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A soil-based approach to rainfall-runoff modelling in ungauged catchments for England and Wales

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ABSTRACT

Hydrological models are powerful tools for the investigation of many hydrological issues. The historical approach for the development of rainfall-runoff models, with regard to the choice of model structure and the calibration of the free parameters, has been to focus on gauged catchments where sufficient data, in particular stream flow data, are available. Applications of models were then extended to the case of ungauged catchments. In recent years, it has become apparent that this approach did not lead to satisfying results in ungauged catchments, and that the main focus should instead be on ungauged catchments for the implementation of new modelling strategies.

This thesis demonstrates the potential of a new conceptual, catchment-scale, semi-distributed, integrated rainfall-runoff model as a modelling tool in both ungauged and gauged catchments for the assessment of water resources management, land use change or climate changes at the catchment scale.

The review of existing model structures and regionalisation methods has lead to the development of the Catchment Resources and Soil Hydrology (CRASH) model following the top-down modelling strategy. The free parameters of the model are directly related to controlling factors of the hydrological processes in the United Kingdom, i.e. soil and land use. The classification of the soils according to their hydrological behaviour is based on the Hydrology Of Soil Types (HOST) system. CRASH also incorporates a novel rainfall disaggregation scheme for the derivation of infiltration excess surface runoff.

A regional set of model parameters has been derived from the calibration of CRASH in 32 catchments throughout England and Wales covering contrasting climatic, soil, geological, and land use conditions.

The single-site and regional CRASH models performed satisfactorily according to reviewed performance criteria for gauged catchments and to a scoring system proposed for ungauged catchments. However the quality of stream flow data in the UK which was used for the calculation of the regional parameter set, in particular the widespread unavailability of naturalised flow data, tends to limit the performance of the regional CRASH model for low flows.

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I would finally like to share this piece of work with my parents, Bénédicte and all the members of my family.

CONTRIBUTION OF THE AUTHOR

Chapters 3 to 6 of this dissertation are reported in the form of articles which have been submitted to peer-reviewed journals or conference proceedings. The author of this thesis is responsible for deriving and analysing the results and writing the papers. I.P. Holman has provided comments during the analysis of the results and writing of the papers.

AWARD

The oral presentation given at the International Environmental Modelling and Software Society conference in Lugano, Switzerland, June 24-27 2002, derived from the work presented in this dissertation was awarded the iEMSs Student Award for natural systems.

Maréchal, D. and Homan I. P. 2002. A soil hydrology-based catchment water resources model. *Proceedings International Conference on Integrated Assessment and Decision Support* (*iEMSs2002*). Lugano, Italy, June 24-27. Volume 1: 452-457.

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1 INTRODUCTION

1.1 General context

Water and rainfall-runoff models

Water is essential to life on Earth. It is thought that life has originated in the ocean to evolve and conquer the continents. The human body is itself composed of more than 80% water, which makes water the most crucial element for our survival. It is not surprising to see how the human body has adapted according to the water's physical and chemical properties. We can quote for instance the normal temperature of the human body (37°C) which is only 0.5°C below the temperature at which the water has its lowest specific heat, giving the human body a great capacity to adapt to dramatic changes of temperature (Schauberger and Coats, 1997).

This is why water has always been a subject of major interest for humans throughout history. We can see how the Romans have developed extraordinary engineering skills to carry fresh water to their cities, and how they extended the use of baths for recreation and as a place for social entertainment.

Technology has evolved since ancient Rome, but issues concerning water still exist all over the world as the Third World Water Forum in Kyoto reminded us (World Water Forum, 2003). They range from insufficient sanitation affecting mainly poor populations, to inadequate water supply, over use of water resources, floods, droughts, poor irrigation or water supply systems and excessive pollution of surface and ground water bodies. Where do rainfall-runoff models and catchment hydrology fit into the solutions for this wide range of issues? What is their aim? And what are they used for?

Rainfall-runoff models are tools to help to answer this simple question formalised by Penman (1961): "What happens to the rain"? Despite the simplicity of the question, the answer is anything but simple due to the complexity of the hydrological processes taking place. Rainfall-runoff modelling has two distinct purposes that can lead to fragmentation and frustration and slow down its own progress (Sivapalan, 2003). On one hand, rainfall-runoff models are developed and applied to test theories and to improve our understanding of hydrological processes. This is the scientific side of the rainfall-runoff modelling exercise. On the other hand, rainfall-runoff models are applied in practical cases to help with decision-making by providing estimates of the states of water bodies. This is the technological side of the rainfall-runoff modelling exercise.

They are employed for flood protection design (e.g. Simonovic and Li, 2003; Onyando *et al.*, 2003), real time flood forecasting (e.g. Aubert *et al.*, 2003; Brath *et al.*, 2002), water supply forecasting (e.g. Merabtene *et al.*, 2003; Kim *et al.*, 2001) and water resources management (e.g. Hiscock *et al.*, 2001; Wooldridge *et al.*, 2001). They can also be applied to assess the changes in stream flows, and reservoir and ground water reserves due to climate change (e.g. Gedney and Cox, 2003; Booij, 2003) or land use change (e.g. Calder *et al.*, 2003; Dye and Croke, 2003). Finally, they can be coupled to water quality models to predict the quality of water bodies (e.g. Liu *et al.*, 2003; Beaujouan *et al.*, 2003) and be associated to other models such as water quality and socio-economic models for an integrated approach to the management of water resources at the catchment scale (e.g. Giraud *et al.*, 2002).

Rainfall-runoff models need stream flow data

Rainfall-runoff models hold parameters that can not be measured either because they represent several physical processes or because the scale at which they are applied in the model does not correspond to the scale at which they can be measured. These parameters therefore need to be determined by means of calibration, i.e. the search for the parameter values that give the best predictions. There exist several strategies to calibrate a model:

_ the manual trial-and-error strategy where the user manually changes the values of the parameters until he/she is satisfied with the model results, usually by testing them graphically against observations,

_ the inverse modelling strategy where a search algorithm is applied to minimise an objective function reflecting the distance between the observations and the simulation,

_ the parameter space browsing strategy where the parameter values are selected from a population of values according to their results. This strategy employs a sampling method such as Monte Carlo Markov Chain or Latin Hypercube, and usually necessitates a large number of model runs.

These three methods are significantly different, but they have in common the simple fact that they all need stream flow data to compare the predictions with. It is now recognised that the availability of stream flow data world-wide is not improving (Takeuchi, 2002) and that it is far from adequate in a lot of countries and especially in developing countries where the costs in time and money to develop reliable networks of gauging stations are too high. It is likely that the majority of catchments world-wide are ungauged (Sivapalan, 2003), i.e. where there are inadequate records of data in terms of both data quantity and data quality or appropriate spatial and temporaral scale to address the needs (Sivapalan *et al.*, 2003). The transfer of information gained in gauged catchments to ungauged catchments is therefore necessary. This transfer of information is called regionalisation (Blöschl and Sivapalan, 1995). Regionalisation has received a fair amount of interest among hydrologists, but methods for reliable predictions in ungauged catchments are still lacking (Sivapalan, 2003).

Ungauged basins: an international hydrological cause

The International Association of Hydrological Sciences (IASH) has recognised the need to shift the main focus of hydrology from gauged to ungauged catchments. This shift is intended to create a significant momentum among the hydrological community and to lead to the improvement of data acquisition and utilisation, theories and models in the field of hydrology (Sivapalan and Schaake, 2003). The IAHS has launched a decadal initiative entitled Predictions in Ungauged Basins (PUB) in order to support this recognition. The PUB fixes five directions of work (Sivapalan *et al.*, 2003) to:

1. “develop an observational field programme for conducting research in highly instrumented and extensively gauged basins in different hydro-climatic regions of the world”,
2. “increase the awareness of the value of data for the management of water resources and water quality worldwide, and demonstrate the need for targeted gauging of currently inadequate or nonexistent data sources by quantifying the links between data and predictive uncertainty”,

3. “advance the technological capability around the world to make predictions in ungauged basins, firmly based on local knowledge of the climatic and landscape controls on hydrological processes”,
4. “advance the scientific foundations of hydrology”,
5. “actively promote capacity building activities in the development of appropriate scientific knowledge and technology to areas and communities where it is needed”.

In summary: hydrology in general and rainfall-runoff modelling in particular have up to now mainly focussed on gauged, rather than ungauged, catchments. There is a recognition that this order of interest should now be inverted to 1) improve the quality and reliability of predictions in ungauged catchments, 2) help with the development of new paradigms in hydrological science.

1.2 Aim and objectives

In the UK, and despite an extended network of stream discharge gauging stations, the majority of river reaches are ungauged (Young and Reynard, 2004). This problem becomes critical when one needs to evaluate the implications of climate, land use or socio-economic changes on river flows and river qualities. The performances of hydrological models have not yet been satisfactory in ungauged catchments in the UK (McIntyre *et al.*, 2004) and new approaches need to be explored and assessed.

The overall aim of this thesis is an attempt to address this issue through objective 3) of the IAHS decadal initiative on Predictions in Ungauged Basins. The aim was to develop a modelling tool to help with water resource issues in ungauged catchments. The modelling tool incorporates pre-existing knowledge of the hydrological processes in the United Kingdom (UK), and is primarily intended to be used in the UK.

The key objectives of the research project presented in this dissertation were to:

1 Develop a continuous, daily, semi-distributed catchment-scale rainfall-runoff model based upon the hypothesis that the transformation of rainfall into discharge at the catchment-scale in the UK can be driven by existing datasets of soil, land use and weather.

2 Evaluate this rainfall-runoff model in different soil, land use and climatic conditions in England and Wales.

3 Regionalise this rainfall-runoff model for England and Wales.

4 Test and evaluate the performances of this regional rainfall-runoff model.

1.3 Research approaches

Research approaches for each one of the objectives are described in this section. Because the dissertation is composed of independent articles, the objectives can be addressed in more than one chapter.

Objective 1: *Development of a continuous, daily, semi-distributed catchment-scale rainfall-runoff model.*

Based on a review of existing modelling approaches in gauged and ungauged catchments (chapter 2, sections 3.3 and 5.2), an approach that can be regarded as following the top-down methodology (Klemeŝ, 1983) has been adopted. At first, the main factors affecting the hydrological response at the catchment-scale in the UK were defined from previous work (NERC, 1975; Sefton and Howart, 1998) i.e. soil and land use (sections 3.3, 5.2). Then, the Catchment Resources and Soil Hydrology (CRASH) model was developed to represent the main hydrological processes at the catchment scale (sections 3.4, 3.5). CRASH was mainly based on similar modelling techniques to the ones used in the point scale SWBCM model (Evan *et al.*, 1999) but it is adapted to catchment scale applications.

Unlike the SWBCM model, CRASH incorporates infiltration excess surface runoff in addition to saturation excess runoff. The subsurface lateral flow is calibrated at the catchment scale. Flow routing procedures have been added to route the flows within sub-catchments, catchments and basins. A surface depression module is present to account for the volume of water trapped in surface depressions at the beginning of an event. Finally, CRASH incorporates a rainfall disaggregation scheme to improve the derivation of the infiltration excess runoff (chapter 4).

CRASH was also developed to make an extensive use of the Hydrology Of Soil Type (HOST) classification (Boorman *et al.*, 1995). HOST is used qualitatively to classify soils according to their hydrological behaviour, and quantitatively when model parameters in CRASH are directly related to parameters derived for the HOST system (section 3.5).

The main characteristics of CRASH as a modelling tool are that i) it was built around existing data sets to work exclusively with existing data, ii) it explicitly separates the influence of the two main driving factors (soil and land use) on the hydrological behaviour of a catchment, iii) it was developed to fulfil the requirements of the homogeneous unit regionalisation method (section 2.2.2.3.1), iv) it integrates artificial impacts on the river flow.

Due to these characteristics, CRASH is suitable for water resources issues, and land use and soil types changes. It is for instance potentially possible to explore impacts of agricultural soil compaction by agricultural machinery. CRASH can also be used for flood modelling because it includes saturation and infiltration excess surface runoff. It should be noted that, for this purpose, hourly precipitation data should be supplied to the model instead of using the CRASH precipitation disaggregation scheme.

Objective 2: *Evaluation of the CRASH model in England and Wales.*

CRASH was evaluated using a multi-criteria approach in three gauged catchments in England representing three distinct soil conditions and in contrasting climate conditions (sections 3.6 – 3.9).

Objective 3: *Regionalisation of the CRASH model for England and Wales.*

Model parameters for each soil type were inferred from the catchment-specific calibration of CRASH in 32 catchments in England and Wales (section 5.5). These parameters are then used and referred to as regional parameters.

Objective 4: *Evaluation of the performances of the regional CRASH model.*

The regional CRASH model was first evaluated in the catchments used for the derivation of the regional parameter set (section 5.6). A multicriteria analysis of the results was carried out and the regional CRASH was compared to the single-site CRASH. The factors affecting the performance of the regional CRASH were identified.

Secondly, the regional CRASH was applied in three catchments located in East-Anglia – eastern England (chapter 6). A multicriteria evaluation was performed and the uncertainty of the predictions due to the uncertainty in the regional parameters was assessed. The regional CRASH was also compared to the single-site CRASH and to the results from similar regionalisation studies with other models in England and Australia.

1.4 Thesis structure

This dissertation is divided into seven chapters. Chapters 4 to 6 are presented in the form of papers. These papers have been submitted to peer-reviewed journals or conference proceedings. The structure of the thesis is summarised in Box 1.

For more convenience for the reader, the section headings of chapters 4 to 6 have been renumbered to be consistent with the other chapters.

Chapter 1 is an introduction to the general context of the research presented in this dissertation and introduces the structure of the dissertation.

Chapter 2 succinctly reviews the main approaches to rainfall-runoff modelling in gauged and ungauged catchments.

Chapter 3 describes the structure of the Catchment Resources and Soil Hydrology (CRASH) model. The model is evaluated in three catchments in England.

Chapter 4 describes a parsimonious rainfall disaggregation method from daily to hourly time step. The method is assessed by verifying the statistical properties of simulated hourly rainfall intensities against observed ones.

Chapter 5 describes the method to regionalise CRASH in England and Wales. The performance of the regional CRASH is assessed in the catchments used for its regionalisation.

Chapter 6 presents the evaluation of the regional CRASH in three catchments independent from the regionalisation procedure and treated as ungauged.

Chapter 7 provides a conclusion to the dissertation with a discussion, conclusions and recommendations for future work.

Box 1: Thesis Structure

Chapter 1	Introduction
Chapter 2	Research context: Rainfall-runoff modelling in gauged and ungauged catchments
Chapter 3	Maréchal, D. and Holman, I.P. 2003. Development and application of a soil classification-based conceptual catchment-scale hydrological model. *Journal of Hydrology* (Submitted).
Chapter 4	Maréchal, D. and Holman, I.P. 2003. A robust and parsimonious regional disaggregation method for deriving seasonal rainfall intensities at the hourly timescale for the UK. *Hydrology and Earth System Sciences* (Submitted).
Chapter 5	Maréchal, D. and Holman, I.P. 2004. Regionalisation of a conceptual catchment-scale hydrological model for England and Wales. *Hydrological Processes* (Submitted).
Chapter 6	Maréchal, D. and Holman, I.P. 2004. Comparison of hydrologic simulations using regionalised and catchment-calibrated parameter sets for three catchments in England *Proceedings International Conference on Integrated Assessment and Decision Support* (*iEMSs2004*). *Osnabrück, Germany, June 14-17 2004* (Accepted).
Chapter 7	Discussion, conclusions and way forward.

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2 RESEARCH CONTEXT: RAINFALL-RUNOFF MODELLING APPROACHES IN GAUGED AND UNGAUGED CATCHMENTS

2.1 Gauged catchments

Rainfall-runoff modelling approaches are various and there is a plethora of models. Beven (2001) mentioned his attempt to draw an exhaustive list of rainfall-runoff models nearly 25 years ago and his abandoning of the task when he reached 100 models. A clear classification system is therefore very difficult if not impossible, but the most commonly used system classifies the models as metric, physically-based and conceptual (e.g. Beck, 1991). In metric models, one considers the fact that a great amount of information is held in measured data that the model can extract to conduct predictions. It is therefore a mainly empirical approach and is also called the black box approach. Because it is based on data, the techniques employed do not all originate from the hydrological sciences but also from other domains of science. Metric models are usually lumped, i.e. they treat the catchment as a single element. Physically-based models should be a true representation of the physical processes. They are developed following the bottom-up approach (Sivapalan *et al*, 2003) and are based on *a priori* perception of the importance of the various physical processes and how they interact. Beven (2001) argued that it is not currently possible to build this true representation and that empiricism has to be introduced. He mentioned these models as almost deductive. Conceptual models can be described as all the other models that can not be classified as metric or physically-based. They represent the important processes in a simplified conceptualisation – often by the means of reservoirs or buckets. Conceptual models are lumped or semi-distributed. Semi-distributed models recognise that in a catchment areas can have similar hydrological behaviour and react in the same way. The aim is thus to define these areas and to group them together to simplify the computation.

2.1.1 Metric models

Metric models treat the catchment as a single unit and relate its output (the flow $Q(t)$) to its input (the rainfall $I(t)$) where t is the time, through an operator Φ (Figure 2.1). Φ is called a transfer function.

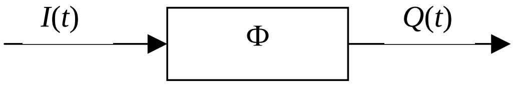

Figure 2.1: Metric models

The first attempt to develop a mathematical method to transform rainfall into runoff was probably the rational method reported by Mulvaney (1851). This method relates the peak discharge to the catchment area, the rainfall intensity and an empirical coefficient to be defined for the catchment. This method is still in use to calculate the peak discharge of storms, especially in urban hydrology (e.g. Hua *et al.*, 2003; Tolland *et al.*, 1998).

It was only in the 1930's that the second major method was introduced: the unit hydrograph (Sherman, 1932). The unit hydrograph is a linear method based on the principle of superposition and can therefore be applied to a complete hyetograph to produce a hydrograph and not only the peak discharge as with the rational method (Todini, 1988b). The unit hydrograph method assumes that the rainfall-runoff relation is invariant in time and does not depend on the rainfall intensity. It also assumes that the variability of other outputs is small during the period of application (Amorocho and Brandstetter, 1971). This method has two main difficulties: 1) the determination of the effective rainfall and 2) the determination of the shape of the hydrograph. The latter is the less difficult of the two as it is usually more of a problem to answer the question "how much" than the question "when" (Todini, 1996). Various methods to define the shape of the hydrograph from catchment characteristics have been implemented: e.g. in the UK: NERC (1975), Institute of Hydrology (1985), or Institute of Hydrology (2000). The Geomorphological Unit Hydrograph is another approach which seeks to relate the unit hydrograph to geomorphological characteristics representing the channel network (e.g. Rodriguez-Iturbe and Valdes 1979; Shamseldin and Nash, 1998).

The applicability of a linear relation between rainfall and runoff, as assumed in the unit hydrograph method, has however proved to be not suited to all cases (e.g. Amorocho and Brandstetter, 1971; Sivakumar *et al.*, 2001). Techniques learnt from other branches of science were adopted to help with the development of non-linear transfer functions. The first one was borrowed from the work of Volterra (1930) developed for non-linear electrical systems. The Volterra series were applied in a number of studies (e.g. Diskin and Boneh, 1972; Amorocho and Brandstetter, 1971; Todini and Wallis, 1977). Other attempts to represent the non-linear behaviour of catchments were made using techniques derived from the theory of chaos with successful results (e.g. Islam and Sivakumar, 2002). Some authors not only questioned the linearity of the transfer function but also its stationarity in time (e.g. Labat *et al.*, 2000). The wavelet analysis used in fields such as image coding and compression (e.g. for the jpeg file format) or signal de-noising is an example of a non-linear non-stationary transfer function (Labat *et al.*, 1999, 2000, 2001; Nakken, 1999).

These methods can be very successful in mimicking the observed flow data – Islam and Sivakumar (2002) obtained a Nash and Sutcliffe efficiency index of 0.98 which is near perfection. But the drawback is that they have the potential to be only mathematical problems and to lose their perception of reality (Todini, 1988b). The data-based mechanistic approach described by Young and Beven (1994) was implemented with the aim of developing metric models with meaningful structures. The idea is to let the data choose the most adequate structure to reproduce the observations, but this structure must also describe the physical processes and can not be any mathematical formula (Young 2002). The search for the corresponding structure is a compromise between its efficiency and its simplicity. In a general way, the more complex a structure is, the better the fit to observed data because of the number of parameters that can be tuned. The best structure provides a good fit but is also parsimonious. Numerous studies have made use of the data-based mechanistic approach in recent years (e.g. Young, 2003; Mwakalila *et al.*, 2001; Price *et al.*, 2000).

Finally, artificial neural networks have been used recently to represent the transformation of rainfall into discharge (e.g. Baratti *et al.*, 2003, Lallahem and Mania, 2003; Hsu *et al.*, 2002; Maier and Dandy, 2000). Artificial neural networks try to reproduce the functioning of the human brain: they are composed of nodes connected by neurons. These nodes are organised by layers (an input layer, hidden layers and an output layer). The numbers of hidden layers and of nodes in each layer dictate the degree of freedom of the artificial neural network. A training period is necessary to establish the connections among the nodes. It is interesting to notice that unlike any other methods (metric, physically-based or conceptual), the output does not only depend on the input but also on the output at previous time steps.

2.1.2 Physically-based models

Physically-based models were first constructed in the hope of being true representations of the physical processes. It was thought that they could provide a true picture at any point in the catchment (Freeze and Harlan, 1969), and that they could be easily transferable to ungauged catchments thanks to the physical meaning of their parameters (Todini, 1988b). Physically-based models follow the blue-print by Freeze and Harlan (1969) and are based on the laws of the conservation of mass, momentum and energy. They include a full range of physical processes including canopy interception and snow pack routines. They solve the differential equations for overland and channel flows, and unsaturated and saturated subsurface flows; and they link these subsystems to meet their boundary conditions. The first physically-based models were not completely 3-dimensional models in order to reduce the computing time: e.g. the Système Hydrologique Européen (SHE) (Abbott, 1986a,b) or IHDM (Rogers *et al*, 1985). But the latest models are now truly 3-D to make use of the calculation power of modern personal computers (Sudicky *et al.*, 2000).

Despite the great expectations accompanying the development of these models, they have not been the solution to all the problems present in hydrology. In fact, the questions that hydrologists are nowadays trying to solve are very much the same as those from 20 years ago. In the last decade, the criticism about the physically-based models has been somehow proportional to the initial expectations and to the effort employed to build these models. The first problem is that the parameters that were thought to have a physical meaning can not be directly related to measured values (e.g. Beven, 1989; Grayson *et al.*, 1992). The reason is that the scale at which the measurement is done and the scale at which the parameter is applied in the model are different. It has also been extensively reported in the literature that due to their large number of parameters to calibrate, physically-based models were overparameterised (e.g. Jakeman and Hornberger, 1993; Perrin *et al.*, 2001). The correctness of the equations at a grid scale have been questioned (Seyfried and Wilcox, 1995; Beven, 1996). It is not proved that equations derived usually in laboratories can be applied to larger scales. Finally, physically-based models do not perform better than simpler (conceptual) models when simulating the rainfall-runoff processes at the catchment scale (e.g. Perrin *et al.*, 2001; Refsgaard and Knudsen, 1996). In that case, it is generally recognised that conceptual models should be used.

Despite these problems, physically-based models are still valuable tools when detailed spatial information is needed (e.g. Xu *et al.*, 2001). It can also be hoped that remote sensing data can help to provide new sources of data suited to physically-based models.

2.1.3 Conceptual models

Conceptual models differ from metric models in that they are built from an *a priori* representation of the hydrological processes. Some conceptual models can be very similar to data-based mechanistic models described previously in metric approaches, but the distinction is that their structure has been decided according to the developer's perception of the important processes (Young, 2002). On the other hand, conceptual models differ from physically-based models in that they are built to be only a simplification of reality. This simplification can be through the choice of the most important physical processes and by deliberately accepting that some processes are not significant in some cases. It can also be by the mathematical representation of the processes, such as by representing an unconfined aquifer by a non-linear tank. The number of conceptual models is very large, each one different from the others; and their application is very extended for both research and practical purposes.

Conceptual models can be classified into two groups, corresponding roughly to two periods of time. The first group is composed of storage based models: e.g. Stanford (Crawford and Linsley, 1966), HBV (Bergström and Forsman, 1973), they were mainly developed in the 1960's and 1970's and were adapted later when it was realised that some of them were over-parameterised (e.g. Jakeman and Hornberger, 1993; Perrin *et al.*, 2001). Models composing the second group were developed in the 1980's and 1990's and are based on hydrological similarities: e.g. TOPMODEL (Beven and Kirkby, 1979; Beven, 1997), SWAT (Arnold *et al.*, 1998a). Hydrologically similar areas of the catchment are defined and grouped together. These models vary in the definition and representation of the similar areas.

Storage based models were the first attempt to integrate various subsystems at the catchment scale in digital models (Singh and Woolhiser, 2002). One of the first storage based models was the Stanford Watershed Model (Crawford and Linsley, 1966). It is composed of five water stores: an interception, an upper zone, a lower zone, a ground water and a deep or inactive ground water store. The stream flow originates from impermeable areas, overland flow, interflow and base flow. Evapotranspiration is taken from all the water stores except for the deep groundwater store. This model has been successful and has been used in several other models as the basis for their hydrological routine: HSPF (Johanson *et al.*, 1984), NPS (Donigian and Crawford, 1976), ARM (Davis and Donigian, 1978). It has also been the inspiration for numerous other models: e.g. HBV (Bergström and Forsman, 1973), Xinanjiang model (Zhao *et al.*, 1980), EPIC (Williams *et al.*, 1984), GR4J (Edijatno *et al.*, 1999; Perrin, 2000), ARNO (Todini, 1988a,b). These models have a number of parameters that need to be calibrated. For instance, the original version of the Stanford Watershed Model had 16 parameters (Crawford and Linsley, 1966). It has since become apparent that some of these models had to be simplified and only the ones with a limited number of parameters are still used (e.g. HBV, GR4J, Tank models). Storage based models are generally lumped, but some attempts have been made to distribute them spatially: HBV96 (Sælthun, 1996).

Models based on hydrological similarities can be viewed as the reactions to the physically-based models. They have integrated the main criticisms made of the physically-based models (non correctness of the equations at grid scales, over-parameterisation) but recognise the heterogeneity of the physical conditions at the catchment scale (e.g. Leavesley *et al.*, 1983). These models are semi-distributed. Hydrological Response Units (HRUs) are identified depending on their hydrological behaviour and aggregated. HRUs are usually treated as hydrologically independent units, i.e. there is no lateral flow from one HRU to another. Their identification is based on the physical properties of the catchment. It is usually based on land cover only (Su *et al.*, 2000; Biftu and Gan, 2001), on land cover and soil type (e.g. Schumann *et al.*, 2000; Arnold *et al.*, 1998a), and on topography, land cover and soil type (Eisele *et al.*, 2001). The conceptualisation of the HRUs range from storage based representation: e.g. SLURP (Kite, 1996), NBSM (United States Environmental Protection Agency, 1998), HBV-D (Kryzanova *et al.*, 1999), ARC/EGMO (Pfüzner at al., 1997) and the model by Wooldridge *et al.* (2001), to nearly physically-based models (Kokkonen *et al.*, 2001).

The routing of the runoff produced in the HRUs is also varied, it can be through the use of linear stores (Kokkonen *et al.*, 2001) or non-linear stores (Whitehead *et al.*, 1998), or more sophisticated methods such as the linear advection-dispersion approach used by Schumann *et al.* (2000). Two semi-distributed models have had a fair success: the SWAT model (Arnold *et al.*, 1998a) and TOPMODEL (Beven and Kirkby, 1979; Beven, 1997). SWAT is an integrated tool that incorporates – in addition to the hydrological processes – sediment, nutrient and pesticide routines (Arnold *et al.*, 1998a,b). The success of TOPMODEL was due to its innovative approach with regard to topography. TOPMODEL uses topography and soils information to predict the extent of areas contributing to the production of runoff.

2.2 Ungauged catchments

In the previous section, the main methods to model the rainfall-runoff transformation processes at the catchment scale were presented. The models from the three categories require flow data to calibrate the parameters; even for the physically-based models as it has been found that the parameters could not be directly measured. However, it is not unusual to work with catchments that have only partial sets of stream flow data, or no data at all. For instance in the UK, the network of 1,400 flow gauging stations is extensive but still insufficient to cover the entire network of rivers (Sefton and Howarth, 1998). The catchments with inadequate stream flow data are classified as ungauged (Sivapalan *et al.*, 2003). In contrast to the local procedure of application of a single-site model, the transfer of information from gauged catchments to ungauged catchments is called regionalisation (Blöschl and Sivaplan, 1995). This transfer of information is achieved by extrapolating the model parameters from gauged to ungauged sites belonging to homogeneous regions. A lot of attention has been paid to defining homogeneous hydrological regions (e.g.; Mosley, 1981; Nathan and McMahon, 1990; Hall and Minns, 1999). The first grouping approach encompassed geographical areas by plotting the residuals from an overall regression equation and by defining subjectively the boundaries of the homogeneous regions (e.g. Blake *et al.*, 1970; Natural Environment Research Council, 1975; Mosley, 1981). The high level of subjectivity in this method was seen as a problem because it meant that different hydrologists could get different sets of regions from the same maps of residuals.

Multivariate techniques were then introduced with a particular emphasis on the cluster analysis (e.g. Tasker, 1982; Hawley and McCuen, 1982; Acreman and Sinclair, 1986; Wiltshire, 1986). The use of these techniques did not remove subjectivity from the analysis. The results now depended on the choice of algorithm and of the distance measure (Nathan and McMahon, 1990). Moreover, an ungauged catchment could only be associated with a single region (Hall and Minns, 1999) which creates discontinuities in the predictions (Holmes *et al.*, 2002). Consequently, Acreman and Wiltshire (1989) allowed the ungauged catchment to be associated with more than one region, and Burn (1990a,b) introduced a threshold distance to define the region of influence of one site.

In the next sections, the main methods of extrapolation of the model parameters used for catchment scale rainfall-runoff models within homogeneous hydrological regions are reviewed.

2.2.1 Metric and physically-based models

Metric and physically-based models are only sporadically used in regional studies.

Due to their fundamental principle, metric models are not suited to regionalisation purposes. It is in fact questionable to spatially extrapolate the transfer function derived from a donor catchment and to use it in a receptor catchment when no information on the nature of the processes is known. Camarasa and Tilford (2002) attempted to cross-apply an event-based transfer function model in two ephemeral mid-size catchments in Spain. They found that this method gave poor results when the transfer function was calibrated for a slow response catchment and applied in a fast response catchment. However, they concluded that the model could be transferred from a fast response catchment to a slower response cactchment, under the condition that the model is used for high magnitude flow events. Camarasa and Tilford (2002) explained this performance of the model by the fact that the physical properties of the catchment are of less importance for high flow events.

Physically-based models are also only seldomly used in regional applications because of their complexity of calibration. Refsgaard and Knudsen (1996) compared the capacity of three models - one metric, one conceptual and one physically-based - to be regionalised. The physically-based model was the SHE model (Abbott *et al.*, 1986a,b).

The approach by Refsgaard and Knudsen (1996) was to transfer the models calibrated in a donor catchment to a receptor catchment. The three models presented excellent overall performances, but the metric model predicted the flows with twice more uncertainty than the conceptual and physically-based models (Refsgaard and Knudsen, 1996). However, it could not be concluded that the physically-based model performed better than the conceptual model, despite its fully distributed approach.

2.2.2 Conceptual models

Conceptual models are the most widely used models in regional applications even if their parameters do not necessarily have an explicit physical meaning and though they heavily rely on stream flow data for their calibration. The reasons are their general popularity for any kind of application and their limited number of parameters to calibrate. The regionalisation procedure for conceptual models is based on the assumption that even if *a priori* relations between model parameters and specific physical properties of the catchment can not be established, the parameters are representative of the physical processes taking place and therefore of the physical properties.

2.2.2.1 Constant parameters method

The first approach is obviously to assume that the model parameters are constant in hydrologically similar catchments. This transfer approach has been mainly used to test the variability of the parameter values within large basins. Van der Linden and Woo (2003) applied the parameters of the SLURP model (Kite, 1996) derived for a 227,100km^2 subarctic basin in Canada affected by snowmelt to two of its subbasins of about 23,000km^2. They found that the transfer of parameter, and thus of information, from the larger scale to the smaller scale was degrading the predictions of river flow in the two subbasins. The model parameters when calibrated for the subbasins were significantly different from the parameters when the model was calibrated for the entire basin. Huisman *et al.* (2003) tried to extrapolate the parameters both from the larger to the smaller scale and from the smaller to the larger scale. They applied the SWAT model (Arnold *et al.*, 1998a) in the Dill catchment in Germany (863km^2) and in three of its sub-catchments with areas ranging from 63 to 134km^2. Huisman *et al.* (2003) obtained a successful transfer among the catchment and two of its sub-catchments. But the parameterisation of the third, and smallest, sub-catchment was highly questioned as the parameter set derived for this sub-catchment gave poorer results than parameter sets from the three other sites, even in the sub-catchment where it had been derived.

Micovic and Quick (1999) tried to generate an average parameter set for the UBC watershed model (Quick, 1995) for the British Columbia region in Canada. They selected 12 basins with contrasting conditions of climate, topography, soil types and geology. They concluded that the average parameter set could be applied with success if the impermeable fraction of the watershed can be determined independently and does not require to be calibrated. They even applied the regional model to a catchment located in the Himalayas and obtained very good results in this case.

2.2.2.2 Statistical inference method

In the previous method, the initial condition was to work with donor and receptor catchments with similar physical conditions. To overcome this restriction, another approach is to relate the model parameters to catchment physical properties. The interest of the method is that it defines the important physical characteristics for a model in a specific region. This method has been the standard approach to regionalisation in the past decade (Mwakalila, 2003; Servat and Dezetter, 1993; Sefton and Boorman, 1997; Seibert, 1999; Sefton and Howarth, 1998; Burn and Boorman, 1993; Post and Jakeman, 1999; Yokoo *et al.*, 2001; Kokkonen *et al.*, 2003; Hundecha *et al.*, 2002). The main type of relation between the model parameters and the catchment descriptors is a linear relation, usually using linear multiple regression (e.g. Seibert, 1999; Sefton and Howarth, Mwakalila, 2003; Hundecha *et al.*, 2002). The catchment descriptors can be:

_ topographical indices: mean elevation (e.g. Sefton and Howarth, 1998), channel slope (e.g. Sefton and Boorman, 1997), catchment area (e.g. Seibert, 1999), drainage density index (e.g. Mwakalila, 2003),

_ geology and soil index: percentage of soil types (e.g. Burn and Boorman, 1993),

_ climate indices: annual average rainfall (e.g. Sefton and Howarth, 1998), potential evapotranspiration (e.g. Mwakalila, 2003),

_ land cover indices: percentage of land use types (e.g. Sefton and Howarth, 1998).

This method has been employed with several models: e.g. the HBV model (e.g. Seibert, 1999; Hundecha *et al.*, 2002), the IHACRES model (e.g. Sefton and Howarth, 1998; Sefton and Boorman, 1997; Post and Jakeman, 1999; Kokkonen *et al.*, 2003), the tank model (Yokoo *et al.*, 2001) and the GR3 model (Servat and Dezetter, 1993). The results are variable. Sefton and Howarth (1998) and Yokoo *et al.* (2001) stated that the method was successful in their respective studies. However, such clear conclusion could not be drawn in other studies (e.g. Sefton and Boorman, 1997; Post and Jakeman, 1999; Kokkonen *et al.*, 2003). Kokkonen *et al.* (2003) even mentioned that this method does not necessarily perform better than to simply transfer parameters from a donor to a receptor catchment as presented in the previous section.

Fernandez *et al.* (2000) tried to improve the methodology by developing a dual objective calibration procedure for a monthly water balance model. Instead of dividing the procedure into two steps as in the previously mentioned articles where the models were first calibrated in each catchment and then the relation between model parameters and catchment descriptors was defined, Fernandez *et al.* (2000) tried to carry out the two steps simultaneously. The model was calibrated for all the catchments with the dual objective of i) satisfactorily predicting the stream flows in each catchment and ii) defining appropriate relations between model parameters and catchment descriptors. Fernandez *et al.* (2000) concluded in accordance to Kokkonen *et al.* (2003) that good relations between model parameters and catchment descriptors do not necessarily improve the predictions at ungauged sites. It is not known if this approach has been further applied for daily rainfall-runoff models.

2.2.2.3 Alternative methods

2.2.2.3.1 Homogeneous unit method

This method assumes that areas of a catchment with the same physical characteristics have similar hydrological response. The aim is to calibrate each homogeneous unit and to build a library of parameters for all units. This parameterisation can then be used in ungauged catchments. This type of approach is suited to semi-distributed models that use the principle of hydrological response units or to fully distributed models. Dunn and Lilly (2001) managed to determine parameters of the distributed DIY model (Dunn *et al.*, 1998) according to a soil hydrological classification for two catchments in Scotland. Beldring *et al.* (2003) calibrated a distributed version of the HBV model in 141 catchments in Norway and estimated the model parameter values for 5 land use classes. They used this library of parameter values in 43 independent catchments where they obtained successful results.

2.2.2.3.2 Flow duration curve methods

Some studies have focussed on the flow duration curve as a first step to the prediction of the daily hydrograph in ungauged catchments (e.g. Smakhtin and Masse, 2000; Yu and Yang, 2000). Smakhtin and Masse (2000) justified their methodology by the fact that monthly time series are widely available in South Africa, whilst daily data are not. Various methods have been developed to construct 1-day flow duration curves from flow duration curves calculated with monthly time series (e.g. Pitman, 1993; Schultz *et al.*, 1995; Smakhtin and Hugues, 1995). The method described by Smakhtin and Masse (2000) uses a current precipitation index (CPI) that reflects the wetness of the catchment. Once CPI time series and CPI duration curves are known, the flow time series is built by assuming that an event corresponds to the same percentage of exceedance on the flow and CPI duration curves. Smakhtin and Masse (2000) did not conclude on the performance of this method as it still needs more investigation.

Yu and Yang (2000) suggest using the flow duration curve to calibrate the models. The procedure is composed of two steps: at first the flow duration curve is constructed for the ungauged site by using flow duration curves from neighbouring sites, then the model is calibrated to reproduce the flow duration curve. The method proved to work reasonably well in their case study in Taiwan.

2.2.2.3.3 Physical methods

Some authors try to infer *a posteriori* model parameters from measurements (e.g. Wooldridge *et al.*, 2001). This approach can be viewed as a natural extension of the statistical inference method and attempts to describe physically some model parameters by linking them to a single physical property of the catchment. Wooldridge *et al.* (2001) argued that two parameters at the catchment scale of the Variable Infiltration Capacity model (Wood *et al.*, 1992) seem to be directly linked to soil depth data.

In summary:

Approaches to simulate the rainfall-runoff processes at the catchment scale are various. Metric models can be very successful at mimicking the observations, but they do not necessarily have a physical basis (e.g. neural networks). This characteristic of metric models can be a major limitation for their application in ungauged catchments, and they are not well suited for regionalisation purposes.

Physically-based models, on the other hand, have been developed to integrate the state of the art knowledge about physical processes and computer model development. However, they have been strongly questioned due to their theoretical basis and their practical use. This difficulty to apply physically-based models is one of the main reasons why only little interest has been paid to physically-based models in regionalisation studies.

Conceptual models tend to represent the physical processes in a simplified manner. They can be lumped, when catchments are considered as a single unit, or semi-distributed. Lumped models have been widely used in regionalisation studies because of their limited number of parameters. The most common approach to derive regional parameters for lumped conceptual models is the statistical inference method where model parameters are directly related to catchment physical properties through, for instance, linear multiple regressions. This regionalisation approach has been extensively tested in different countries. But the results were not always convincing. Some authors concluded that it was better to directly transfer model parameters from a donor to a receptor catchment than to apply the statistical inference method (section 2.2.2.2).

Consequently, the next obvious approach to test is the transfer of model parameters from donor to receptor hydrologically homogeneous areas, which is the approach adopted in the work presented in this dissertation. This approach is an extension of the transfer method of parameters for a lumped model from a donor to a receptor catchment, but at the scale of hydrologically homogeneous areas. Semi-distributed conceptual models are the best-suited type of models for this purpose because they recognise the heterogeneity of the properties in a catchment. The homogeneous unit method is naturally associated with semi-distributed models and has been chosen as the regionalisation method in this thesis (section 5.5).

The main drivers for the hydrological processes in the UK are the morphology, soils, land use and climate (NERC, 1975). But Sefton and Howarth (1998) showed that soil and land use were sufficient to satisfactorily represent the physical processes in UK catchments. In fact, with the exception of the quick flow time of decay which is directly related to catchment descriptors, they related all the parameters of the IHACRES model to land use and soil indices in their regionalisation study using the statistical inference method in 60 catchments in England and Wales. These drivers were also selected as the main drivers for the model development and regionalisation in the work hereby presented.

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3 DEVELOPMENT AND APPLICATION OF A SOIL CLASSIFICATION-BASED CONCEPTUAL CATCHMENT-SCALE HYDROLOGICAL MODEL

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3.1 Abstract

A conceptual, continuous, daily, semi distributed catchment-scale rainfall-runoff model with identifiable parameters that has the potential to be ultimately used in ungauged catchments is proposed. The Catchment Resources and Soil Hydrology (CRASH) model is developed from the assumption that the transformation of rainfall into river discharge at the catchment scale in the UK is driven by soil and land use properties and uses exclusively existing data sets of soil and land use. CRASH has been calibrated and evaluated for three catchments in England with contrasting soil characteristics and meteorological conditions. The model proved to be successful during the calibration and evaluation periods with $R^2 \geq 0.50$ but showed a slight tendency to overestimate river flow in one of the three catchments.

The next development stage will be to test CRASH for a large number of catchments covering a wider range of soils, land uses and meteorological conditions in the UK, and to derive a single set of regionalised model parameters.

This work was done during the EU funded ‘MULINO decision support system for sustainable use of water resources at the catchment scale’ project co-ordinated by FEEM, Venice, Italy.

Keywords: Rainfall-runoff, conceptual model, daily time-series, ungauged catchment, semi-distributed, soil hydrology

3.2 Introduction

Rainfall–runoff models can be used to investigate various hydrological issues relevant to environmental managers and decision–makers. Their use can, however, be restricted by the availability and quality of input and parameterisation data. For instance, despite the collection of data from over 1100 gauging stations in the United Kingdom, adequate stream flow data do not exist for many catchments. The only method to truly simulate the hydrological processes occurring in catchments where data are unavailable for calibration is to use models which have identifiable parameters (Wooldridge and Kalma, 2001).

This paper presents the first two stages of the development of a conceptual, continuous, daily, catchment-scale rainfall-runoff model whose ultimate purpose is to be usable in ungauged catchments: i) description of the Catchment Resources and Soil Hydrology (CRASH) model, and ii) evaluation of its performance.

Some approaches to modelling in ungauged catchments are first presented and the approach adopted in CRASH is described. The model is then detailed and finally it is tested in three medium sized catchments in Central, South and South-West of England.

3.3 Some approaches to rainfall-runoff modelling in ungauged catchments

One approach to tackle the challenge of modelling river flows in ungauged catchments appeared with the blue-print for a physically-based, distributed catchment model by (Freeze 1969). The Système Hydrologique Européen (SHE) system was developed following such a blue-print ((Abbott 1986) and was presented in opposition to lumped parameter models that “depend essentially on the availability of sufficiently long meteorological and hydrological records for their calibration“ (Abbott 1986). However the use of such models has since been questioned because of the actual significance of the parameters and the great amount of physical characteristics they require (Beven 1989).

It is generally agreed that the level of complexity of physically-based models is excessive for many practical problems. (Jakeman 1993) stated that a simpler structure based on a low-flow component and a quick-flow component was sufficient. Such conceptual models represent only the most important component processes but are generally optimised using observed streamflow data.

However, because they incorporate many fewer parameters, approaches have been developed to apply conceptual models in ungauged catchments. The first method relates the model parameters to physical descriptors of the catchments (e.g. (Sefton 1998); (Post 1996); (Schmidt 2000); (Seibert 1999)). The procedure of calibration has two stages. Firstly the parameter values are determined for a number of gauged catchments. Then a relationship between the model parameters and physical descriptors of those gauged catchments is derived. This relationship can use simple (e.g. multivariate regression, (Sefton 1998); (Post 1996)) or more sophisticated techniques (such as kriging or clustering, Vandewiele and Elias, 1995) to find similarities among the catchments. (Fernandez 2000) took the method one step further and proposed to implement the two stages simultaneously for their monthly water balance model.

The second method is to calibrate the model using a rule-based approach or the clustering of catchments with similar dominant hydrological processes (Peschke 1999). (Natural Environment Research Council 1975) classifies catchments according to their morphology, soils, land use and climate (Sefton 1998) and (Dunn 2001) showed that it was possible to determine model parameters according to a soil hydrological classification but failed to adequately calibrate the fast response.

Unlike many other studies where the objective has been to relate the parameters of existing models to catchment descriptors, the purpose of this study is to tackle the problem the other way round. In fact, the model is directly built around the hypothesis that the transformation of rainfall into discharge at the catchment-scale can be driven by pre-existing datasets of soil, land use and weather in the UK.

3.4 General principle

As presented above, CRASH has been developed from the premise that the transformation of rainfall into daily discharge at the catchment-scale can be primarily driven by soil properties and land use data. The Hydrology of Soil Type (HOST) system (Boorman 1995) has been used to classify the soils of each catchment according to their hydrological behaviour. HOST is a conceptual representation of the

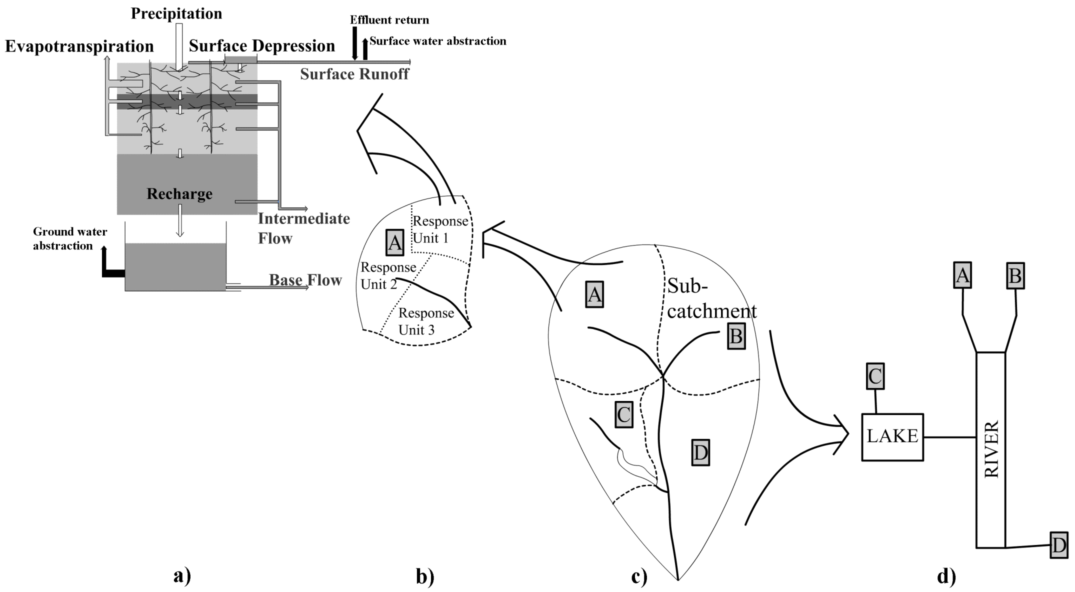

Figure 3.1: Structure of the CRASH model composed of a) Response unit, b) Subcatchment, c) Catchment, and d) the conceptual representation of the catchment.

hydrological processes in the soil zone. All soil types (series) in the United Kingdom have been grouped into one of the 29 response models (or classes) for which calibrated values of Base Flow Index (BFI) and Standard Percentage Runoff (SPR) have been computed (Boorman 1995). BFI is the long-term average proportion of flow that comes from stored sources and SPR is the “percentage of rainfall that causes the short-term increase in flow seen at the catchment outlet” (Boorman 1995).

The catchment in CRASH is composed of four types of objects: the response units, the sub-catchments, the rivers and the reservoirs (Figure 3.1). These objects can be classified into two groups: the primary object where the model is applied (the response unit – Figure 3.1a) and the routing objects (sub-catchment, river and reservoir – Figure 3.1d).

The response units are defined within each sub-catchments as cells with homogeneous hydrological behaviour (Figure 3.1b) based upon a combination of soil type and land use. Similar response units in a sub-catchment are grouped together for computational efficiency.

The following operations are applied to the response unit (Figure 3.1a): derivation of the soil water balance and of the intermediate flow; determination of the recharge to the ground water store and calculation of the base flow to the river; calculation of runoff generation and derivation of actual evapotranspiration according to plant growth stage, soil moisture and weather conditions. Results from response units of similar soil hydrological behaviour (or HOST class) are grouped together so that the unknown parameters are calibrated for each HOST class

The flows produced by the response units are transferred to the sub-catchment and catchment outlets through the three other types of object. The quick flow component (surface runoff and intermediate flow) is routed to the sub-catchment outlet by the means of the unit hydrograph method (Institute of Hydrology, 1985). The Muskingum-Cunge model (Cunge, 1969) is applied to transfer the hydrograph from an upstream sub-catchment to the outlet of a downstream sub-catchment or to the catchment outlet. A reservoir routing procedure (Chow *et al.*, 1988) is also available to take into account the effects of lakes and reservoirs on the hydrograph.

Surface water discharge and surface and ground water abstraction are also included in the model to account for artificial impacts on the water balance.

A flow chart of CRASH is presented on Figure 3.2.

The model requires several types of input data: the spatial distribution of soil and land use data for the definition and parameterization of the response units; daily weather data; catchment physical properties or descriptors for the parameterisation of the unit hydrograph at the sub-catchment scale; and river and reservoir characteristics for the flow routing.

3.5 Model description

A detailed description of CRASH is given starting with the primary object: the response unit which is the core of the model and then following with the routing objects: the sub-catchment, the river and the reservoir. Finally, the disaggregation of daily precipitation data into hourly data is presented.

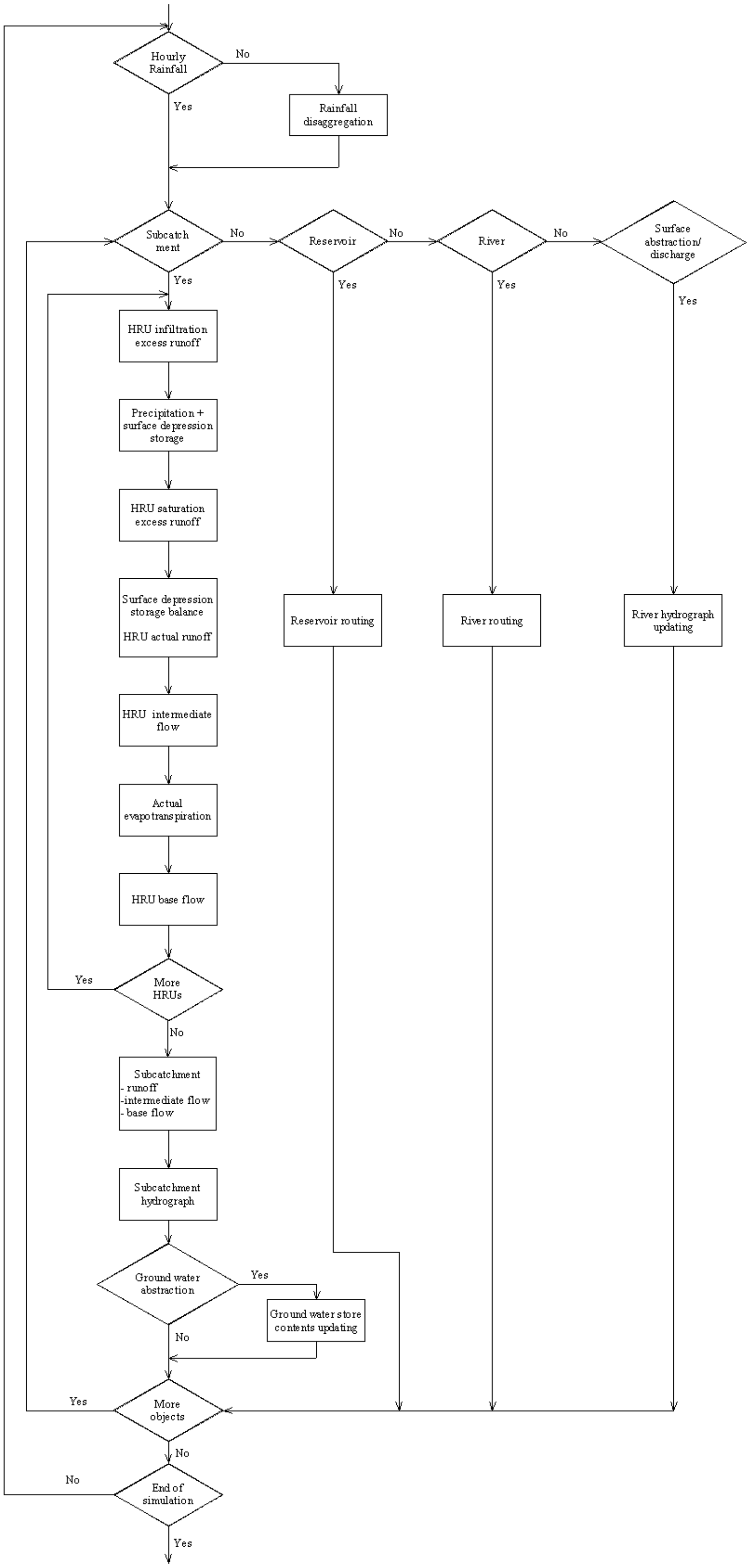

Figure 3.2: Flow chart of the CRASH model

3.5.1 Response unit

The hydrological response unit (HRU) is a cell of homogeneous hydrological conditions. It is defined as a combination of soil type (soil series) and land use/crop within an area with constant rainfall and potential evapotranspiration conditions. In practice, the HRUs are defined by overlaying the soil, land use, rainfall and evapotranspiration maps to create the homogeneous cells.

The conceptual representation of the HRUs is presented below.

3.5.1.1 Soil water balance model

A soil water balance computes the movement of water through each soil horizon using existing soil series data (horizon thickness, water contents at a range of suctions, saturated hydraulic conductivity) to the groundwater store, and allows temporary perched water tables within the soil profile.

The variation in mass balance of layer *i* is expressed as:

$$\Delta\theta_i = \frac{(D_{i-1} - D_i - AET_i - IF_i)\Delta T}{Area * \Delta z_i} \tag{3.1}$$

with θ_i the volumetric water content in m^3/m^3, *D* the drainage (m^3/s), *AET* the actual crop evapotranspiration and *IF* the intermediate flow (m^3/s), ΔT the time step (1 day = 86400s), *Area* the area of the HRU (m^2) and Δz_i the thickness of layer *i* (m).

For the top and bottom horizons, Equation 3.1 becomes respectively:

$$\Delta\theta_1 = \frac{(I - D_1 - AET_1 - IF_1)\Delta T}{Area * \Delta z_i} \tag{3.1'}$$

$$\Delta\theta_n = \frac{(D_{n-1} - Re - AET_n - IF_n)\Delta T}{Area * \Delta z_i} \tag{3.1''}$$

where *I* is the inflitration (m^3/s), *Re* the recharge to the groundwater store (m^3/s) and *n* the index of the bottom layer.

Drainage and recharge

Drainage occurs only from horizons where the water content is above field capacity (defined at 5 kPa, Evans *et al.*, 1999). In that case, the water movement from the layer *i* to the layer *i+1* is derived using (Evans 1999):

$$D_i = Min(K_i^{sat} * Area, K_{i+1}^{sat} * Area, \frac{\theta_i - \theta_i^{FC}}{\Delta T} * Area * \Delta z_i, \frac{\theta_{i+1}^{Sat} - \theta_{i+1}}{\Delta T} * Area * \Delta z_i) \tag{3.2}$$

where K^{sat} is the saturated hydraulic conductivity (m/s), θ^{sat} and θ^{FC} respectively the volumetric water content at saturation and at field capacity (m^3/m^3).

In a similar way, the recharge to the groundwater store occurs (3.3) if the water content of the bottom horizon is above field capacity:

$$Re = Min(K_n^{Sat} * Area, LBK * Area, \frac{\theta_n - \theta_n^{FC}}{\Delta T} * Area * \Delta z_i) \tag{3.3}$$

LBK is the lower boundary hydraulic conductivity (m/s). It parameterises the parent material and values were proposed for each HOST class by (Evans 1999).

3.5.1.2 River flow

The predicted river flow is composed of the contributions of intermediate flow from the soil water store, base flow from the groundwater store and surface runoff (infiltration excess and saturation excess) for each area of soil type/land use combination within the catchment.

3.5.1.2.1 Intermediate and base flows

The intermediate and base flows are proportional to the water contents within each horizon and the groundwater store, respectively:

$$IF = \sum_i IF_i \tag{3.4}$$

where:

$$IF_i = Max\left\{\left(\theta_i - \theta_i^{FC}\right) * Area * \Delta z_i * IFK; 0.0\right\} \tag{3.5}$$

$$BF = BFK * GWSC^2 \tag{3.6}$$

with *IFK* and *BFK* the intermediate flow and base flow coefficient in respectively s^{-1} and $m^{-3}s^{-1}$. *GWSC* is the groundwater store content (m^3). The nonlinear relationship between the base flow *BF* and the groundwater store content *GWSC* represents the common nonlinearity in groundwater systems (Nutbrown and Downing, 1976).

The groundwater store content fluctuates according to the variations in recharge *Re* and discharge: the base flow (*BF* in m^3/s):

$$GWSC_t = GWSC_{t-1} + \Delta T * (Re - BF) \tag{3.7}$$

The groundwater store content is initialised in accordance with SWATCATCH (Hollis and Brown, 1996):

$$GWSC_0 = 0.1 * BFI * SAAR_{41-70} * \frac{Area}{1000} \tag{3.8}$$

Where $SAAR_{4170}$ is the standard average annual rainfall for the period 1941-70 (mm) and *BFI* the dimensionless base flow index.

IFK represents the lateral hydraulic conductivity of the soil. *IFK* is calibrated due to the difference of scale between the catchment scale application of this parameter in CRASH and the plot scale lateral hydraulic conductivity measurements available for each soil type.

The parameter *BFK* is also derived by calibration.

3.5.1.2.2 Surface runoff

Surface runoff *Ru* (m^3/s) from each soil type can be either saturation excess flow or Hortonian flow, if the rainfall intensity exceeds the saturated hydraulic conductivity of the upper horizon. The different cases are summarised below:

Case1 $\theta_1 = \theta_1^{sat}$:

$$I = D_1 \tag{3.9}$$

$$Ru = R * Area - I \tag{3.10}$$

Case2 $\theta_1 < \theta_1^{sat}$:

Case2.1: $R < K_1^{Sat}$

$$I = R * Area \tag{3.11}$$

$$Ru = 0 \tag{3.12}$$

Case2.2: $R > K_1^{Sat}$

$$Ru = R * Area - I \tag{3.13}$$

where R is the rainfall in m/s.

In the Case 2.2, infiltration is computed with the Philip's equation (Philip 1957), in which the infiltration after ponding I_{ap} (m^3) for the one directional Richard's equation for a homogeneous medium can be expressed as:

$$I_{ap} = Area * \sum_j \phi_j T_{ap}^{\frac{j}{2}} \tag{3.14}$$

where T_{ap} is the time after ponding (s) and j an index starting from 1. ϕ_j are coefficients where ϕ_1 is called the sorptivity S and ϕ_2 - noted A in the rest of the text – is related to the saturatured hydraulic conductivity of the soil.

If Equation (3.14) is limited to its first two terms (Chong 1983), the total infiltration after time T (s) becomes:

$$I * T = Area * \left\{ R * T_p + A\left(T - T_p\right) + S\left[\sqrt{T - \frac{S^2}{4A\left(\frac{R^2}{A} - R\right)}} - \sqrt{T_p - \frac{S^2}{4A\left(\frac{R^2}{A} - R\right)}}\right]\right\} \tag{3.15}$$

with time to ponding T_p (s) (Kutilek 1980):

$$T_p = S^2 \frac{1 - \frac{A}{2R}}{2R^2\left(1 - \frac{A}{R}\right)^2} \tag{3.16}$$

and the sorptivity $S = B\sqrt{\theta_1^{Sat} - \theta_1^{Ini}}$ (3.17)

with θ^{ini} the initial volumetric water content (m^3/m^3).

The calibration of the parameter B in Equation (3.17) is achieved in conjunction with the HOST system. In HOST, the response runoff RRu (m^3), defined as the volume of fast flow during a period of 5*LAG, for a soil at field capacity is expressed as a function of the standard percentage runoff SPR (%):

$$RRu = SPR * R * Area \tag{3.18}$$

In CRASH, RRu is the sum of the surface runoff and the intermediate flow. The parameter B is then determined by combining Equations (3.4), (3.5), (3.13), (3.15) and (3.18).

The parameter A needs calibration which gives a total number of three parameters to calibrate per HOST class.

3.5.1.2.3 Surface Depression

The early stages of runoff generation will not necessarily lead to increased river flow due to surface storage within depressions in the landscape. The amount of water captured depends mainly on the land use and slope, although it can also be influenced by tillage, vegetation and soil type in agricultural land. Several modelling studies have presented values of the depression storage for different conditions, which can be as large as 20 mm (Moore and Larson, 1979), but in most cases is much lower.

For example, (Hicks 1944) suggested values of 5.1, 3.8 and 2.5 mm for sand, loam and clay soils in urban areas. (Miller 1972) proposed values between 2.5 and 3.8 mm for four urban catchments. (Huber W.C. and Dickinson 1988) recommended depression storage of 2.5 mm for grassed urban surfaces. (Zobeck 1987) reported values of random roughness for agricultural lands after harrowing and rotary tillage below 20 mm, which gives a depression storage of less than 3 mm on a zero slope when using the model(Onstad 1984). Similarly, (Cremers 1996) listed random roughness for various crops and tillage directions which were, with the exception of potatoes and fallow with tillage perpendicular to the slope, below 18 mm. Consequently, the depression storage in CRASH has been set to 4.0 mm.

3.5.1.3 Actual Evapotranspiration

The evapotranspiration is computed according to (Allen 1998) as the potential evapotranspiration PET (m/s) corrected by a crop coefficient C_c and a water stress coefficient C_s.

$$AET = PET * C_c * C_s * Area \tag{3.19}$$

The potential evapotranspiration is supplied to the model as an input and must be derived externally. Following guidance from Allen (1998), PET should be derived using the Penman-Monteith method.

C_c is a crop coefficient to relate the transpiration from a crop to that of a reference crop (grass). C_c varies with crop type and time within the cropping year (Figure 3.3, Table 3.1) (Allen, 1998).

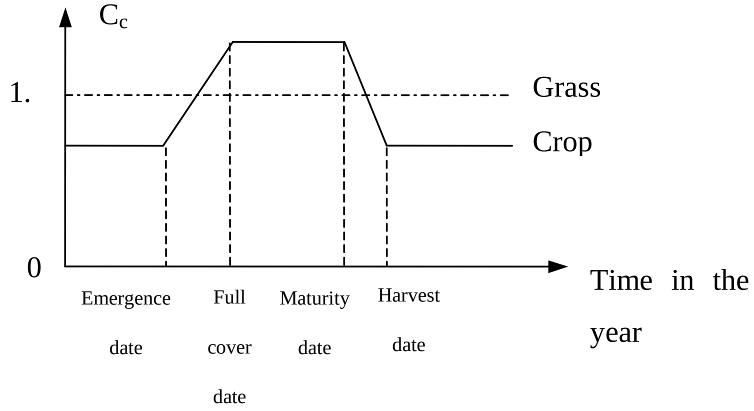

Figure 3.3: Example variation in the crop coefficient (C_c) according to crop growth during the year.

Table 3.1: Example of crop coefficient (C_c) values (Allen, 1998)**.**

Crop	C_c at emergence date	C_c at full cover date	C_c at harvest date
Winter wheat	0.7	1.15	0.25-0.4
Potato	0.5	1.15	0.75
Sweet maize	0.7	1.15	1.05
Sunflower	0.35	1.0-1.15	0.35
Carrots	0.7	1.05	0.95

C_s is a water stress coefficient which allows for the reduced ability of the crop to extract water as the soil moisture content decreases (Figure 3.4).

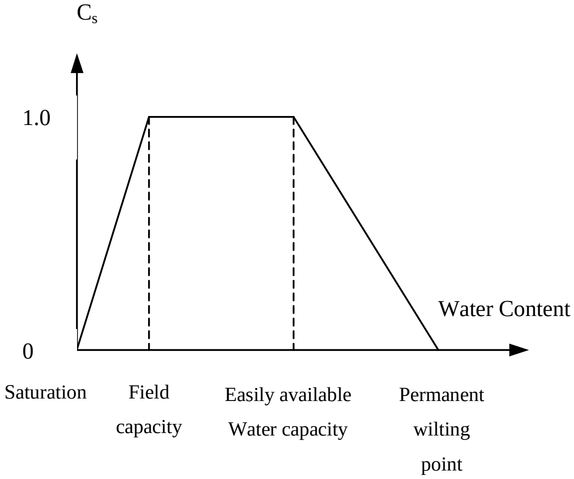

Figure 3.4: Example variation in the water stress coefficient (C_s) according to soil water content.

The water root uptake is calculated following the model of (Jarvis 1989) where the sink term SI (m^3/s) in each soil horizon is expressed as:

$$SI_i = \frac{AET}{\Delta z_i}\frac{P_i\alpha_i}{\bar{\alpha}} \tag{3.20}$$

P_i and α_i are respectively the proportion of root length density within a layer and a reduction factor due to water shortage. They are functions of the mid-point depth of the layer below the soil surface for P_i and of the water content within the layer for α_i. $\bar{\alpha}$ is the average value of the α_i.

Finally, the development of the root zone depth *RD* (m) is predicted following the empirical equation of (Borg H. and Grimes 1986).

$$RD = RD^{\max} * \left[0.5 + 0.5 * \sin\left(3.03 * \frac{TFP}{DRG} - 1.47 \right) \right] \tag{3.21}$$

where RD^{max} is the maximum root zone depth (m), TFP the time from planting (s) and DRG the duration of root growth (s).

3.5.1.4 Input data requirements

The data required to define HRUs are soil, land use and meteorological information.

The soil and land use data are the spatial distribution of respectively soil series and crops/land uses. Spatial precipitation data can be input as hourly or daily precipitation. In the case of daily data, CRASH has the functionality to disaggregate the values to an hourly time step (see 3.5.5). Finally, the model requires spatial daily PET values computed using the Penman-Monteith method.

In the present study, the spatial distributions of soil units were taken from the digital national soil map of England and Wales (Ragg *et al.*, 1984) and the distribution of land use classes (aggregate of crops/land uses) from the Land Cover Map (Centre for Ecology and Hydrology, Land Cover Map 1990). The composition of soil units in terms of soil series was supplied by the National Soil Resources Institute, and the DEFRA agricultural statistics from the 1988 data set were used to define the proportion of each crop in arable land areas of the catchment.

It was assumed that a crop/land use was spread uniformly among the soil series within an area composed of a soil unit and a land use class.

The Thiessen polygon method was used to create spatial maps of rainfall depths from point values at meteorological stations.

3.5.2 Sub-catchment

There are various methods to transfer the surface and intermediate flows towards the catchment or sub-catchment outlets. However, the choice of method does not have a major impact on the shape of the hydrograph (Todini 1996).

The unit hydrograph method has been selected to transform surface runoff and intermediate flow production into river flow. Several studies have reported equations to derive parameters specific to the UK (e.g. (Natural Environment Research Council 1975); (IH 1985); (Burg 1993); (Marshall); (Marshall 1999)0), (IH 1985)) has been selected for its simplicity to derive the catchment parameters. The unit hydrograph time-to-peak *Ttp* (h) is estimated as:

$$Ttp(0) = 283 * S1085^{-0.33} * SAAR_{4170}{}^{-0.54} * MSL^{0.23} * (1 + URBAN_{FSR})^{-2.2} \tag{3.22}$$

with *S1085* the 10-85% channel slope (m/km), $SAAR_{4170}$ the standard average annual rainfall for the period 1941-70 (mm.y^{-1}), *MSL* the main stream length (km) and $URBAN_{FSR}$ the urbanisation index.

3.5.3 River routing

The Muskingum-Cunge (Cunge, 1969) technique is used to route the upstream hydrograph through the main channel. This non-linear method requires a representative channel cross section, the main channel length, the Manning roughness coefficient and the channel bed slope.

3.5.4 Reservoir routing

The level pool routing technique developed by (Chow 1988) can be activated to account for reservoirs in the catchment. The continuity equation in the reservoir is expressed as:

$$\frac{dL}{dT} = \frac{In(T) - Q(L)}{RArea(L)} \tag{3.23}$$

with *L* the reservoir level (m), *Q* the reservoir outflow (m^3/s) and *RArea* the reservoir area (m^2).

A third order Runge-Kutta scheme is performed to solve Equation (3.23) (Chow 1988). The area-level relationship *RArea*(*L*) depends on the topography of the shore. This relationship is assumed to be linear in the model as it only fails in exceptional cases (IH 1999).

3.5.5 Hyetograph

For Case 2.2, the Hortonian flow is determined by the means of Philip's equation, which requires a finer resolution of temporal rain data than the daily values available. The daily precipitation can be disaggregated if no hourly rainfall is available to create a hyetograph at an hourly time step using the method developed by Maréchal and Holman (Submitted-2003) to determine the proportion of time during the day when the rainfall intensity is greater than the saturated hydraulic conductivity of the topsoil.

3.6 Case studies

Three study catchments were selected which represent the three physical settings within the HOST classification (Figure 3.5). Amesbury is located on the South of England and is an example of a catchment where the soils overlie a permeable substrate in which groundwater usually exists at a depth of more than 2 m (Boorman 1995). Gwills is situated in the South-West of England and the soils are typified by having a water table within 2 m, either in the soil or permeable substrate. Finally, the third catchment is located in Central England (Avon). It represents the third physical setting where there is no significant underlying aquifer or groundwater but usually a shallow impermeable substrate which impedes vertical movement of water.

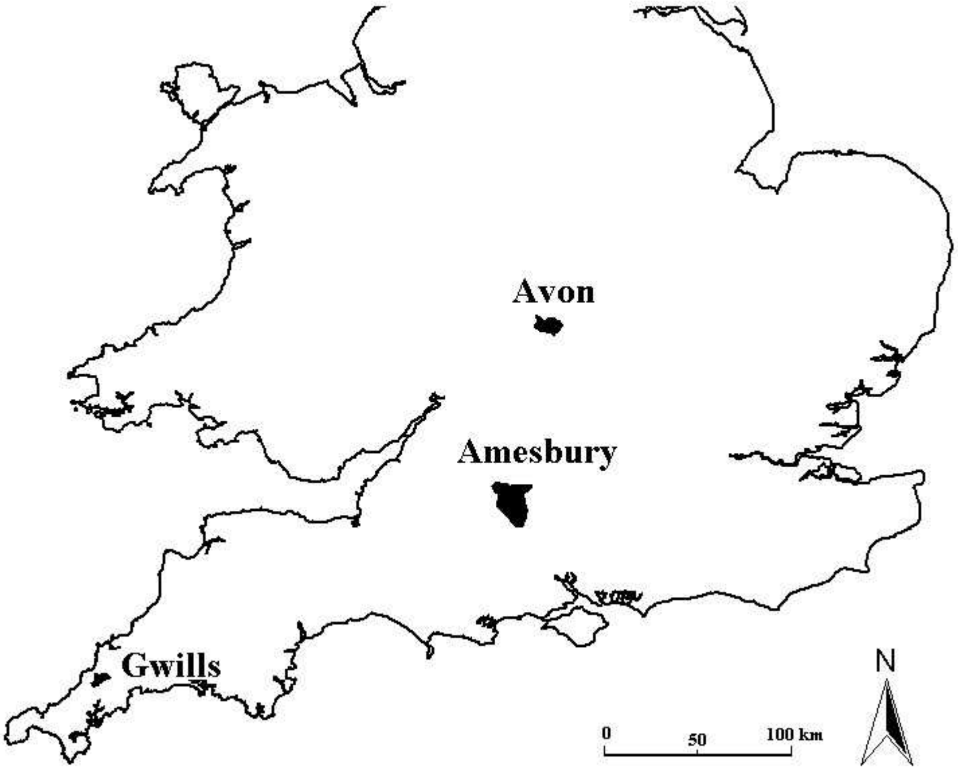

Figure 3.5: Location of the study catchments

3.6.1 Amesbury catchment

The catchment covers an area of 320 km^2 with an elevation between 54 to 303 m above sea level (asl). Average annual precipitation is 735 mm and the annual average river flow at the catchment outlet is 300 mm.

The main soil units in the catchment (Figure 3.6a) are characterised by permeable loamy or silty soils over chalk (341, 342a, 342b, 511d and 511f) or limestone (343h and 343i), or medium silty over clayey drift (581d) (Findley *et al.*, 1984). Together they account for about 60% of the area and are all are well-drained soils in which the main flow path is recharge to an aquifer (HOST class 1- (Boorman 1995). HOST class 16 is the second most significant HOST class in the catchment, in which soils where there is no significant underlying aquifer and where surface runoff is likely cover 12% of the catchment.

The main land use is grassland (Figure 3.6b), with arable crops found in the northern part of the catchment (Centre for Ecology and Hydrology, Land cover map 1990). The rural development areas (also called suburban areas) were treated as grass lands.

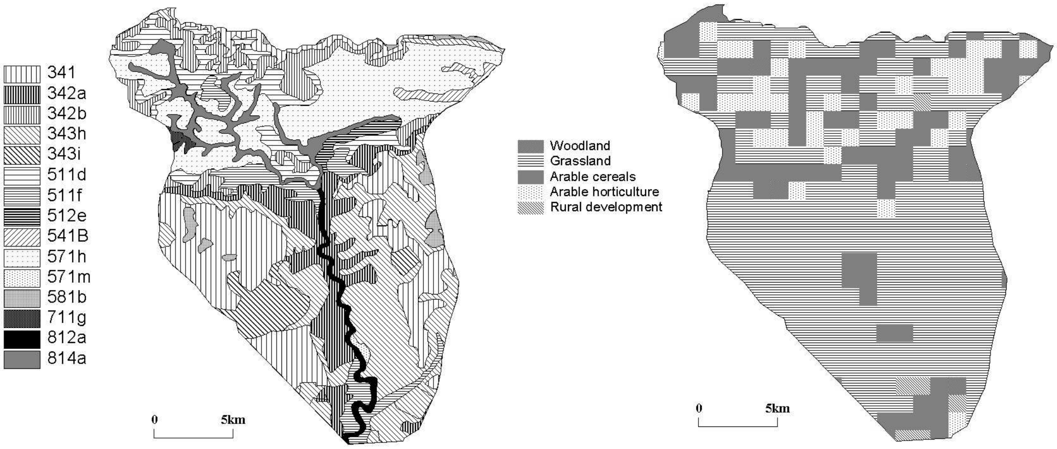

Figure 3.6: Amesbury catchment: a) Soil map units; b) Land use

3.6.2 Gwillls catchment

The Gwills catchment is the smallest (42 km^2) and wettest (average annual rainfall and river flow of 970 mm and 540 mm, respectively) of the three study catchments. Elevation ranges from 10 to 217 m.a.sl.

The two main soil units are units 541j and 541k (Figure 3.7a). They are equally composed of soil series belonging to HOST class 17 on one hand and to HOST classes 6, 8 and 9 on the other hand. Class 17 has similar properties to those presented above for class 16 and it covers about 46% of the catchment. Classes 8 and 9 belong to the second of the three main conceptual models of the HOST classification. They have aquifer within the first 2 m of the profile; the water table can rise frequently to up to 40 cm below the surface in class 9 whereas this only happens rarely in class 8 (Boorman 1995). Classes 8 and 9 cover 32% of the area.

The land use (grassland followed by arable) is similar to that of the Amesbury catchment (Figure 3.7b).

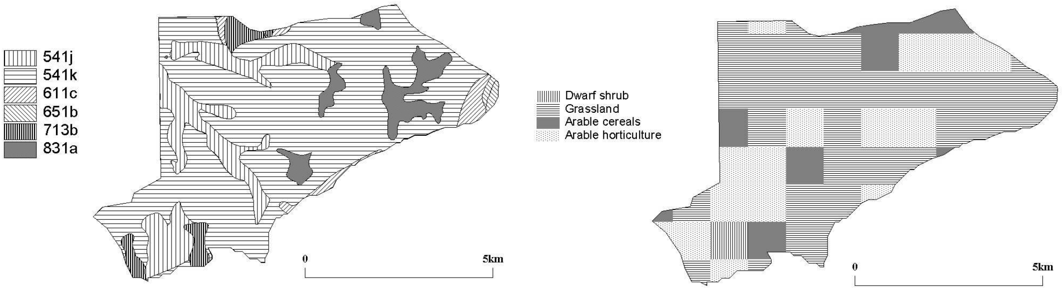

Figure 3.7: Gwills catchment: a) Soil map units; b) Land use

3.6.3 Avon catchment

The Avon catchment differs from the other catchments regarding various physical conditions. It is the only catchment with a significant reservoir (Figure 3.8a), which receives inflows from an area of 12 km^2 of the 100 km^2 of the entire catchment. Also the catchment is mainly covered by arable crops with grassland found in the eastern part of the area where the topography is less favourable to agriculture (Figure 3.8b). The area is relatively flat except for the eastern boundary, and the elevation ranges from 30 to 225 m.a.s.l. The annual average rainfall and river flow are 650 mm and 180 mm, respectively.

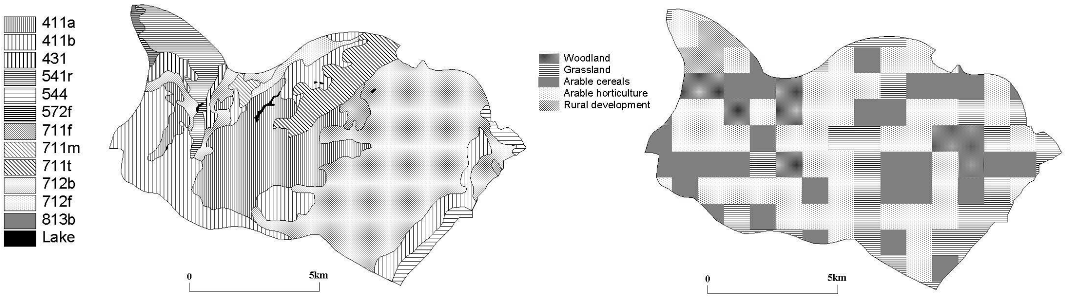

Figure 3.8: Avon catchment: a) Soil map units; b) Land use

Nearly 90 % of the area is characterised by soils developed in swelling clayey material, clay or soft mudstone (units 411a, 411b, 712b and 712g).

3.7 Calibration

CRASH has been calibrated for the three study areas using Monte Carlo modelling. Monte Carlo sampling has been used to generate 5000 parameter sets for which the distributions of the parameters were assumed to be uniform in their range of variation. The best parameter set was selected as the one giving the best fit between observed and simulated flows according to a multi-objective function.

(Yu 2000) demonstrated the advantages of a multi-objective function for the calibration of a hydrological model and suggested a fuzzy multi-objective function (FMOF). The FMOF is designed to account for all the parts of the hydrograph. The flow duration curve is divided into a number of stages and the calibration process aims to find the best compromise for all these stages. Yu and Yang (2000) suggested a FMOF as follows:

$$FMOF = 1 - \min_{j} \mu_j \left(MPE_j \right) \tag{3.24}$$

where MPE_j is the mean absolute percentage error for the *j*th flow stage (Equation 3.25) and $\mu_j(MPE_j)$ is the membership function of the MPE (Figure 3.9).

$$MPE_j = \frac{1}{N_j} \sum_p \left| \frac{Obs_p - Sim_p}{Obs_p} \right| * 100\% \tag{3.25}$$

with *Obs* and *Sim* respectively the observed and simulated values, and *N* the number of data for the *j*th flow stage.

The boundaries of the 11 stages are the flows at 0, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100th percentiles.

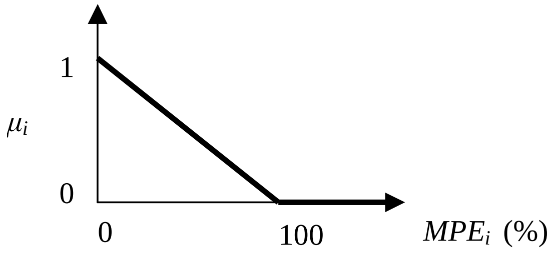

Figure 3.9: Membership function of the mean percentage error (MPE) used in the fuzzy multi-objective function (FMOF).

The calibration periods for the catchments were 1980-1984 (Amesbury) and 1979-1984 (Gwills and Avon). The results for the FMOF and the Nash-Sutcliffe (R^2) efficiency index are listed in Table 3.2. The FMOF gives an indication of the goodness of fit for the stage of the flow duration curve where the simulation is the most different from observations. The optimal value is 0.0 which means that there is no difference between the two flow duration curves and a FMOF of 1.0 means that the mean absolute percentage error is 100% in all parts of the flow duration curve. On the other hand, R^2 is based on the time series and accounts for the entire hydrograph. It indicates the overall goodness of fit of the simulation. Sefton and Howarth (1998) proposed that R^2 be adopted as the criteria to reject the calibration of a model, and suggested the value of 0.5 as the threshold. CRASH fulfils this requirement and can be considered as sufficiently calibrated.

The time series and flow duration curves for the three simulations are compared to observations in Figure 3.10.

Table 3.2: Statistical results – Calibration period

	Amesbury	**Gwills**	**Avon**
FMOF	0.32	0.35	0.22
R^2	0.83	0.64	0.54

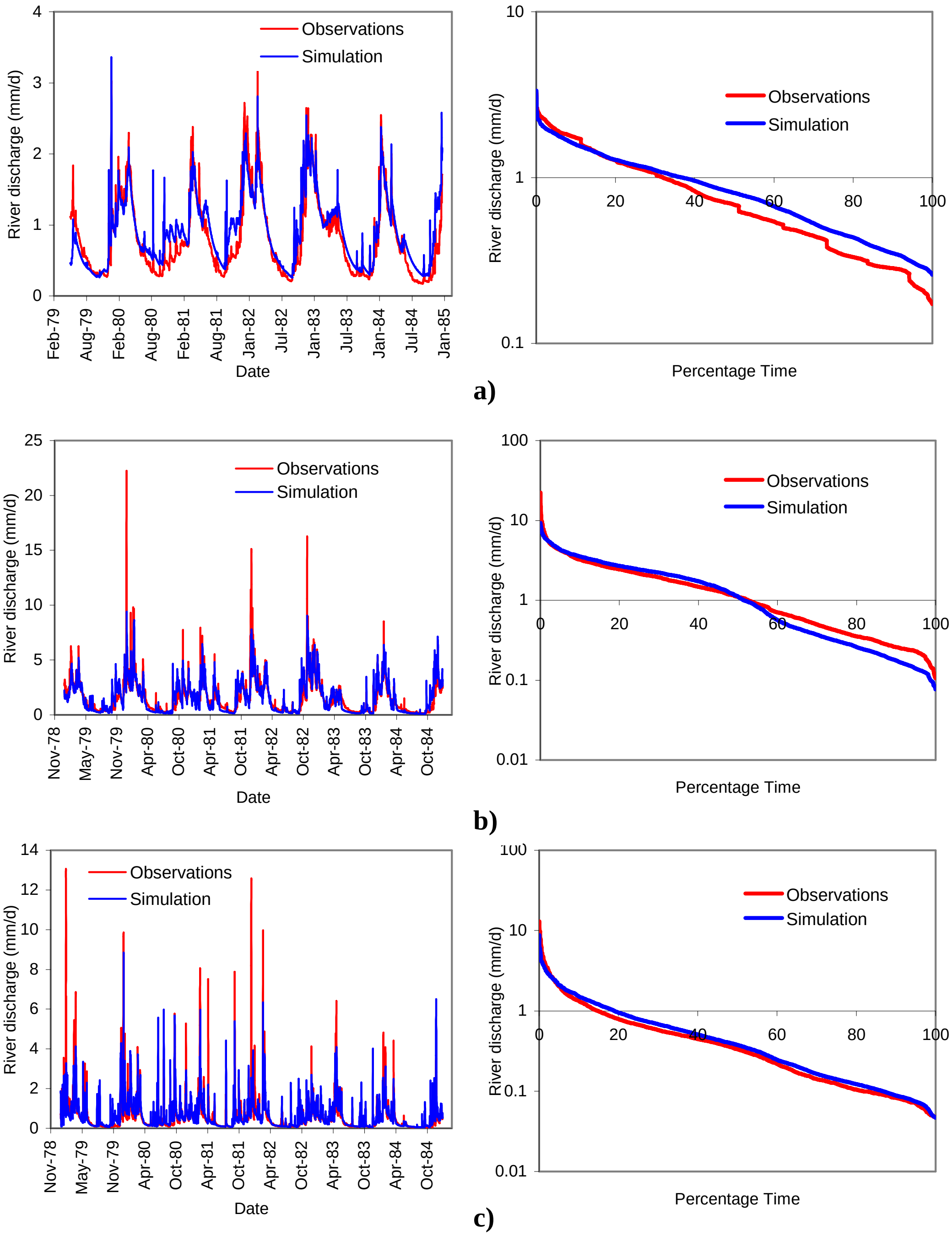

Figure 3.10: Calibration results - Time series and flow duration curves for a) Amesbury, b) Gwills and c) Avon

3.8 Evaluation

Whether a theory can or can not be validated has been extensively discussed, but it is now generally agreed that a theory, and thus a model, can only be invalidated. (Konikow 1992) state that “validation has no place in hydrology”. The aim of this section is i) to determine whether CRASH should be invalidated for one or more of the study areas, and if it is not, ii) to evaluate its performance over the 5 years following the calibration period.

i) The first step is to define a criteria to be able to reject or accept the model and its calibration. The criteria chosen is the same as that used during the calibration exercise (Nash-Sutcliffe efficiency index $R^2<0.5$). It can be seen from the results in Table 3.3 that CRASH should not be invalidated for any of the three simulations. It can then be concluded that CRASH adequately matches the observed data in the three catchments after it has been calibrated specifically for each of the catchments.

ii) Once the invalidation test has been performed and rejected – i.e. the model has not been invalidated - it is possible to further evaluate the matches between simulated and observed flows. This evaluation is performed through numerical (Table 3.3) and graphical (Figure 3.11) comparisons. Table 3.3 summarises the results in terms of Fuzzy Multi-Objective Function (FMOF), Nash-Sutcliffe efficiency index (R^2) and percent bias (PBIAS). The third index, PBIAS, is a measure of the bias of the model (Equation 3.26). A tendency of the model to overestimate is reflected by a positive value of PBIAS and similarly a tendency to underestimate is indicated by a negative value.

$$PBIAS = \frac{\sum_{j}\left(Sim_j - Obs_j\right)}{\sum_{j} Obs_j} * 100\% \tag{3.26}$$

Table 3.3: Statistical results – Evaluation period

	Amesbury	**Gwills**	**Avon**
FMOF	0.51	0.43	0.24
R^2	0.86	0.54	0.55
PBIAS (%)	16.3	6.5	8.8

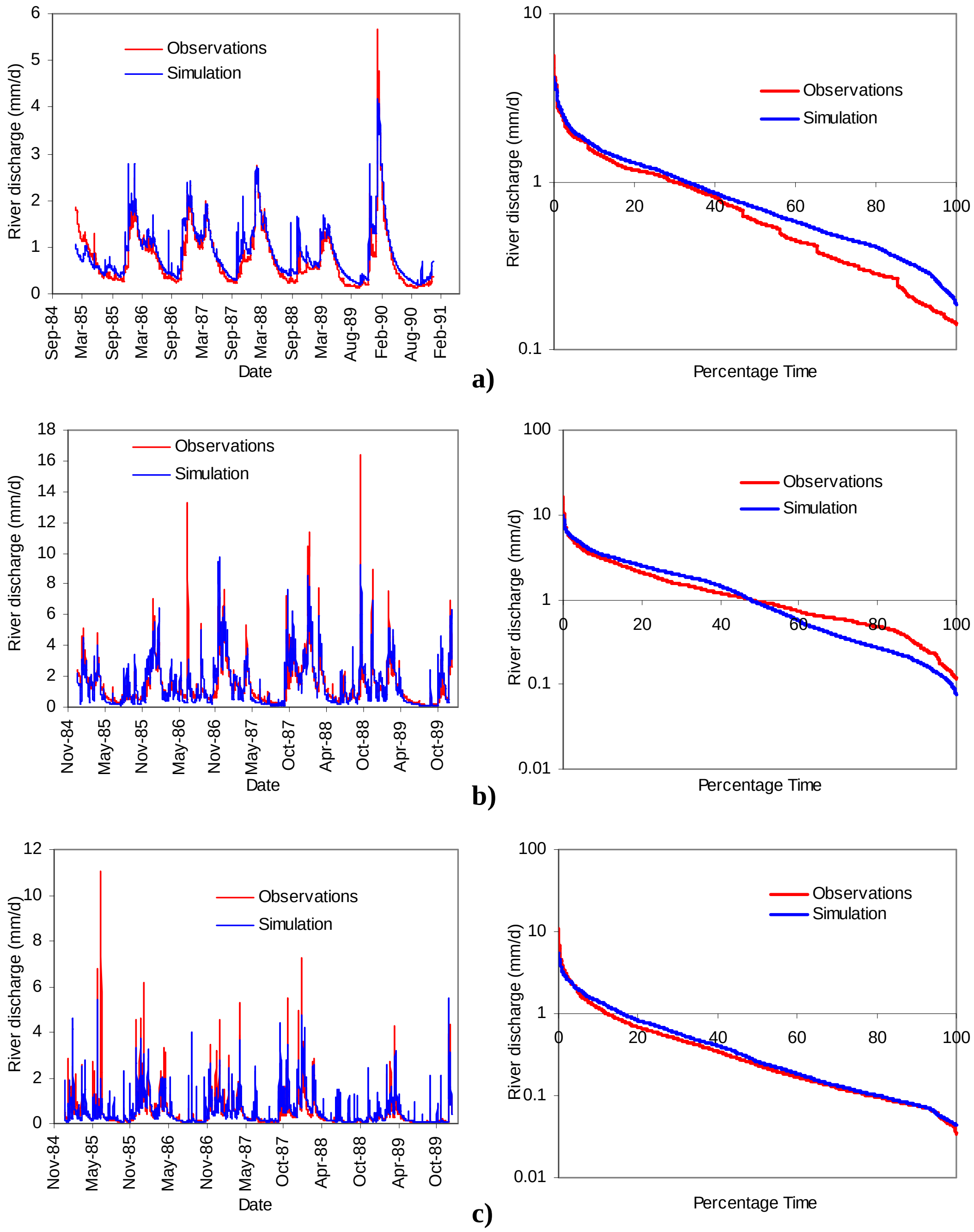

Figure 3.11: Evaluation results - Time series and flow duration curves for a) Amesbury, b) Gwills and c) Avon

CRASH tends to overestimate the river flows for the Amesbury catchment during the evaluation period (PBIAS = 16.3%). The overestimation is mainly related to the low flows (Figure 3.11a) and explains the change of FMOF from 0.32 in the calibration period to 0.51 in the evaluation period. However, the overall behaviour of the model is very acceptable and has even slightly improved, as the R^2 has increased from 0.83 to 0.86. This improvement results from the fact that even if the relative difference between observations and simulation has increased in the low flows, the absolute difference on the whole hydrograph has decreased.

It is in the Gwills catchment, the wettest of the three sites, that CRASH has the lowest tendency to overestimate river flow. Flows are even underestimated between the 50 and 95 percentiles in the flow duration curve (Figure 3.11b) which are mainly associated with recession flows. It is concluded that the recharge to the ground water store is slightly underestimated for this simulation. The decrease in the efficiency index (from 0.64 during calibration to 0.54 during evaluation) is not solely the consequence of the underestimation of the recession flows, but also of the timing of the high flows (Figure 3.11b). Although the flow duration curves from the observations and the simulation match well in the high flows, the high flow events are not always occuring at the same time.

The two flow duration curves match well in the Avon catchment (Figure 3.11c) and the FMOF shows that there is no stage where the simulated flow duration curve is significantly different from the observed one. Also CRASH only has a slight tendency to overestimate river flow. The R^2 value is limited to 0.55 because the main soils of the Avon catchment are slowly permeable, and therefore, peak events are rather frequent (Figure 3.11c). Differences in the estimation of the high flow events can have a significant effect on the value of R^2, and CRASH tends to underestimate these high flows in this catchment (Figure 3.11c).

3.9 Discussion and conclusion

The objective of this paper was to present the first two stages of the development of a catchment-scale rainfall-runoff model predicting daily river flows: i) description and ii) evaluation of CRASH in three study areas.

i) CRASH has been developed from the assumption that the processes of transformation of rainfall into river discharge can be related to physical descriptors at the catchment scale. The novelty of this approach is that CRASH is directly built around the hypothesis that this transformation is primarily driven by soil properties and land use data in the UK, which makes the parameters identifiable. During the development of the model, it has been clear that if a model is to be widely applicable, it has to have limited data demands. In that respect, CRASH has been designed to work entirely with existing data sets. The structure has also been kept simple to limit the number of parameters to calibrate. CRASH incorporates the results of previous work and especially of the HOST system which is used on two different levels. Firstly, qualitatively whereby the soils in each catchment are grouped according to their HOST classification, which groups soils of similar hydrological behaviour. Secondly, the values of the Standard Percentage Runoff for each HOST class are directly used within the calibration of a free parameter in CRASH.

ii) CRASH has been tested in three diverse catchments located in different regions of England. These sites have been chosen to contain soils from the three main physical settings of soil hydrology developed within HOST.

From the tests, it was shown that CRASH was successful in simulating both time series and flow duration curves when calibrated specifically for each catchment. The term successful in this context means that the model has not been rejected during either the calibration or evaluation stages according to a rejection criteria. From the evaluation of the model performances in the three catchments, it was demonstrated that CRASH only has a slight tendency to overestimate river flow.

The next developmental stage with CRASH in challenging the initial hypothesis will be to regionalise the parameter set in order to assess whether it is possible to obtain a single set. (Fernandez 2000) and (Kuczera 1997) suggested that the regionalisation of the calibration brings more constraints and that these constraints can actually improve the efficiency of the parameterisation. Early results have been presented (Maréchal 2002) that show some promise for the approach presented here.

3.10 Acknowledgements

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4 A ROBUST AND PARSIMONIOUS REGIONAL DISAGGREGATION METHOD FOR DERIVING SEASONAL RAINFALL INTENSITIES AT THE HOURLY TIMESCALE FOR THE UK

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4.1 Abstract

A regional rainfall disaggregation method from daily to hourly intensities is presented for the United Kingdom. This method was developed to be used with rainfall-runoff models mainly for water resources applications. The approach is based on the inter-dependence of the hourly rainfall intensities during a rainfall event. The analysis of 23,229 days with at least 15mm of precipitation from 238 weather stations throughout the UK allowed regional parameters for climatically homogeneous regions of the UK to be derived for each season. The method reproduces well the main statistical characteristics of the data (mean, minimum and maximum intensity and standard deviation). The method is fully operational and can potentially be applied to any location in England, Wales, Scotland and Northern Ireland.

Keywords: Rainfall; Disaggregation; Regional analysis; Stochastic processes

4.2 Introduction

The availability of rainfall data at a fine (sub-daily) timescale can be a necessity to estimate infiltration excess surface runoff for the design of agricultural systems (e.g. Burt, 2001; Jarvis, 1992), the prediction of infiltration-excess runoff for flood protection (e.g. Cameron *et al.*, 2000) or to estimate the impacts of land management (e.g. Holman *et al*., 2003). In fact, it is generally accepted that infiltration excess surface runoff was rare in humid and temperate regions. However, it seems to become a much more important process in some areas due to land use changes (Burt, 2001) or to farming practices. Furthermore, climate change will result in changes in land cover and different antecedent soil moisture conditions (Bronstert *et al.*, 1999) that will have an impact on the infiltration characteristics of the soil and therefore on the production of surface runoff.

Infiltration excess surface runoff is especially critical as in addition to water quantity problems – ie. flooding - it is often associated with soil erosion and therefore with water quality problems. The erosion of soils and especially of agricultural soils create two types of problems. Firstly, the loss of agricultural soil can be so significant that it impacts the production of crops (e.g. Biot and Lu, 1995). Secondly, eroded soils carry pollutants such as phosphate and pesticides (e.g. Stoate *et al.*, 2001) into the surface water network and surface water bodies and they create problems of discoloration of water and sedimentation and water quality problems in reservoirs (e.g. Walling *et al.*, 2003).

In many countries there are insufficient numbers of rainfall stations recording sub-daily data. For example, although the Meteorological Office in the United Kingdom runs a network of more than 5,000 rainfall stations, hourly rainfall data are only collected for a few hundred stations (Meteorological Office, 2001).

One solution to obtain fine temporal resolution rainfall data is to disaggregate the coarse (e.g. daily) data. Disaggregation is achieved by applying stochastic rainfall models to reproduce the main statistics of the data (Guenni, 2002). The two main categories of such stochastic models are profile-based (e.g. Valencia and Schaake, 1972; Hershenhorn and Woolhiser, 1987; Koutsoyiannis and Xanthopoulos, 1990) and pulse-based (e.g. Rodriguez-Iturbe *et al.*, 1987; Onof and Wheater, 1993; Cowperwait *et al.*, 1996a) rainfall models. But all were developed for use with individual station data (Cameron *et al.*, 2000).

Only a few attempts have been made to derive regional parameters for stochastic rainfall models. Econopouly *et al.* (1990) found that it was possible to export the calibrated Hershenhorn and Woolhiser model (1987) over a long distance in the United

States of America if the condition of climatic similarity was respected. Gyasi-Agyei (1999) tried to compute regional parameters in Australia for the Gyasi-Agyei - Willgoose model. Cowperwait *et al.* (1996b) derived regional parameters for Great Britain but used only 27 sites with hourly records. Koutsoyiannis *et al* (2003) presented a methodology for spatial-temporal disaggregation aimed at generating hourly rainfall series for several sites from daily rainfall series from all the sites and hourly rainfall series from at least one site.

These methods showed the relevance of regional rainfall disaggregation but failed to propose robust operational methods as it has been recognised that multi-site parameter estimation is complex for these types of models (Kottegoda *et al.*, 2003; Favre *et al.*, 2002).

The aim of this study is to develop a robust and parsimonious rainfall disaggregation method from daily to hourly intensities that is applicable at a large scale in the United Kingdom. It is implemented to be used with rainfall-runoff models which are aimed at water resources applications (quantity and quality) (e.g. CRASH: Maréchal and Holman, 2002). The proposed rainfall disaggregation method should allow a simple and time-efficient computation of rainfall intensities used for the prediction of infiltration excess runoff at sites where hourly rainfall data are not available.

4.3 Data set

A total of 389 stations spread over England, Wales, Scotland and Northern Ireland corresponding to 5,798 station/years with hourly rainfall data between 1983 and 1999 have been analysed. Only intense rainfall episodes have been selected, defined as days (from 9am to 9am) when the total daily rainfall was ≥15mm (CRCCH, 2000). 238 stations with 23,229intense rainfall events were finally selected (Figure 4.1). Table 4.1 summarises the distribution of the stations and intense events for the 9 homogeneous regions defined following Gregory *et al.* (1991). The number of events per homogeneous region ranges from 942 in North Ireland where there are only 15 stations to 5,260 in South-West England where the network of stations is denser.

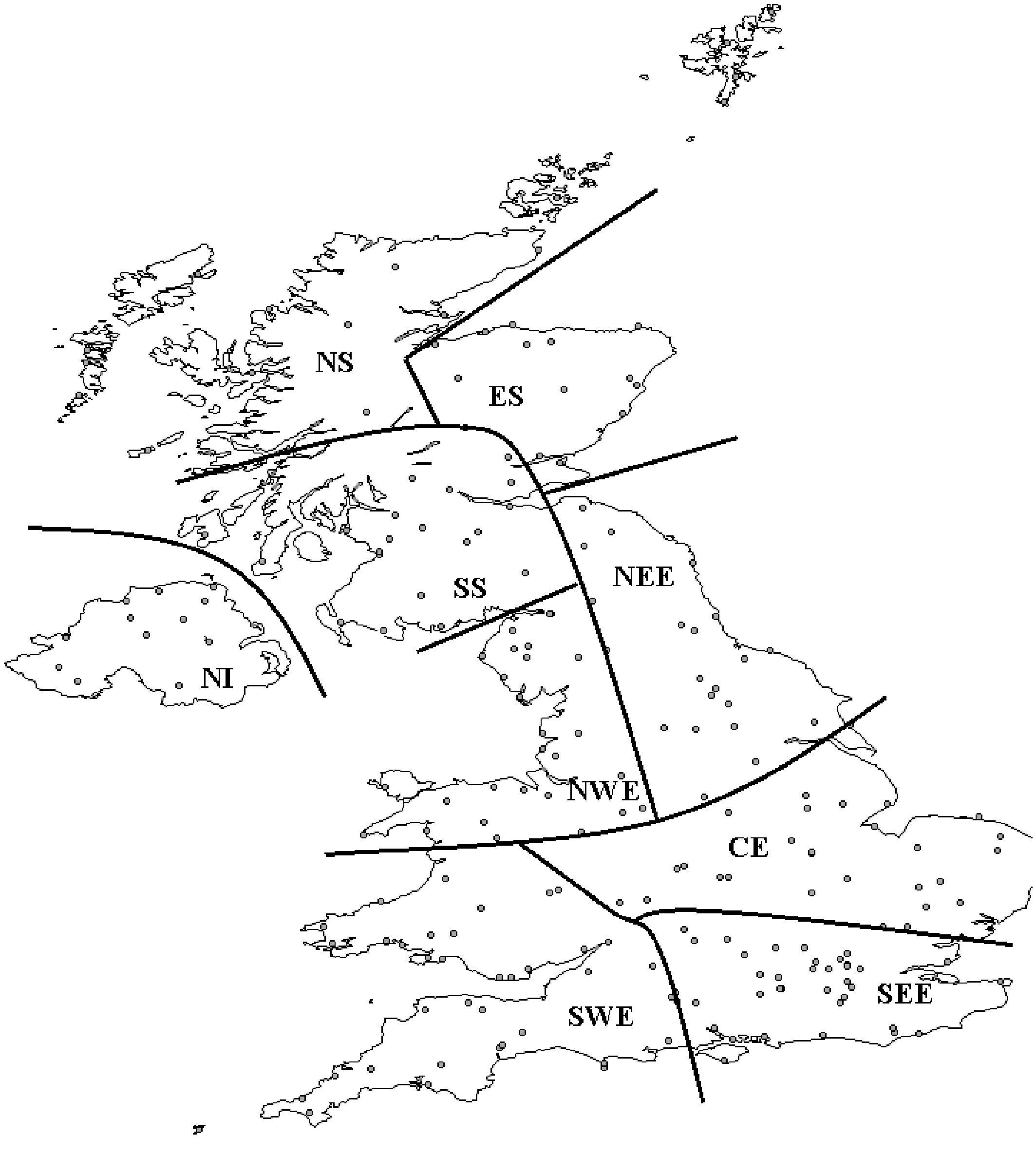

Figure 4.1: The homogenous climate regions (adapted from Gregory *et al.*, 1991) and the location of the meteorological stations providing hourly data

Table 4.1: Distribution of the meteorological stations and rainfall events

Region	Number of Stations	Number of events
Northern Ireland(NI)	15	942
North of Scotland (NS)	21	3,284
East of Scotland (ES)	16	1,241
South of Scotland (SS)	32	4,443
North West of England (NWE)	14	1,689
North East of England (NEE)	22	1,107
South West of England (SWE)	49	5,260
Central England (CE)	28	2,089
South East of England (SEE)	41	3,216
Total	**238**	**23,229**

4.4 Statistical analysis

It is recognised that meteorological processes may vary depending on the period of the year (Guntner *et al.*, 2001). However the small number of intense rainfall events for the summer months in some regions necessitated the aggregation of several months to get significant samples of data. Consequently the following analysis has been carried out for 4 seasons (winter: January - March; spring: April - June; summer: July - September; autumn: October - December) in the 9 regions.

4.4.1 Analysis strategy

Let h_k be the dimensionless hourly rainfall intensity at hour k in its discrete form:

$$h_k = \frac{q_k}{\sum_{j=1}^{n} q_j} \tag{4.1}$$

where q is the observed hourly intensity in mm/h and n the length of the rainfall event. In this study, the adopted approach is equivalent to assuming that there was only one rainfall event per day, Equation (4.1) becomes:

$$h_k = \frac{q_k}{\sum_{j=1}^{24} q_j} \tag{4.2}$$

The dimensionless hyetograph expresses the dimensionless accumulated quantity of rainfall after k hours (H_k).

$$H_k = \sum_{j=1}^{k} h_j = \frac{\sum_{j=1}^{k} q_j}{\sum_{j=1}^{24} q_j} \tag{4.3}$$

Kottegoda *et al.* (2003) and Garcia-Guzman and Aranda-Oliver (1993) suggested that the successive values of H_k were not independent. We propose here to describe this dependence of the dimensionless hourly rainfall intensities by representing the dimensionless intensity during the most intense hour by a statistical distribution, and by defining explicit relations between the dimensionless intensities during the most intense hour and the other hours (CRCCH, 2000). In the remainder of the text, the most intense hour will be referred to as the 1st hour and so on until the least intense hour which will be referred to as the 24th hour.

4.4.2 Hour of maximum rainfall

The 24 hourly rainfall intensities are first classified from the most intense hour to the least intense hour and noted as q_1 to q_{24}. h_1 is derived from Equation (4.2) and then represented by a statistical distribution covering all rainfall events in the climatically homogeneous region. It was hypothesised that h_1 was best described by the Log-Normal distribution (Figure 4.2), which was tested using a Kolmogorov-Smirnov two-sample. In 81% of the 36 Kolmogorov-Smirnov tests (9 climate zones and 4 seasons) the hypothesis could not be rejected at α=0.05, and in 95 % of the cases at the 0.01 level. The Log-Normal distribution was therefore adopted as the best description of the dimensionless intensity of the hour of maximal rainfall.

The fitted mean and standard deviations of the Log-Normal distributions show regional variations due to the climatic variations over the British Isles. In the summer, the fitted mean values increase when moving Eastward showing more intense events on the eastern side of the British Isles than on the western side (Figure 4.3). The two reasons for this are the difference in types of rainfall events taking place and a purely numerical reason. In fact, the western side is very much influenced by the depressions coming from the Atlantic to create frontal precipitation events with a moderate intensity over rather long periods. Whereas the climate is dryer on the eastern side, to even being semi-arid in some parts (East-Anglia). Rainfall characteristics are therefore influenced by convectional events generating heavy showers and thunderstorms. The second reason is numerical as the summer months are dry months where the total amount of precipitation can be limited during this period. Even if the analysis has been carried out with reasonably wet days, the ratio between the rainfall amount during the most intense hour and the total daily rainfall amount is usually greater when the total daily rainfall amount is lower.

Unlike during the summer, the fitted mean values decrease from west to east during the winter periods when the main type of precipitation events is frontal. This decrease is explained by the fact that the British Isles are the first land met by fronts coming from the Atlantic which get weaker as they move east. This decrease in intensity is amplified by the orography as most of the mountains are found on the western sides of Scotland, England and Wales.

The fitted mean values have been found to increase when moving southward as the North of the British Isles is wetter and more affected by the frontal events and due to the numerical reason as explained above.

Finally, in all regions the mean values have their maximum for the summer period and their minimum for the winter period due to the combination of physical reasons where convectional - short and intense - events happen during the summer months, and for numerical reasons. Consequently, these seasonal variations are more severe for the eastern regions than the western regions where the precipitation events are more stable in both amount and type.

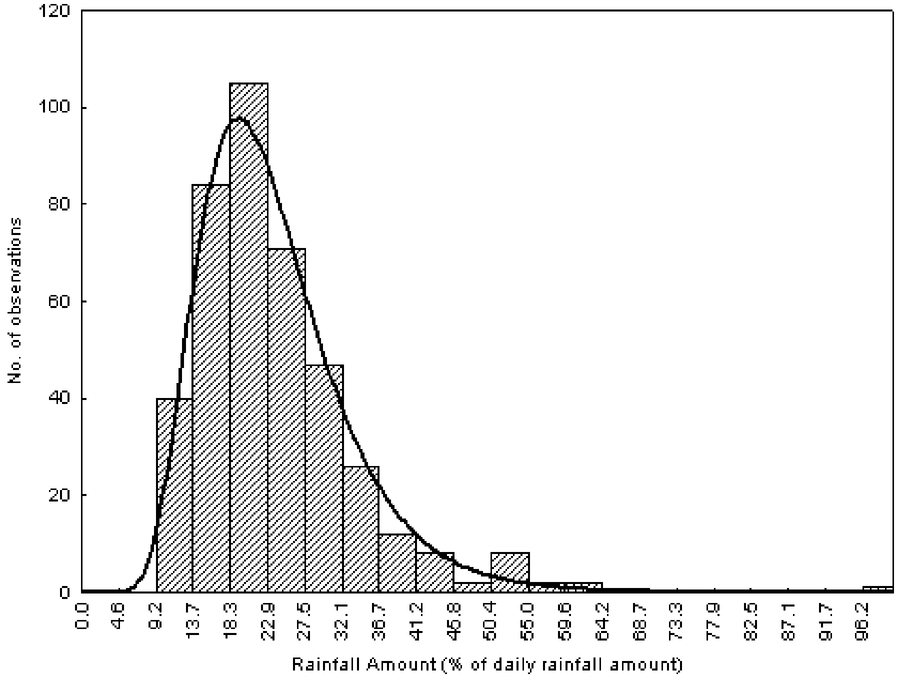

Figure 4.2: Distribution of the relative rainfall intensity of the 1st hour h_1 – Central England region in spring

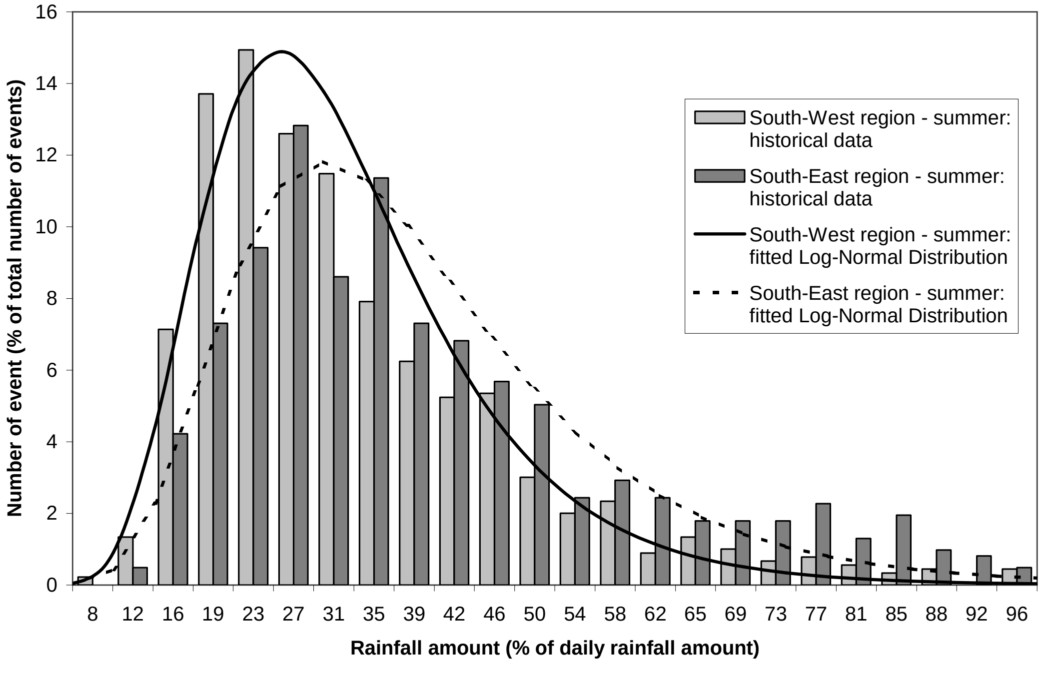

Figure 4.3: Regional variability in rainfall characteristics

4.4.3 Other 23 fractions

The other 23 dimensionless intensities h_k are directly related to the rainfall amount during more intense hours:

$$h_k = \frac{q_k}{\sum_{j=1}^{24} q_j} = r_k * \left(\sum_{j=1}^{k-1} h_j \right) \tag{4.4}$$

with k the hour number between 2 and 24 and r_k the dimensionless ratio:

$$r_k = \frac{q_k}{\sum_{j=1}^{k-1} q_j} \tag{4.5}$$

It was found that the best type of regression to express the relationship between the ratio r_k and h_1, h_2…, h_{k-1} is exponential (Figure 4.4). The distributions of the coefficients of determination (R^2) for the regressions are graphically presented in Figure 4.5 for the 2nd, 3rd, 4th and 5th hours. These coefficients of determination tend to improve as we move towards the less intense rain hours as the information on the shape of the hyetograph held by previous hours increases as the number of the hour increases.

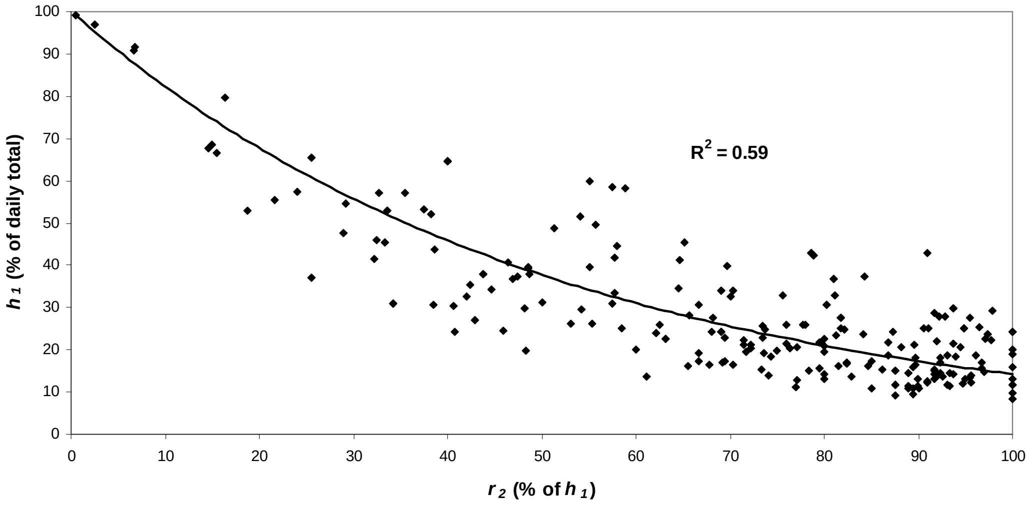

Figure 4.4: Regression analysis of the relative rainfall intensity of the 2nd hour r_2 – spring CE region

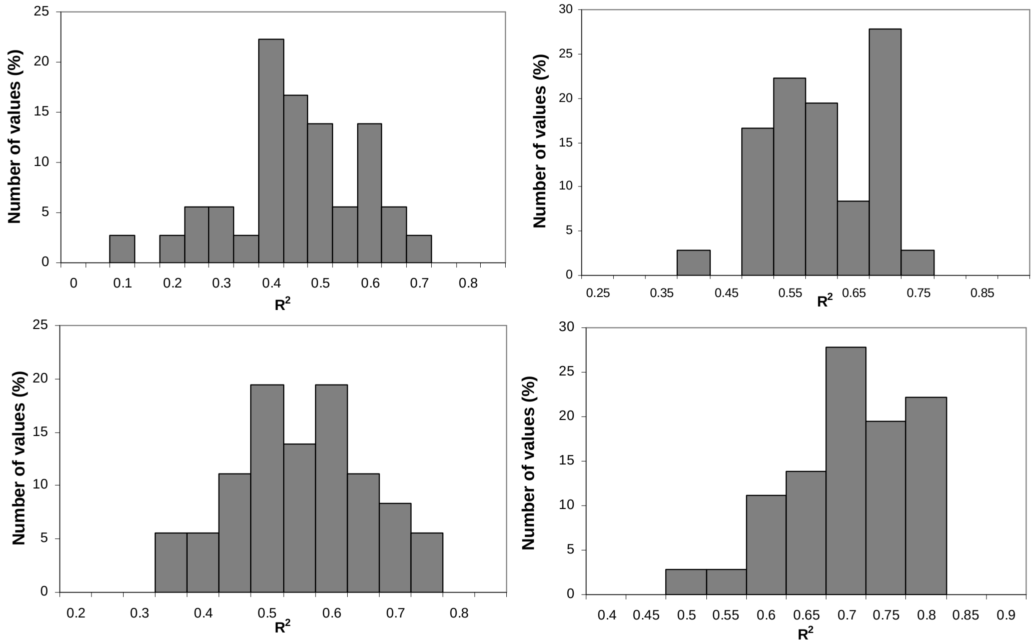

Figure 4.5: Distribution of coefficients of determination for the regression for a) 2nd hour, b) 3rd hour, c) 4th hour and d) 5th hour for all climatic regions and seasons

4.5 Evaluation

The disaggregation method was applied and evaluated for the 9 climate regions of the UK. The relative intensities of the first hours were selected randomly from the calibrated Log-Normal distributions and then the intensities in subsequent hours were derived using the correlation formulae.

As an example, Figure 4.6 compares the observed and predicted rainfall intensities for the Central England region in summer for the first 4 hours.

The evaluation was performed against two criteria:

a) does the disaggregation method reproduce the standard and extreme statistics (Cameron *et al.*, 2000) of the observations for each hour?

b) if yes, do the observed and simulated samples belong to the same population?

4.5.1 Main statistics

Because the disaggregation method outputs rainfall intensities and not time series, the analysis was limited to the mean intensity, standard deviation, maximum intensity and minimum intensity. The minimum intensity is well reproduced. The results for the mean intensity, standard deviation and maximum intensity for the first 4 hours are presented in Figure 4.7, Figure 4.8 and Figure 4.9.

The two-sample t test was used to determine if the observed and predicted intensities were drawn from populations with the same mean. In 90% of the cases the hypothesis could not be rejected at the 5% level for the first 4 hours. However, this proportion deteriorated for the 5th hour, when the hypothesis could not be rejected in only 45% of the cases.

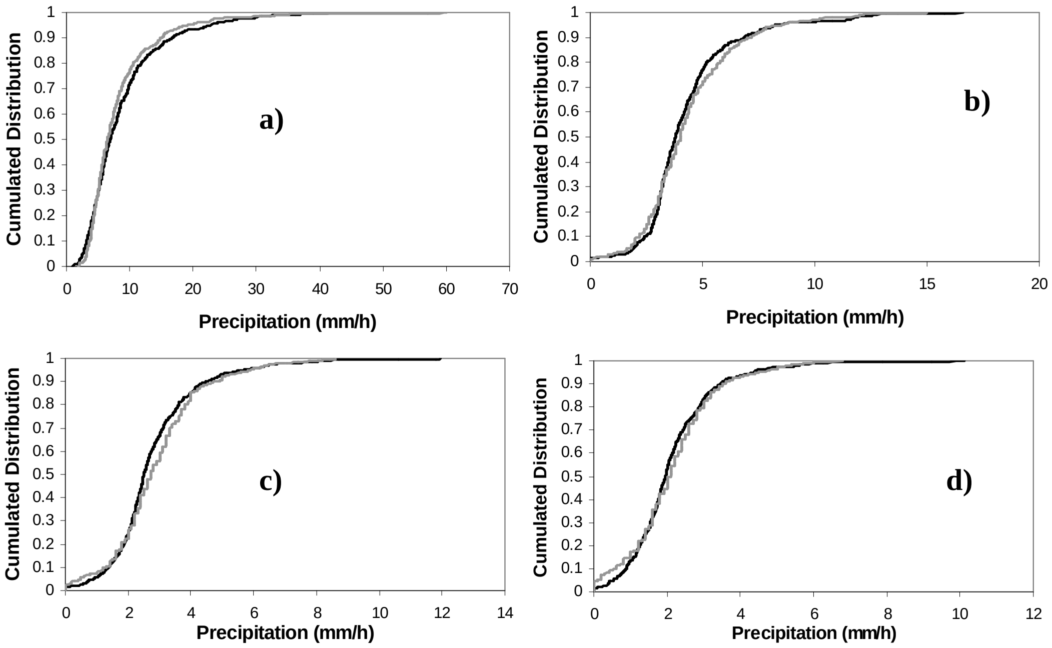

Figure 4.6: Comparison of observed (grey line) and predicted (black line) rainfall intensities for a) the 1st hour, b) the 2nd hour, c) the 3rd hour and d) the 4th hour – Central England region in summer

The standard deviation is generally well predicted, it is only slightly underestimated for the highest intensities of the first and second hours.

The prediction of the maximum hourly intensities was also generally good, however a greater dispersion of the predictions for the high events above 30 mm/h around the 1:1 line, was observed (Figure 4.9).

Globally, this disaggregation method proves to be robust and to give satisfactory results for the first evaluation criteria.

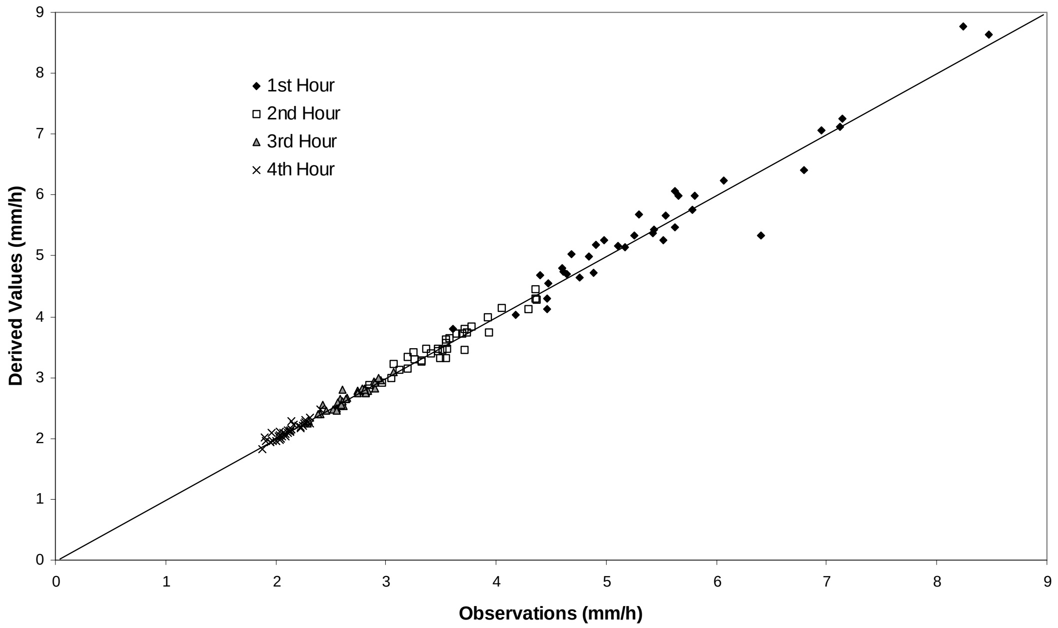

Figure 4.7: Comparison predicted vs observed hourly mean intensities for all climatic regions

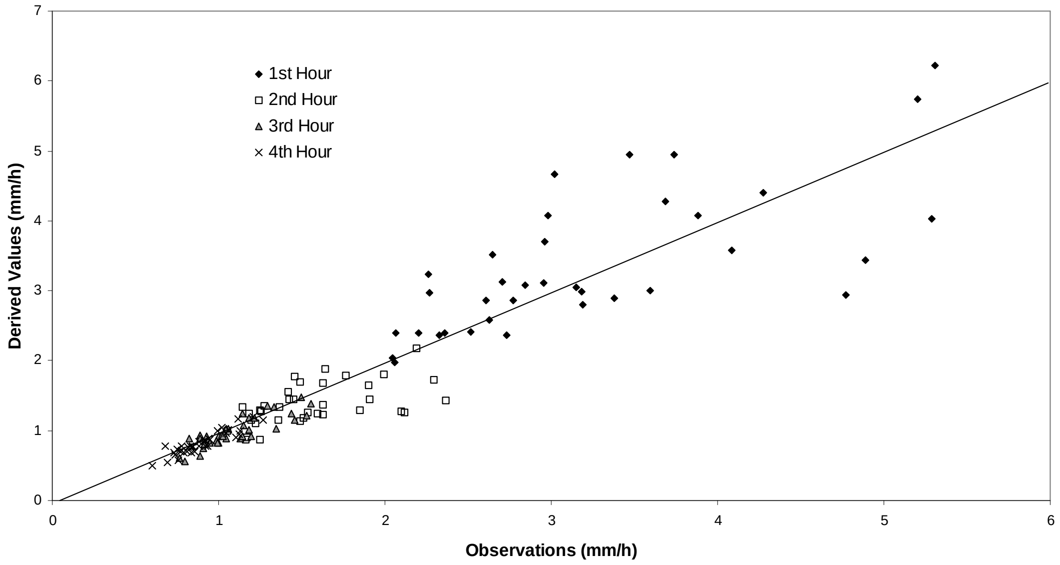

Figure 4.8: Comparison predicted vs observed standard deviation of hourly intensities for all climatic regions

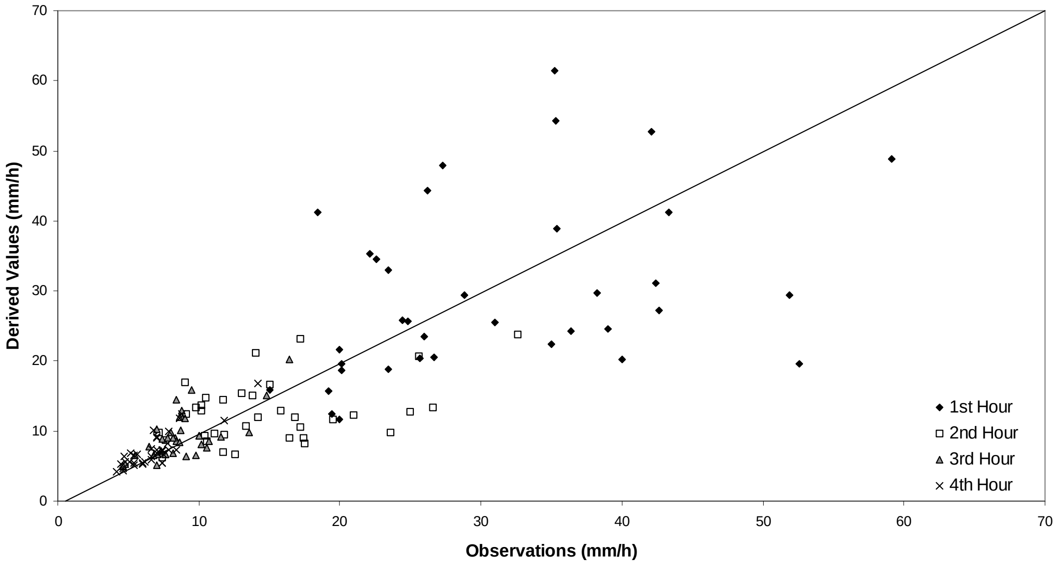

Figure 4.9: Comparison predicted vs observed hourly maximum hourly intensities for all climatic regions

4.5.2 Statistical test

The second evaluation criterion determines whether the simulated hourly intensities came from the same population as the observed ones, using the Kolmogorov-Smirnov two-sample test. The test was applied to the first 5 hours of the 36 region-season combinations. Only in 50% of the cases was the test not rejected for the 1st hour at $\alpha=0.05$. The reason this value is significantly different from the 81% presented previously is the test has been applied to actual intensities and not to relative intensities as during the calibration of the Log-Normal distributions. The difference between the two distributions is found in the high intensity end of the distribution as was seen for the first criteria. The proportion of cases where the test is not rejected decreases to 31% for the 2nd hour at the 0.05 level and to less for the other hours.

It must therefore be concluded from this stringent test that i) the hypothesis that observed and predicted hourly intensities come from the same populations should be rejected but that ii) the method works best for the most intense hours which are of most interest for the modelling of infiltration excess runoff.

4.6 Discussion and conclusion

A robust and parsimonious disaggregation method from daily to hourly rainfall intensities applicable in homogeneous regions of the UK for water resources modelling is presented. The method assumes that the intensity during the most intense hour dictates the type of rainfall event and therefore the intensities during the other 23 hours of the day. Consequently, these 23 fractions are directly related to the rainfall amount falling during more intense hours. 23,229 days with at least 15mm of precipitation from 238 meteorological stations spread over the United Kingdom were analysed. In 81% of the cases the Log-Normal distribution represents well the relative rainfall intensities during the most intense hour, and the relations between rainfall depths are well explained using an exponential regression.

An evaluation of its capability to reproduce the main statistics of the data concluded that it is successful for its purpose for water resources modelling, even if it showed some discrepancies with the observations for very intense events. In a more stringent statistical test it was observed that the method performs better during hours of maximum rainfall but the hypothesis that measured and predicted samples came from the same populations was rejected.

Some restrictions apply for its use outside its original application field of simulating infiltration-excess runoff within water resources modelling of multiple catchments. This method is not appropriate for applications where dry periods between multiple rainfall events within a single day play important roles (e.g. sewer system design) or where the timing of the peak rainfall intensity is important (e.g. flood modelling). It should also be tested against other temporal rainfall disaggregation methods for flood protection system design, as stressed by Cameron *et al.* (2000). Furthermore, the method is based on past and present rainfall characteristics and is suitable for present and near future studies. Its use in climate change studies should be carried out with great care as it is generally expected that the increase in heavy precipitation will be greater in the future than the increase in mean precipitation (Senior *et al.*, 2002). In consequence the assumption of stability of the precipitation distribution on which the method is based is inadequate for climate change studies.

However, the advantages of the proposed method are: 1) its national applicability, as all parameters have been determined for 9 regions dividing the UK, and 2) its extreme simplicity of use.

4.7 Acknowledgements

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5 REGIONALISATION OF A CONCEPTUAL CATCHMENT-SCALE HYDROLOGICAL MODEL FOR ENGLAND AND WALES

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5.1 Abstract

This paper describes the development and the assessment of a regional, continuous, daily hydrological model for England and Wales. The Catchment Resources and Soil Hydrology (CRASH) model is a conceptual, catchment-scale rainfall-runoff model based upon the assumption that the transformation of rainfall into river discharge at the catchment scale in the UK is driven by soil and land use properties. In this study, a regional model parameter set has been derived. Firstly, CRASH has been calibrated for 32 mid-size catchments located throughout England and Wales covering a wide variety of physical conditions. From this, a single - or regional - model parameter set has been derived. The regional CRASH has been assessed in the 27 catchments with data for an evaluation period, and compared to the single-site CRASH. Finally, the factors affecting the performance of the regional CRASH have been identified. It is shown that the regional CRASH meets the chosen performance criteria in 52% of the catchments for the Nash-Sutcliffe efficiency index during the evaluation period, and in 56% of the cases for the percent bias index and that there is only a slight degradation of the results between the single-site and the regional models. CRASH is demonstrated to

be sensitive to the dominant soils, the import and export of water in the catchment and the rainfall conditions.

Keywords: rainfall-runoff; catchment-scale model; large-scale application, regionalisation, ungauged

5.2 Introduction

Regionalisation in hydrology is the transfer of information from a gauged catchment to an ungauged catchment (Blöschl and Sivaplan, 1995) and can be described as the extrapolation of the information held in the values of numerical model parameters (Littlewood *et al.*, 2003). The underlying principle is that the transfer of information can be applied to catchments belonging to the same homogeneous region. Holmes *et al.* (2002) reviewed the various definitions of homogeneous regions and listed them as regions based on their geography, stream flow characteristics or on the physical characteristics of the catchments.

The development of physically-based, distributed models based on the blue-print by Freeze and Harlan (1969) was viewed at the time as a major step towards regionalisation of continuous hydrological models (Todini, 1988). However, it was soon realised that despite incorporating the maximum knowledge of physical processes into these models, they did not reduce the amount of data required for their calibration. It was even argued that their demand for calibration data was greater than for conceptual models with simpler structures (Beven, 1989; Bergström, 1991; Sivapalan *et al.*, 2003b).

Several studies have discussed the over-parameterisation of models (e.g. Jakeman and Hornberger, 1993; Perrin *et al*., 2001) and continuous hydrological models at the catchment scale were generally redirected towards simpler conceptual models (e.g. Beven *et al.*, 1984; Todini, 1996; Jakeman and Hornberger, 1993). The efforts of regionalisation were also affected by this debate, and studies started to focus on using conceptual models (Seibert, 1999; Schmidt *et al.*, 2000; Yokoo *et al.*, 2001; Schumann *et al.*, 2000). The two most widely used regionalisation methods were i) to directly apply model parameters calibrated for a gauged catchment to an ungauged catchment if those catchments could be estimated as sufficiently similar (Kokkonen *et al.*, 2003) and ii) to relate the dynamic response characteristics (DRC) of a catchment represented by the model parameters to the physical catchment descriptors (PCD) (e.g. Sefton and Howarth, 1998). The relationships between DRCs and PCDs have been explored using multivariate regression (Post and Jakeman, 1996; 1999; Sefton and Howarth, 1998; Seibert, 1999; Mwakalila, 2003) and kriging and clustering techniques (Vanderwiele and Elias, 1995). Kokkonen *et al.* (2003) found by comparing the two methods with the IHACRES model for 13 catchments in the United States that it could be preferable to directly transfer the whole parameter set if the user has enough confidence in the similarity of the gauged and ungauged catchments.

In parallel to the debate on parametrically simple and complex models, the downward approach introduced by Klemeŝ (1983) was having increasing influence on the approaches for continuous hydrological modelling, compared to the upward approach exemplified by the Système Hydrologique Européen (Abbott *et al.*, 1986). The downward approach, also called top-down (Littlewood *et al.*, 2003), seeks to “learn about a catchment’s functioning from data obtained at the catchment scale” (Sivapalan *et al.*, 2003a).

In fact, the upward approach was shown to have limitations not only from a practical angle due to data limitations as described previously (Sivapalan *et al*, 2003b) but also because it could lead to unnecessary complexity in the model when small scale processes do not have a significant influence at larger scales (Sivapalan *et al.*, 2003b). This recognition had a major consequence: the upward approach alone could not be viewed as the most promising method for regionalisation purposes. More conceptual models started then to be based on the interpretation of the hydrological behaviour of a catchment, at the catchment scale.

Several regionalisation studies adopted the downward approach, either explicitly or not. For instance, Kokkonen *et al.* (2003) stated that their approach could be regarded as downward as they first defined the factors controlling the parameter variability. The rule-based approach adopted by Peschke *et al.* (1999) could also be viewed as downward as they try to cluster and evaluate the controlling factors of the production of quick-runoff for two basins in Germany. Dunn and Lilly (2001) focussed their work on the relationship between model parameters and soil type and showed that it was possible to determine model parameters according to a soil hydrological classification.

The aim of the paper is to explore the feasibility of defining a regional parameter set for England and Wales for the soil classification-based conceptual catchment-scale CRASH model (Maréchal and Holman, Submitted-2003a) where the parameters are explicitly a function of the soil types. The approach can be viewed as downward as the CRASH model was developed after the main factors affecting the hydrological response of a catchment were defined. These factors were recognised to be the soils and land use (NERC, 1975; Boorman *et al.*, 1995; Sefton and Howarth, 1998; Holmes *et al.*, 2002).

The paper is structured as follows. In section 5.3 CRASH is presented. In section 5.4 the catchments and data sources are described. The calibration of the model and the evaluation of the results are presented in sections 5.5 and 5.6 respectively. Finally conclusions are given in section 5.7.

5.3 Model

The Catchment Resources and Soil Hydrology (CRASH) model (Maréchal and Holman, Submitted-2003a) was developed from the assumption that the transformation of rainfall into river discharge at the catchment scale in the UK is driven by soil and land use properties and was built to be used exclusively with existing data sets of soil and land use. CRASH uses the Hydrology of Soil Type (HOST) system (Boorman 1995) to classify the soils, which is a conceptual representation of the hydrological processes in the soils. It defines the hydrological behaviour of soils in terms of their influence on river flow at the catchment scale and gives a classification of all the soil types of the United Kingdom into 29 response models (or classes).

CRASH structures a catchment using four types of objects: the response units, the sub-catchments, the rivers and the reservoirs (Figure 5.1) and includes surface water discharges and surface and ground water abstraction. The response units are where the production of flow is predicted. They are defined within each sub-catchment as cells with homogeneous hydrological behaviour (Figure 5.1b) based upon a combination of soil type, land use and weather. Results from response units of similar soil hydrological behaviour (or HOST class) are grouped together so that the model parameters are

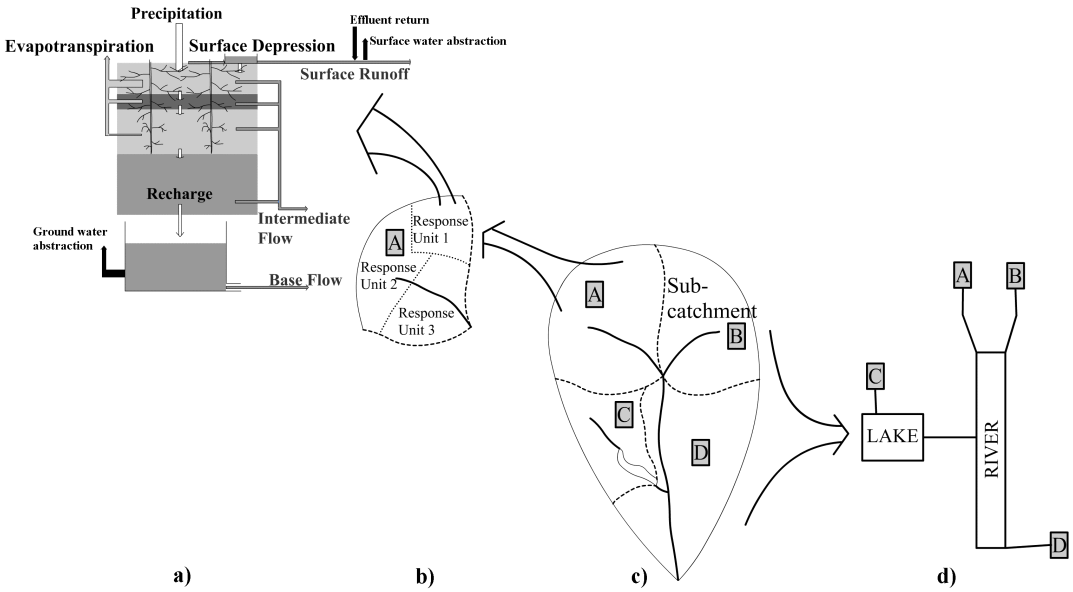

Figure 5.1: Structure of the CRASH model composed of a) Response unit, b) Subcatchment, c) Catchment, and d) the conceptual representation of the catchment

calibrated for each HOST class. The sub-catchments, rivers and reservoirs are routing objects to transfer the flows to sub-catchment and catchment outlets (Figure 5.1d).

Only a brief description of the model is given in the following sections, for a complete description refer to Maréchal and Holman (Submitted- 2003a).

5.3.1 Response units

A response unit is a homogeneous cell composed of the soil water and a ground water store that has one input: precipitation and four outputs: evapotranspiration, runoff, intermediate flow and base flow (Figure 5.1a).

Soil water store

A soil water balance computes the movement of water through each soil horizon using existing soil series data (horizon thickness, water contents at a range of suctions, saturated hydraulic conductivity) to the groundwater store, and allows temporary perched water tables within the soil profile.

The mass balance of soil layer *i* is expressed as:

$$\Delta\theta_i = \frac{(D_{i-1} - D_i - AET_i - IF_i)\Delta T}{Area * \Delta z_i} \tag{5.1}$$

where $\Delta\theta_i$ is the variation of the volumetric water content (m^3/m^3) of soil layer *i*, D_{i-1} the drainage (m^3/s) from layer *i-1*, AET_i the actual daily evapotranspiration (m^3/s) from layer *i*, IF_i the intermediate flow (m^3/s) from layer *i*, ΔT the time step (1 day = 86400s), *Area* the HRU area (m^2) and Δz_i the thickness of layer *i*. It must be noted that for the layer *i=1*, D_{i-1} is replaced in Equation (5.1) by the infiltration, and that for the bottom layer of the soil profile D_i is the recharge to the ground water store.

Drainage occurs only from horizons where the water content is above field capacity, and occurs at a rate controlled by the hydraulic conductivity at saturation. The contribution of root water uptake from each soil layer to actual crop evapotranspiration, derived following Allen (1998), is predicted according to Jarvis (1989). The intermediate flow from layer *i* is proportional to the water content of the layer:

$$IF_i = Max\left\{\left(\theta_i - \theta_i^{FC}\right) * Area * \Delta z_i * IFK ; 0.0\right\} \tag{5.2}$$

with θ_i^{FC} is the soil volumetric water content at field capacity (m^3/m^3) and *IFK* is the intermediate flow parameter (s^{-1}) and first calibrated model parameter.

Ground water store

The ground water store balance is as follows:

$$GWSC_t = GWSC_{t-1} + \Delta T * (Re - BF) \tag{5.3}$$

where $GWSC_t$ is the ground water store content (m^3) at time *t*, Re is the recharge from the soil water store (m^3/s) and BF is the base flow (m^3/s) derived as:

$$BF = BFK * GWSC^2 \tag{5.4}$$

The base flow parameter BFK is the second calibrated model parameter ($m^{-3}s^{-1}$).

Runoff and infiltration

Surface runoff from each soil type can be either saturation excess flow or Hortonian flow, if the hourly rainfall intensity exceeds the saturated hydraulic conductivity of the upper horizon. CRASH either uses measured hourly rainfall data, or uses a regionally parameterised rainfall disaggregation procedure (Maréchal and Holman, Submitted- 2003b). The different cases are summarised below:

Case1 $\theta_1 = \theta_1^{sat}$:

$$I = D_1 \tag{5.5}$$

$$Ru = R * Area - I \tag{5.6}$$

Case2 $\theta_1 < \theta_1^{sat}$:

Case2.1: $R < K_1^{Sat}$

$$I = R * Area \tag{5.7}$$

$$Ru = 0 \tag{5.8}$$

Case2.2: $R > K_1^{Sat}$

$$Ru = R * Area - I \tag{5.9}$$

with θ_1^{Sat} and K_1^{Sat} the water content (m^3/m^3) and hydraulic conductivity (m/s) of the top layer at saturation, R the rainfall (m/s), I the infiltration (m^3/s) and Ru the runoff (m^3/s).

In the Case 2.2, infiltration is computed with the two parameter Philip's equation (Philip 1957). One of the parameter is defined using the Standard Percentage Runoff (SPR) computed for the HOST classification (Boorman *et al.*, 1995). The second parameter of the runoff equation in the case of infiltration excess is the third calibrated model parameter per HOST class.

Surface runoff must fill in a surface depression store before the net contribution to the river flow is derived.

5.3.2 Sub-catchment

The quick flow component (surface runoff and intermediate flow) is routed to the sub-catchment outlet by the means of the unit hydrograph method (Institute of Hydrology, 1985).

5.3.3 River

The Muskingum-Cunge model (Cunge, 1969) is applied to transfer the hydrograph from an upstream sub-catchment to the outlet of a downstream sub-catchment or to the catchment outlet.

5.3.4 Reservoir

A reservoir routing procedure (Chow *et al.*, 1988) takes into account the effects of lakes and reservoirs on the hydrograph.

5.3.5 Input data

The response units are defined as combinations of soil type (soil series) and land use/crop within an area with constant rainfall and potential evapotranspiration conditions. In practice, they are defined by overlaying the soil series, crops/land uses, precipitation and evapotranspiration maps to create the homogeneous cells.

The precipitation data can be input as hourly or daily precipitation. In the case of daily data, CRASH has the functionality to disaggregate the values to an hourly time step (Maréchal and Holman, Submitted- 2003b).

In this study, the spatial distributions of soil units were taken from the digital national soil map of England and Wales (Ragg *et al.*, 1984) and the distribution of land use classes (aggregate of crops/land uses) from the Land Cover Map (Centre for Ecology and Hydrology, Land Cover Map 1990). The composition of soil units in terms of soil series was supplied by the National Soil Resources Institute, and the DEFRA agricultural statistics from 1988 data set was used to define the proportion of each crop in arable land areas of the catchment.

It was assumed that a crop/land use was spread uniformly among the soil series within an area composed of a soil unit and a land use class.

The Thiessen polygon method was used to create spatial maps of rainfall depths from point values at meteorological stations.

The model also requires catchment physical properties or descriptors for the parameterisation of the unit hydrograph at the sub-catchment scale; river and reservoir characteristics for the flow routing, surface water discharge and surface and ground water abstraction data.

5.4 Catchments and data availability

CRASH has been calibrated and evaluated using 32 catchments spread across England and Wales (Figure 5.2). This section presents the catchment characteristics and the availability of soil, land use, stream flow, precipitation and potential evapotranspiration data.

Figure 5.2: Catchment locations

5.4.1 Catchment characteristics

The catchments have been selected to represent the contrasting physical, climatic and hydrological conditions encountered in England and Wales. These conditions range from the flat, low-lying lands with a dry, nearly continental climate in East Anglia (east of England) to mountainous landscapes with a wet and mild climate in the north west of England. The main physical characteristics of the catchments are summarised in Table 5.1.

The soils and geology play a major role in the hydrological response of a catchment (Holmes et al., 2002). The distributions of the soils and geology in the 32 catchments and in the UK are presented in terms of their HOST class in Table 5.2. Three main groups corresponding to three physical settings have been recognised in HOST (Boorman et al, 1995):

i) soils overlying a permeable substrate in which groundwater usually exists at a depth of more than 2 m (classes 1 to 6, 13 to 15). This is the second most extensive group nationally. It is characterised by a slow hydrological response where the main flow path through the soil is downward to the underlying aquifer, unless the soil profile holds a slowly permeable layer (class 14) or is a peat soil (class 15). Base flow is the main component of the hydrograph for this group;

ii) soils having a water table within 2 m, either in the soil or permeable substrate (classes 7 to 12). These only cover 10% of the catchments and are therefore less significant for the hydrological behaviour than the two other groups;

iii) soils with no significant underlying aquifer or groundwater but with a shallow impermeable substrate which impedes vertical movement of water (classes 16 to 29). This is the most nationally extensive of the three groups and covers about 60% of the selected catchments. The main classes are classes 17, 18, 21, 24, 25, 26 and 29. They have a quick hydrological response characterised by a low base flow index and a high standard percentage runoff (Boorman *et al*., 1995) except for the class 17.

Table 5.1: Catchment characteristics. (-) Flows affected by effluent return and/or abstraction with no effluent return and/or abstraction data available.

River and station names	Area (km^2)	Mean Altitude (m)	Dominant HOST class (Boorman *et al.*, 1995)	Dominant Land Use (Centre for Ecology Land Cover Map 1990)	Naturalisation of the flow
Alconbury Brook at Brampton	202	43	21	Arable cereals	Naturalised
Avon at Amesbury	324	132	1	Improved grassland	Naturalised
Ribble at Arnford	204	325	26	Neutral grass	Natural
Taf at Clog-y-Fran	218	118	17	Improved grassland	Natural
Cober at Helston	41	95	4	Improved grassland	-
Gipping at Bramford	300	47	21	Arable cereals	-
Bain at Goulceby Bridge	63	106	1	Arable horticulture	-
Great Stour at Wye	226	69	25	Arable horticulture	-
Irthing at Greenholme	334	215	26	Improved grassland	-
Gannel at Gwills	41	77	17	Improved grassland	-
Bourne at Hadlow	50	89	25	Broad-leaved / mixed woodland	-
Hayle at St Erth	49	78	17	Arable horticulture	-
Meden at Church Warsop	97	124	2	Arable horticulture	-
Mole at Kinnersley Manor	147	79	25	Improved grassland	-
Leven at Newby Bridge	241	190	19	Bracken	-
Perry at Perry Farm	181	96	5	Improved grassland	-
Teign at Preston	380	217	4	Improved grassland	Naturalised
Neath at Resolven	191	310	26	Neutral grass	Naturalised
Roden at Rodington	262	82	24	Improved grassland	Naturalised

River and station names	Area (km^2)	Mean Altitude (m)	Dominant HOST class (Boorman *et al.*, 1995)	Dominant Land Use (Centre for Ecology Land Cover Map 1990)	Naturalisation of the flow
Tas at Shotesham	153	41	24	Arable cereals	-
West Avon at Upavon	76	141	1	Arable cereals	Natural
Weaver at Audlem	203	86	24	Improved grassland	-
Bourne (South) at Addlestone	107	50	25	rural development	-
Yare at Colney	285	32	24	Arable cereals	-
Tawe at Ynystanglws	228	285	26	Neutral grass	Natural
Dene at Wellesbourne	100	91	25	Arable horticulture	Naturalised
Lod at Halfway Bridge	53	82	25	Broad-leaved / mixed woodland	-
Greta at Low Briery	146	392	29	Acid grassland	Natural
Exe at Pixton	148	314	17	Improved grassland	-
Avon at Stareton	352	113	24	Improved grassland	-
Kird at Tanyards	67	57	25	Broad-leaved / mixed woodland	Naturalised
Nene-Kislingbury at Upton	223	120	25	Arable horticulture	-

Table 5.2: Proportions of the HOST classes in the 32 investigated catchments and in the UK (Boorman *et al.* (1995), Holmes *et al.* (2002))

HOST class	Description	% in catchments	% in UK
1	Chalk, chalk drift	6.5	5.3
2	Soft magnesian and oolitic limestone	1.9	2.6
3	Soft sandstone, weakly consolidated sands	2.5	2.0
4	Hard fissured sandstone/limestone	5.6	3.3
5	Blown sand, gravels, sand	6.2	6.2
6	Colluvium, coverloam, sand	1.3	2.1
7	Blown sand, gravel, snd	1.4	0.6
8	Hard deeply shattered rock, river colluvium, alluvium, coverloam	0.8	1.0
9	Hard deeply shattered rock, river colluvium, alluvium, coverloam	2.1	4.4
10	Shattered sandstone, river colluvium, alluvium, coverloam	2.9	1.8
11	Drained earthy peat, underlain by hard rock, river alluvium, coverloam	1.0	0.5
12	Un-drained peat, underlain by hard rock, river alluvium, coverloam	1.2	1.2
13	Permeable soils, underlain by hard sandstone, weathered intrusive/metamorphic Rock, coverloam	0.3	0.3
14	Permeable soils, underlain by weather intrusive/metamorphic rock, coverloam	0.0	0.5
15	Permeable soils, underlain by hard sandstone, weathered intrusive/metamorphic Rock, coverloam	2.8	12.7
16	Slowly permeable soils – very soft, bedded shales, mudstones, loams, clays, sands	1.6	0.3
17	Hard coherent rock	8.1	11.3
18	Slowly permeable soils – very soft, bedded shales, mudstones, loams, clays, sands	7.1	5.5
19	Hard coherent rock	1.3	2.4
20	Soft massive clays	2.1	0.1
21	Slowly permeable soils – very soft, bedded shales, mudstones, marls	5.7	4.0
22	Hard coherent rock	1.1	0.4
23	Soft massive clays	2.2	1.0
24	Shales, mudstones, marls, loams, clays, sands	16.0	17.1
25	Soft massive clays	7.6	5.0
26	Shales, mudstones, marls, loams, clays, sands, till, clay and flints	6.2	2.7
27	Hard coherent rock	0.9	0.3
28	Eroded peat	0.0	0.5
29	Raw peat	3.6	4.9

The main land use is grassland (improved or natural) as it is the dominant land use in 50% of the catchments. These catchments are mainly located in the western part of the study area, whereas catchments where arable crops (cereals and horticulture) are important are mainly located in the eastern part. Four of the five catchments where the dominant land use is arable cereals are located in the two main regions for the production of cereals in England: East Anglia and East Midlands.

The catchments are mid-sized, ranging in area from 41 km^2 to 380 km^2, but they exhibit significant differences in topography. One extreme is found in East Anglia with flat, low-lying lands, where the altitude of the 285 km^2 Yare catchment ranges between sea level and 66 m above sea level (asl). The other extreme is the mountainous landscape of the north west of England where the 241 km^2 Leven catchment varies from sea level to 1270 masl.

Despite the relatively small area of England and Wales, major differences in climate and especially in rainfall conditions exist among the catchments. The British Isles are very much influenced by maritime tropical and polar air. Western areas receive considerably more rain than eastern areas. The mean annual precipitation among the selected catchments ranges from 550 mm in the south east of England to 2250 mm in the north west. However, no such significant difference exists for the temperature, which is more homogeneous over England and Wales. The mean annual potential evapotranspiration only varies between 470 mm and 680 mm.

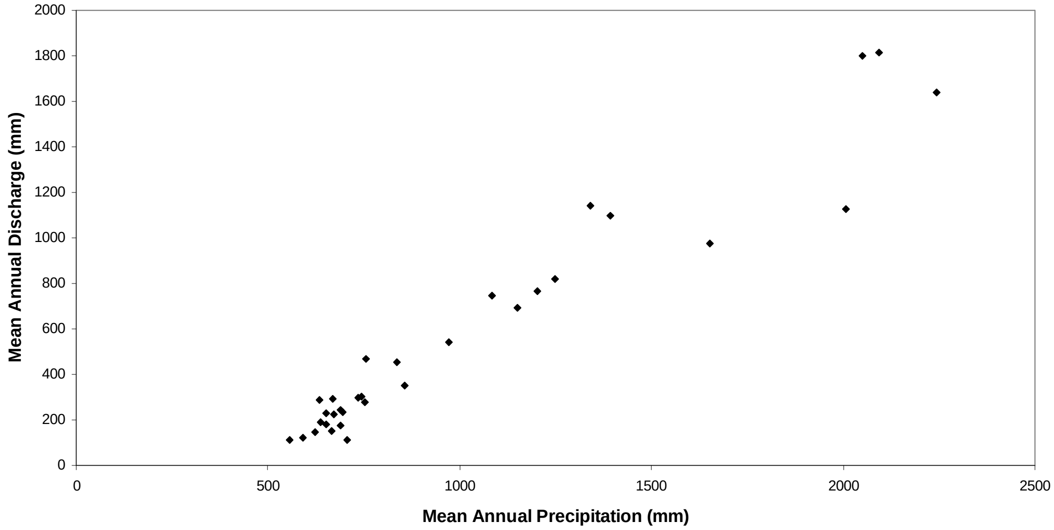

Figure 5.3: Mean annual discharge and precipitation

Due to the great variation in precipitation conditions, the mean annual river flow varies between 110 mm in the south east of England and 1800 mm in the north west of England (**Figure 5.3**). Five catchments have a natural regime (Centre for Ecology and Hydrology, 2003) where abstraction and discharge into the river does not have a significant impact on the river flow (Table 5.1). Data existed to naturalise the flows of seven other catchments either directly on the time series when abstraction and discharge data were available, or on the flow duration curve when correction coefficients were known from other studies. The flows for all other catchments could not be corrected due to the absence of adequate data.

5.4.2 Data availability

The soil data were taken from the digital national soil map of England and Wales (Ragg *et al.*, 1984). The Centre for Ecology Land Cover Map 1990 was used in conjunction with the Department of Environment, Food and Rural Affairs agricultural census statistics for 1988 to define the land use and the proportion of each crop in the arable land classes, respectively.

Daily river flow data were available at all the gauging stations from 1979 to 1998, but for some stations correction data to naturalise the flows were only available for shorter periods of time.

The limiting data for the study have been meteorological data, either precipitation or the necessary parameters to derive potential evapotranspiration data with the Penman-Monteith method. The shortest record of data was for the West Avon catchment with only 3 years of concomitant precipitation data. For the other sites, the length of the concomitant data set was between 4 and 14 years. The data sets of 27 catchments were long enough to be split into a calibration and an evaluation period with at least 4 years for the calibration and 3 years for the evaluation. The remaining 5 catchments have been used only during the calibration phase.

5.5 Calibration

Unlike in other regionalisation studies where the objective is to relate model parameters to descriptors of a single catchment (e.g. Sefton and Howart, 1998; Post and Jakeman, 1999; Yokoo *et al.*, 2001; Kokkonen *et al.*, 2003), the aim here is to define the optimal parameter set for a group of catchments. Dunn and Lilly (2001) calibrated the DIY model for two catchments individually, selected the parameter sets giving the best results according to efficiency criteria and verified whether the results were consistent between the two catchments. The adopted procedure is similar to that of Dunn and Lilly (2001) and has three distinct stages:

i) an objective function is defined;

ii) the parameter space is explored by Monte Carlo modelling, and;

iii) the optimal regional parameter set is selected.

i) Madsen (2000) stresses the importance of adequately defining a suitable objective function for the purpose of calibration. It has been accepted that a single objective function is not sufficient because it can only cover one aspect of the behaviour of a model (Gupta *et al.*, 1998) and that it is usually necessary to adopt a multi-objective function (MOF) as the efficiency criteria of a model.

The MOF adopted in this study is composed of a fuzzy multi-objective function (FMOF) (Yu and Yang, 2000) and the Nash-Sutcliffe efficiency index (R^2) (Nash and Sutcliffe, 1970). These two efficiency indices have been selected because the FMOF is derived from the flow duration curve whereas R^2 is derived from the time series and indicates the overall goodness of fit of a simulation.

The FMOF defines a maximum distance between the observed and simulated flow duration curves, i.e.

$$FMOF = 1 - \min_{j} \mu_j \left(MPE_j \right) \qquad (5.10)$$

where $\mu_j(MPE_j)$ is the membership function of the mean absolute percentage error (MPE_j) for the jth flow stage of the flow duration curve (Figure 5.4).

$$MPE_j = \frac{1}{N_j} \sum_{p=1}^{N_j} \left| \frac{Obs_p - Sim_p}{Obs_p} \right| * 100\% \qquad (5.11)$$

with *Obs* and *Sim* the observed and simulated values of the flow duration curves and N_j the number of data in the jth flow stage. In the present case, the flow duration curves have been divided into 11 flow stages, and the stage boundaries are the flows at 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95 and 100 percents of exceedance. The FMOF varies between 0.0 and 1.0 and where 0.0 indicates a perfect fit between the two flow duration curves.

The MOF was defined as the difference between the two objective functions:

$$MOF(\theta) = R^2(\theta) - FMOF(\theta) \tag{5.12}$$

where θ is a set of model parameters to be calibrated.

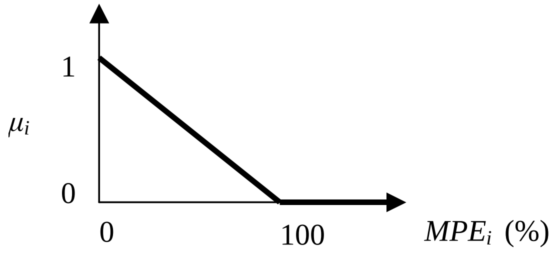

Figure 5.4: Membership function of the mean percentage error (MPE) used in the fuzzy multi-objective function (FMOF)

ii) 5,000 simulations were performed for each catchment using parameter sets randomly generated by Monte Carlo sampling. There was no prior information on the parameters distributions which were chosen as uniform. In total, 160,000 simulations were performed for the calibration phase.

The R^2 results for the single-site model were above 0.25 for all the catchments except in the Bourne and the Nene-Kislingbury catchments where R^2 was below 0.0. There is only a limited confidence in the flow data for the two catchments: the data in the Bourne catchment need reprocessing to account for site effects around the gauging station (Centre for Ecology and Hydrology, 2003), and the simulation problems for the Nene-Kislingbury catchment are partly explained by the fact that high flows by-pass the gauging station (Centre for Ecology and Hydrology, 2003). The results from those two catchments were not used to derive the regional parameter set but they were used, together with the other 30 catchments, to assess the differences between the results from the regional and single-site models.

The results in the catchments where the river flows were natural or naturalised are on average slightly better than in the catchments where the flows could not be naturalised. The average R^2 results were 0.60 for the natural or naturalised catchments against 0.56 for the other catchments. It must be noted that this average value was derived without the Bourne and Nene-Kislingbury catchments. However, this difference in results can not be concluded as significant for the single-site model.

iii) The best 200 parameter sets of the 5,000 simulations for the 30 catchments were selected based upon the MOF results. Examples of distributions of parameters from behavioural models are shown in Figure 5.5. It was found that the parameters of HOST classes that were not widely represented in at least one of the catchments had large ranges of variation (see HOST class 2 in Figure 5.5a). As a consequence, parameters for some HOST classes still have a large uncertainty despite the additional constraints due to the calibration of the model in 32 catchments (Kuczera, 1997). But the results at the catchment scale only have a limited sensitivity to these parameters in the 32 catchments. Therefore, it must be noted that the parameters derived from this calibration should only be used in ungauged catchments where the dominant HOST classes are those with parameters defined with limited uncertainty.

The values of the regional parameters were defined as the most probable values from the distributions of the parameters built with the results from behavioural models. These most probable values were inevitably influenced by the fact that the river flows in some catchments could not be naturalised due to a lack of data or information. This fact is demonstrated by the example of two catchments with similarities. The Cober and Teign catchments are located in the South-West of England, they have the same dominant soil type (HOST class 4) and land use (improved grassland). But the flows of the Teign catchment have been naturalised whilst those of the Cober catchment are affected by public water supply, industrial and agricultural abstraction (Centre for Ecology and Hydrology, 2003). The results in the two catchments of the single site model are similar: R^2 of 0.78 for Cober and 0.77 for Teign. However, the distribution of the most sensitive parameter of the dominant HOST class are different (Figure 5.6). The base flow parameter values are more spread in Cober with a mean value of 6.7E-5 whilst the mean value is 5.8E-5 for Teign. This tendency to have a higher value for the base flow parameter in Cober is to compensate for the effect of abstraction on the river discharge.

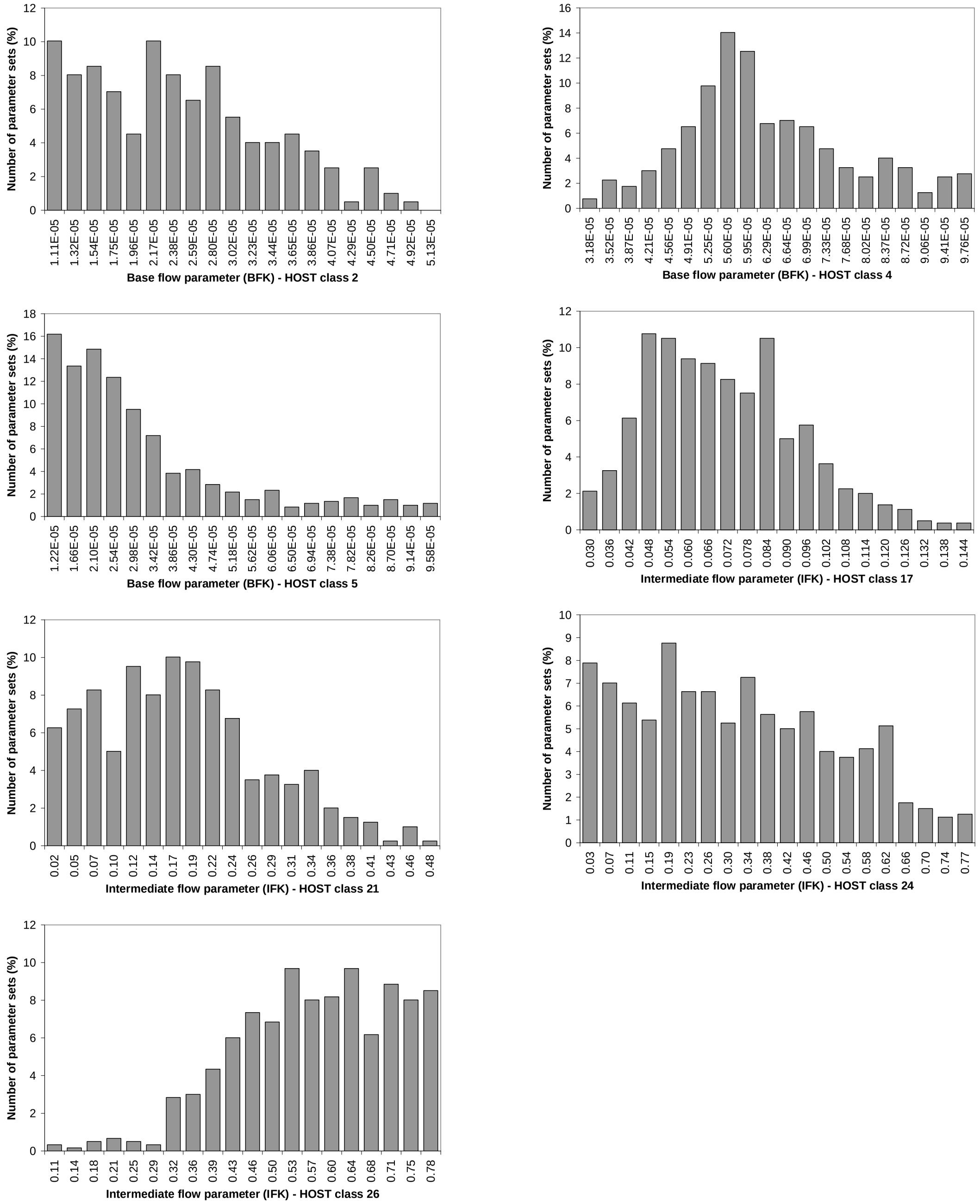

Figure 5.5: Distribution of the a) base flow parameter – HOST class 2 b) base flow parameter – HOST class 4 c) base flow parameter – HOST class 4 d) intermediate flow parameter – HOST class 17 e) intermediate flow parameter – HOST class 21 f)

intermediate flow parameter – HOST class 24 g) intermediate flow parameter – HOST class 26.

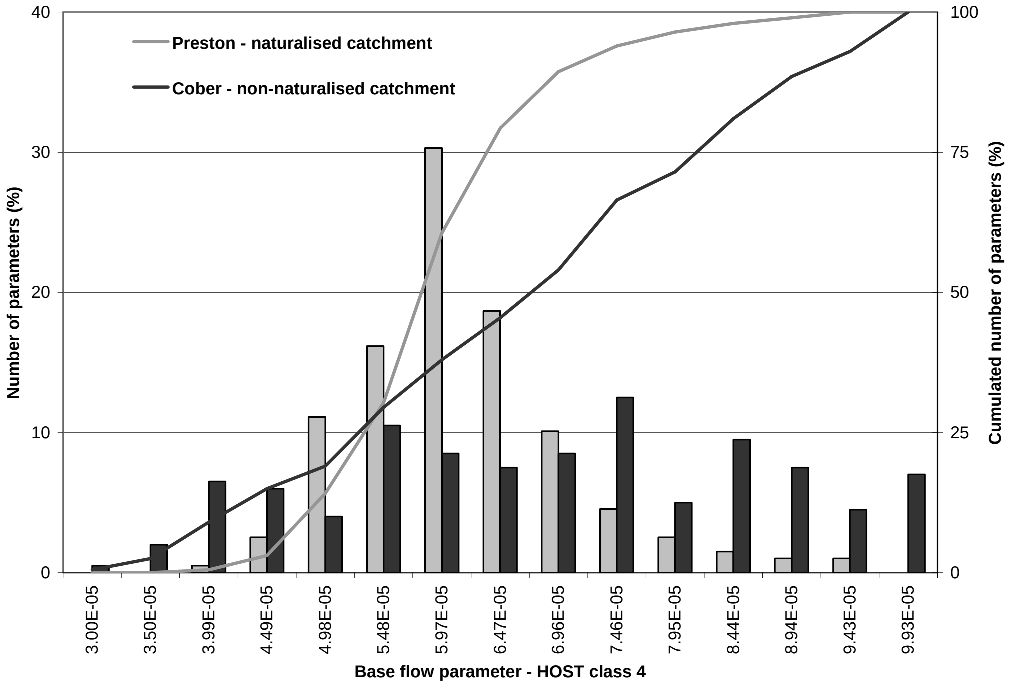

Figure 5.6: Parameter distribution: naturalised vs non-naturalised catchments

5.6 Results of the regional parameter set and discussion

The aim of this section is to evaluate the performance of the regional model in accordance with the view of Orekes and Belitz (2001) ie. to define the strengths and weaknesses of a model rather than only accept or reject it. The objectives are i) to evaluate the deterioration (if any) in the results when the regional parameter set is applied in the 32 catchments for the period used for the calibration of the single-site model, ii) to assess the model's performances with the regional parameter set for the evaluation period and iii) to determine the factors affecting the performance of the regional CRASH. It has been widely accepted that it is preferable to evaluate the performance of a model using several efficiency indices to increase the amount of information gained from the results (Wagener, 2003). Three efficiency indices are used in the following sections: the Nash-Sutcliffe index (R^2) and the fuzzy multi-objective function (FMOF) presented for the calibration procedure, and the PBIAS efficiency index, a measure of the bias of the model, i.e.

$$PBIAS = \frac{\sum_j \left(Sim_j - Obs_j \right)}{\sum_j Obs_j} * 100\% \tag{5.13}$$

The methodology from Henriksen *et al.* (2003) is applied for the classification of the results. Henriksen *et al.* (2003) classified their results into 5 categories: excellent, very good, good, poor and very poor and defined the limits of the classes for each of the efficiency indices based on results from previous studies (Table 5.3). They proposed the limit between a good and poor performance in terms of R^2 at $R^2=0.5$ which is in agreement with Sefton and Howarth (1998). Due to the lack of prior information on models' performances in terms of FMOF, it has not been possible to define prior performance intervals as for the two other indices.

Table 5.3: Performance intervals

Efficiency index	Excellent	Very good	Good	Poor	Very poor
R^2	>0.85	0.65-0.85	0.5-0.65	0.2-0.5	<0.2
$\lvert PBIAS \rvert$ (%)	<5	5-10	10-20	20-40	>40
Score	+++	++	+	+	-

5.6.1 Assessment of the regional parameter set for the calibration period of the single-site model

The regional parameter set has first been applied and assessed for the 32 catchments during the original calibration period of the single-site model.

The R^2 and PBIAS efficiency indices are independent as no significant statistical relationship between them could be found from the results of the 32 catchments. This is in accordance with studies by Gupta *et al.* (1998) and Węglarczyk (1998).

The results prove that the regional parameter set can be applied with reasonable success during this period with respect to R^2 (Figure 5.8 and Table 5.4). The performance requirements – at least a good performance according to Henriksen *et al.* (2003) - are met in 60% of the simulations and 35% of the results are classified as either very good or excellent. In only three cases were the simulations very poor. The situation in two of these catchments, the Bourne and the Nene-Kislingbury, have

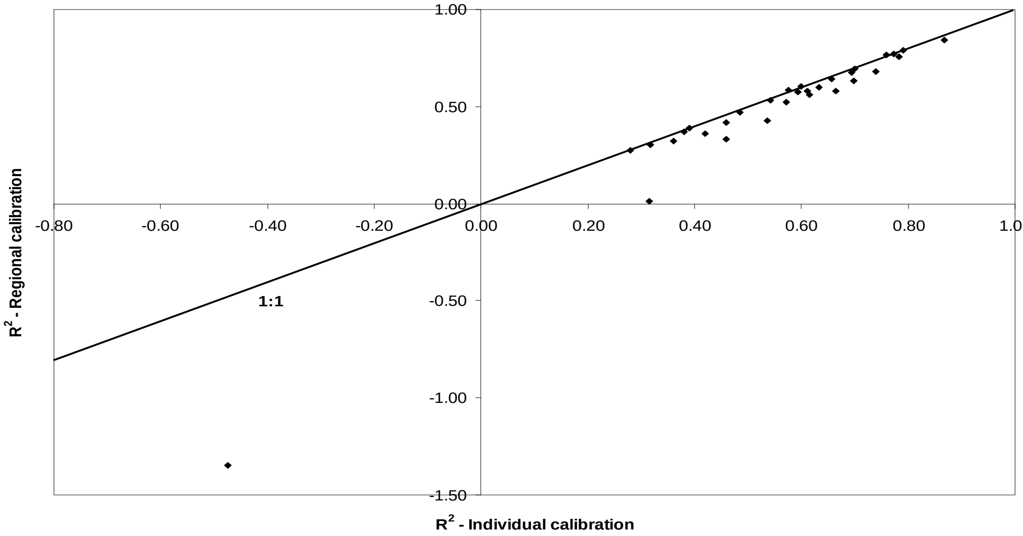

Figure 5.7: Comparison of the Nash-Sutcliffe efficiency index results for the regional and single-site model. All sites except the Nene-Kislingbury catchment.

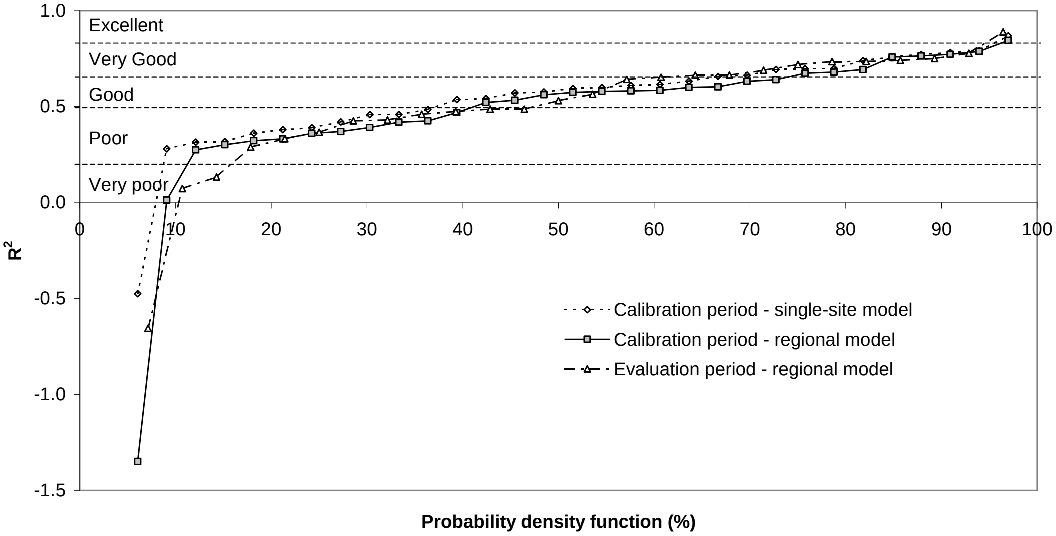

Figure 5.8: Nash-Sutcliffe efficiency index results

already been presented previously, and the third catchment is the Tas catchment. In a general manner, the catchments performing poorly (Bourne at Addlestone, Nene-Kislingbury, Tas, Irthing and Bourne at Hadlow) are all affected by data quality: e.g.

surface water abstraction, ground water abstraction or effluent return (Centre for Ecology and Hydrology, 2003).

The performance criteria – at least a good performance - for PBIAS was met in 50% of the catchments (Figure 5.9 and Table 5.4). The four catchments where the model overestimates river flow and the PBIAS index shows a poor performance are located in the south-east or south of England where the dominant land use is either arable cereals or arable horticulture. The average effective rainfall in these catchments does not exceed 250 mm/y which turns small differences in rainfall or evapotranspiration into large differences in effective rainfall (National Rivers Authority, 1994). As a consequence, the performance of CRASH in this region is affected by the uncertainty in the estimation of evapotranspiration which has large repercussions on the stream flow predictions. Furthermore the poor performance of CRASH for the PBIAS index can be also influenced by the fact that the flows in some of the catchments are altered by groundwater or surface water abstraction for irrigation such as in the Gipping catchment (Centre for Ecology and Hydrology, 2003).

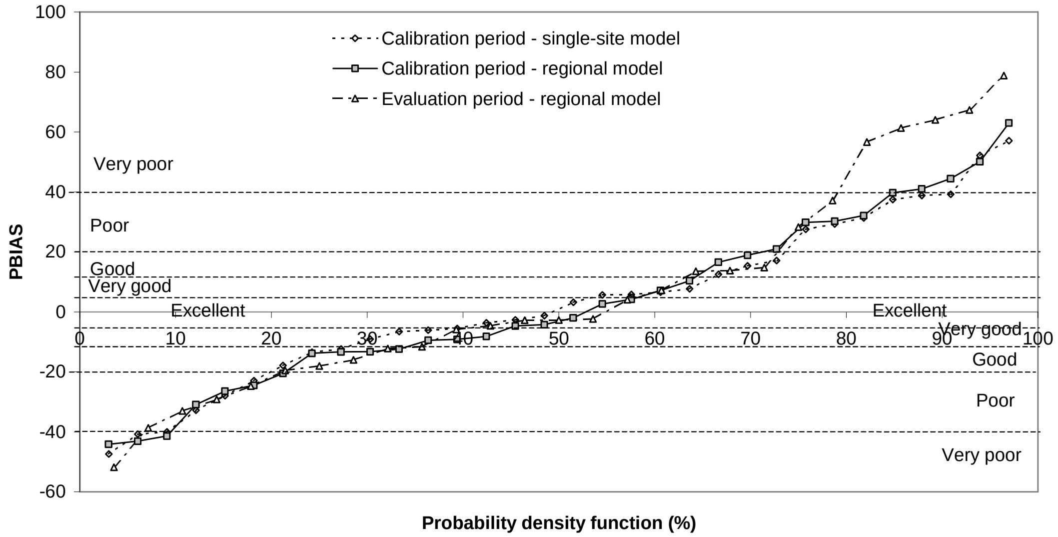

Figure 5.9: PBIAS efficiency index results

Table 5.4: Model performances for R^2 and PBIAS

	Nash-Sutcliffe			**PBIAS**		
River and station names	Single-site model – calibration period	Regional model – calibration period	Regional model – evaluation period	Single-site model – calibration period	Regional model – calibration period	Regional model – evaluation period
Alconbury Brook at Brampton	-	-	-	-	-	--
Avon at Amesbury	+++	++	+++	++	++	+
Ribble at Arnford	-	-	-	++	+	+++
Taf at Clog-y-Fran	++	+		+	-	
Cober at Helston	++	++	++	+++	+++	++
Gipping at Bramford	-	-	--	-	--	--
Bain at Goulceby Bridge	+	+	--	-	-	--
Great Stour at Wye	+	+	++	+	+	+
Irthing at Greenholme	-	-	-	-	-	-
Gannel at Gwills	+	+	-	+++	+++	++
Bourne at Hadlow	-	-		-	-	
Hayle at St Erth	+	+	+	++	+++	+++
Meden at Church Warsop	-	-	-	+	-	+
Mole at Kinnersley Manor	-	-	-	--	--	--
Leven at Newby Bridge	++	++	++	+	+	+
Perry at Perry Farm	-	-	-	++	++	+
Teign at Preston	++	++	++	++	++	+
Neath at Resolven	+	+	+	-	-	-
Roden at Rodington	++	++	++	+++	++	+
Tas at Shotesham	-	--	--	--	--	--
West Avon at Upavon	++	++		-	--	
Weaver at Audlem	+	+	++	++	+	-

	Nash-Sutcliffe			PBIAS		
River and station names	Single-site model – calibration period	Regional model – calibration period	Regional model – evaluation period	Single-site model – calibration period	Regional model – calibration period	Regional model – evaluation period
Bourne (South) at Addlestone	--	--		--	--	
Yare at Colney	++	+	+	-	-	-
Tawe at Ynystanglws	-	-	-	--	--	-
Dene at Wellesbourne	+	-	-	++	+	+
Lod at Halfway Bridge	+	+	++	-	-	-
Greta at Low Briery	+	+		+	+	
Exe at Pixton	++	++	++	+	+	+++
Avon at Stareton	++	++	++	+++	+++	+++
Kird at Tanyards	++	+	++	++	+++	+++
Nene-Kislingbury at Upton	--	--	--	--	--	--

When comparing the results of the regional parameter set with the results of the single-site calibrated models, it is found that in most cases there is only a slight deterioration in the performance (Figure 5.7, Figure 5.8, Figure 5.9 and Table 5.4). The average R^2 has reduced from 0.58 for the single-site model to 0.54 for the regional model, with the Bourne and Nene-Kislingbury catchments excluded from the analysis. None of the catchments showing a very poor performance with the regional parameter set could be satisfactorily calibrated. The main difference between the two sets of results is the distribution of the results between the very good and excellent categories on one side and the good category on the other. There is a decrease of excellent and very good results: from a total of 11 catchments to 8. It must be noted that this decrease is not large in terms of R^2 values because all 3 catchments change from excellent to very good or from very good to good.

The regional parameter does not have a significant influence on the bias of the results (Figure 5.9). The mean absolute PBIAS value only changes from 21.2% for the single-site model to 22.9% for the regional model; and the distribution of the results in the performance categories varies in the same way as for R^2 (Table 5.4).

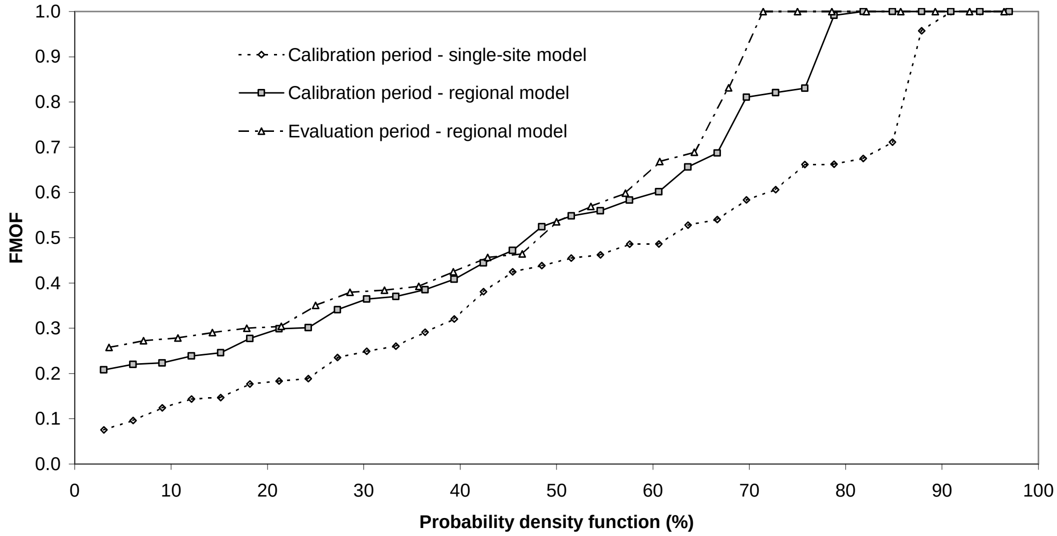

Figure 5.10: FMOF efficiency index results

Of the three efficiency indices, the FMOF is the one showing the largest deterioration (Figure 5.10). The average FMOF is 0.45 for the single-site model and

0.58 for the regional model. In most cases, it shows the deterioration in the simulation of low flows.

The deterioration between the single-site and the regional CRASH does not show any significant difference between natural or naturalised catchments and non-naturalised catchments. The average R^2 results change from 0.60 to 0.57 for the naturalised catchments and from 0.56 to 0.51 for the non-naturalised ones. On the other hand, the deterioration for non-naturalised catchments is smaller in terms of PBIAS (from 20.5% to 22%) than for the natural and naturalised catchments (from 17.5% to 20%).

5.6.2 Assessment of the regional parameter set for the evaluation period

The regional model has then been tested and evaluated in 27 catchments with between 3 and 8 years of data.

There are only minor differences between the results with the regional model during the calibration and evaluation periods in terms of R^2 (Table 5.4 and Figure 5.8) which improved in 15 of the catchments. It can be noted that the 14 catchments (52% of the catchments) with an R^2 above 0.5 (Table 5.4) are the same during the calibration period of the single-site model and the evaluation period. The ratio of catchments showing excellent and very good performance performances is higher than the ratio during the calibration period for the single-site model. The two catchments with enough data for evaluation where there were very poor results with the regional model during the calibration period of the single-site model (Nene-Kislingbury and Tas) also showed very poor results during the evaluation (respectively R^2 = -4.61 and R^2 = -0.65). However, the Bain and Gipping catchments showed a significant deterioration of results (Table 5.4). The main explanation for this decrease in performance is the large over-prediction of river flow in these two south-east catchments due to similar causes to the ones described previously for other catchments of this region. This relative overestimation of river flow is amplified during the evaluation period as it is performed during a dryer period than the calibration period of the single-site model. At the Bain catchment, the mean annual rainfall for the years 1989 to 1992 is 550 mm against 750 mm for the calibration period. The observed mean annual discharge is reduced from 230 mm during the calibration period to 80 mm for the period 1989-1992. The ratio between observed and simulated total flow of 0.64 reveals a significant over-prediction by the model. Similarly, the mean annual precipitation for the years 1988 to 1992 is 10% lower than during the calibration period for the Tas catchment and the ratio between observed and simulated total flows is 0.57.

The PBIAS values during the evaluation improve in 8 of the catchments compared with the calibration period of the single-site model, and the total number of cases meeting the performance criteria increased to 56% (Table 5.4). The number of excellent results is stable but two south-east catchments (Bain and Alconbury Brook) move from poor to very poor performance. It can be noted that this deterioration does not affect the R^2 performance in the Alconbury Brook catchment, whereas R^2 significantly decreased in the Bain catchment.

5.6.3 Factors affecting CRASH

In order to make use of the maximum number of catchments, the analysis was carried out with the results of the regional model applied to the the calibration period of the single-site model, except for the three catchments with the worst efficiency indices (Bourne, Nene-Kislingbury and Tas). The choice to exclude some catchments was made so as not to overrate the importance of the extreme results; the reasons for the poor performances have already been described above. The analysis was performed by looking at the influence of some catchment characteristics on the three efficiency indices FMOF, R^2 and PBIAS. These catchment characteristics were the two dominant HOST classes, the two dominant land uses, the area of the catchment, the proportion of urban area, the mean altitude and slope, the mean annual potential evapotranspiration and precipitation, the geographical position (longitude and latitude) and if there were groundwater or surface water abstraction and effluent returns.

Factors affecting FMOF

No significant relationship can be defined between any of the catchment characteristic and the FMOF efficiency index.

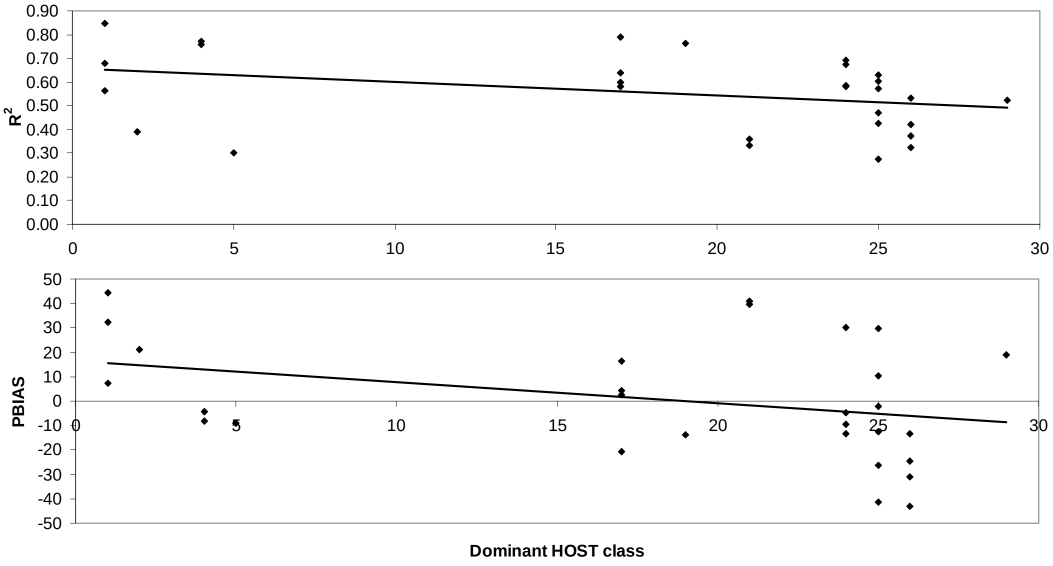

Figure 5.11: Influence of the dominant soil type on the model's performance.

Factors affecting R^2 and PBIAS

The dominant HOST class affects both efficiency indices which tend to decrease with increasing HOST class numbers (Figure 5.11). The effect of the HOST class on R^2 results from the contrasting shapes of the hydrograph and on the nature of the index. It was presented previously that classes with low numbers have base flow as the main contribution to the hydrograph whereas for the classes at the other end of the classification, quick flows are of great importance. Therefore variations between observed and predicted values for peak flows tend to have a significant effect on R^2 for HOST classes with high numbers.

CRASH is sensitive to artificial impacts on the hydrograph (imports and exports of water). Because the regional parameter set has inevitably been derived with both naturalised and not naturalised flow data, CRASH tends to underestimate the results when there is no abstraction (PBIAS negative) and to overestimate them when there is abstraction (PBIAS positive).

Finally there is a significant relationship between both R^2 and PBIAS and the rainfall conditions. The range of mean annual precipitation where R^2 is the highest is between 1000 mm and 1500 mm although catchments with very good R^2 are found throughout the precipitation range and it is also in this range of precipitation conditions that the PBIAS results are close to 0%. The performance of the model tends to decrease as the mean annual precipitation decreases because the artificial flows of water (abstraction and effluent return) and the uncertainty in evapotranspiration predictions have a greater impact proportionally on the flows in the dry regions. The tendency of the model to underestimate river flows in areas of wet climate is caused by a tendency to overestimate the actual evapotranspiration due to the difficulty to adequately estimate evapotranspiration crop coefficients for natural vegetation. Furthermore, the decrease in model performance for wet conditions can be also partly explained by the quality of rainfall data in mountainous regions of the north west of England where the rain gauges network can not give a complete representation of the complex physical system.

The other catchment characteristics did not prove to have a significant influence on the model performances for R^2 and PBIAS.

5.7 Conclusion

This paper presents the second stage of the development of a conceptual, continuous, daily, semi distributed catchment-scale rainfall-runoff model for use in ungauged catchments first described in Maréchal and Holman (Submitted-2003a). In the first stage, the soil classification-based conceptual catchment-scale CRASH model has been developed and evaluated for three catchments in England (Maréchal and Holman, Submitted-2003a). In this second stage, CRASH has been regionalised using 32 catchments throughout England and Wales.

The approach adopted for the development of the model can be viewed as following the top-down approach to modelling. At the outset, the main hydrological processes were defined and the factors affecting the hydrological response at the catchment scale identified. As a consequence, the Catchment Resources and Soil Hydrology (CRASH) model is based on the assumption that the transformation of rainfall into discharge at the catchment-scale in the UK is driven by soil, land use and weather and can be described using pre-existing datasets (Maréchal and Holman, Submitted-2003a). The interest of the model is that the model parameters are explicitly related to the main factors influencing the hydrological behaviour of a catchment (i.e. the soil type).

The regionalisation of CRASH has been achieved using 32 catchments in England and Wales covering a wide variety of soils, land uses, climatic and topographical conditions. A series of conclusions can be listed from the calibration and the evaluation of the results.

i) The regional parameter set was applied with reasonable success. The performance criteria – at least a good performance - for R^2 was met in respectively 60% and 52% of the catchments during the calibration period of the single-site model and during the evaluation period, and in 50% and 56% of the catchments for PBIAS.

ii) There is only a slight deterioration with the regional model compared to the single-site model. The results for R^2 and PBIAS indices did not show any significant differences and the main deterioration was found for the FMOF index and was located at the low flows end of the flow duration curve.

iii) No relationship between the FMOF results and catchment characteristics were found. Concerning R^2 and PBIAS, CRASH is most sensitive to the dominant soils, the import and export of water in the catchment and the rainfall conditions. CRASH tends to underestimate river flows in wet climates due to an overestimation of the evapotranspiration of natural grassland, and to overestimate river flows in catchments located in the south-east of England due to the impact of the uncertainty in evapotranspiration predictions and of water abstraction on the flows. It is also affected by the quality of precipitation data, especially in wet mountainous regions due to the complexity of the physical system.

iv) The derivation of the regional parameter set is dependent on the artificial impacts on the river discharge. Artificial impacts have been shown to have an influence on the distribution of model parameters. However, it could not be concluded that the model performed significantly better for natural and naturalised catchments than for non-naturalised catchments.

v) Despite incorporating a relatively large number of catchments, some soil types were not extensively covered. For those soil types, the parameters were defined with a relatively large uncertainty. The regional parameter set should therefore only be used in catchments where the main soil types belong to the dominant HOST classes in the 32 catchments used for the derivation of the regional parameter set.

vi) Further calibration should be done to include some soil types that were not extensively covered by the 32 investigated catchments. This is especially true for HOST classes 15, 29 and to some extend for HOST class 9.

vii) Further work should be done to quantify the effect of the uncertainty of the parameter values on the stream flow results by using the posterior distributions of the model parameters from the calibration procedure of the regional model to define the uncertainty bounds of the model parameters.

The results presented are promising. It is especially promising to see that a complete approach starting from the development of a model aimed at being regionalised can lead to satisfactory results. It is hoped that the results obtained through the development of this new modelling tool will contribute to the IAHS decadal initiative on Prediction in Ungauged Basins (Sivapalan and Schaake, 2003; Sivapalan, 2003).

5.8 Acknowledgements

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6 COMPARISON OF HYDROLOGIC SIMULATIONS USING REGIONALISED AND CATCHMENT-CALIBRATED PARAMETER SETS FOR THREE CATCHMENTS IN ENGLAND

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6.1 Abstract

The objective of this study is to assess the performance of a regional hydrological model in catchments treated as ungauged. The Catchment Resources and Soil Hydrology (CRASH) model is a daily, catchment-scale, rainfall-runoff model that has been previously regionalised for England and Wales. In this paper, the regional CRASH is evaluated in three catchments located in East Anglia – eastern England - and it is compared to the single-site calibrated CRASH. The results demonstrate that the performance criteria are met in two of the three catchments for both the Nash-Sutcliffe (R^2) and the percent bias (PBIAS) efficiency indices and it is close to the performance criteria for R^2 in the third catchment where there is a transfer of groundwater out of the catchment. The R^2 results of the regional CRASH in the three catchments (0.70, 0.56 and 0.48) are within the range of results from other simulation studies in ungauged catchments in England, Australia, Canada and Norway. The degradation between the regional and the single-site models is only limited for all the efficiency indices. Finally, the uncertainty analysis on the model parameters shows that there is a reasonable confidence in the regional model.

Keywords: Rainfall-runoff, assessment, ungauged, catchment-scale model.

6.2 Introduction

The availability of reliable hydrological data is recognised to be a world-wide issue due to the costs and logistics involved in running extensive gauging networks, and because existing sets of data often include missing periods. For example, despite 1,100 river flow gauging stations in the UK, a large number of catchments are still without proper records of flow data. To address this global issue, the International Association of Hydrological Sciences (IAHS) launched the Predictions in Ungauged Basins (PUB) decadal initiative (Sivapalan *et al*., 2003). Ungauged basins are defined as catchments without adequate records of data in both data quantity and data quality or appropriate spatially and temporarily to the needs (Sivapalan *et al*., 2003).

The work undertaken by Maréchal and Holman (Submitted-2003, Submitted-2004) addresses one of the five PUB directions of work: objective 3 - to further develop methodologies for predictions in ungauged basins and for minimising uncertainty (Sivapalan *et al*., 2003). The aim was to develop a conceptual, continuous, daily, semi distributed catchment-scale rainfall-runoff model to be used in ungauged catchments. The modelling approach can be regarded as following the top-down methodology because the Catchment Resources And Soil Hydrology (CRASH) model was developed after the main factors affecting the hydrological response at the catchment scale were identified (Maréchal and Holman, Submitted-2003). A regional parameter set for England and Wales has been derived from the calibration of CRASH for 32 mid-size catchments (Maréchal and Holman, Submitted-2003).

The aim of this paper is to assess the performance of the regional CRASH in three catchments, not used for the derivation of the regional parameter set, located in East Anglia (eastern England). The assessment of CRASH comprises a multi-criteria evaluation of the performance and an analysis of the effect of the uncertainty in the regional model parameters (Wagener, 2003).

6.3 Model

The CRASH model (Maréchal and Holman, Submitted-2003) was developed from the assumption that the transformation of rainfall into river flow at the catchment scale is driven by soil and land use properties. It was designed to be used solely with existing datasets of soil and land use. CRASH uses the Hydrology of Soil Type (HOST) system (Boorman *et al*., 1995), a conceptual representation of the hydrological processes in UK soils. It defines the hydrological behaviour of soils in terms of their influence on river flow at the catchment scale and gives a classification of all the soil types of the United Kingdom into 29 conceptual response models (or classes).

CRASH structures a catchment using four types of objects: the response units where the production of flow is predicted, and three routing objects: the sub-catchments, the rivers and the reservoirs. It also includes surface water discharge and surface and ground water abstraction.

The response units are defined within each sub-catchment as cells with homogeneous hydrological behaviour based upon a combination of soil type, land use and weather. Response units are composed of soil water and groundwater stores. They have a single hydrological input: precipitation and four hydrological outputs: actual evapotranspiration, runoff, intermediate flow and base flow. Actual evapotranspiration depends on climate, plant growth stage and soil moisture conditions. Both saturation and infiltration excess runoff processes are explicitly taken into account for the production of surface runoff. The surface depression store must be full before any excess surface runoff can be released from the response unit. The intermediate and base flows are proportional to the soil water store and ground water store contents, respectively.

CRASH has three parameters needing calibration for each HOST class, one for each flow path: surface runoff, intermediate flow and base flow. Results from response units of similar soil hydrological behaviour (or HOST class) are grouped together so that the model parameters are calibrated for each HOST class.

The sub-catchments, rivers and reservoirs are routing objects to transfer the flows to sub-catchment and catchment outlets using respectively the unit hydrograph method, the Muskingum-Cunge method (Cunge, 1969) and the reservoir routing routine from Chow (Chow *et al.*, 1988).

The model requires several types of input data: the spatial distribution of soil and land use data for the definition and parameterisation of the response units; daily weather data; catchment physical properties or descriptors for the parameterisation of the unit hydrograph at the sub-catchment scale; river and reservoir characteristics for the flow routing, surface water discharge and surface and ground water abstraction data.

6.4 Catchments

The Bure, Wensum and Tud catchments are located in East Anglia (eastern England) (Figure 6.1) and drain areas of respectively 342, 501 and 88 km^2. They are flat and low-lying with altitude ranging from a few metres to 115 metres above sea level. The climate is relatively dry with annual average precipitation and potential evapotranspiration of 670 mm and 490 mm between 1979 and 1983, respectively.

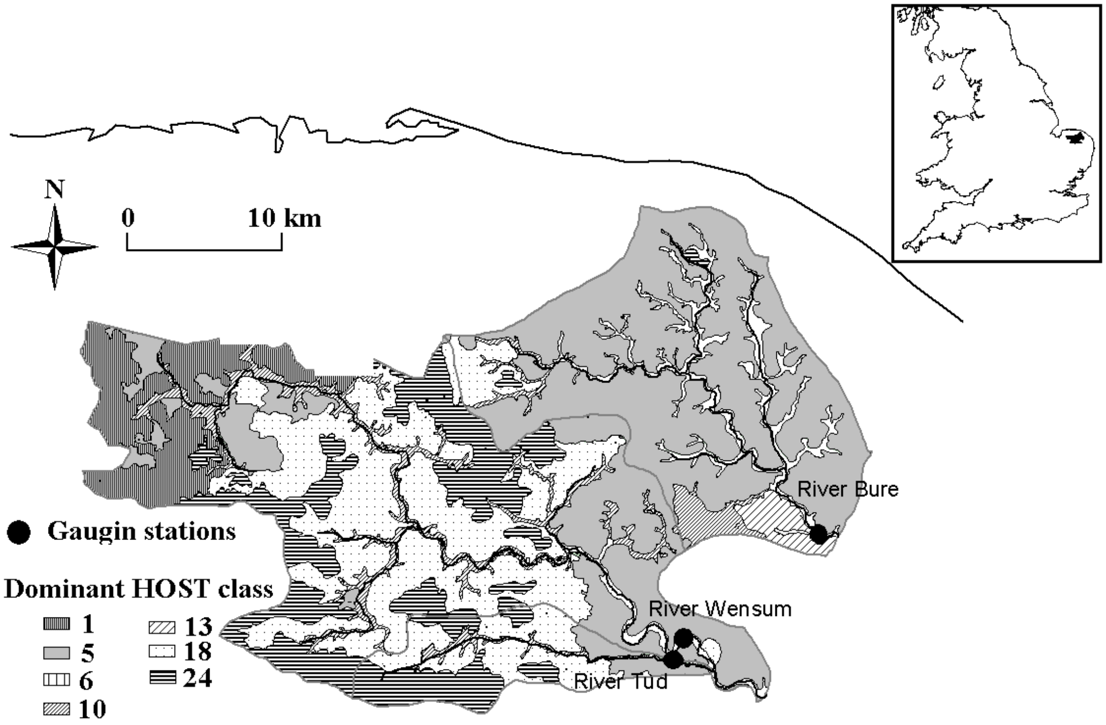

Figure 6.1: Location of the study catchments and their dominant HOST classes (Boorman *et al.*, 1995).

Despite an excess of precipitation over potential evapotranspiration of 180 mm, water resources are under significant stress during the summer months, when intensive farming practices require a significant amount of irrigation due to evaporation exceeding precipitation. Arable lands cover 80% of the three catchments where the main crops cultivated are cereals and irrigated potatoes and sugar beet. There are two major surface water intakes for public water supply in the Wensum catchment, and one sewage treatment work in each of the Wensum and Bure catchments.

The area is covered by the Chalky Boulder Clay in the Tud, Wensum and the upper part of the Bure catchments and by the North Sea Drift in the middle and lower parts of the Bure catchment (Soil Survey of England and Wales, 1984). Soils in the Chalky Boulder Clay typically have a slowly permeable subsoil and are seasonally waterlogged. These soils belong to HOST classes 18 and 24 (Boorman *et al.*, 1995) and are characterised by likely surface runoff and seasonal saturated subsurface flows. On the other hand, soils developed in the North Sea Drift are sandy with permeable surface and subsurface layers (Soil Survey of England and Wales, 1984). They are well drained and are not affected by ground water. These soils typically belong to HOST class 5. The spatial distribution of the HOST classes is presented in Figure 6.1.

Mean daily river flow data were available at stations located at the outlet of the three catchments. The groundwater catchment for the Tud is smaller than the surface water one (Centre for Ecology and Hydrology, 2003). The Tud catchment has therefore a tendency to lose water to its neighbour catchments among which is the Wensum. However, the effects of this transfer of water are smaller on the Wensum than on the Tud catchment due to the difference in surface area.

Abstraction licences were used to estimate the water abstraction from both surface and ground water for public water supply. It was assumed that the ratio between actual abstraction and licenced volumes was 80% (Anglian Water - *pers. comm.*). The water demand for spray irrigation was estimated following the method of Knox *et al.* (1996) with a ratio between surface and ground water based on the spray irrigation licences. No specific data for industrial uses were available, it was therefore assumed that the percentage of licensed abstraction for industrial purposes over total licensed abstraction was constant for the three catchments. This percentage was taken as equal to the regional value for the Norfolk region. Finally, effluent return flows from the two sewage treatment works were used to account for the discharges into the rivers Bure and Wensum.

6.5 Regional model

CRASH has been regionalised for England and Wales (Maréchal and Holman, Submitted-2004). Firstly, it was calibrated individually for 32 catchments covering a wide range of climatic, topographic, soil and land use conditions in England and Wales.

Secondly, a single, or regional, parameter set was defined from the results of the single-site calibrations.

6.6 Single-site model

CRASH has been calibrated specifically for the three catchments for the period 1979-1983 by optimising the multi-objective function (MOF):

$$MOF(\theta) = R^2(\theta) - FMOF(\theta) \tag{6.1}$$

where θ is a set of model parameters, R^2 the Nash-Sutcliffe efficiency index and *FMOF* the fuzzy multi-objective function defined by Yu and Yang (2000). The most sensitive parameters of the four main HOST classes in the catchments are presented on Figure 6.2. It should be noted on Figure 6.2 that not all HOST classes are present in the three catchments (e.g. HOST class 6 only in the Bure catchment). The effect of the transfer of ground water from the Tud catchment has an influence on the base flow parameters and especially on the base flow parameter of HOST class 5. Consequently, the parameter's value is significantly lower in the Tud catchment than in the regional parameter set (Figure 6.2).

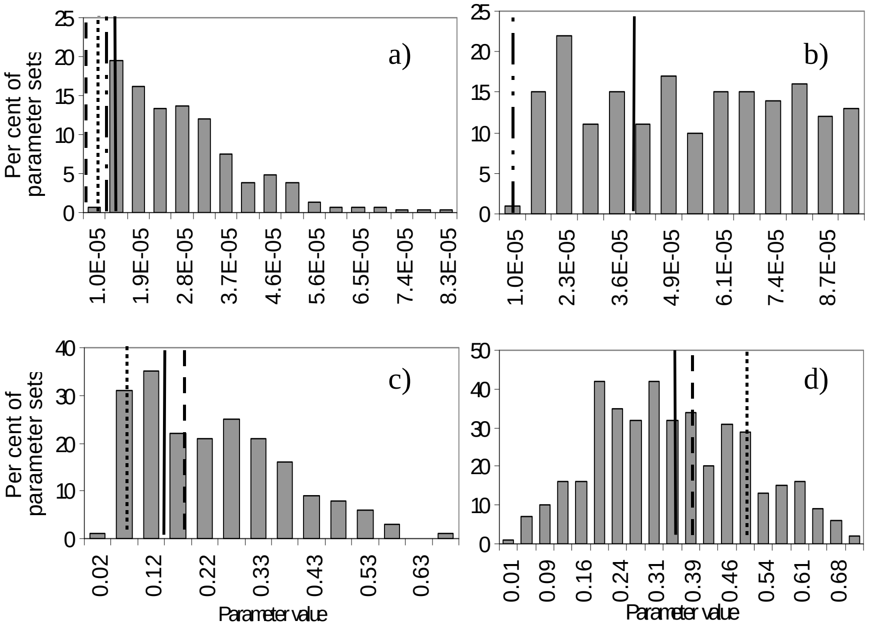

Figure 6.2: Model parameters for the catchments Bure (—···), Tud (- - -) and Wensum (·········) and the regional model (——) with their uncertainty distribution; a) base flow

HOST class 5, b) base flow HOST class 6, c) intermediate flow HOST 18, d) intermediate flow HOST 24

6.7 Results

6.7.1 Multi-criteria evaluation

Daily hydrographs are presented in Figure 6.3, Figure 6.4 and Figure 6.5, and the results for the R^2, FMOF and PBIAS efficiency indices are summarised in Table 6.1, with the 50 first days of the simulations removed from the calculation. The percent bias PBIAS is defined as:

$$PBIAS = \frac{\sum_j \left(Obs_j - Sim_j\right)}{\sum_j Obs_j} * 100\% \tag{6.2}$$

with *Sim* and *Obs* the simulated and observed river flows and *j* the time step index.

The results reveal that the general performance of the regional CRASH is slightly better in the Bure and Wensum catchments than in the Tud catchment

Table 6.1: Model performances for R^2, PBIAS and FMOF

Catchment		R^2	PBIAS (%)	FMOF
Bure	Single-site	0.63	-2.5	0.30
	Regional	0.56	-2.3	0.32
Tud	Single-site	0.58	18.4	0.55
	Regional	0.48	36.6	0.62
Wensum	Single-site	0.71	0.1	0.21
	Regional	0.70	0.7	0.25

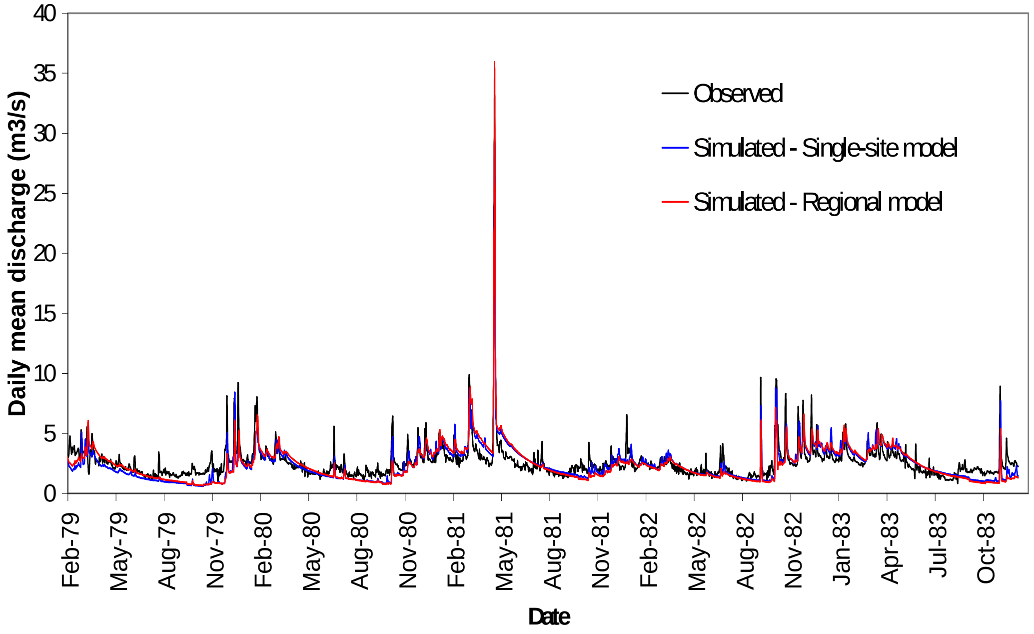

Figure 6.3: Daily results – Bure

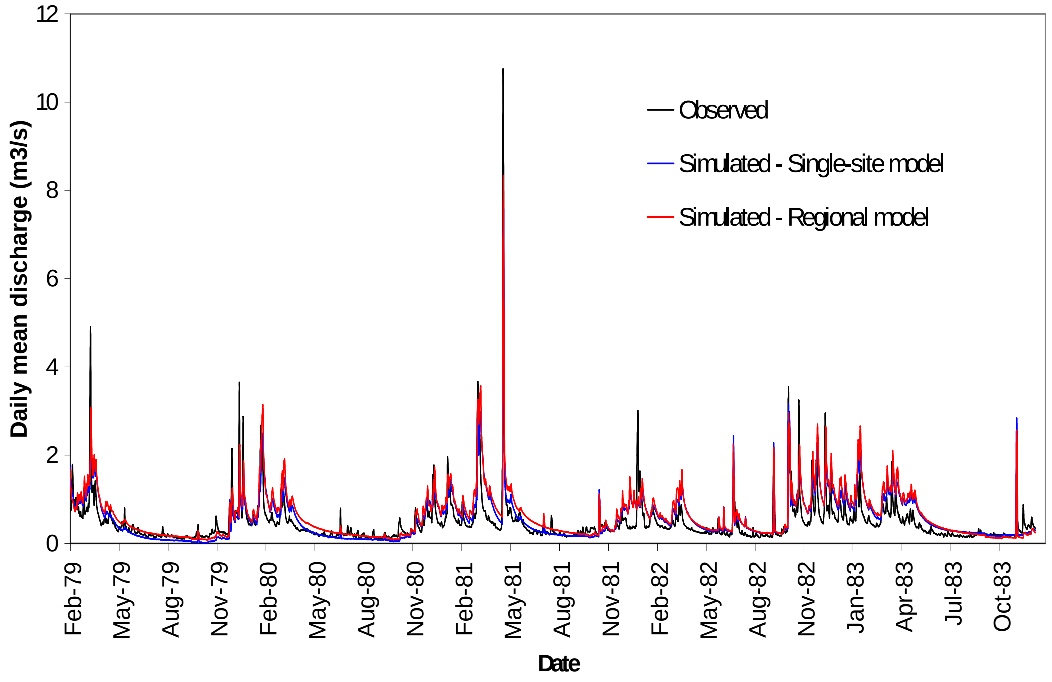

Figure 6.4: Daily results – Tud

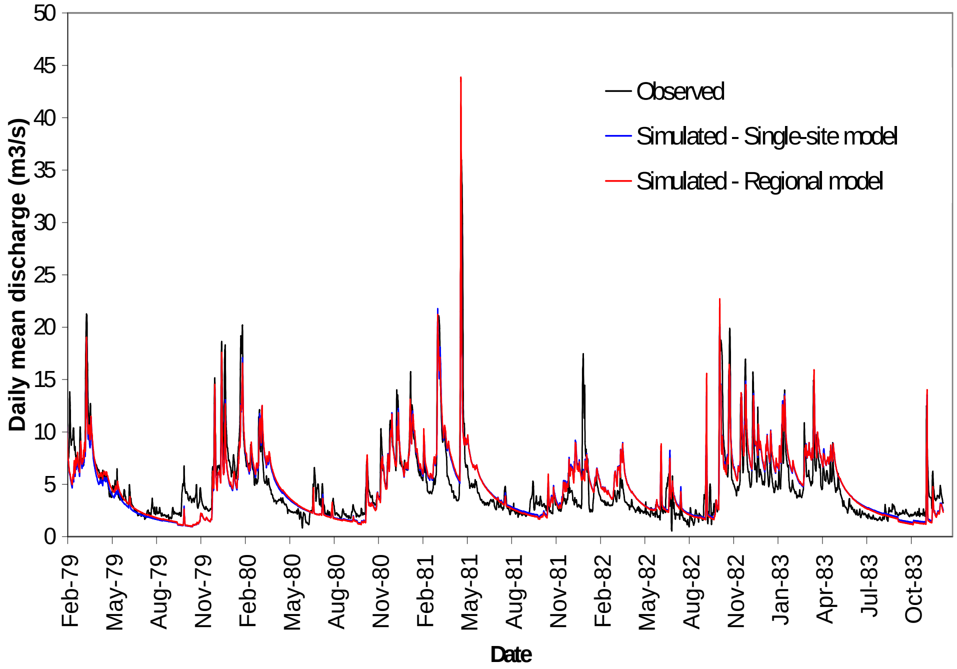

Figure 6.5: Daily results – Wensum

According to the scoring system proposed by Henriksen *et al.* (2003) (Table 6.2), the regional CRASH performance is very good in the Wensum catchment and good and poor in respectively the Bure and Tud catchments for the R^2 index. It is excellent in the Wensum and Bure catchments and poor in the Tud catchment for the PBIAS index.

Table 6.2: Performance intervals

Efficiency index	Excellent	Very good	Good	Poor	Very poor
R^2	>0.85	0.65-0.85	0.5-0.65	0.2-0.5	<0.2
$\lvert PBIAS \rvert$ (%)	<5	5-10	10-20	20-40	>40

6.7.2 Multi-study comparison

The results for the three catchments are also within the range of values presented in other studies carried out in a wide variety of climates. Post and Jakeman (1999) tested their approach on 16 catchments in Australia by cross-evaluating the relationships between physical catchment descriptors (PCDs) and dynamic response characteristics (DRCs) derived from the 15 other catchments. Their R^2 results ranged from 0.71 to -1.53 with an average of 0.37. Sefton and Howarth (1998) obtained R^2 of 0.61 and 0.53 for two catchments in England by applying PCDs-DRCs relations derived in other catchments. Van der Linden and Woo (2003) obtained R^2 results from 0.6 to 0.8 when they applied the parameters derived in a subarctic catchment in Canada to three catchments of similar size and characteristics. Beldring *et al*. (2003) derived model parameter values for 5 land use classes from the calibration of a distributed version of the HBV model in 141 catchments in Norway. R^2 was above 0.5 in 60% of the 43 independent catchments where these parameter values were used.

6.7.3 Regional vs Single-site CRASH

There is only a limited deterioration in performance from the single-site and regional CRASH in the three catchments. The results stay in the same categories for the Wensum and Bure catchments for R^2 and PBIAS, and but they change from good to poor for the Tud catchment for both indexes.

The main deterioration experienced is for the Tud catchment (Table 6.1) where PBIAS increases from 18% to 37%. This overestimation of the flows is the consequence of the transfer of groundwater from the Tud to its neighbour catchments as illustrated by the difference between the single-site and regional base flow coefficient of HOST class 5.

6.7.4 Uncertainty in the model parameters

The uncertainty in model simulations have four main sources (Refsggard and Storm, 1996): i) the random or systematic errors in input data (e.g. precipitation, evapotranspiration, soil characteristics); ii) the random or systematic errors in data used for comparison with the simulation for the model calibration (e.g. discharge); iii) the errors due to non-optimal parameter values and iv) the errors due to incomplete model structure. The difficulty to define optimal model parameters – and their associated uncertainty - is a consequence of these four sources of errors. The objective of this section is to evaluate the influence on model results of the parameter uncertainties in the case of the regional CRASH for the three catchments.

The posterior distributions of the model parameters from the calibration procedure of the regional model (Maréchal and Holman, Submitted-2004) were used to define the uncertainty bounds of the model parameters. The choice of the limit between a behavioural and a non-behavioural model is always a subjective choice (Beven and

Freer, 2001). It was decided to select the best 200 parameter sets for each HOST class as it allows to have at least four catchments with R^2 above 0.5 for most of the HOST classes. The distributions of the four most sensitive parameters are presented in Figure 6.2.

The model was run for 500 sets of parameters generated from the parameter distributions of the behavioural models using the Latin Hypercube Sampling method. The results for the three efficiency indices are presented in Figure 6.6. There is a relatively good confidence in the regional model as it performs better, in terms of R^2, than 95% of the behavioural models in the Bure and Wensum catchments. The largest uncertainty for the R^2 efficiency index is in the Bure catchment where 90% of the R^2 results are between 0.55 and 0.05. There is only a limited influence of the parameters uncertainty on the PBIAS index. Finally, the variations of FMOF due to the parameters uncertainty are mainly the consequence of variations in the prediction of low flows.

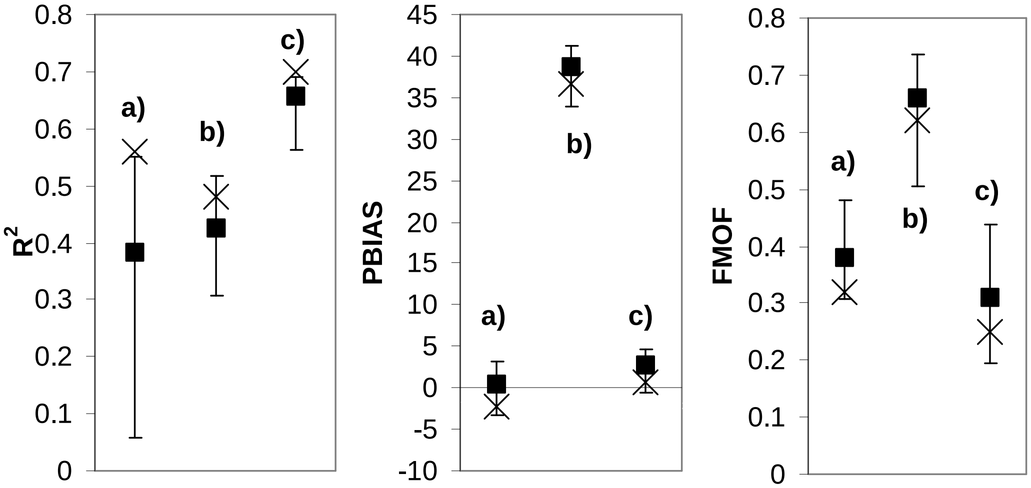

Figure 6.6: Uncertainty analysis. X regional model, ■ median result from the uncertainty simulations with its 90% probability limits for the a) Bure, b) Tud and c) Wensum catchments.

6.8 Conclusion

The aim of this paper was to independently evaluate the performance of a regional daily hydrological model for England and Wales in three catchments located in the East of England.

The overall performance of the regional CRASH is satisfactory as it meets the performance criteria in two of the three catchments for both the Nash and Sutcliffe (R^2) and the percent bias (PBIAS) indices. But it performs poorly in the third catchment due to an over-prediction of the river flows in the Tud catchment. The R^2 results range between 0.70 and 0.48.

The results from the uncertainty analysis on the model parameters showed that there is a reasonable confidence in the regional model as it performed better than 95% of the 500 behavioural models in two catchments for R^2. The uncertainty in regional model parameters showed limited influence on the PBIAS index.

The deterioration between the regional and the single-site models is only slight in the two catchments where the model performs the best. It is more significant for the Tud where the single-site base flow parameters are influenced by the transfer of ground water to its neighbour catchments.

Finally, the R^2 results have been compared to results from similar studies in different climates and they are within the same range of values.

Therefore, it is found from the above-presented performances of the model that the modelling approach developed with CRASH gives promising results. It is especially noted that the incorporation of pre-existing knowledge, like the HOST soil classification, into new modelling tools has a valuable impact on simulating ungauged basins.

6.9 Acknowledgements

This work was part of the MULINO project funded by the European Commission Framework V Programme (EVK1-2000-22089). We would like to thank the Environment Agency for the flow data, the British Atmospheric Data Centre for providing access to the UK Meteorological Office Land Surface Observation Stations Data and to the UK Meteorological Office for the use of their data, the Centre for Ecology and Hydrology for the land cover map and the National Soil Resources Institute for the soil information.

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7 CONCLUSIONS AND RECOMMENDATIONS

This thesis addresses mainly the technological aspect of hydrology as described by Sivapalan (2003) rather than its theoretical aspect. In fact, the aim of the work presented in this dissertation was to improve the modelling of rainfall-runoff processes in ungauged catchments with a special interest for applications regarding water resources issues. The overall approach has been influenced by the availability and features of pre-existing data sets: meteorological and stream flow observations, soil and land use characteristics. It has also been based on the use of pre-existing knowledge of the hydrological processes at the catchment scale in the UK, through the application of the HOST classification. Finally, it has been influenced by the current modelling knowledge and practices in hydrological and environmental sciences.

In the first section of this chapter, the results and findings of this thesis are summarised and discussed with respect to the initial four objectives. Concluding remarks are also given with regard to the initial aim. In the second section, a way forward for further development and improvement of the CRASH model is presented. In the last section, the conclusions of this thesis are viewed in the broad context of hydrological modelling within the Predictions in Ungauged Basins initiative.

7.1 Results and findings: discussion and conclusion

7.1.1 Objective 1: *Development of a continuous, daily, semi-distributed catchment-scale rainfall-runoff model.*

The Catchment Resources And Soil Hydrology (CRASH) model (sections 3.4, 3.5) has been developed to address the initial hypothesis that the transformation of rainfall into daily discharge at the catchment scale in the UK is driven by soil, land use and weather conditions. CRASH recognises that similar hydrological processes take place in zones or units of a catchment with similar physical properties, and that these similar units have similar hydrological response when they are activated by rainfall. CRASH uses the principle of Hydrological Response Units (HRUs) to define hydrologically homogeneous units within a catchment. HRUs are a conceptual representation of the hydrological processes. In the model, an HRU is composed of a soil water store that dictates the production of fast flow to the sub-catchment or catchment outlet, and of a ground water store that is responsible for the base flow component of the hydrograph.

The main features of CRASH are as follows:

- CRASH has been developed with the intention to relate the free model parameters to the controlling factors of the hydrological processes in the UK (soil and land use).
- CRASH incorporates pre-existing knowledge gained from previous studies, in particular through the use of the HOST classification. HOST is employed qualitatively to group soils according to their hydrological behaviour and to capture the main physical processes within each soil type. This definition of physical processes – by the means of HOST – is also the base for the regionalisation of the model. In fact, the regionalisation strategy is to export model parameters to regions where similar physical processes happen.

  HOST is also used quantitatively when the values of the Standard Percentage Runoff are directly used within the calibration of a free parameter (sections 3.5).
- CRASH separates the calculation of infiltration and saturation excess surface runoff.
- To estimate the production of infiltration excess runoff, a novel regional temporal disaggregation scheme of rainfall intensities was worked out to predict hourly rainfall intensities at any location in the UK (chapter 4). A parsimonious disaggregation scheme was implemented for the 9 meteorologically homogeneous regions of the UK. The goal of the disaggregation scheme was to conserve the statistical properties of the hourly rainfall intensities. The main assumption of the approach was that the intensity during the most intense hour defines the type of rainfall event and dictates the intensities for the other 23 hours of the day. Extensive data sets (23,229 days with at least 15mm of precipitation from 238 meteorological stations) were analysed to derive robust relations between hourly and daily rainfall intensities for the 9 meteorological regions.
- The regional rainfall disaggregation scheme was accepted as successful for its purpose of water resources modelling, but it was concluded that it needs further evaluation to be used in other types of applications.

- Detailed existing soil data are used to describe the soil water store: number of horizons, physical characteristics of each horizon (thickness, soil water storage at various pressures, hydraulic conductivity) and the hydraulic boundary condition between the soil water store and the ground water store.
- CRASH enables the modelling of complex systems composed of several sub-catchments, reservoirs, river reaches and effects from human activities on the state of the water bodies (surface and ground water abstraction, effluent returns, import and export of water from the catchment).
- CRASH has been coded with the C++ language in an Object-Oriented Programming manner to assure minimum running times and an extended re-usability of the code.

7.1.2 Objective 2: *Evaluation of the CRASH model in England and Wales.*

CRASH has first been tested and evaluated in three catchments located in England with contrasting soil and climatic conditions (sections 3.6 – 3.9). The model could not be rejected in any of the three catchments during both the calibration and evaluation periods according to the criteria used by Sefton and Howarth (1998) and Henriksen *et al.* (2003). CRASH showed a slight tendency to overestimate river flows in one of the three catchments.

In the light of these results, CRASH demonstrated its ability to satisfactorily predict daily river flows, at the catchment scale, in catchments where flow data are available.

7.1.3 Objective 3: *Regionalisation of the CRASH model for England and Wales.*

To the author’s knowledge, this study is the first attempt to regionalise a semi-distributed hydrological model at the national scale in the UK using the homogeneous unit parameters regionalisation method. The HOST system (Boorman *et al.*, 1995) was used to classify soils according to the hydrological processes taking place in order to define homogeneous units.

A regional parameter set for England and Wales was derived from the multi-criteria calibration of the model in 32 catchments (section 5.5). Regional parameters were determined by analysing the distribution of the parameter values giving the best performances. Regional parameters were fixed as the most probable values from these distributions.

The following observations were made from the derivation of the regional parameter set:

- The model parameter distributions were influenced by the fact that not all river flow data could be naturalised.
- In cases of HOST classes covering a small proportion of the catchments, the ranges of variation of the parameters were large.
- For these HOST classes, the regional parameter value was defined with a large uncertainty.
- The regional parameter set can be applied in catchments where the dominant HOST classes are classes with parameters defined with limited uncertainty. In that case, the parameters with a large uncertainty have only a restricted influence on the flow predictions.
- Further calibration is needed if the regional CRASH is to be exported to catchments where the dominant HOST classes have a large uncertainty in their parameters.

7.1.4 Objective 4: *Evaluation of the performances of the regional CRASH model.*

A multi-efficiency criteria assessment of the performance of the regional CRASH was carried out in the 32 catchments used for the computation of the regional parameter set (chapter 4).

The regional CRASH was also applied in three catchments independent from the 32 catchments used during the regionalisation process to perform a multi-efficiency criteria analysis and a parametric uncertainty analysis (section 6.7.4).

From these evaluations, the following observations were made:

- The regional CRASH is demonstrated to be reasonable and is proved to be a promising tool for prediction in ungauged catchments. The results from the simulations in the 32 calibration catchments revealed that the performance criteria adopted for the Nash-Sutcliffe efficiency index - at least a good performance according to Henriksen *et al.* (2003) - were met in respectively 60 % and 52 % of the cases during the calibration and evaluation periods, and in respectively 50 % and 56 % of the cases for the performance criteria selected for the PBIAS index. The performance criteria were met for both efficiency indices when the model was employed in two independent catchments. The poor performance of the model in the third independent catchment was explained by a transfer of groundwater out of the catchment that is not simulated by the model.

- There is generally only a restricted decrease of performance between the single-site model and the regional one. The main deterioration usually occurs in the low flows due to their sensitivity to artificial impacts and to the fact that a small absolute difference is a large relative difference for small flows.

- The performances of the regional CRASH were sensitive to the dominant soils in the catchment, the artificial impacts on the stream flow and the rainfall conditions.

  CRASH reproduces the hydrograph better when flows are primarily driven by base flow rather than by quick flow due to soils with slowly permeable layers.

  The regional parameter set has inevitably been derived using a mixture of natural or naturalised flows and non-naturalised flows. Regional CRASH tends thus to underestimate the stream flows when there is no abstraction and to overestimate them when there is abstraction.

  Regional CRASH also has the tendency to underestimate stream flows in wet climates due to an overestimation of the evapotranspiration of natural grassland and to overestimate them in some dry catchments due to the impact of the uncertainty in evapotranspiration predictions and of water abstraction on the flows. A good estimation of the evapotranspiration component is essential for a good performance of the model.

  Regional CRASH, as with any model, depends heavily on the input data. This was especially clear in wet and mountainous regions where the model performance was generally lower than in other conditions. One reason being the uncertainty in the representativity of the precipitation data in those regions.

- The uncertainty analysis on the model parameters revealed that there is a relatively good confidence in the regional model and that this uncertainty in the model parameters did not significantly affect the water balance of the model.
- The results of the regional CRASH are within the range of results from other non UK studies where regional rainfall-runoff models have been applied.

7.1.5 Concluding remarks

By principle, an hypothesis or a model can not be validated but only invalidated ((Konikow 1992). In the light of the above results, this thesis has shown that the initial hypothesis suggesting that soil and land use characteristics were the major driving factors for hydrological processes at the catchment scale in the UK could not be invalidated.

Despite this impossibility to validate an hypothesis, it is valuable until it has been rejected. Consequently, the following conclusions can be made about the regional CRASH model.

The representation of hydrological processes within the soils in the CRASH model is based on the process-based HOST system developed - at the catchment scale – for the UK. Despite the fact that the model parameters can not be defined *a priori* but must be set through calibration, they are representative of the physical processes and of the physical characteristics of the soils. This representativeness of the model parameters is the base for the development of the regional CRASH.

CRASH showed a promising potential as a modelling tool in ungauged catchments. Currently, the regional CRASH has been calibrated for England and Wales only, but it can be extended to Scotland and Northern Ireland.

Because of its integrated approach, CRASH can be used to assess management practices at the catchment scale. Outside the scope of this report, CRASH has been applied in five catchments in East Anglia as part of the EU-funded MULINO project (Holman *et al.*, 2004) to investigate the effects of alternative prices of ground water and surface water for maximising irrigation abstraction while minimising the adverse ecological impacts on the rivers (Holman *et al.*, 2004). In that context, CRASH has been linked to the Environment Agency's Resource Assessment and Management methodology. A graphical user interface has also been developed to enable an easy application of the model outside research.

Regional CRASH is an attractive tool for large-scale studies. It will be used for hydrological modelling within the climate change project RegIS2 (RegIS2, 2004) focussing on the impact of climate change on the agriculture, biodiversity, hydrology and coasts of East Anglia and the north west of England.

CRASH also has the potential to assess the impact of land use or soil conditions changes on the state of water bodies.

7.2 Way forward for CRASH

In the previous section, the conclusions from the results of this thesis showed the potential for CRASH as a modelling tool in gauged and ungauged catchments. However, it was also demonstrated that some aspects of the model could still be improved or completed. Some additional effort should be put into trying to reduce the error due to the uncertainty in the estimation of actual evapotranspiration. Other suggestions for future improvements and refinements of the model are also proposed.

- In accordance with Oliver (1985) who stated that evapotranspiration was "the most difficult component of the water balance to determine with any accuracy", it was found that a main source of error was the computation of the actual evapotranspiration (AET). There are three main sources of uncertainties in the computation of AET:

  _ the calculation of the potential evapotranspiration (Andréassian *et al.*, 2004),

  _ the estimation of the crop coefficient,

  _ the estimation of the plant growth stage.

  Further work should be done to first assess the impact of each one of these three sources of uncertainty on the model results.

- Because of its semi-distributed approach and the fact that the land use is explicitly used in the definition of homogeneous hydrological cells, CRASH is well suited for land use change studies. However in its current version, it does not offer the facility to model land uses other than natural (e.g. agriculture, semi-natural) ones. Urban and suburban land uses should be implemented to complete the library of land uses. Urban and suburban land uses are different from the others, from a modelling point of view, in that the runoff flows can take non-natural paths (e.g. in pipes). Storm water models can usually provide a detailed description of surface water flows networks created by pipes and roads and of the hydraulic processes: e.g. MIKE-SWMM (DHI, 2004b), SWMM (Huber and Dickinson, 1998), MOUSE (DHI, 2004a). In catchment scale models where urban areas only cover a small portion of the total area and are not the main focus, the urban land use type is generally simplified. Liu *et al.* (2003) used a two-tank model to account for an urban zone in association with the TOPMODEL. In most cases, urban areas are represented as both permeable and impermeable areas. For the models using the USDA Soil Conservation Service (SCS), such as SWAT (Arnold *et al.* 1998), AnnAGNPS (Young *et al.*, 1989), and the model by Weng (2001), percentages of permeable and impermeable areas and curve numbers for the permeable areas are provided for several categories of urban and suburban land use. In TOPURBAN (Valeo and Moin, 2000), it is assumed that all rainfall over impermeable areas runs off to the stream without any consideration of the amount of water that might be trapped in surface storage, or the flow paths. The calculation for the permeable areas, and in the rest of the catchment, uses the principle developed in TOPMODEL. Other models adopt a more sophisticated representation for the water budget and the flow path: e.g. HSPF (Johanson *et al.*, 1984), WEP (Jia *et al.*, 2001). Surface water storage and evapotranspiration are accounted for in the estimation of the quantity of surface runoff from impermeable areas. This runoff is also divided between effective flow, when it is directed to the storm water/sewage networks, and ineffective flow, when it drains onto permeable areas.

For CRASH, it is suggested to adopt the approach developed by de Rouffignac (2003) which is similar to the ones in HSPF and WEP. de Rouffignac found through calibration that the effective area contributing flow to the receiving sewage treatment works was between 3 and 9% of the urban area in 5 catchments located in East Anglia, south-eastern England.

- It has been quoted throughout this dissertation that the information held in data used for the calibration of hydrological models is generally insufficient to determine a unique set of model parameters (sections 2.1.2, 2.1.3, 3.3 and 5.2). Calibration is therefore an “always can be improved” exercise. The set of catchments studied for the definition of the CRASH regional parameter set could be increased with additional catchments. Several authors have reported that the use of stream flow data from multiple sites brought more constraints onto the parameter estimation (Fernandez *et al.*, 2000; Kuczera, 1997) and that it could improve the consistency of the parameter values (Beldring, 2002; Beldring *et al.*, 2003).

- Some of these additional catchments will have to be more significantly covered by soils from HOST classes covering only a small proportion of the catchments used in this thesis. If the use of CRASH is to be extended to Scotland, this is the case for HOST classes 14 and 28 that can mainly be found in Scotland and that were not present at all in the 32 catchments investigated in England and Wales. More importantly, special interest should be taken in HOST class 15 because it is the second most widely spread class in the UK but only covers about 3 % of the studied areas (Table 5.2). HOST class 15 is also extensively present in Scotland. In a smaller proportion, HOST 9 should also be more significantly represented, by using for instance catchments from the Linconshire and northern Cambridgeshire regions.
- Other sources and types of information can also help to reduce the uncertainty on model parameters (Sorroshian and Gupta, 1995). Siebert and McDonnell (2002) made the distinction between quantitative data that they called hard data, and qualitative data, called soft data. Hard data are measurements of the states of water bodies, typically soil moisture conditions and ground water level, and can be represented in models as internal state variables. Soft data represent the qualitative knowledge of the hydrological processes in the catchment and usually hold information on the type of water with respect to its path. Soft data can be gained, for instance, by using chemical tracers.

  Wooldridge *et al.* (2003) and Kuczera (1983) found that a dual objective calibration to reproduce stream flow measurements and soil moisture conditions could significantly reduce parameter uncertainty for their models. But the attempt by Wooldridge *et al.* (2003) to include the evapotranspiration as an extra calibration objective showed that it could not further decrease the parameter uncertainty for the

VIC model. Seibert (2000) also succeeded in reducing the parameter uncertainty for a modified version of the HBV model by considering the ground water levels in his calibration procedure.

The use of soft data has not yet had as clear a success as hard data. Lischeid and Uhlenbrook (2003) and Dunn *et al.* (2003) concluded that the use of a natural tracer in their models did not improve the stream flow predictions or reduce the uncertainty in the parameters.

Despite these mitigated successes with soft data, Seibert and McDonnell (2002) claim that their incorporation into the calibration procedure is a valuable tool to better link the modelling exercise to our knowledge of the “real” world. They argue that the reduction in performance, as defined by modellers through efficiency criteria, they experienced in their example is worth accepting when one considers the extra knowledge injected into the model and therefore the extra confidence into its behaviour.

With regard to the above results, the first step to use alternative information for the calibration of CRASH could be to consider soil moisture conditions with the aim to maximise the predictions of the stream flow and of the soil moisture conditions. The National Water Archive used to run a national databank of soil moisture content data (Institute of Hydrology, 1981). However this databank holds only measurements from 53 point sites in the UK with the latest data from 1981. Other research projects have monitored soil moisture conditions but only restrictively in time and space: e.g. LOCAR project (NERC, 2004). One promising alternative to manual observations is remote sensing measurements. Remote sensing observations of soil moisture content use the sensitivity of the microwave signals to moisture. They have great potential to allow spatial coverage of an area. But they have a number of technical difficulties due to their sensitivity to soil type, landscape roughness and vegetation cover (Pathmathevan *et al.*, 2003). Their major limitation is, however, that they only measure the soil moisture conditions near the soil surface, typically to a depth of 5-6 cm. Numerous attempts have been made to retrieve soil moisture profiles from near surface measurements (e.g. Heathman *et al.*, 2003; Wilson *et al.*, 2003; Walker *et al.*, 2002; Li and Islam, 2002; Entekhabi *et* *al.*, 1994). Even if no general method to estimate soil moisture profiles from remote sensing observations has been defined yet, remote sensing is viewed as a technology full of promises.

- The methods to search optimum parameter sets are numerous due to the difficulty of the task. One interesting alternative calibration procedure to the one adopted in this thesis is the sequential method developed by Lamb *et al.* (2000). The sequential method is an iterative method where only one model parameter is defined at a time. The model is first calibrated but only the parameter having the greatest impact is selected and defined (Wagener, 2002). This parameter is then fixed for the following iterations. The sequential method has been found to improve the identification of parameter values (Wagener, 2002), but it also has the drawback to require a large number of model runs. This is especially a problem when working with several catchments.
- The previous points presented suggestions to complete the model or to improve the definition of the parameters. But CRASH is a new model that needs to be further evaluated in gauged and ungauged catchments in the UK. It would also be interesting to determine its portability to other countries with similar climate such as in the north of Europe, or to different climates.

7.3 Conclusions in the context of PUB

In the previous sections, the results of this thesis were reviewed against the initial objectives, and a way forward for future developments of CRASH was suggested. The aim of this section is to look at this work within the broader context of the Predictions in Ungauged Basins (PUB) initiative by the IAHS and to see how the findings and conclusions of this thesis can respond to some of the targeted research programmes from the PUB science and implementation plan (Sivapalan and Schaake, 2003).

Targeted research: *What are the information requirements to reduce predictive uncertainty in the future* (Sivapalan and Schaake, 2003)*?*

Targeted research programme: *Develop approaches to evaluate predictability limits and compare the prediction performances of models in ungauged and poorly gauged basins to these limits* (Sivapalan and Schaake, 2003).

A new scoring system to evaluate the performance of models in qualitative terms has been proposed for ungauged catchments (section 5.6). This scoring system classifies the model performance within one of these four categories: excellent, very good, good and poor. Performance classes are proposed for the two most commonly used efficiency indices in rainfall-runoff modelling: the Nash-Sutcliffe and PBIAS indices.

The limits of the classes have been selected subjectively and can consequently be easily questioned. However, the main interest of this scoring system is to assign a judgement value to a model's performance in order to have a common framework for model evaluation and to help with the comparison of models.

Targeted research: *What experimentation is needed to underpin the new knowledge required* (Sivapalan and Schaake, 2003)?

Targeted research programme: *Well-defined space-time resolution of new data acquisition systems for […] improving process descriptions in models* (Sivapalan and Schaake, 2003).

The difficulty to infer a clear optimum parameter set for the regional CRASH (section 5.5) confirms the need for extra data. It is not surprising after all to realise that the use of stream flow data only is not sufficient to understand the hydrological processes taking place at the catchment scale. It is believed that the observations of soil moisture conditions would be extremely valuable as it is in the soil that the critical processes usually occur. Remote sensing of soil moisture measurements are viewed with great interest because they can bring spatial information into the modelling exercise, which is not the case with stream flow data.

Targeted research: *How can we improve the hydrological process descriptions that address key knowledge elements that can reduce uncertainty* (Sivapalan and Schaake, 2003)?

Targeted research programme: *Advance process description through […] comparative evaluation of existing models, conditioned upon data in selected basins in a variety of environments* (Sivapalan and Schaake, 2003).

The results from this thesis together with the ones from Dunn and Lilly (2001) and Beldring *et al.* (2003) are a first step towards this research programme. These results tend to show that distributed and semi-distributed models are well suited for an adequate description of physical processes. They also have the advantage over lumped models to entirely benefit from spatial hard data like remote sensing observations.

Targeted research: *How can we maximise the scientific value of available data in generating improved predictions* (Sivapalan and Schaake, 2003)?

Targeted research programme: *Advance the theoretical framework for interpreting patterns in data […]* (Sivapalan and Schaake, 2003).

The relevance of the HOST system both in this study and in numerous other works in the UK recognises the importance of extra information for the improvement of predictions. HOST can be used to classify soils according to their hydrological behaviour, or by applying flow separation coefficients.

HOST is a unique attempt to generate soft data about soils and could be examples for similar approaches.

7.4 References

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