FEH rainfall runoff method

Spreadsheet application report

User name	Cranfield University	**Catchment name**		**Date/time model**	08-Jul-2011 09:51
Company name		**Catchment easting**	515450	**Version**	1.4
Project name		**Catchment northing**	252600		
		Catchment area	540.69		

Summary of model setup

Design rainfall parameters		Loss model parameters		Routing model parameters		Baseflow model parameters	
Return period (yr)	50	C_{max} (mm)	540	T_p (hr)	15.42	**BL (hr)**	72.6
Duration (hr)	15	C_{ini} (mm)	87	U_p	0.65	**BR**	1.46
Timestep (hr)	3	α factor	0.88	U_k	0.8	BF_0 (m³	5.9
Season	Winter						

Summary of results

FEH DDF rainfall (mm	70.6	**Peak rainfall (mm)**	18.6
Design rainfall (mm)	41.8	**Peak flow (m³/s)**	53.7

Results

Series	Design Rainfall	Net rainfall	Direct runoff	Baseflow	Total flow
Unit	mm	mm	m³/s	m³/s	m³/s
0	2.9	0.4	0.0	5.9	5.9
3	8.8	1.4	0.3	5.6	5.9
6	18.6	3.3	1.6	5.5	7.1
9	8.8	1.8	5.8	5.5	11.3
12	2.9	0.6	13.2	5.8	19.0
15	0.0	0.0	22.1	6.6	28.8
18	0.0	0.0	31.1	7.9	39.0
21	0.0	0.0	38.6	9.7	48.3
24	0.0	0.0	42.1	11.7	53.7
27	0.0	0.0	40.1	13.6	53.7
30	0.0	0.0	35.5	15.3	50.8
33	0.0	0.0	30.1	16.6	46.7
36	0.0	0.0	25.0	17.6	42.6
39	0.0	0.0	20.6	18.2	38.8
42	0.0	0.0	17.3	18.6	35.9
45	0.0	0.0	14.7	18.8	33.5
48	0.0	0.0	12.3	18.8	31.1
51	0.0	0.0	9.9	18.7	28.6
54	0.0	0.0	7.5	18.5	25.9
57	0.0	0.0	5.1	18.1	23.2
60	0.0	0.0	2.8	17.6	20.4
63	0.0	0.0	1.1	17.0	18.1
66	0.0	0.0	0.3	16.3	16.6
69	0.0	0.0	0.0	15.7	15.7
Total (mm	41.8	7.5	7.5	6.5	14.0

Graph

Audit comments

Model run with ReFH dll version 1.4.0005

Catchment
Catchment descriptors imported from file
Catchment descriptor file = 'Tem Subject Site R.csv'
Catchment decriptor file exported from CD ROM version 3
Catchment descriptor file exported on 06-Jul-2011 11:34
BFIHOST value of 0.646 used
PROPWET value of 0.27 used
SAAR value of 582 used
DPLBAR value of 26.6 used
DPSBAR value of 31.1 used
URBEXT value of 0.0441 used
C value of -0.02783 used
D1 value of 0.32686 used
D2 value of 0.27696 used
D3 value of 0.29368 used
E value of 0.31909 used
F value of 2.43193 used

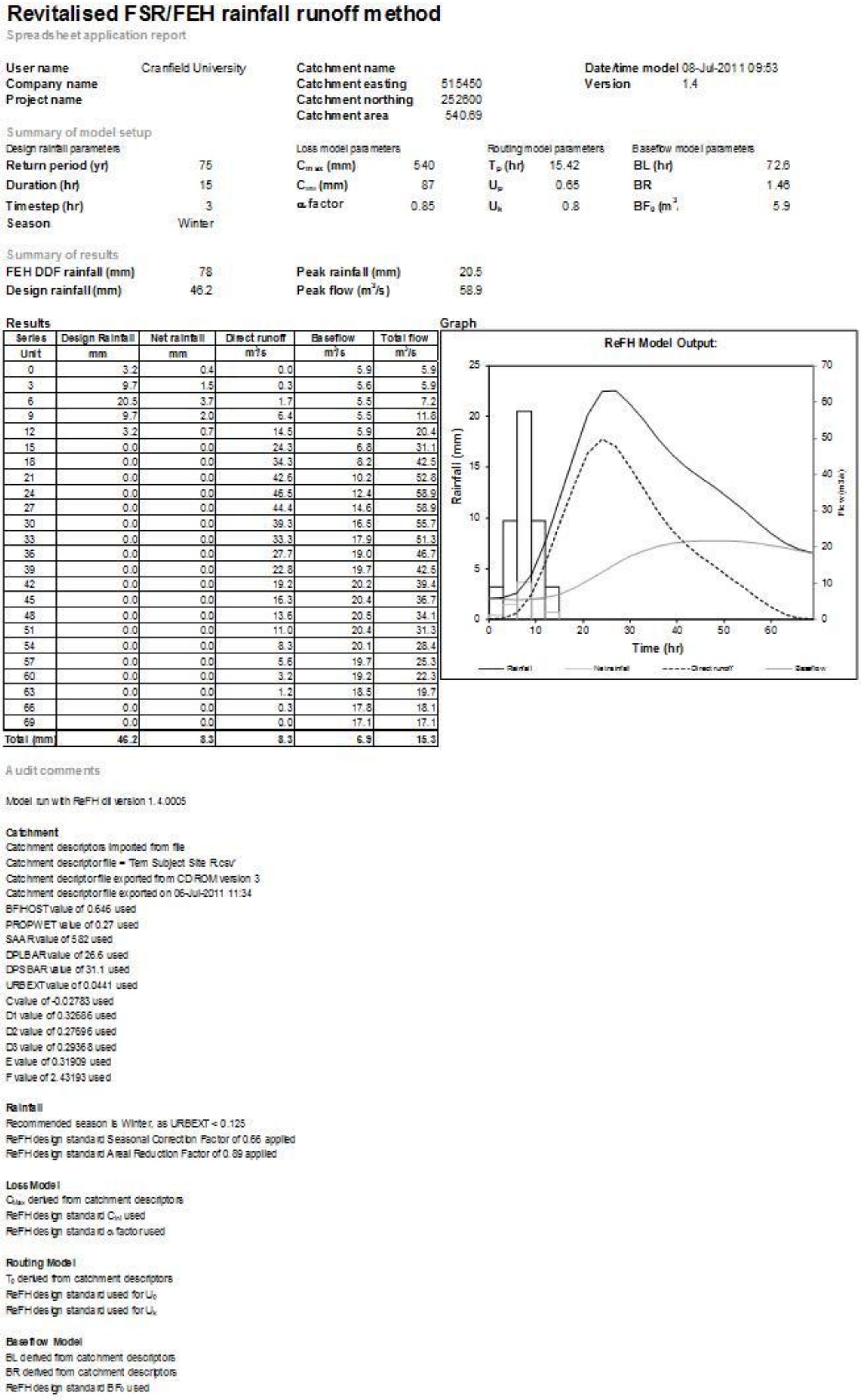
Rainfall
Recommended season is Winter, as URBEXT < 0.125
ReFH design standard Seasonal Correction Factor of 0.66 applied
ReFH design standard Areal Reduction Factor of 0.89 applied

Loss Model
C_{Max} derived from catchment descriptors
ReFH design standard C_{ini} used
ReFH design standard α factor used

Routing Model
T_0 derived from catchment descriptors
ReFH design standard used for U_0
ReFH design standard used for U_k

Baseflow Model
BL derived from catchment descriptors
BR derived from catchment descriptors
ReFH design standard BF_0 used

Table B.2.6 ReFH model, 1.33% AEP model run parameters and results



Revitalised FSR/FEH rainfall runoff method

Spreadsheet application report

User name	Cranfield University	**Catchment name**		**Date/time model**	08-Jul-2011 09:53
Company name		**Catchment easting**	515450	**Version**	1.4
Project name		**Catchment northing**	252600		
		Catchment area	540.69		

Summary of model setup

Design rainfall parameters		Loss model parameters		Routing model parameters		Baseflow model parameters	
Return period (yr)	75	**C_{max} (mm)**	540	**T_p (hr)**	15.42	**BL (hr)**	72.6
Duration (hr)	15	**C_{ini} (mm)**	87	**U_p**	0.65	**BR**	1.46
Timestep (hr)	3	**α factor**	0.85	**U_k**	0.8	**BF_0 (m^3**	5.9
Season	Winter						

Summary of results

FEH DDF rainfall (mm)	78	**Peak rainfall (mm)**	20.5
Design rainfall (mm)	46.2	**Peak flow (m^3/s)**	58.9

Results

Series	Design Rainfall	Net rainfall	Direct runoff	Baseflow	Total flow
Unit	mm	mm	m^3/s	m^3/s	m^3/s
0	3.2	0.4	0.0	5.9	5.9
3	9.7	1.5	0.3	5.6	5.9
6	20.5	3.7	1.7	5.5	7.2
9	9.7	2.0	6.4	5.5	11.8
12	3.2	0.7	14.5	5.9	20.4
15	0.0	0.0	24.3	6.8	31.1
18	0.0	0.0	34.3	8.2	42.5
21	0.0	0.0	42.6	10.2	52.8
24	0.0	0.0	46.5	12.4	58.9
27	0.0	0.0	44.4	14.6	58.9
30	0.0	0.0	39.3	16.5	55.7
33	0.0	0.0	33.3	17.9	51.3
36	0.0	0.0	27.7	19.0	46.7
39	0.0	0.0	22.8	19.7	42.5
42	0.0	0.0	19.2	20.2	39.4
45	0.0	0.0	16.3	20.4	36.7
48	0.0	0.0	13.6	20.5	34.1
51	0.0	0.0	11.0	20.4	31.3
54	0.0	0.0	8.3	20.1	28.4
57	0.0	0.0	5.6	19.7	25.3
60	0.0	0.0	3.2	19.2	22.3
63	0.0	0.0	1.2	18.5	19.7
66	0.0	0.0	0.3	17.8	18.1
69	0.0	0.0	0.0	17.1	17.1
Total (mm)	46.2	8.3	8.3	6.9	15.3

Graph

Audit comments

Model run with ReFH dll version 1.4.0005

Catchment
Catchment descriptors imported from file
Catchment descriptor file = 'Tem Subject Site R.csv'
Catchment decriptor file exported from CD ROM version 3
Catchment descriptor file exported on 06-Jul-2011 11:34
BFIHOST value of 0.646 used
PROPWET value of 0.27 used
SAAR value of 582 used
DPLBAR value of 26.6 used
DPSBAR value of 31.1 used
URBEXT value of 0.0441 used
C value of -0.02783 used
D1 value of 0.32686 used
D2 value of 0.27696 used
D3 value of 0.29368 used
E value of 0.31909 used
F value of 2.43193 used

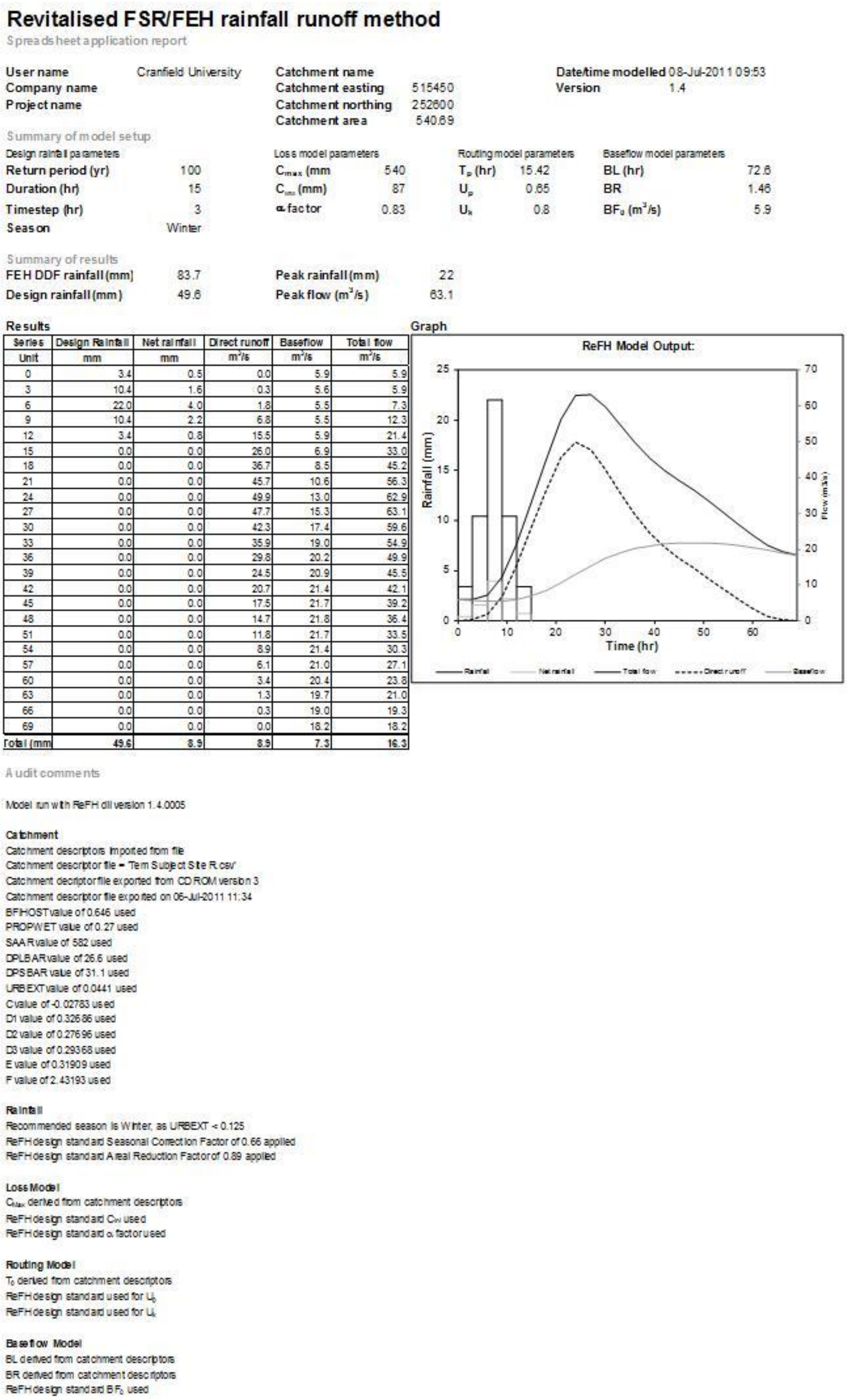
Rainfall
Recommended season is Winter, as URBEXT < 0.125
ReFH design standard Seasonal Correction Factor of 0.66 applied
ReFH design standard Areal Reduction Factor of 0.89 applied

Loss Model
C_{max} derived from catchment descriptors
ReFH design standard C_{ini} used
ReFH design standard α factor used

Routing Model
T_p derived from catchment descriptors
ReFH design standard used for U_p
ReFH design standard used for U_k

Baseflow Model
BL derived from catchment descriptors
BR derived from catchment descriptors
ReFH design standard BF_0 used

Table B.2.7 ReFH model, 1% AEP model run parameters and results



Revitalised FSR/FEH rainfall runoff method

Spreadsheet application report

User name	Cranfield University	**Catchment name**		**Date/time modelled**	08-Jul-2011 09:53
Company name		**Catchment easting**	515450	**Version**	1.4
Project name		**Catchment northing**	252600		
		Catchment area	540.69		

Summary of model setup

Design rainfall parameters		Loss model parameters		Routing model parameters		Baseflow model parameters	
Return period (yr)	100	C_{max} (mm	540	T_p (hr)	15.42	BL (hr)	72.6
Duration (hr)	15	C_{ini} (mm)	87	U_p	0.65	BR	1.46
Timestep (hr)	3	α factor	0.83	U_k	0.8	BF_0 (m^3/s)	5.9
Season	Winter						

Summary of results

FEH DDF rainfall (mm)	83.7	**Peak rainfall (mm)**	22
Design rainfall (mm)	49.6	**Peak flow (m^3/s)**	63.1

Results

Series	Design Rainfall	Net rainfall	Direct runoff	Baseflow	Total flow
Unit	mm	mm	m^3/s	m^3/s	m^3/s
0	3.4	0.5	0.0	5.9	5.9
3	10.4	1.6	0.3	5.6	5.9
6	22.0	4.0	1.8	5.5	7.3
9	10.4	2.2	6.8	5.5	12.3
12	3.4	0.8	15.5	5.9	21.4
15	0.0	0.0	26.0	6.9	33.0
18	0.0	0.0	36.7	8.5	45.2
21	0.0	0.0	45.7	10.6	56.3
24	0.0	0.0	49.9	13.0	62.9
27	0.0	0.0	47.7	15.3	63.1
30	0.0	0.0	42.3	17.4	59.6
33	0.0	0.0	35.9	19.0	54.9
36	0.0	0.0	29.8	20.2	49.9
39	0.0	0.0	24.5	20.9	45.5
42	0.0	0.0	20.7	21.4	42.1
45	0.0	0.0	17.5	21.7	39.2
48	0.0	0.0	14.7	21.8	36.4
51	0.0	0.0	11.8	21.7	33.5
54	0.0	0.0	8.9	21.4	30.3
57	0.0	0.0	6.1	21.0	27.1
60	0.0	0.0	3.4	20.4	23.8
63	0.0	0.0	1.3	19.7	21.0
66	0.0	0.0	0.3	19.0	19.3
69	0.0	0.0	0.0	18.2	18.2
Total (mm	49.6	8.9	8.9	7.3	16.3

Graph

Audit comments

Model run with ReFH dll version 1.4.0005

Catchment
Catchment descriptors imported from file
Catchment descriptor file = 'Tern Subject Site R.csv'
Catchment decriptor file exported from CD ROM version 3
Catchment descriptor file exported on 06-Jul-2011 11:34
BFIHOST value of 0.646 used
PROPWET value of 0.27 used
SAAR value of 582 used
DPLBAR value of 26.6 used
DPSBAR value of 31.1 used
URBEXT value of 0.0441 used
C value of -0.02783 used
D1 value of 0.32686 used
D2 value of 0.27696 used
D3 value of 0.29368 used
E value of 0.31909 used
F value of 2.43193 used

Rainfall
Recommended season is Winter, as URBEXT < 0.125
ReFH design standard Seasonal Correction Factor of 0.66 applied
ReFH design standard Areal Reduction Factor of 0.89 applied

Loss Model
C_{Max} derived from catchment descriptors
ReFH design standard C_{ini} used
ReFH design standard α factor used

Routing Model
T_p derived from catchment descriptors
ReFH design standard used for U_p
ReFH design standard used for U_k

Baseflow Model
BL derived from catchment descriptors
BR derived from catchment descriptors
ReFH design standard BF_0 used

Appendix C Lateral connectivity model

C.1 ISIS 1D model river survey and Manning's 'n' values

Table C.1.1 River Ivel channel survey and observed water levels and discharge

Channel geometry			**Survey**			
Chainage ID	**Distance (m)**	**Roughness description**	**Date**	**Time**	**Water level (mAOD)**	**Discharge ($m^3.s^{-1}$)**
IV-03418	225	Gravel	04/02/2009	14:15	18.46	3.49
IV-03193	199	Gravel	04/02/2009	13:30	18.47	3.49
IV-02994	198	Mud & Gravel	04/02/2009	12:20	18.37	3.49
IV-02796	201	Gravel	04/02/2009	11:15	18.36	3.53
IV-02595	244	Gravel	04/02/2009	09:35	18.43	3.71
IV-02351	99	Mud/Gravel	29/01/2009	10:30	18.09	8.92
IV-02252	6	Concrete	28/01/2009	14:00	18.14	5.98
IV-02246	60	Concrete	28/01/2009	11:45	18.05	5.11
IV-02186	58	Stones/Gravel	28/01/2009	09:30	18.02	4.57
IV-02128	106	Stones/Gravel	27/01/2009	15:20	18	4.72
IV-02022	205	Gravel	27/01/2009	14:00	18.01	4.82
IV-01817	243	Gravel	27/01/2009	13:00	18	4.87
IV-01574	191	Mud/Gravel	27/01/2009	12:00	17.96	4.89
IV-01383	190	Mud/Stones	26/01/2009	15:30	18.03	6.4
IV-01193	180	Mud/Gravel	26/01/2009	13:30	18.05	6.46
IV-01013	287	Mud/Stones	26/01/2009	10:00	18.05	6.96
IV-00726	127	Mud/Gravel	14/01/2009	09:30	15.92	2.88
IV-00599	73	Mud/Gravel	13/01/2009	14:00	15.77	3.16
IV-00526	104	Mud/Gravel	13/01/2009	13:00	15.68	3.14
IV-00422	221	Gravel	13/01/2009	09:30	15.68	3.13
IV-00201	149	Mud/Gravel	12/01/2009	14:00	15.45	2.6
IV-00052	0	Mud & Gravel	12/01/2009	12:00	15.19	2.46
					Mean	**4.49**

C.2 ISIS 1D model weir cross section geometry

Table C.2.1 ISIS 1D model IV-02595 and IV-01013 cross section weir geometry

Cross section	**Bed Elevation (mAOD)**	**Breadth of crest (m)**	**Height of crest of above riverbed**	
			Upstream p1 (m)	**Downstream p2 (m)**
IV-02595	18.023	15.02	1.182	0.805
IV-01013	17.535	15.14	2.219	2.924

C.3 ISIS 1D model sensitivity tests

Table C.3.1 Manning's 'n' river stage (mAOD) sensitivity test ISIS 1D model results

Cross section	Flow ($m^3.s^{-1}$)	Manning's 'n' value and river stage (mAOD)			River bed (mAOD)
		C.b.5 MAX	C.b.2 NORM	C.b.6 MAX	
		0.040	0.030	0.050	
IV-03418	4.5	18.496	18.417	18.593	17.52
IV-03193	4.5	18.464	18.396	18.554	16.888
IV-02994	4.5	18.44	18.38	18.525	16.934
IV-02796	4.5	18.404	18.355	18.481	17.111
IV-02595U	4.5	18.38	18.341	18.449	16.841
IV-02595D	4.5	18.305	18.203	18.397	16.841
IV-02595Di	4.5	18.296	18.195	18.386	16.935
IV-02595Dii	4.5	18.278	18.18	18.366	17.029
IV-02595Diii	4.5	18.24	18.147	18.323	17.124
IV-02351	4.5	18.127	18.039	18.202	17.218
IV-02252	4.5	17.952	17.902	18.002	17.322
IV-02246	4.5	17.949	17.904	17.996	17.144
IV-02186	4.5	17.914	17.884	17.949	16.72
IV-02128	4.5	17.912	17.887	17.943	16.506
IV-02022	4.5	17.905	17.882	17.933	16.519
IV-01817	4.5	17.888	17.872	17.909	16.434
IV-01574	4.5	17.868	17.86	17.879	15.827
IV-01383	4.5	17.862	17.857	17.867	15.28
IV-01193	4.5	17.856	17.854	17.858	15.574
IV-01013U	4.5	17.852	17.852	17.852	15.316
IV-01013D	4.5	16.036	15.941	16.122	15.316
IV-01013Di	4.5	15.739	15.628	15.834	14.964
IV-00726	4.5	15.681	15.578	15.773	14.611
IV-00599	4.5	15.603	15.492	15.703	14.674
IV-00526	4.5	15.494	15.377	15.597	14.521
IV-00526i	4.5	15.454	15.348	15.551	14.275
IV-00422	4.5	15.437	15.339	15.529	14.03
IV-00422i	4.5	15.394	15.303	15.478	14.306
IV-00201	4.5	15.266	15.178	15.349	14.582
IV-00052	4.5	15.019	14.919	15.109	14.158

Table C.3.2 Downstream boundary ±0.5 m river stage (mAOD) sensitivity test ISIS 1D model sensitivity results

Cross section	**Flow ($m^3.s^{-1}$)**	**Downstream boundary change and river stage (mAOD)**			**River bed (mAOD)**
		0	**-0.5 m**	**+0.5 m**	
IV-03418	4.5	18.496	18.496	18.496	17.52
IV-03193	4.5	18.464	18.464	18.464	16.888
IV-02994	4.5	18.44	18.44	18.44	16.934
IV-02796	4.5	18.404	18.404	18.404	17.111
IV-02595U	4.5	18.38	18.38	18.38	16.841
IV-02595D	4.5	18.305	18.305	18.305	16.841
IV-02595Di	4.5	18.296	18.296	18.296	16.935
IV-02595Dii	4.5	18.278	18.278	18.278	17.029
IV-02595Diii	4.5	18.24	18.24	18.24	17.124
IV-02351	4.5	18.127	18.127	18.127	17.218
IV-02252	4.5	17.952	17.952	17.952	17.322
IV-02246	4.5	17.949	17.949	17.949	17.144
IV-02186	4.5	17.914	17.914	17.914	16.72
IV-02128	4.5	17.912	17.912	17.912	16.506
IV-02022	4.5	17.905	17.905	17.905	16.519
IV-01817	4.5	17.888	17.888	17.888	16.434
IV-01574	4.5	17.868	17.868	17.868	15.827
IV-01383	4.5	17.862	17.862	17.862	15.28
IV-01193	4.5	17.856	17.856	17.856	15.574
IV-01013U	4.5	17.852	17.852	17.852	15.316
IV-01013D	4.5	16.036	16.035	16.05	15.316
IV-01013Di	4.5	15.739	15.731	15.82	14.964
IV-00726	4.5	15.681	15.669	15.784	14.611
IV-00599	4.5	15.603	15.586	15.739	14.674
IV-00526	4.5	15.494	15.463	15.687	14.521
IV-00526i	4.5	15.454	15.416	15.669	14.275
IV-00422	4.5	15.437	15.397	15.66	14.03
IV-00422i	4.5	15.394	15.347	15.639	14.306
IV-00201	4.5	15.266	15.143	15.601	14.582
IV-00052	4.5	15.019	14.511	15.505	14.158

C.4 Linked ISIS 1D-2D model sensitivity test results

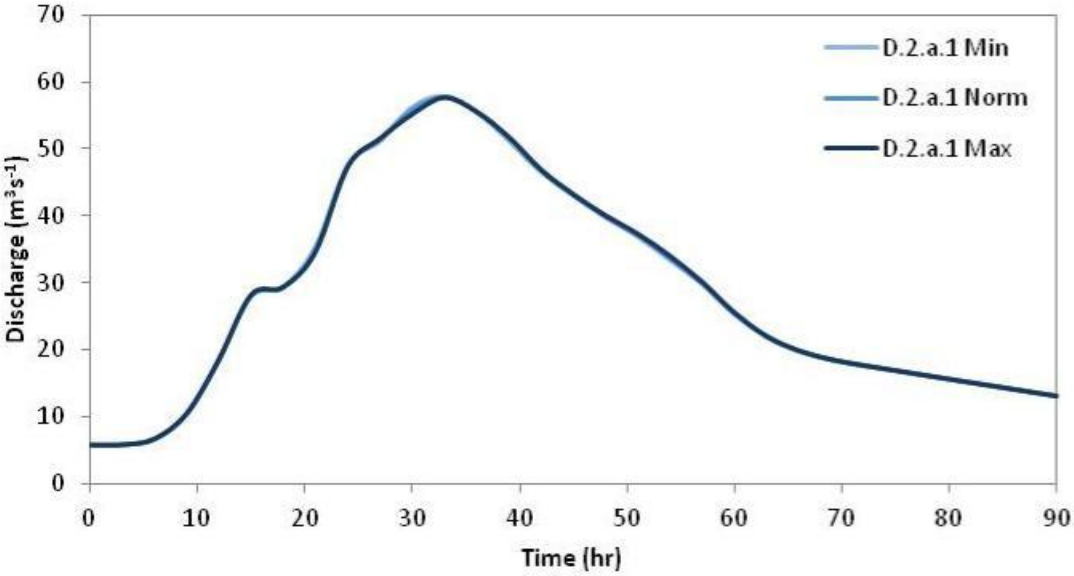


Figure C.4.1 Linked ISIS 1D-2D model floodplain Manning's 'n' discharge hydrograph sensitivity test results

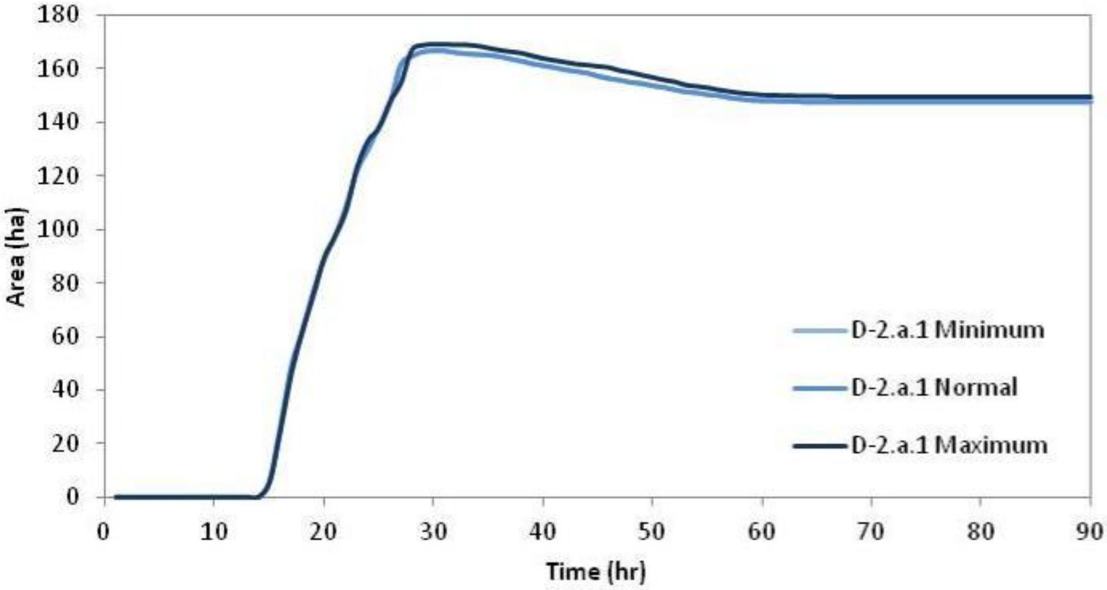


Figure C.4.2 Linked ISIS 1D-2D model floodplain Manning's 'n' inundation area (ha) sensitivity test results

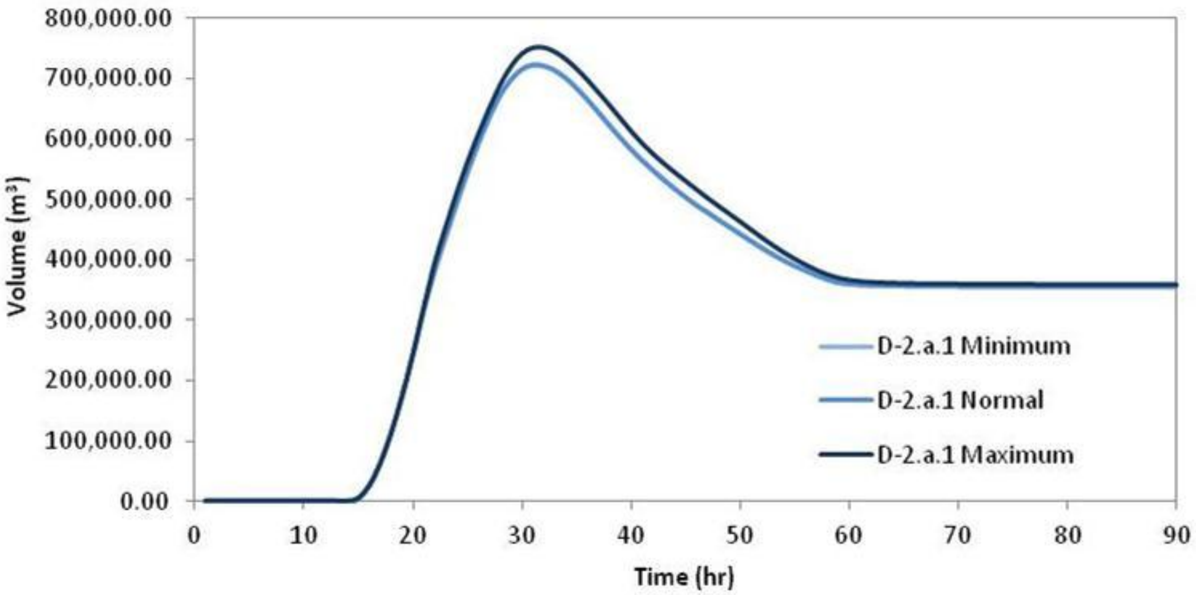


Figure C.4.3 Linked ISIS 1D-2D model floodplain Manning's 'n' inundation volume (m^3) sensitivity test results

Table C.4.1 Linked ISIS 1D-2D model floodplain Manning's 'n' inundation depth (m) sensitivity test results

Manning's 'n'		Hydrograph depth (m)	
Description	**Value**	**Peak**	**90th hour**
D2a1 NORM	0.03	2.01	1.60
D2a1 MIN	0.025	1.99	1.57
D2a1 MAX	0.035	2.02	1.60

Table C.4.2 Linked ISIS 1D-2D model floodplain Manning's 'n' inundation velocity (m.s^{-1}) sensitivity test results

Manning's 'n'		Hydrograph velocity (m.s^{-1})	
Description	**Value**	**Peak**	**90th hour**
D2a1 NORM	0.03	1.27	0.14
D2a1 MIN	0.025	1.42	0.19
D2a1 MAX	0.035	1.11	0.14

C.5 ISIS 1D model parameterisation and validation

C.5.1 ISIS 1D model parameterisation

Table C.5.1 Global roughness Chow table lookup method for the river channel Manning's 'n' roughness values:

	Type of Channel	Description	Manning's 'n'		
			Minimum	Normal	Maximum
1	C. Excavated or dredged	b. Earth, winding and sluggish 2. Grass, some weeds	0.025	0.03	0.033
2	C. Excavated or dredged	b. Earth, winding and sluggish Stony bottom and weedy banks	0.025	0.035	0.04

Table C.5.2 Chow table lookup method for the floodplain Manning's 'n' roughness value

	Type of Channel	Description	Manning's 'n' values		
			Minimum	Normal	Maximum
1	D-2. Floodplains	Pasture, no brush Short grass	0.025	0.03	0.035

Table C.5.3 Cowan's equation Manning's 'n' values

Cross section	n_0	n_1	n_2	n_3	n_4	m_5	n
IV-03418	0.024	0.005	0.005	0	0.005	1	0.039
IV-03193	0.024	0.005	0.005	0	0.005	1	0.039
IV-02994	0.024	0.005	0.005	0	0.005	1.3	0.051
IV-02796	0.024	0.01	0.01	0	0.005	1	0.049
IV-02595	0.024	0.01	0.005	0	0.005	1.15	0.051
IV-02351	0.024	0.005	0.005	0.01	0.005	1	0.049
IV-02252	0.024	0.01	0.005	0.01	0.005	1	0.054
IV-02246	0.024	0.01	0.005	0.01	0.005	1	0.054
IV-02186	0.024	0.005	0.005	0	0.005	1.15	0.045
IV-02128	0.024	0.02	0.01	0	0.005	1.15	0.068
IV-02022	0.024	0.005	0.005	0	0.005	1	0.039
IV-01817	0.024	0.01	0.01	0	0.005	1.15	0.056
IV-01574	0.024	0.005	0.01	0	0.005	1	0.044
IV-01383	0.024	0.01	0.01	0	0.005	1	0.049
IV-01193	0.024	0.005	0.005	0	0.005	1.3	0.051
IV-01013	0.024	0.005	0.005	0	0.005	1	0.039
IV-00726	0.024	0.01	0.005	0	0.005	1.15	0.051
IV-00599	0.024	0.02	0.01	0	0.005	1.15	0.068
IV-00526	0.024	0.005	0.01	0	0.005	1.15	0.051
IV-00422	0.024	0.01	0.01	0	0.005	1.15	0.056
IV-00201	0.024	0.02	0.01	0	0.005	1.15	0.068
IV-00052	0.024	0.02	0.005	0	0.005	1	0.054

C.5.2 ISIS 1D model validation results

Table C.5.4 Manning's 'n' C.b.2 and C.b.5 minimum values ISIS 1D model results

Cross section	Flow ($m^3.s^{-1}$)	Stage (mAOD)	Froude (No.)	Velocity ($m.s^{-1}$)	Z (mAOD)
IV-03418	4.5	18.394	0.162	0.419	17.52
IV-03193	4.5	18.38	0.079	0.273	16.888
IV-02994	4.5	18.368	0.103	0.329	16.934
IV-02796	4.5	18.35	0.122	0.362	17.111
IV-02595U	4.5	18.341	0.072	0.247	16.841
IV-02595D	4.5	18.148	0.093	0.294	16.841
IV-02595Di	4.5	18.141	0.123	0.372	16.935
IV-02595Dii	4.5	18.127	0.17	0.49	17.029
IV-02595Diii	4.5	18.095	0.255	0.689	17.124
IV-02351	4.5	17.988	0.505	1.179	17.218
IV-02252	4.5	17.877	0.464	0.802	17.322
IV-02246	4.5	17.884	0.306	0.606	17.144
IV-02186	4.5	17.871	0.157	0.455	16.72
IV-02128	4.5	17.876	0.062	0.196	16.506
IV-02022	4.5	17.873	0.07	0.224	16.519
IV-01817	4.5	17.865	0.076	0.245	16.434
IV-01574	4.5	17.857	0.074	0.267	15.827
IV-01383	4.5	17.856	0.039	0.157	15.28
IV-01193	4.5	17.853	0.048	0.198	15.574
IV-01013U	4.5	17.852	0.036	0.155	15.316
IV-01013D	4.5	15.892	0.635	1.24	15.316
IV-01013Di	4.5	15.564	0.381	0.743	14.964
IV-00726	4.5	15.522	0.126	0.263	14.611
IV-00599	4.5	15.432	0.412	0.879	14.674
IV-00526	4.5	15.312	0.455	0.986	14.521
IV-00526i	4.5	15.293	0.245	0.645	14.275
IV-00422	4.5	15.288	0.153	0.472	14.03
IV-00422i	4.5	15.257	0.213	0.563	14.306
IV-00201	4.5	15.133	0.534	1.007	14.582
IV-00052	4.5	14.865	0.348	0.737	14.158

Table C.5.5 Manning's 'n' C.b.2 normal value ISIS 1D model results

Cross section	Flow ($m^3.s^{-1}$)	Stage (mAOD)	Froude (No.)	Velocity ($m.s^{-1}$)	Z (mAOD)
IV-03418	4.5	18.417	0.154	0.405	17.52
IV-03193	4.5	18.396	0.077	0.27	16.888
IV-02994	4.5	18.38	0.101	0.325	16.934
IV-02796	4.5	18.355	0.121	0.36	17.111
IV-02595U	4.5	18.341	0.072	0.247	16.841
IV-02595D	4.5	18.203	0.086	0.279	16.841
IV-02595Di	4.5	18.195	0.114	0.352	16.935
IV-02595Dii	4.5	18.18	0.156	0.461	17.029
IV-02595Diii	4.5	18.147	0.232	0.644	17.124
IV-02351	4.5	18.039	0.443	1.08	17.218
IV-02252	4.5	17.902	0.413	0.742	17.322
IV-02246	4.5	17.904	0.284	0.577	17.144
IV-02186	4.5	17.884	0.153	0.448	16.72
IV-02128	4.5	17.887	0.061	0.194	16.506
IV-02022	4.5	17.882	0.069	0.222	16.519
IV-01817	4.5	17.872	0.075	0.243	16.434
IV-01574	4.5	17.86	0.074	0.267	15.827
IV-01383	4.5	17.857	0.039	0.157	15.28
IV-01193	4.5	17.854	0.048	0.197	15.574
IV-01013U	4.5	17.852	0.036	0.155	15.316
IV-01013D	4.5	15.941	0.536	1.098	15.316
IV-01013Di	4.5	15.628	0.311	0.637	14.964
IV-00726	4.5	15.578	0.111	0.233	14.611
IV-00599	4.5	15.492	0.344	0.778	14.674
IV-00526	4.5	15.377	0.378	0.867	14.521
IV-00526i	4.5	15.348	0.219	0.598	14.275
IV-00422	4.5	15.339	0.142	0.449	14.03
IV-00422i	4.5	15.303	0.194	0.529	14.306
IV-00201	4.5	15.178	0.448	0.895	14.582
IV-00052	4.5	14.919	0.295	0.658	14.158

Table C.5.6 Manning's 'n' C.b.2 maximum value ISIS 1D model results

Cross section	Flow ($m^3.s^{-1}$)	Stage (mAOD)	Froude (No.)	Velocity ($m.s^{-1}$)	Z (mAOD)
IV-03418	4.5	18.432	0.15	0.397	17.52
IV-03193	4.5	18.406	0.076	0.268	16.888
IV-02994	4.5	18.387	0.1	0.323	16.934
IV-02796	4.5	18.359	0.12	0.359	17.111
IV-02595U	4.5	18.341	0.072	0.247	16.841
IV-02595D	4.5	18.234	0.082	0.271	16.841
IV-02595Di	4.5	18.226	0.109	0.341	16.935
IV-02595Dii	4.5	18.21	0.149	0.446	17.029
IV-02595Diii	4.5	18.175	0.22	0.621	17.124
IV-02351	4.5	18.066	0.416	1.034	17.218
IV-02252	4.5	17.917	0.386	0.71	17.322
IV-02246	4.5	17.917	0.272	0.56	17.144
IV-02186	4.5	17.892	0.151	0.444	16.72
IV-02128	4.5	17.894	0.06	0.193	16.506
IV-02022	4.5	17.888	0.068	0.221	16.519
IV-01817	4.5	17.876	0.075	0.242	16.434
IV-01574	4.5	17.862	0.073	0.266	15.827
IV-01383	4.5	17.859	0.039	0.157	15.28
IV-01193	4.5	17.854	0.047	0.197	15.574
IV-01013U	4.5	17.852	0.036	0.155	15.316
IV-01013D	4.5	15.972	0.489	1.025	15.316
IV-01013Di	4.5	15.663	0.28	0.586	14.964
IV-00726	4.5	15.61	0.101	0.217	14.611
IV-00599	4.5	15.527	0.313	0.729	14.674
IV-00526	4.5	15.414	0.343	0.811	14.521
IV-00526i	4.5	15.381	0.206	0.573	14.275
IV-00422	4.5	15.369	0.136	0.436	14.03
IV-00422i	4.5	15.331	0.184	0.511	14.306
IV-00201	4.5	15.206	0.406	0.837	14.582
IV-00052	4.5	14.952	0.269	0.619	14.158

Table C.5.7 Manning’s ‘n’ C.b.5 normal value ISIS 1D model results

Cross section	**Flow ($m^3.s^{-1}$)**	**Stage (mAOD)**	**Froude (No.)**	**Velocity ($m.s^{-1}$)**	**Z (mAOD)**
IV-03418	4.5	18.446	0.145	0.389	17.52
IV-03193	4.5	18.418	0.075	0.265	16.888
IV-02994	4.5	18.398	0.099	0.32	16.934
IV-02796	4.5	18.366	0.119	0.356	17.111
IV-02595U	4.5	18.347	0.072	0.246	16.841
IV-02595D	4.5	18.255	0.08	0.266	16.841
IV-02595Di	4.5	18.246	0.106	0.334	16.935
IV-02595Dii	4.5	18.23	0.145	0.437	17.029
IV-02595Diii	4.5	18.194	0.213	0.607	17.124
IV-02351	4.5	18.084	0.399	1.006	17.218
IV-02252	4.5	17.927	0.369	0.69	17.322
IV-02246	4.5	17.926	0.263	0.548	17.144
IV-02186	4.5	17.898	0.15	0.441	16.72
IV-02128	4.5	17.899	0.06	0.192	16.506
IV-02022	4.5	17.893	0.068	0.22	16.519
IV-01817	4.5	17.88	0.075	0.242	16.434
IV-01574	4.5	17.864	0.073	0.266	15.827
IV-01383	4.5	17.859	0.039	0.157	15.28
IV-01193	4.5	17.855	0.047	0.197	15.574
IV-01013U	4.5	17.852	0.036	0.155	15.316
IV-01013D	4.5	15.991	0.462	0.982	15.316
IV-01013Di	4.5	15.686	0.264	0.556	14.964
IV-00726	4.5	15.631	0.096	0.207	14.611
IV-00599	4.5	15.55	0.295	0.7	14.674
IV-00526	4.5	15.438	0.323	0.778	14.521
IV-00526i	4.5	15.403	0.198	0.558	14.275
IV-00422	4.5	15.39	0.132	0.428	14.03
IV-00422i	4.5	15.35	0.178	0.498	14.306
IV-00201	4.5	15.223	0.382	0.804	14.582
IV-00052	4.5	14.971	0.256	0.597	14.158

Table C.5.8 Manning’s ‘n’ C.b.5 normal value 1D model results

Cross section	Flow ($m^3.s^{-1}$)	Stage (mAOD)	Froude (No.)	Velocity ($m.s^{-1}$)	Z (mAOD)
IV-03418	4.5	18.496	0.132	0.364	17.52
IV-03193	4.5	18.464	0.072	0.256	16.888
IV-02994	4.5	18.44	0.093	0.307	16.934
IV-02796	4.5	18.404	0.112	0.342	17.111
IV-02595U	4.5	18.38	0.069	0.239	16.841
IV-02595D	4.5	18.305	0.075	0.255	16.841
IV-02595Di	4.5	18.296	0.099	0.319	16.935
IV-02595Dii	4.5	18.278	0.135	0.415	17.029
IV-02595Diii	4.5	18.24	0.198	0.575	17.124
IV-02351	4.5	18.127	0.364	0.942	17.218
IV-02252	4.5	17.952	0.334	0.644	17.322
IV-02246	4.5	17.949	0.245	0.522	17.144
IV-02186	4.5	17.914	0.146	0.434	16.72
IV-02128	4.5	17.912	0.059	0.189	16.506
IV-02022	4.5	17.905	0.067	0.218	16.519
IV-01817	4.5	17.888	0.074	0.24	16.434
IV-01574	4.5	17.868	0.073	0.265	15.827
IV-01383	4.5	17.862	0.038	0.157	15.28
IV-01193	4.5	17.856	0.047	0.197	15.574
IV-01013U	4.5	17.852	0.036	0.155	15.316
IV-01013D	4.5	16.036	0.405	0.893	15.316
IV-01013Di	4.5	15.739	0.232	0.497	14.964
IV-00726	4.5	15.681	0.083	0.187	14.611
IV-00599	4.5	15.603	0.259	0.641	14.674
IV-00526	4.5	15.494	0.284	0.71	14.521
IV-00526i	4.5	15.454	0.181	0.525	14.275
IV-00422	4.5	15.437	0.124	0.409	14.03
IV-00422i	4.5	15.394	0.164	0.472	14.306
IV-00201	4.5	15.266	0.334	0.735	14.582
IV-00052	4.5	15.019	0.226	0.55	14.158

Table C.5.9 Manning's 'n' Cowan's equation value ISIS 1D model results

Cross section	Flow ($m^3.s^{-1}$)	Stage (mAOD)	Froude (No.)	Velocity ($m.s^{-1}$)	Z (mAOD)
IV-03418	4.5	18.575	0.114	0.33	17.52
IV-03193	4.5	18.551	0.065	0.24	16.888
IV-02994	4.5	18.528	0.083	0.285	16.934
IV-02796	4.5	18.484	0.099	0.315	17.111
IV-02595U	4.5	18.453	0.063	0.226	16.841
IV-02595D	4.5	18.402	0.067	0.235	16.841
IV-02595Di	4.5	18.391	0.087	0.293	16.935
IV-02595Dii	4.5	18.37	0.119	0.378	17.029
IV-02595Diii	4.5	18.329	0.173	0.521	17.124
IV-02351	4.5	18.212	0.308	0.837	17.218
IV-02252	4.5	18.004	0.275	0.567	17.322
IV-02246	4.5	17.996	0.212	0.474	17.144
IV-02186	4.5	17.947	0.138	0.418	16.72
IV-02128	4.5	17.939	0.057	0.185	16.506
IV-02022	4.5	17.928	0.065	0.213	16.519
IV-01817	4.5	17.907	0.072	0.236	16.434
IV-01574	4.5	17.875	0.072	0.264	15.827
IV-01383	4.5	17.866	0.038	0.156	15.28
IV-01193	4.5	17.857	0.047	0.197	15.574
IV-01013U	4.5	17.852	0.036	0.155	15.316
IV-01013D	4.5	16.081	0.358	0.819	15.316
IV-01013Di	4.5	15.895	0.161	0.358	14.964
IV-00726	4.5	15.857	0.054	0.139	14.611
IV-00599	4.5	15.793	0.175	0.491	14.674
IV-00526	4.5	15.688	0.193	0.543	14.521
IV-00526i	4.5	15.652	0.135	0.424	14.275
IV-00422	4.5	15.631	0.097	0.349	14.03
IV-00422i	4.5	15.578	0.124	0.387	14.306
IV-00201	4.5	15.426	0.22	0.555	14.582
IV-00052	4.5	15.144	0.171	0.455	14.158

C.6 Linked 1D-2D model scenario simulation results

C.6.1 Linked ISIS 1D-2D model inundation area scenario results

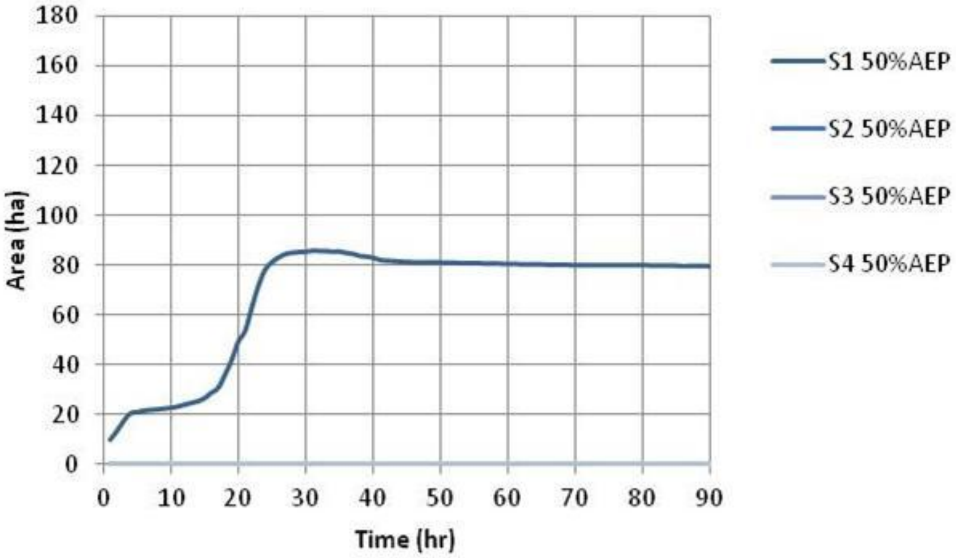


Figure C.6.1 Linked ISIS 1D-2D model 50% AEP flood event inundation area (ha) results

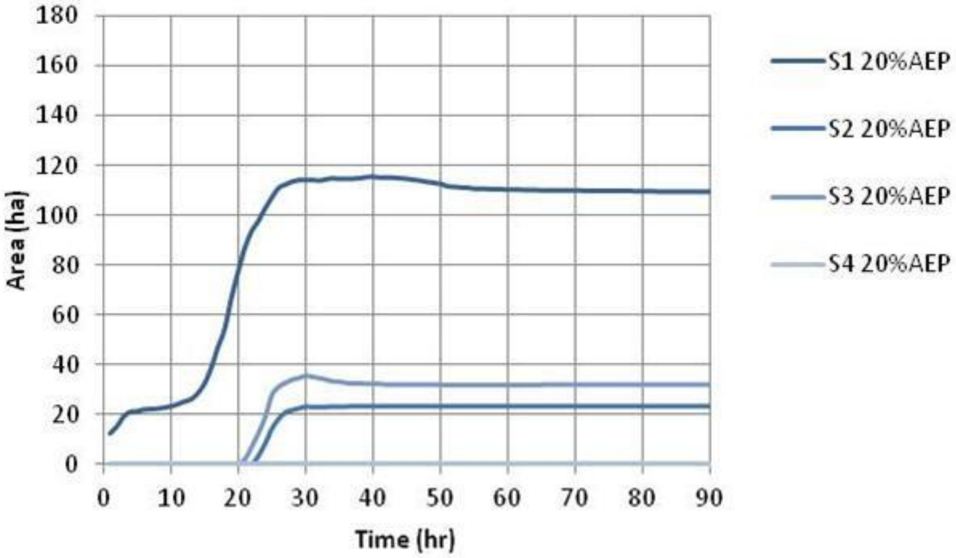


Figure C.6.2 Linked ISIS 1D-2D model 20% AEP flood event inundation area (ha) results

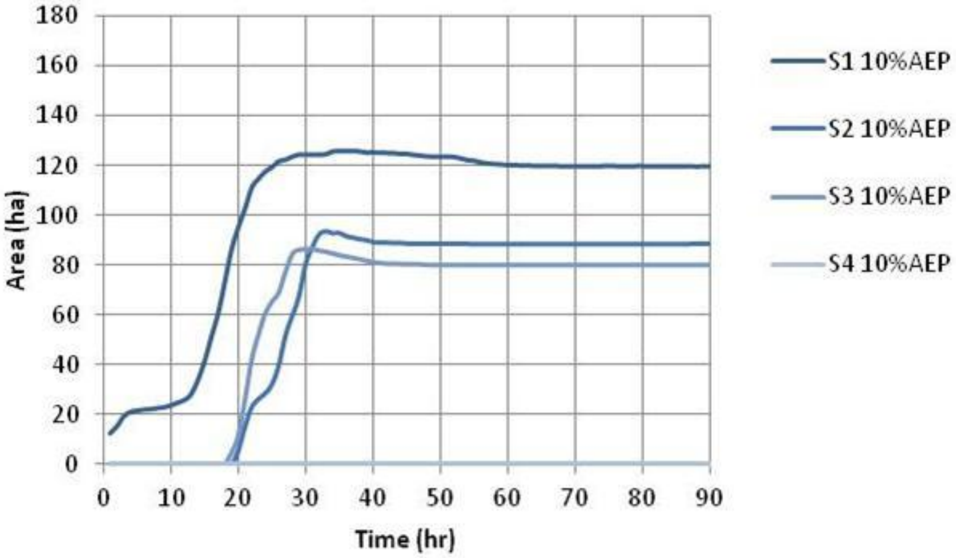


Figure C.6.3 Linked ISIS 1D-2D model 10% AEP flood event inundation area (ha) results

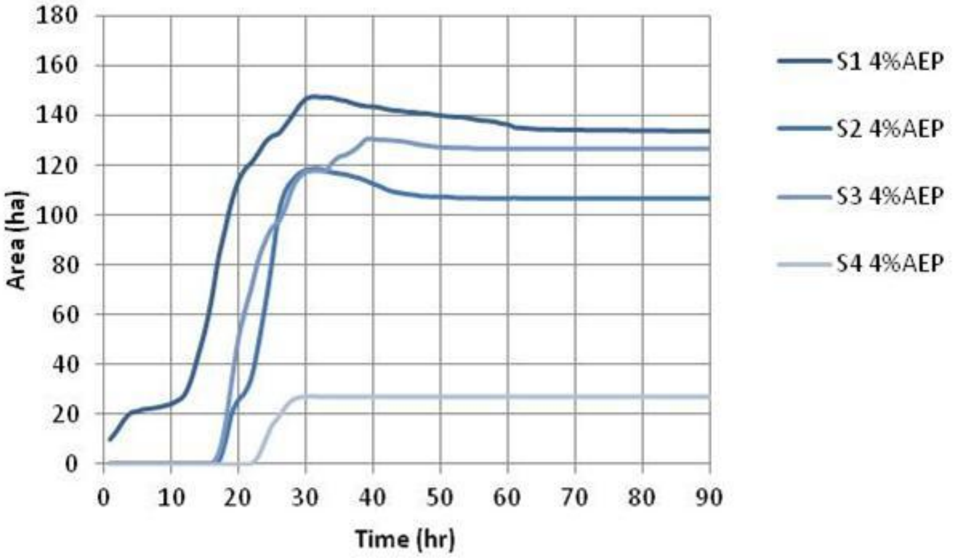


Figure C.6.4 Linked ISIS 1D-2D model 4% AEP flood event inundation area (ha) results

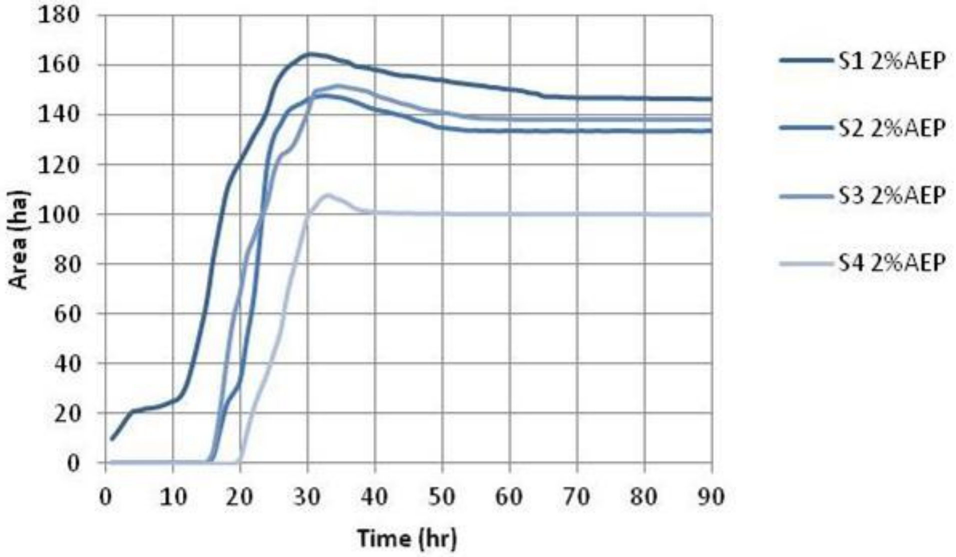


Figure C.6.5 Linked ISIS 1D-2D model 2% AEP flood event inundation area (ha) results

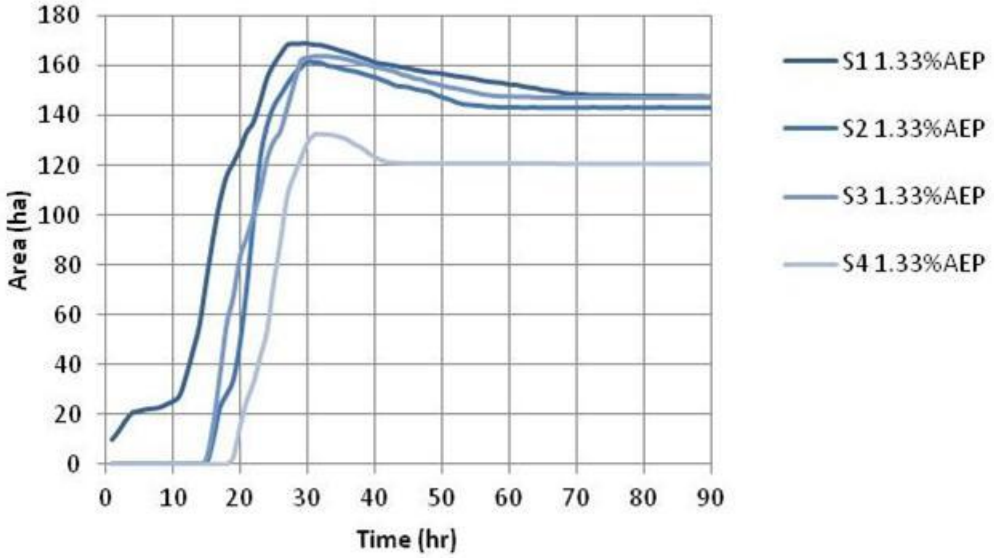


Figure C.6.6 Linked ISIS 1D-2D model 1.33% AEP flood event inundation area (ha) results

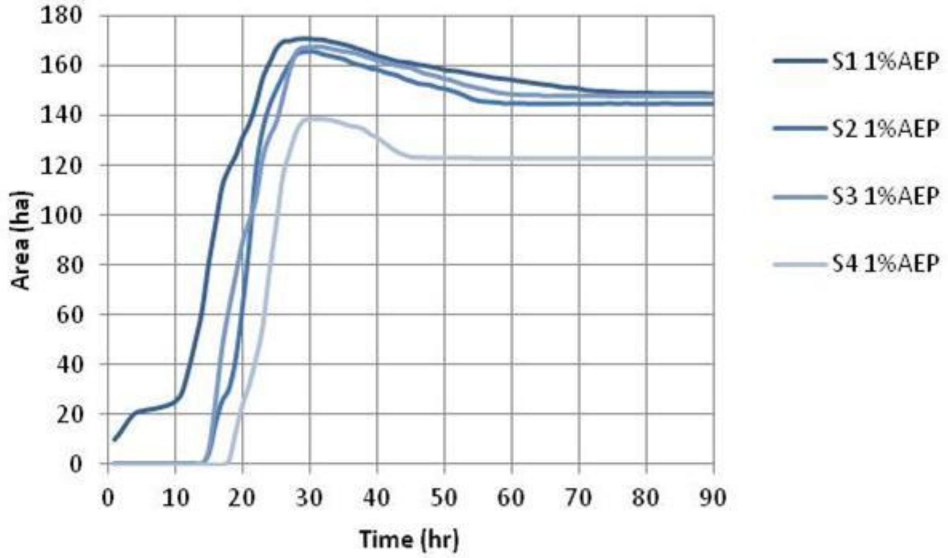


Figure C.6.7 Linked ISIS 1D-2D model 1% AEP flood event inundation results

C.6.2 Linked ISIS 1D-2D model inundation volume scenario results

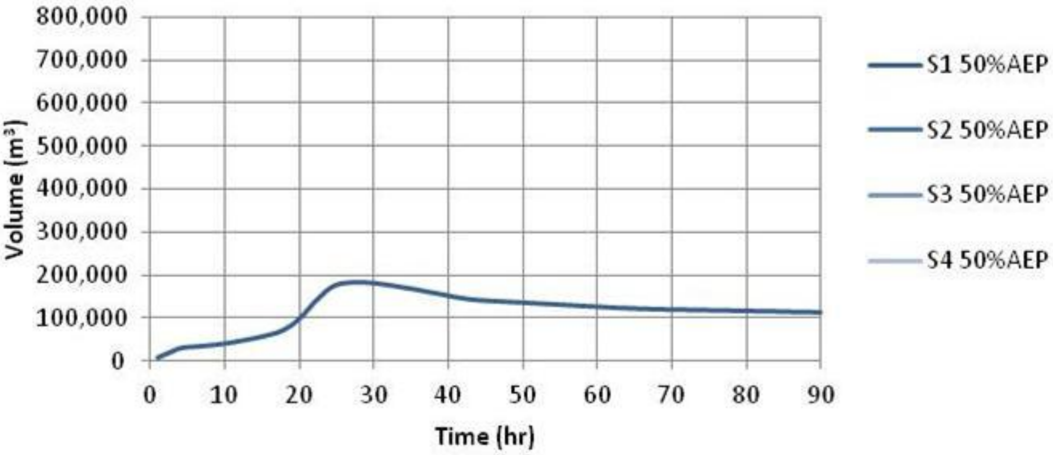


Figure C.6.8 Linked ISIS 1D-2D model 50% AEP flood event inundation volume (m^3) results

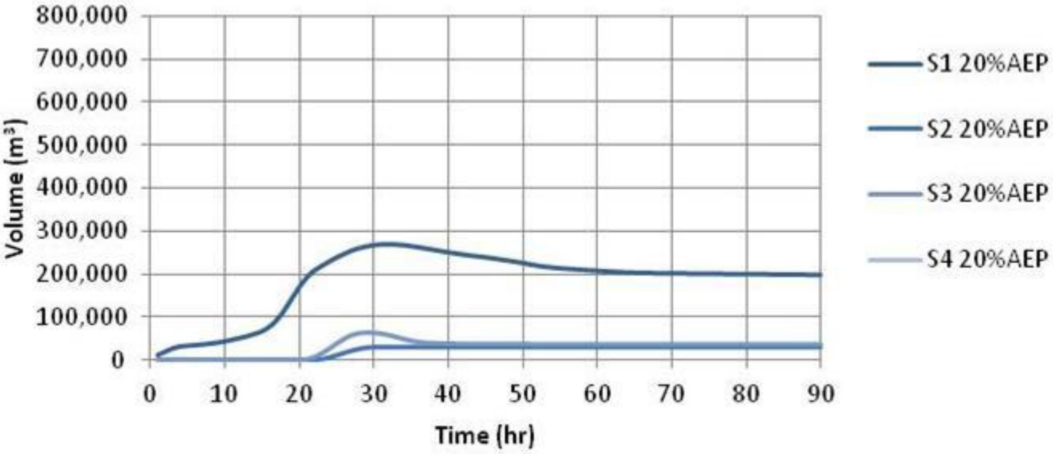


Figure C.6.9 Linked ISIS 1D-2D model 20% AEP flood event inundation volume (m^3) results

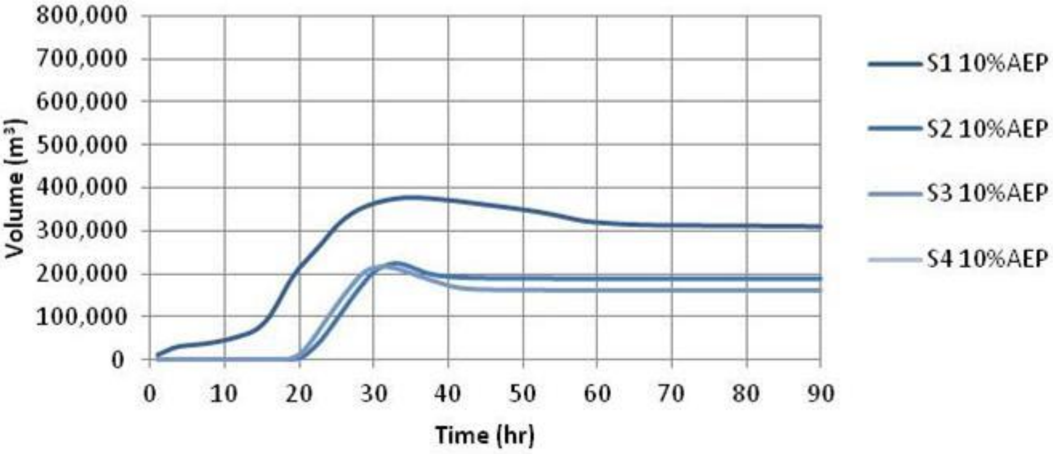


Figure C.6.10 Linked ISIS 1D-2D model 10% AEP flood event inundation volume (m^3) results

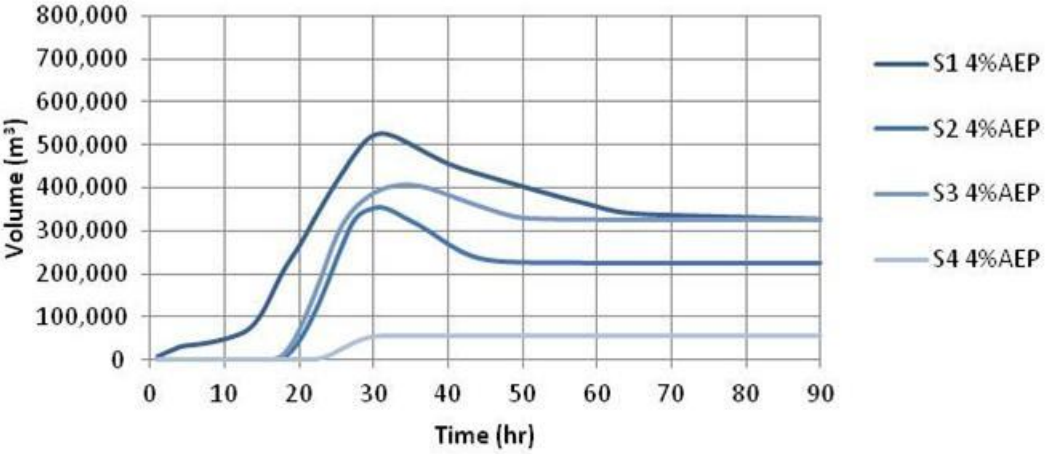


Figure C.6.11 Linked ISIS 1D-2D model 4% AEP flood event inundation volume (m^3) results

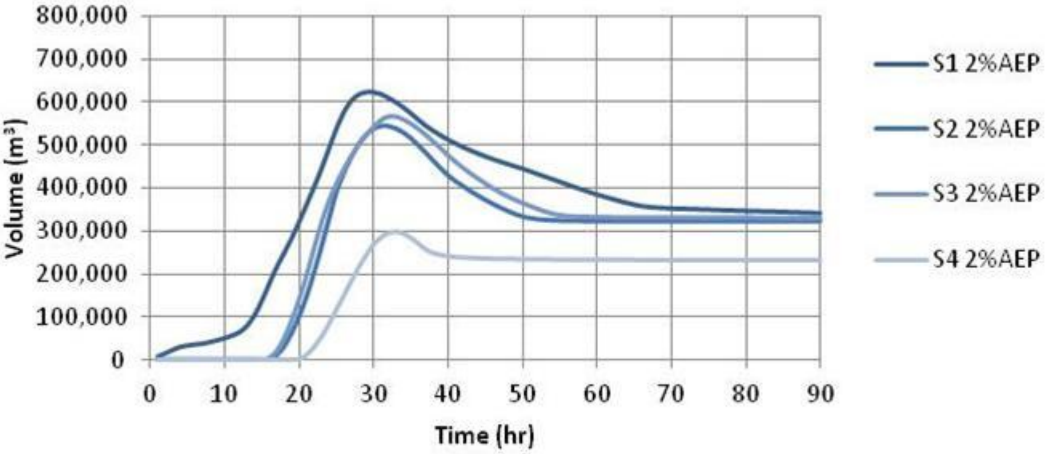


Figure C.6.12 Linked ISIS 1D-2D model 2% AEP flood event inundation volume (m^3) results

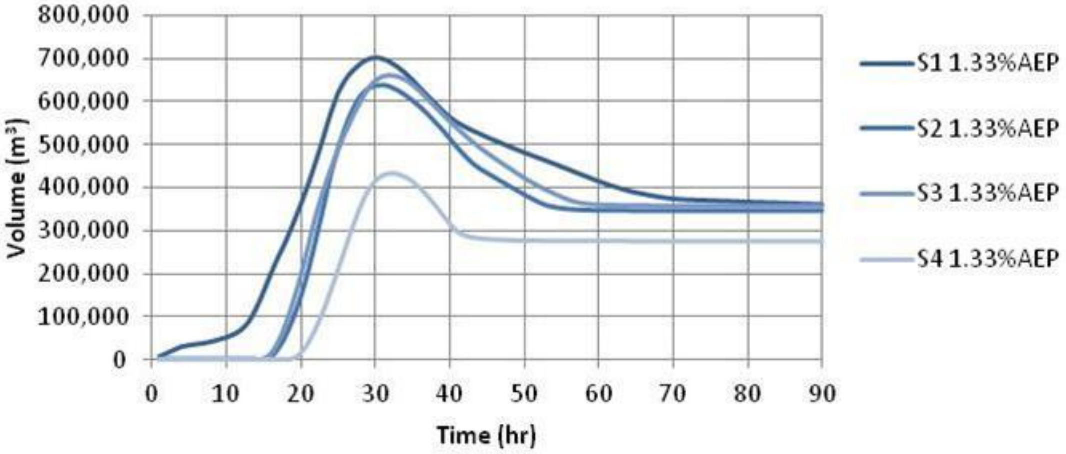


Figure C.6.13 Linked ISIS 1D-2D model 1.33% AEP flood event inundation volume (m^3) results

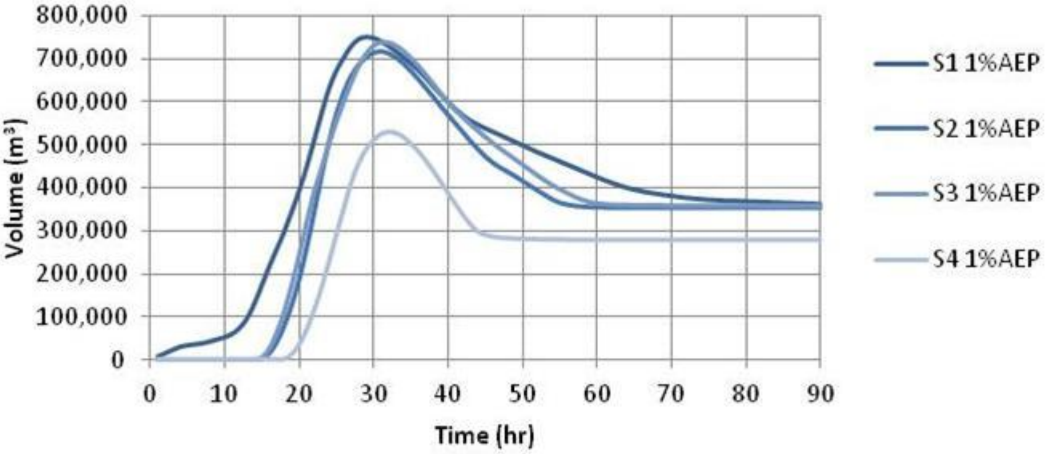


Figure C.6.14 Linked ISIS 1D-2D model 1% AEP flood event inundation volume (m^3) results

C.6.3 Linked ISIS 1D-2D model flood event discharge downstream boundary hydrographs

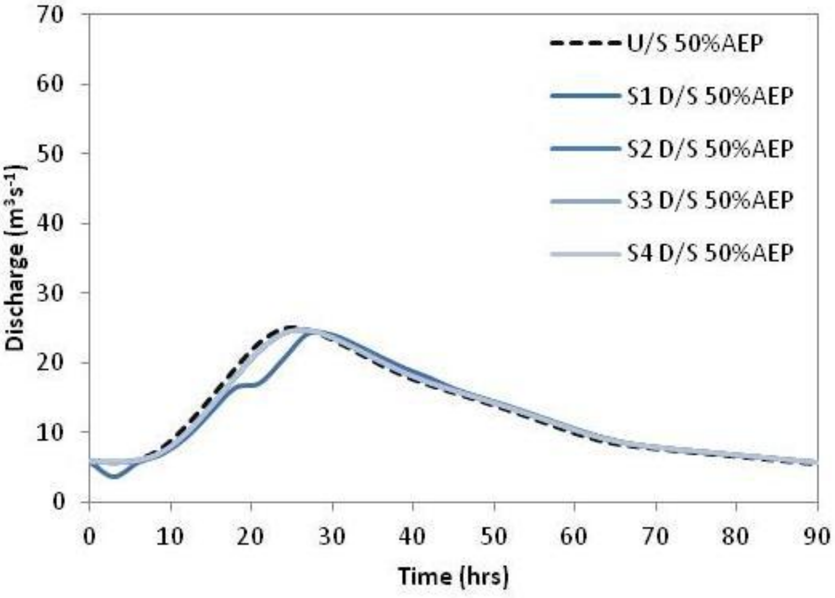


Figure C.6.15 Linked ISIS 1D-2D model 50% AEP flood event discharge ($m^3.s^{-1}$) hydrograph results

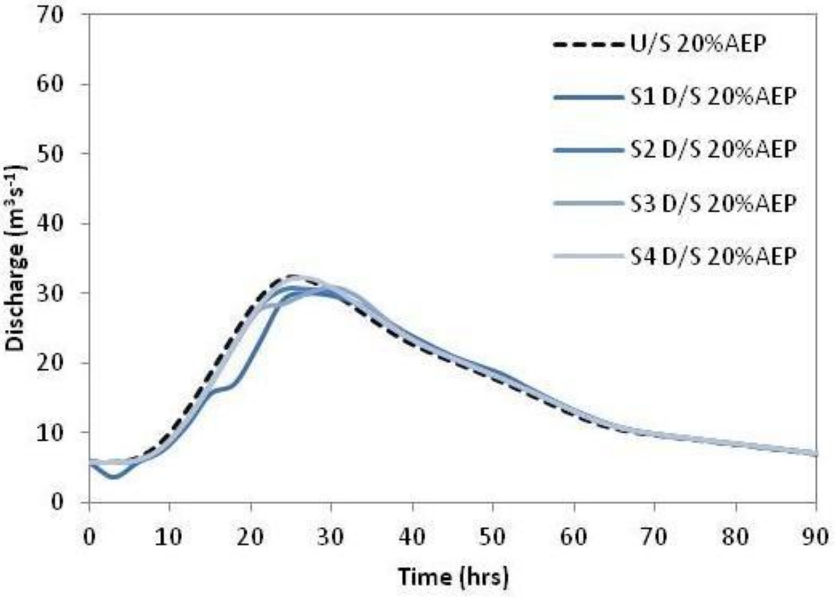


Figure C.6.16 Linked ISIS 1D-2D model 20% AEP flood event discharge ($m^3.s^{-1}$) hydrograph results

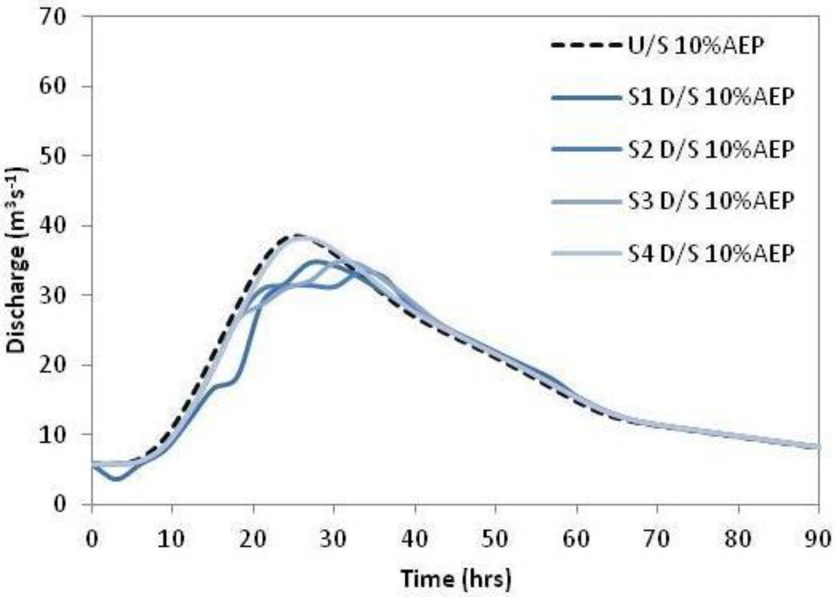


Figure C.6.17 Linked ISIS 1D-2D model 10% AEP flood event discharge ($m^3.s^{-1}$) hydrograph results

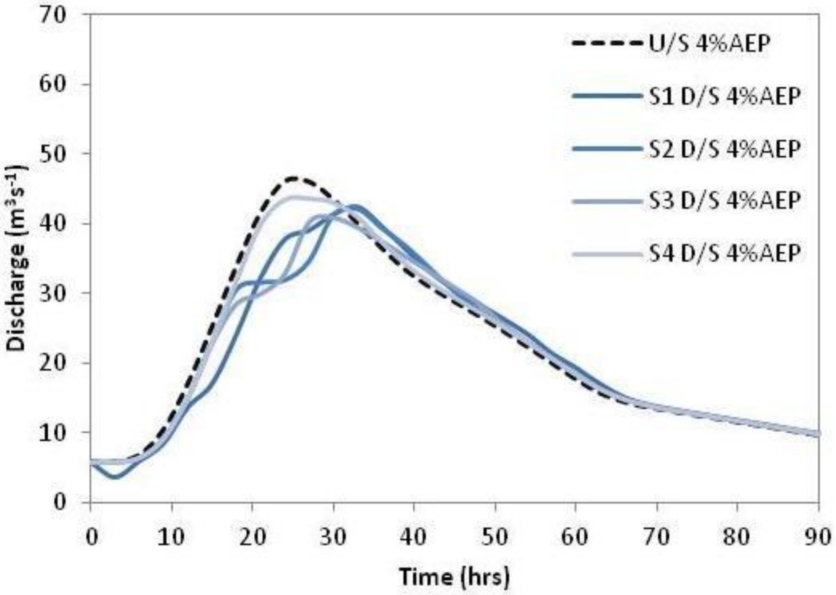


Figure C.6.18 Linked ISIS 1D-2D model 4% AEP flood event discharge ($m^3.s^{-1}$) hydrograph results

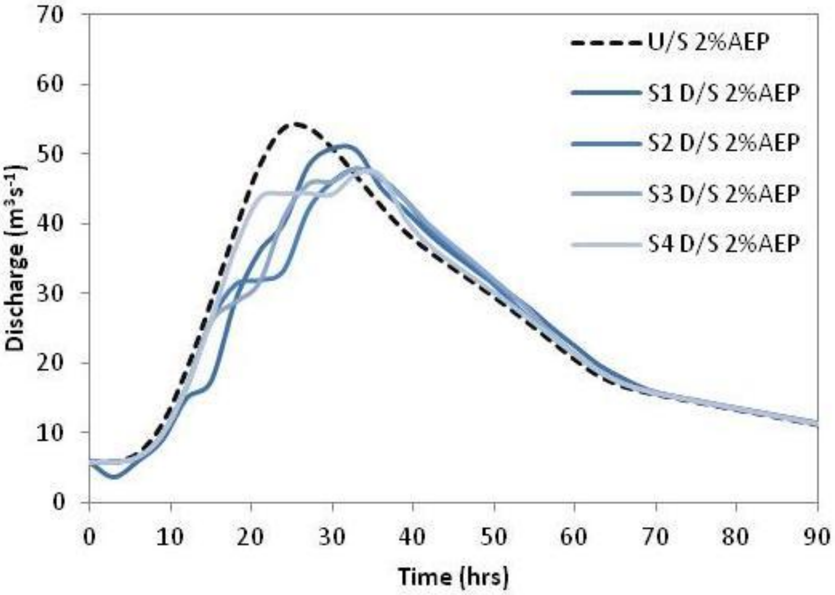


Figure C.6.19 Linked ISIS 1D-2D model 2% AEP flood event discharge ($m^3.s^{-1}$) hydrograph results

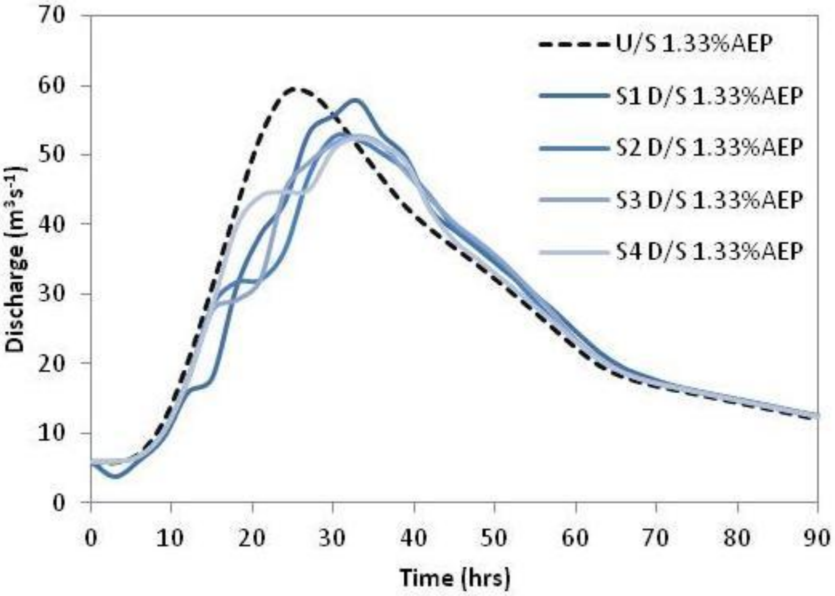


Figure C.6.20 Linked ISIS 1D-2D model 1.33% AEP flood event discharge ($m^3.s^{-1}$) hydrograph results

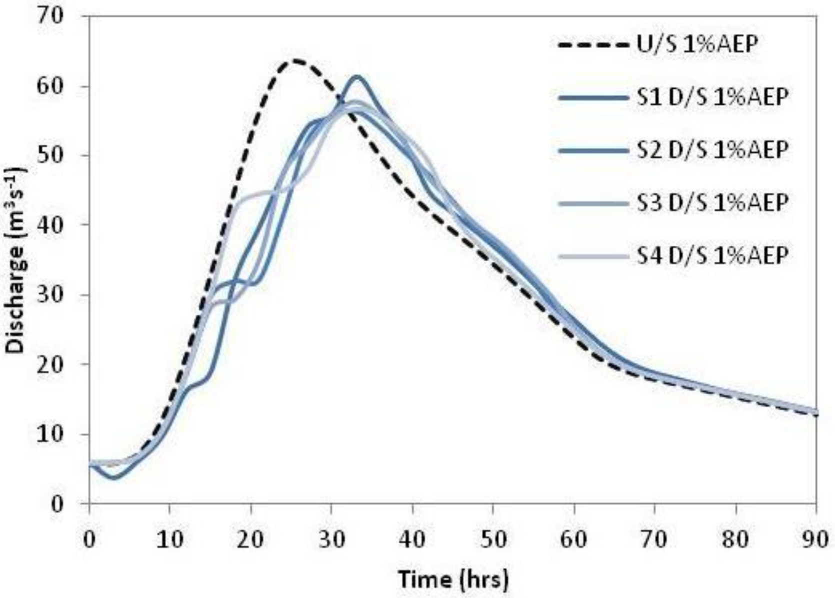


Figure C.6.21 Linked ISIS 1D-2D model 1% AEP flood event discharge hydrograph ($m^3.s^{-1}$) results

C.6.4 Linked ISIS 1D-2D model flood event inundation depth and area at the 90th hour discharge hydrographs

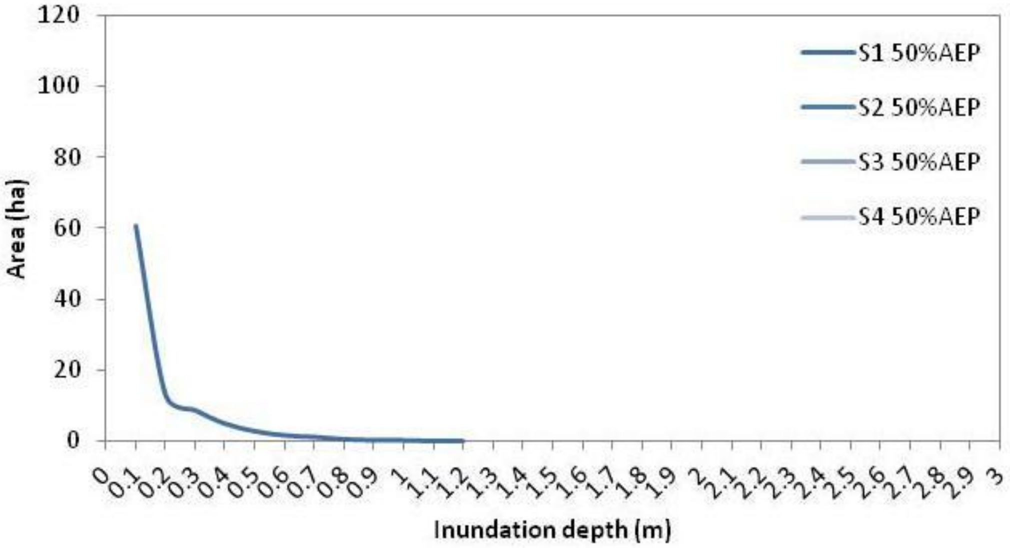


Figure C.6.22 Linked ISIS 1D-2D model 50% AEP flood event inundation depth (m) and area (ha) at the 90th hour discharge hydrograph results

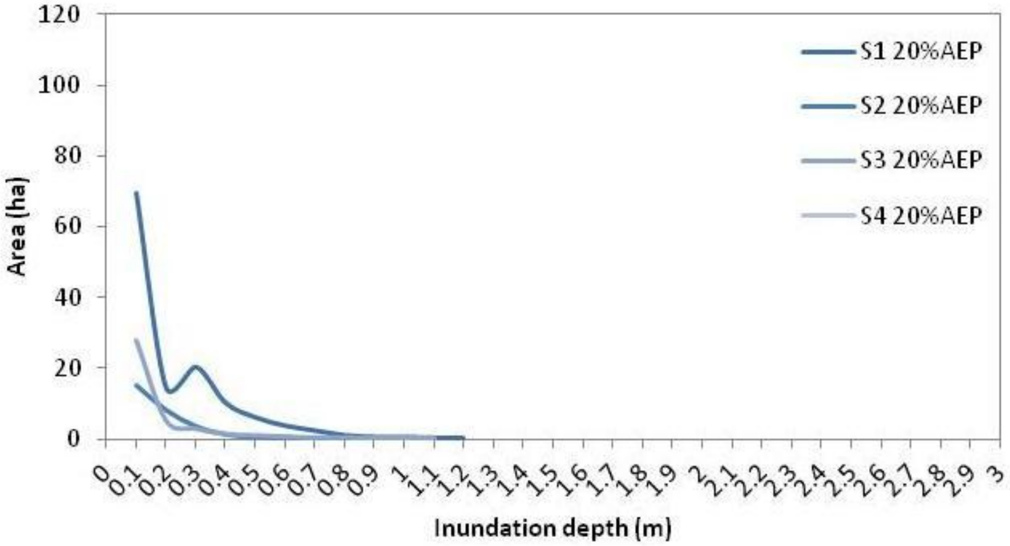


Figure C.6.23 Linked ISIS 1D-2D model 20% AEP flood event inundation depth (m) and area (ha) at the 90th hour discharge hydrograph results

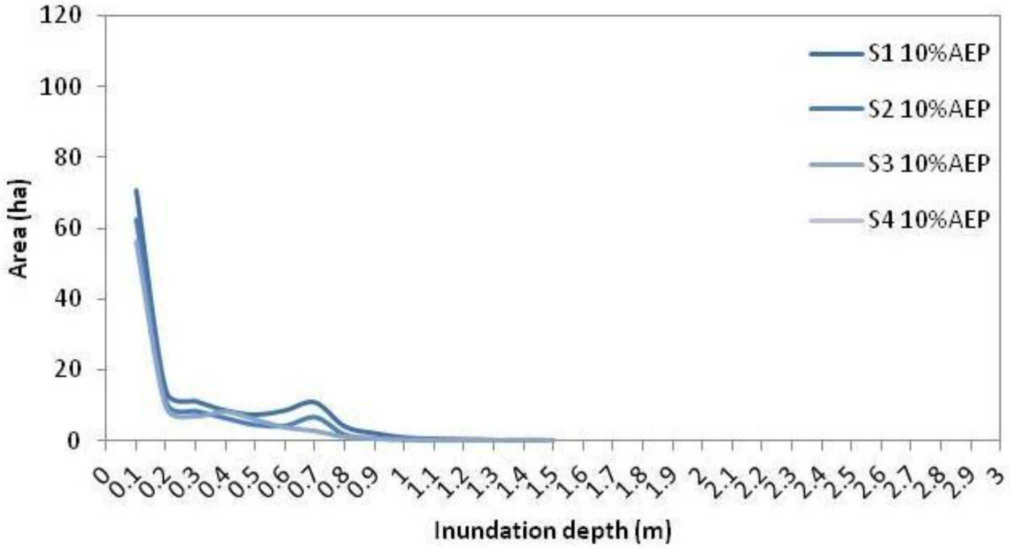


Figure C.6.24 Linked ISIS 1D-2D model 10% AEP flood inundation depth (m) and area (ha) at the 90th hour discharge hydrograph results

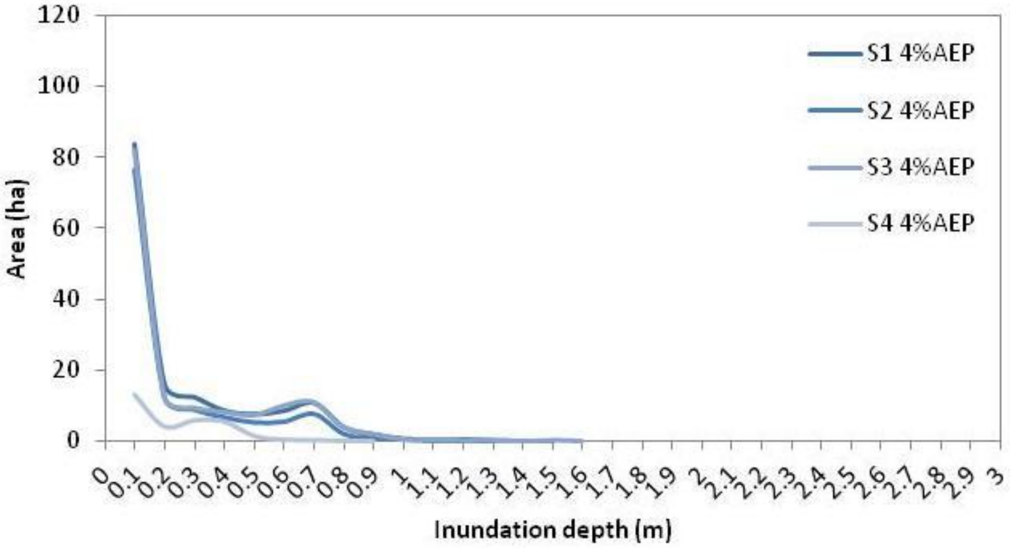


Figure C.6.25 Linked ISIS 1D-2D model 4% AEP flood event inundation depth (m) and area (ha) at the 90th hour discharge hydrograph results

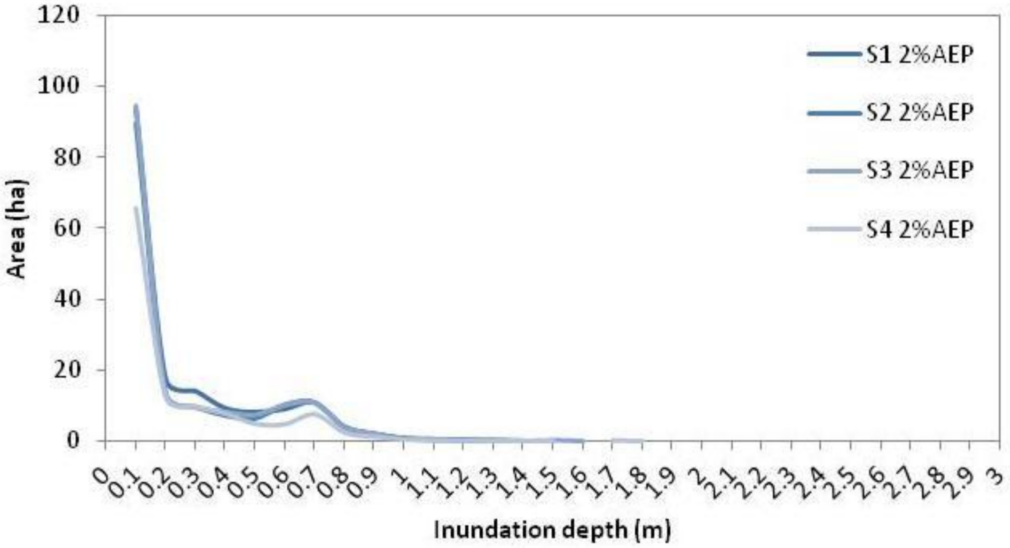


Figure C.6.26 Linked ISIS 1D-2D model 2% AEP flood event inundation depth (m) and area (ha) at the 90th hour discharge hydrograph results

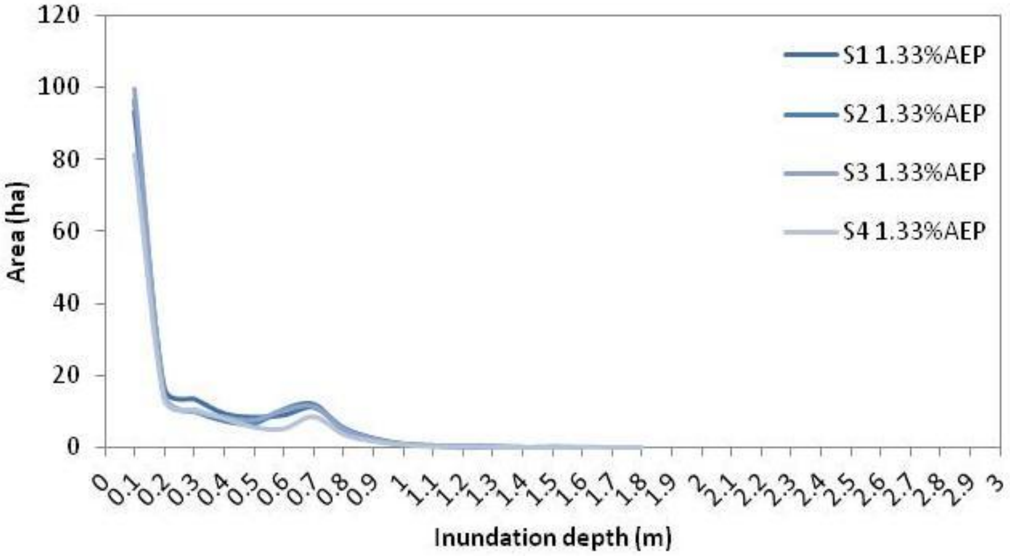


Figure C.6.27 Linked ISIS 1D-2D model 1.33% AEP flood event inundation depth (m) and area (ha) at the 90th hour discharge hydrograph results

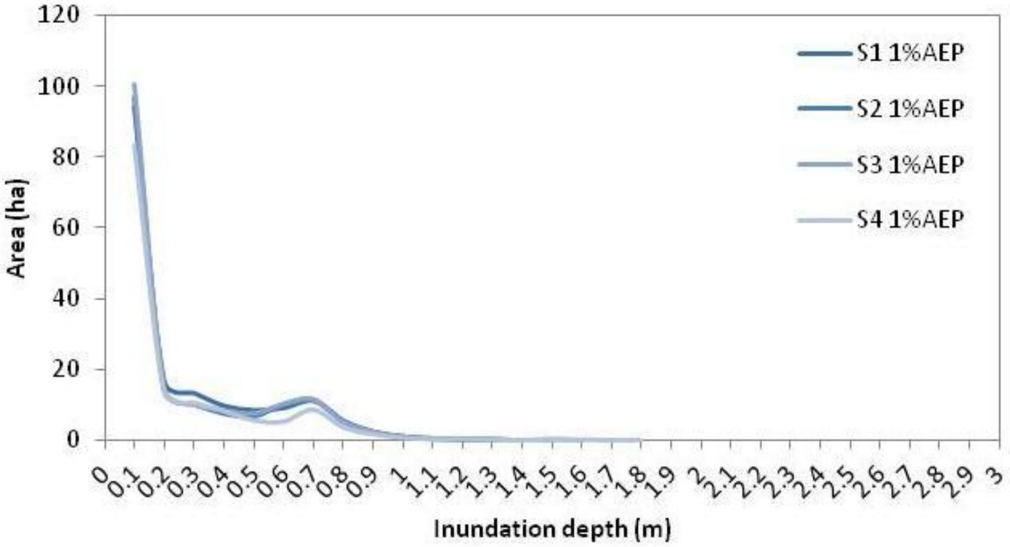


Figure C.6.28 Linked ISIS 1D-2D model 1% AEP flood event inundation depth (m) and area (ha) at the 90th hour discharge hydrograph results

C.6.5 Linked ISIS 1D-2D model flood event inundation velocity and area at the 90th hour discharge hydrograph results

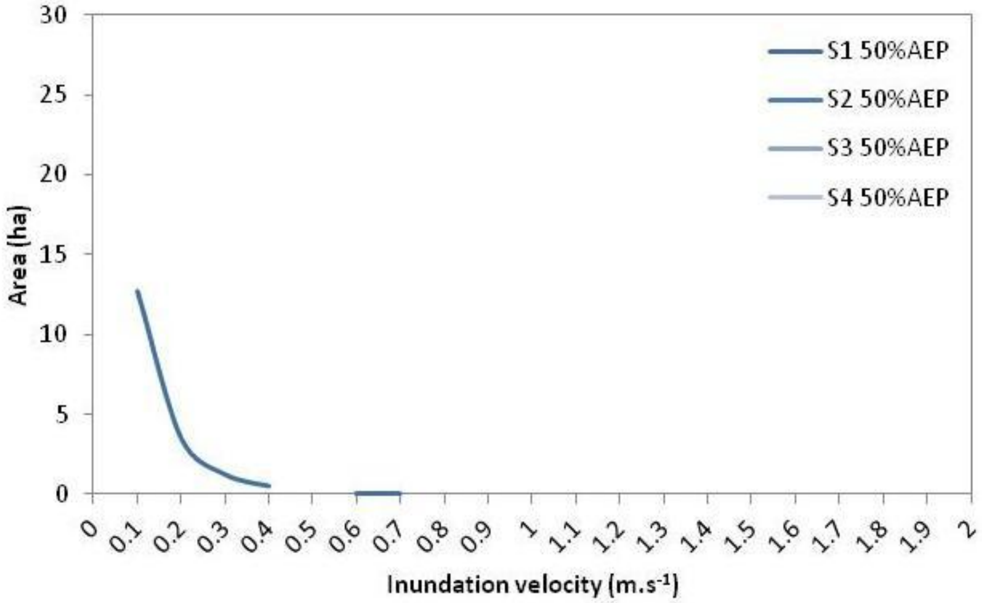


Figure C.6.29 Linked ISIS 1D-2D model 50% AEP flood event inundation velocity ($m.s^{-1}$) and area (ha) at the 90th hour discharge hydrograph results

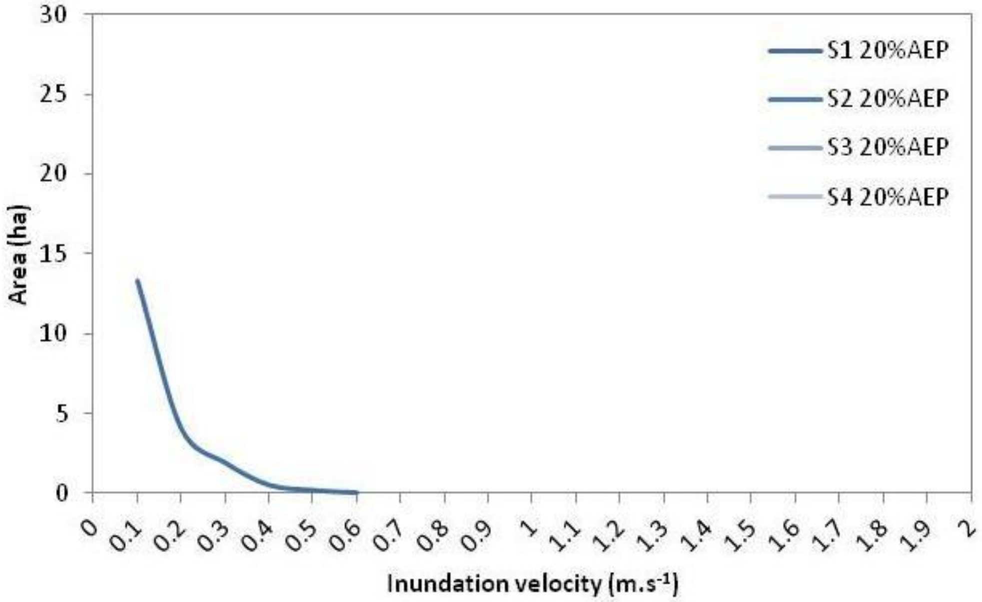


Figure C.6.30 Linked ISIS 1D-2D model 20% AEP flood event inundation velocity ($m.s^{-1}$) and area (ha) at the 90th hour discharge hydrograph results

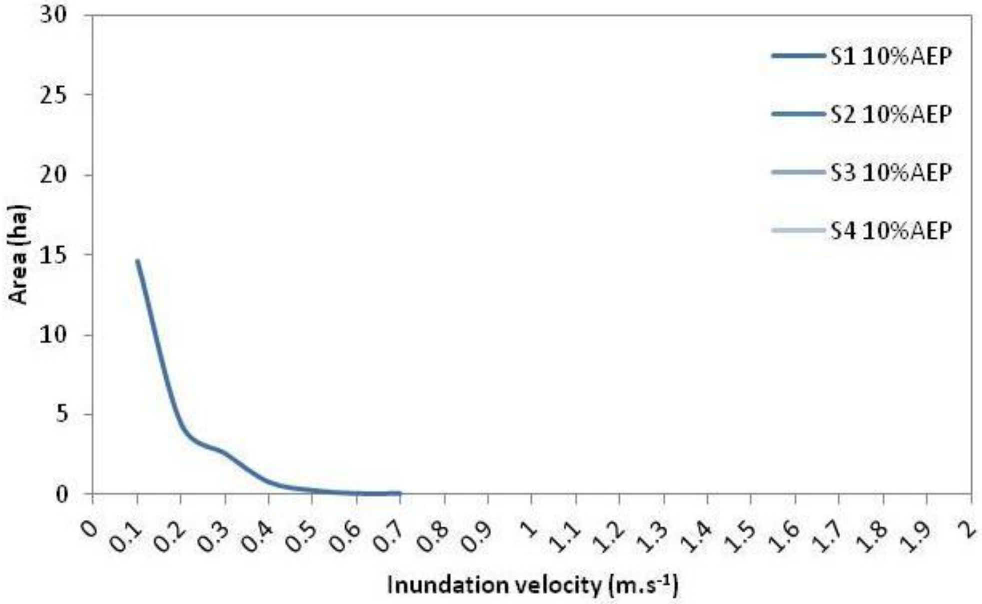


Figure C.6.31 Linked ISIS 1D-2D model 10% AEP flood event inundation velocity (m.s^{-1}) and area (ha) at the 90th hour discharge hydrograph results

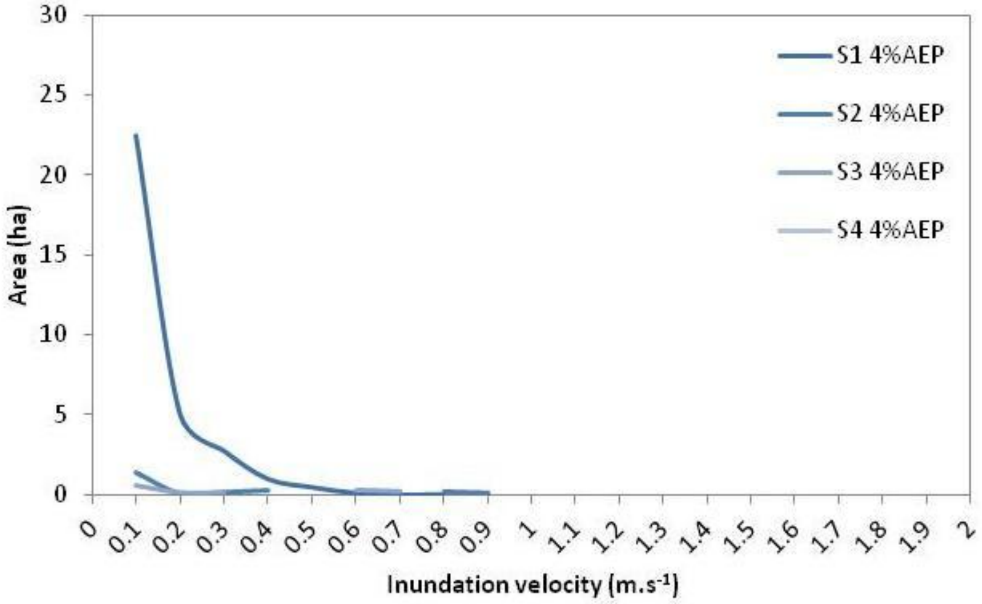


Figure C.6.32 Linked ISIS 1D-2D model 4% AEP flood event inundation velocity (m.s^{-1}) and area (ha) at the 90th hour discharge hydrograph results

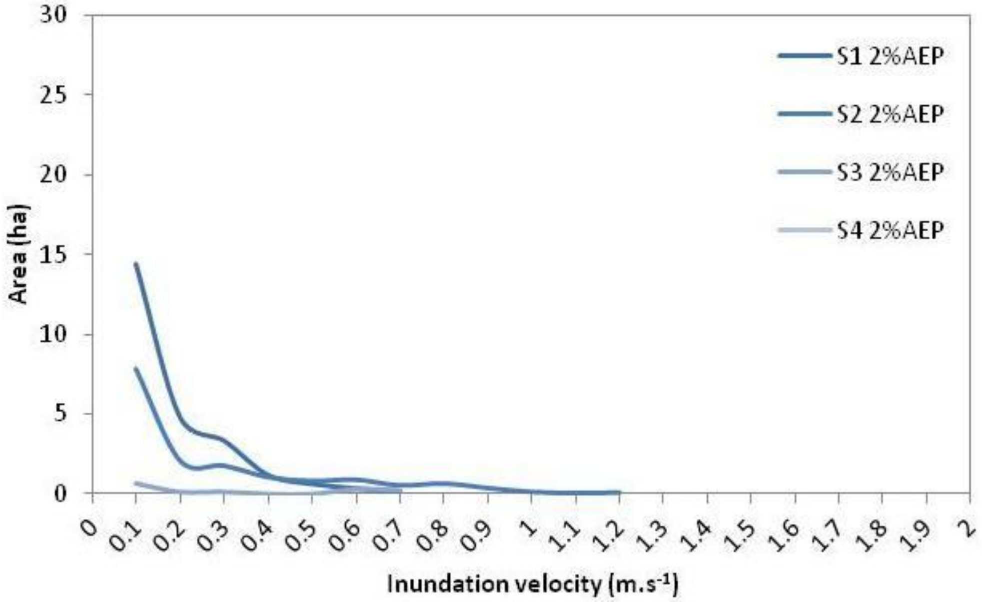


Figure C.6.33 Linked ISIS 1D-2D model 2% AEP flood event inundation velocity (m.s^{-1}) and area (ha) at the 90th hour discharge hydrograph results

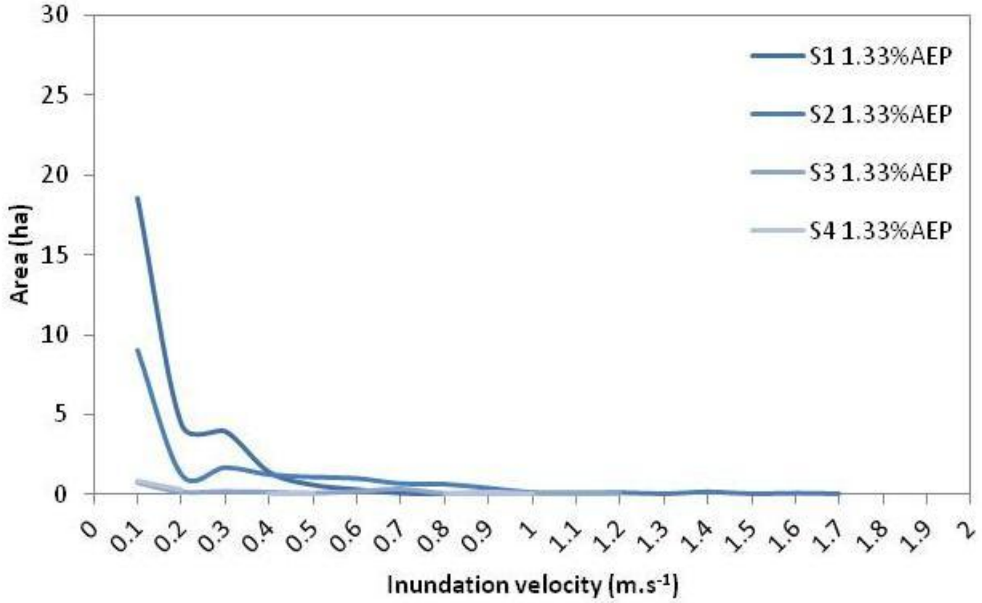


Figure C.6.34 Linked ISIS 1D-2D model 1.33% AEP flood event inundation velocity (m.s^{-1}) and area (ha) at the 90th hour discharge hydrograph results

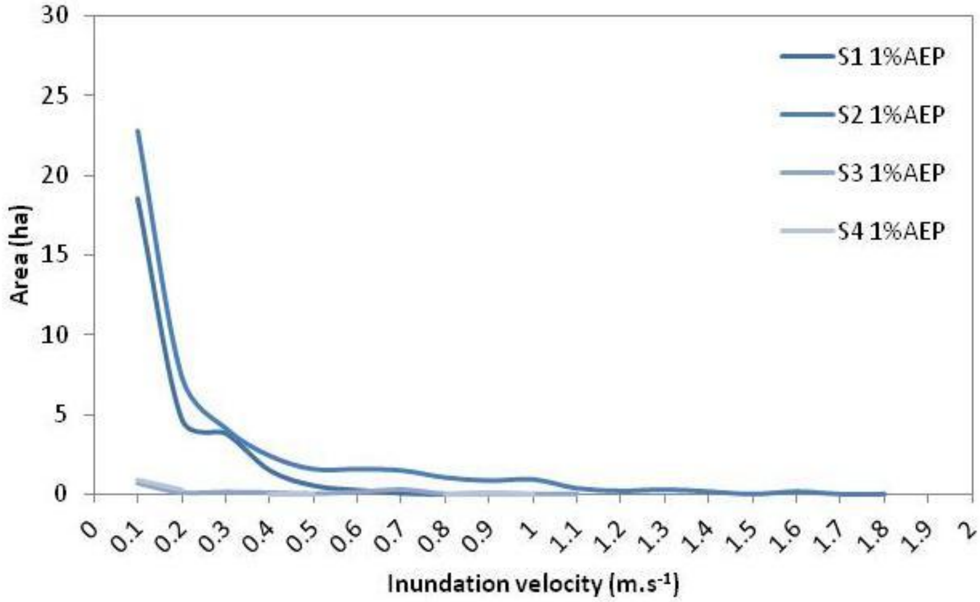


Figure C.6.35 Linked ISIS 1D-2D model 1% AEP flood event inundation velocity (m.s^{-1}) and area (ha) at the 90th hour discharge hydrograph results

Appendix D Ecosystem service indicators

D.1 Freshwater fish habitat

Table D.1.1 UK Coarse fish species habitat characteristics: water depth and flow requirements

Family	**Species**	**Common name**	**Life stage**	**Time of year**	**River type**	**Water depth requirements (cm)**	**Flow requirements ($cm.s^{-1}$)**	**Source**
Cyprindae	Abramis brama	Common bream	Larvae	May to Oct	River Great Ouse, eastern England	<100	<5	Garner (1996b)
			Juvenile	May to Oct	River Great Ouse, eastern England	<100	<5	Garner (1996b)
			Spawning	May to June	Lowland rivers	~50	<20	Mann (1996), Cowx & Welcomme, 1998 Welcomme (1998), Cowx (2001)
	Alburnus alburnus	Common bleak	Larvae	May - Oct	River Great Ouse, eastern England	<100	<5	Garner (1996b)
			Juvenile	Apr - Sept	Lower River Rhine, The Netherlands	<50	<5	Grift et al. (2003)
			Spawning	-	Lowland rivers	-	<20	Mann (1996)
Anguillidae	Anguilla anguilla	European Common Eel	Juvenile	Sept	Frémur basin, northwest France	<600	>10	Laffaille et al. (2003)
Nemadcheilidae	Barbatula barbatula	Stone Loach	Juvenile (<26mm)	Aug - Oct	Rivers Great Ouse, Rib, Lee and Hiz, eastern England	10 - 20	Little or no flow	Kováč et al. (1999)
			Juvenile (26-47mm)	Aug - Oct	Rivers Great Ouse, Rib, Lee and Hiz, eastern England	0 - 10	Weak to medium flow	Kováč et al. (1999)

Family	**Species**	**Common name**	**Life stage**	**Time of year**	**River type**	**Water depth requirements (cm)**	**Flow requirements (cm.s^{-1})**	**Source**
Nemadcheilidae			Juvenile (>47mm)	Aug - Sept	Rivers Great Ouse, Rib, Lee and Hiz, eastern England	10 - 20	Moderate flow	Kováč et al. (1999)
	Barbus barbus	Barbel	Larvae	Apr - Sept	Lower River Rhine, The Netherlands	Shallow	<20	Grift et al. (2003)
			Juvenile (>30mm)	Apr - Sept	Lower River Rhine, The Netherlands	0-100	0-30	Grift et al. (2003)
			Adult	June - Sept	River Nidd, northeast England	-	40 - 100	Lucas & Batley (1996)
			Spawning	May - June	Rivers Hull (northeast England) and Meuse(Belgium)	15-40	28-43	Hancock (1975), Philippart
	Blicca bjoerkna	Silver bream	Larvae	Apr - Sept	Lower River Rhine, The Netherlands	>50	-	Grift et al. (2003)
			Juvenile	Apr - Sept	Lower River Rhine, The Netherlands	<50	<5	Grift et al. (2003)
			Spawning	-	River Sieg, Germany	10-25	Velocities 5-60 (but thought to be sub-optimal conditions)	Freyhof (1998)
Cottidae	Cobitis taenia	Spined loach	Larvae	July	Haaren Creek, northwest Germany	25 - 45	Still/negligible	Bohlen (2000, 2003)
			Adult	All year	River Great Ouse, eastern England	-	<15	Robotham (1978)
			Spawning	July	Haaren Creek, northwest Germany	25 - 45	No preference	Bohlen (2003)
	Cottus gobio	European Bullhead	Adult		French lowland stream	20-40	>40	Roussel & Bardonnet (1996)
Cyprindae	Cyprinus carpio	Common carp	Spawning	Feb - June		>5	-	Tomlinson & Perrow (2003)

Family	**Species**	**Common name**	**Life stage**	**Time of year**	**River type**	**Water depth requirements (cm)**	**Flow requirements (cm.s^{-1})**	**Source**
			Spawning	May - July	Lowland rivers	80-100	<5	Mann (1996), Cowx & Welcomme (1998), Cowx, 2001
Esocidae	Esox lucius	Northern pike	Larvae	May - Sept	Kyrönjoki River estuary Finland,	Shallow bays (<150)	-	Urho et al. (1990)
			Juvenile	May - Sept	Kyrönjoki River estuary, Finland	~175	-	Urho et al. (1990)
Gasterosteidae	Gasterosteus aculeatus	Three spined stickleback	Spawning	March - May	Lowland rivers	200 - 350	<5	Mann (1996), Cowx (2001)
			Adult	Aug - Nov, March	Numerous locations in the Great Ouse catchment, eastern England	>20	Slow	Copp & Kováč (2003)
Cyprindae	Gobio gobio	Gudgen	Larvae	Apr - Sept	Lower River Rhine, The Netherlands	Shallow	<20	Grift et al. (2003)
Cyprindae			Juvenile	May - Oct	River Great Ouse, eastern England	<100	<5	Garner (1996b)
			Adult	-	Lowland rivers	-	<55	Mann (1996)
			Spawning	June	A small rivulet entering the Inniscarra Reservoir, Ireland	5-8	-	Kennedy & Fitzmaurice (1972)
Percidae	Gymnocephalus cernua	Ruffe	Larvae	Apr - July	St. Louis River, USA	50	-	Brown et al. (1998)
Petromyzontidae	Lampetra planeri	Eurpoean brook lamprey	Larvae	-	-	<50	-	Maitland (2003)
			Spawning	-	-	< 40	30 - 50	Hardisty & Potter (1971)

Family	**Species**	**Common name**	**Life stage**	**Time of year**	**River type**	**Water depth requirements (cm)**	**Flow requirements ($cm.s^{-1}$)**	**Source**
Cyprindae	Leuciscus cephalus	European Chub	Larvae	May - Oct	River Great Ouse, eastern England	<100	<5	Garner (1996b)
Cyprindae			Juvenile	May - Oct	River Great Ouse, eastern England	<100	<5	Garner (1996b)
			Spawning		Lowland rivers	10-30	15-75	Cowx & Welcomme (1998)
Cyprindae	Leuciscus leuciscus	Common dace	Larvae	Apr - May	River Frome, southern England	2-40	0-2.5	Mills et al. (1985)
Cyprindae			Juvenile	June - Sept	A braided side-channel of the upper River Rhône, France	<20 (but 20-50 during low discharge conditions)	Lentic waters	Copp (1992b)
			Adult	March - Apr	River Frome, southern England	Depths 17-113 (mean 62)	0-57 (mean 6)	Clough et al. (1998)
			Spawning	-	River Frome, southern England	-	20-50	Mann (1996), Cowx & Welcomme, 1998 Welcomme (1998)
Percidae	Perca fluviatilis	European perch	Larvae	May - Sept	Kyrönjoki River estuary, Finland	Shallow bays (<150 deep)	-	Urho et al. (1990)
Percidae			Juvenile	May - Sept	Kyrönjoki River estuary, Finland	- ~300	-	Urho et al. (1990)
			Spawning	Apr - May	Lowland rivers	200 - 300	-	Cowx (2001)
Cyprindae	Phoxinus phoxinus	Common minnow	Larvae	-	Upland and lowland rivers	0->15	-	Mann (1996)
			Adult	-	River Frome, southern England	-	Velocities 0-10	Garner (1997a)
			Adult	July	River Frome, southern England	Depths 10 to >50	-	Garner et al. (1998)

Family	**Species**	**Common name**	**Life stage**	**Time of year**	**River type**	**Water depth requirements (cm)**	**Flow requirements ($cm.s^{-1}$)**	**Source**
			Spawning	-	Upland and lowland rivers	10-25	20 - 30	Mann (1996), Cowx & Welcomme, 1998 Welcomme (1998)
Gasterosteidae	Pungitius pungitius	Ninespine stickleback	Adult	Aug - Nov, March	Numerous locations in the Great Ouse catchment, eastern England	>20	Low water velocity	Copp & Kováč (2003)
Cyprindae	Rutilus rutilus	Roach	Adult	Aug - Nov, March	Numerous locations in the Great Ouse catchment, eastern England	>20	Low water velocity	Copp & Kováč (2003)
			Larvae	May - Oct	River Great Ouse, eastern England	<100	<5	Garner (1996b)
			Juvenile	May - Oct	River Great Ouse, eastern England	<100	<5	Garner (1996b)
			Spawning	-	Lowland rivers	15 - 45	- >20	Mann (1996), Cowx & Welcomme (1998), Cowx, 2001
Salmonidae	Salmo trutta	Brown trout	Fry	Summer	Small streams of the Kings River basin, California	< 60	< 30	Lambert & Hanson (1989)
			0+	-	-	< 30	20-50	Roussel & Bardonnet (1999)
			Young	June, Aug, Oct, Nov	Norwegian river	30 - 100	10 - 30	Heggenes & Saltveit (1990)

Family	**Species**	**Common name**	**Life stage**	**Time of year**	**River type**	**Water depth requirements (cm)**	**Flow requirements ($cm.s^{-1}$)**	**Source**
			Juvenile (<7 cm)	Aug - Sept	Dartmoor, upland area in southwest England	-	Snout Velocities (0-21 (range) and 4 (mean). Most fishes selected snout velocities 0-5	Heggenes et al. (2002)
			Juvenile (=7cm)	Aug - Sept	Dartmoor, upland area in southwest England	-	Snout Velocities 0-44 (range) and 7 (mean). Most fishes selected snout velocities 0-5c	Heggenes et al. (2002)
Salmonidae			1+	Sept - Oct	Shelligan Burn, Scotland	> 25	-	Egglishaw & Shackley (1982)
			Parr	Aug - Sept	Todalselva and Vindøla Rivers, central Norway	> 50 to < 300	< 50	Bremset (2000)
			Adult	Summer	Norwegian and Scottish streams	9 - 305 (range) and 69 (mean)	0 - 142 (range of water column velocities), 24 (mean) and 14 (mean focal water velocity)	Heggenes (2002)
			Spawning	-	-	15-91 range, 24 (minimum) and 30-24 (optimum)	20 - 81	Jones & King (1950), Smith, 1973
Percidae	Sander lucioperca	Zander	Larvae	Apr - Sept	Lower River Rhine, The Netherlands	>50	-	Grift et al. (2003)

Family	**Species**	**Common name**	**Life stage**	**Time of year**	**River type**	**Water depth requirements (cm)**	**Flow requirements (cm.s^{-1})**	**Source**
Percidae			Adult	All year	Pyhakoski Reservoir, Finland	1.2 - 38m*	0.01 - 0.86 (mostly <0.3)	Vehanen & Lahti (2003)
			Spawning	Apr - June	Lowland rivers	50 - 100	10 - 20	Deelder & Willemsen (1964), Cowx (2001)
Cyprindae	Scardinius erythrophth-almus	Common rudd	Juvenile	May - Oct	A small abandoned channel(Les Nappes) on the upper River Rhône, France	>100	Still	Copp (1993)
			Spawning	May - July	-	10 - 90	-	Svärdson (1949), Cowx (2001)
Salmonidae	Thymallus thymallus	Grayling	Larvae (17-21mm)	June	River Kuusinkijoki, northern Finland	10 - 30	<10	Nykänen & Huusko (2003)
			Larvae (22-25mm)	June	River Kuusinkijoki, northern Finland	30 - 90	10 - 50	Nykänen & Huusko (2003)
			Larvae (26-31mm)	June	River Kuusinkijoki, northern Finland	>50	<10	Nykänen & Huusko (2003)
			Larvae	Apr - June	River Pollon, France	<40	<20	Sempeski & Gaudin (1995b)
			0+	-	Ain river, France (Rhône catchment)	50-60	70-110	Mallet et al. (2000)
			Juvenile	Apr - June	River Pollon, France	40 - 60	20 - 40	Sempeski & Gaudin (1995b)
			Adult	Autumn	River Kuusinkijoki, northeast Finland	100 - 240	<30	Nykänen et al. (2004)
			Spawning	-	Rivers Pollon and Suran, France	10 - 40	25.8 - 91.7 (mean 48.9)	Sempeski & Gaudin (1995a)
Cyprindae	Tinca tinca	Tench	Spawning	-	Lowland rivers	-	<20	Cowx & Welcomme (1998)

* Sander lucioperca (adult) fish species has a water depth requirement of 1.2-38 m.

Source: after Cowx et al. (2004)