Land use, climate change & water availability (Phase 2a)

Task C: Preliminary modelling of the effects of land use and management change on available water

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Final Report – February 2014

Cite as:

Holman, I.P. and Hess, T.M. (2014). Land use, climate change and water availability (Phase 2a)- Task C: Preliminary modelling of the effects of land use and management change on available water. Unpubl. Cranfield Water Science Institute, Cranfield, UK

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Funding and Management

This project was commissioned and funded by the Department for Environment, Food and Rural Affairs (Defra). The project team reported to a Project Board which is led by Henry Leveson-Gower (Defra) and includes David Boorman (CEH), Ian Holman (Cranfield University), Andrew Hughes (British Geological Survey; BGS), David Seccombe (Environment Agency; EA) and Rob Soley (AMEC).

Contents

Summary

This task has provided an initial quantification of the effects of changes in land use and land management on average annual Hydrological Effective Rainfall (AAHER) and Potential Baseflow using a soil water balance model (WaSim). The effects were considered in present and future climates by using the FutureFlows climate change ensemble. The changes modelled were informed by the plausible future land use and management changes (induced by climate or social change by the 2050s) identified in the literature review in Task B - in particular regarding changes in land use (e.g., changes in agricultural and forest areas) and changes in cropping calendars and sowing/harvest dates. The Task has identified a number of key issues:

1. Climate change and land-use / land management change, in isolation or combination, can have potentially significant positive or negative impacts on average annual Hydrologically Effective Rainfall and Potential Baseflow, depending on the nature of the change;

2. Land-use change under the baseline climate tends to have the greater impact on average annual Hydrologically Effective Rainfall and Potential Baseflow than climate change alone. However, in combination with land-use change, climate change slightly extends the range of the impacts on AAHER. However, the FutureFlows climate change scenarios used are only for a single emissions scenario (A1B) so that future changes in climate may be greater or less;

3. The modelled impacts result from complex interactions between the weather, crop properties and soil properties, which together affect soil moisture availability, evapotranspiration and flow partitioning between surface runoff and infiltration;

4. The modelled results suggest that the impacts of future changes in land use and land management on Hydrologically Effective Rainfall and Potential Baseflow will depend on:

    - Type of land use – the greatest modelled impacts are associated with changes in the vegetation type. Taller and deeper rooted vegetation or crops are better connected to both the atmosphere and soil moisture stores, leading to higher evapotranspiration and reduced AAHER.
    - Agroclimate – impacts generally increase with increasing Potential Soil Moisture Deficits (PSMD) (i.e. increasing dryness), with wetter areas (low PSMD) being less sensitive to land-use change due to the lack of soil moisture limitations. However, climate change leads to a general increase in PSMD and therefore increased sensitivity to land-use and land management change;
    - Soil type – the range of future impacts are greatest on the lower permeability drained soils and least on the freely draining soils with low available water capacity;

5. Improving soil conditions may reduce Hydrologically Effective Rainfall by reducing runoff, increasing infiltration and the soil water storage, and therefore enabling greater evapotranspiration. However, improving soil conditions is generally beneficial for Potential Baseflow as the higher soil water contents lead to a longer Field Capacity period;

6. The relative magnitude of the hydrological impacts are generally greater for Potential Baseflow than for average annual Hydrologically Effective Rainfall.

7. The impacts of future changes in land use and land management on ‘water availability’ across England and Wales will therefore differ spatially according to agroclimate, soil type, soil condition and land-use type / vegetation and the magnitude and type of changes to the rural landscape. The effect of the upscaling of such changes in land use is described in the companion report of Hughes and Mansour (2014).

1. INTRODUCTION

This report describes an initial quantification of the relationship between land use and management, climate change and water availability carried out by the Cranfield Water Science Institute at Cranfield University. It is informed by the results of the Rapid Evidence Assessment (Houghton-Carr et al., 2013) and the review of the plausible future land use, land management and growing season changes (Holman and Hess, 2013) from Tasks A and B, respectively. This report evaluates the sensitivity of Average Annual Hydrologically Effective Rainfall and Potential Baseflow from a range of soil types, to changes in land use, climate change, soil conditions and crop timings. The effect of the upscaling of such individual changes to the landscape scale is described in the companion report of Hughes and Mansour (2014).

O'Connell *et al.* (2007) and Beven *et al.* (2008) recognised that it is difficult to model the impacts of land management changes on runoff generation and any attempt to provide such a broad-scale model will inevitably be subject to considerable uncertainty. However, given the scarcity and specificity of the empirical evidence for the effect of land-use and land management changes on the measured river hydrographs (O'Connell et al., 2004a; Haycock Associates, 2008), a modelling approach is the only way to attempt to produce a nationally applicable assessment. The chosen modelling approach for the current study needs to be widely applicable across the range of agro-climatic conditions across England and Wales without the need for calibration, and be sensitive to the effects of both land use and land management on runoff generation and recharge. As such, this initial quantification study has used the approach of Hess et al. (2010) and Holman et al. (2011). This integrates the use of the Curve Number method within a soil water balance model (WaSim), which are briefly described below.

2. THE MODELLING APPROACH

2.1 Curve Number method

The Soil Conservation Service (SCS) Curve Number (CN) model is an event model to predict runoff volumes (that is, the total stream flow excluding baseflow) for individual storms developed from many years of storm flow records in catchment in the United States The method was developed to estimate the runoff frequency distribution from the rainfall frequency distribution, and is applicable to small catchments (maximum area 6,500 ha) with a time of concentration for any sub-area of 0.1 - 10 hours (NRCS, 2002). A set of empirical equations relate direct runoff volume to the rainfall amount, catchment characteristics and antecedent wetness (USDA, 2004). Four catchment variables are considered; land use, soil conservation practice (e.g. contouring, terracing), soil hydrologic condition, and soil (runoff and infiltration characteristics). These are represented by a Curve Number (0 – 100) where a Curve Number of 0 represents maximum storage (taken to be 254 mm) and a curve number of 100 represents zero storage (i.e. a totally impermeable or saturated catchment).

The CN approach has been widely used to model the impacts of land-use changes on hydrological response – not only in the USA (where the method was developed) but also throughout Europe (e.g. Svoboda (1991) in Slovakia; Camorani *et al*. (2005) in northern Italy; van der Ploeg *et al*. (1999) in Germany; and Holman et al. (2009), Hess et al. (2010), Holman et al. (2011) and Warren and Holman (2012) in the UK). The CN approach is implemented in a number of catchment models (e.g. SWAT - Arnold et al., 1998) and has been shown to be robust across a wide range of climatic, soil and land covers within many modelling studies in the UK, Europe and wider (see review by Gassman *et al*., 2007).

Typical values of curve numbers for different land use and management conditions can be estimated from NRCS (2002). These cover a wide range of land uses and soil conditions and are therefore appropriate to the present study. Although the published curve numbers are empirical and were calibrated in the USA, they have been applied successfully in many parts of the world and were validated at the catchment scale across England and Wales in Holman et al (2011).

The main equation describing the relationship between storm rainfall and direct, or rapid response, runoff in the river is:

$$q = \frac{(P - 0.2S)^2}{(P + 0.8S)}$$

where
q direct runoff[1] depth (mm)
P storm rainfall (mm)
S the potential maximum soil moisture retention after runoff begins (mm)

For ungauged catchments S was defined as:-

$$S = \frac{25400}{N} - 254$$

where N is a C*urve Number* between 0 and 100.

Four catchment variables are considered in the determination of the Curve Number under these conditions:

- Land use, classified into Pasture, Small Grains, Row Crops, etc.
- Soil conservation practice (e.g. contouring, terracing);
- Soil hydrologic condition:
    - For arable land the hydrologic condition reflects whether the rotation will encourage good tilth and infiltration
    - For grassland hydrologic condition is assessed upon the density of vegetation; >75% is good, <50% is poor.
    - For forest, hydrologic condition is based on the depth of litter and humus.
- Soil are classified into one of four Hydrologic Soil Groups (HSG's) to indicate the minimum rate of infiltration obtained for bare soil after prolonged wetting. The infiltration rate is the rate at which water enters the soil at the soil surface and is controlled by surface conditions. The HSG also indicates the transmission rate - the rate at which the water moves within the soil, which is controlled by the soil profile:
    - **Group A** soils have low runoff potential and high infiltration rates even when thoroughly wetted. They consist chiefly of deep, well to excessively drained sand or gravel and have a high rate of water transmission (greater than 7.6 mm/hr).
    - **Group B** soils have moderate infiltration rates when thoroughly wetted and consist chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission (3.8 - 7.6 mm/hr).
    - **Group C** soils have low infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes downward movement of water and soils with moderately fine to fine texture. These soils have a low rate of water transmission (1.3 - 3.8 mm/hr).
    - **Group D** soils have high runoff potential. They have very low infiltration rates when thoroughly wetted and consist chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very low rate of water transmission (0- 1.3 mm/hr).

Typical values of Curve Numbers (Table A1.1) can be estimated from NRCS (2002).

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[1] Direct runoff is the total runoff, excluding baseflow (USDA, 2004)

2.2 Water balance modelling

The maximum retention or storage, *S*, is a dynamic variable as it will depend on the wetness of the soil (Figure 2.1). Therefore, the antecedent condition of soils has a significant effect on the predicted runoff volume and infiltration, and will itself be a function of land use and management- a wet soil will generate more runoff from a particular rainfall event that the same soil in a drier state. Therefore a daily soil water balance model was used to simulate the soil water content under different soil types and land management conditions in order to estimate the antecedent conditions before each rainfall event. The CN method was then used to estimate the runoff and infiltration arising from those events.

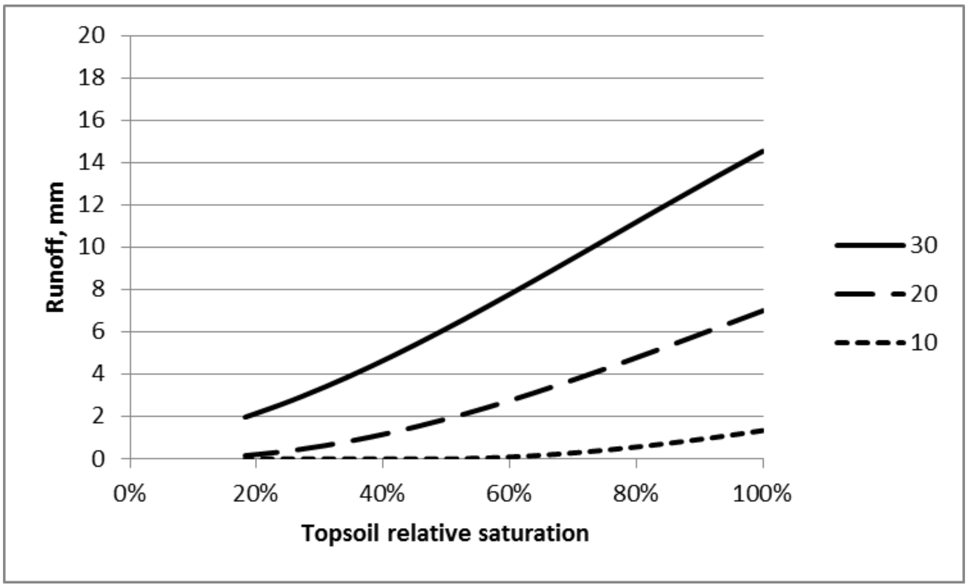


Figure 2.1 Impact of topsoil relative saturation on modelled runoff from rainfall events of 10, 20 and 30 mm (based on a runoff curve number of 84 for average antecedent conditions).

2.2.1 WaSim Water Balance Model

WaSim is a one-dimensional, daily, soil water balance model that simulates the soil water storage and rates of input (infiltration) and output (evapotranspiration, runoff and drainage) of water in response to weather (Figure 2.2). Although developed as a teaching and learning tool (Hess & Counsell, 2000), its value as a research tool has been demonstrated (e.g. Hirekhan *et al.*, 2007; Holman *et al.*, 2011). The unsaturated zone is divided into three compartments, the upper 0.15 m layer, the active root zone and the layer below the root zone. The thickness of the latter two layers varies as the active root zone changes. The root development is assumed to increase from the planting depth to the maximum depth following a sigmoidal root growth curve between the planting date and the date of maximum root depth (Borg and Grimes, 1986). The crop cover fraction on a particular day is determined by linear interpolation between the specified dates of emergence, 20% cover, maximum cover, maturity and harvest. Senescence is simulated by a linear reduction in crop cover fraction between maximum cover at maturity and zero at harvest.

Evapotranspiration from the soil is taken as the area-weighted average of crop transpiration, soil evaporation and evaporation of intercepted water from the mulch cover (if present). Plant transpiration is assumed to occur at a rate proportional to the reference evapotranspiration (Allen et al. 1998) depending on the plant type and occurs at the potential rate whilst the root zone soil water content is between field capacity (FC) and the easily available water capacity (EAWC). For restricted water supply, it decreases linearly to permanent wilting point (PWP) and remains zero thereafter (Brisson, 1998). Soil evaporation is estimated using the method of Ritchie (1972).

Soil water moves from one layer to the layer below only when its water content exceeds field capacity. The rate of drainage is a function of the relative saturation of the layer (Raes and van Aelst, 1985) and the hydraulic properties of the soil. Water draining out of the lower layer is taken to be potential recharge.

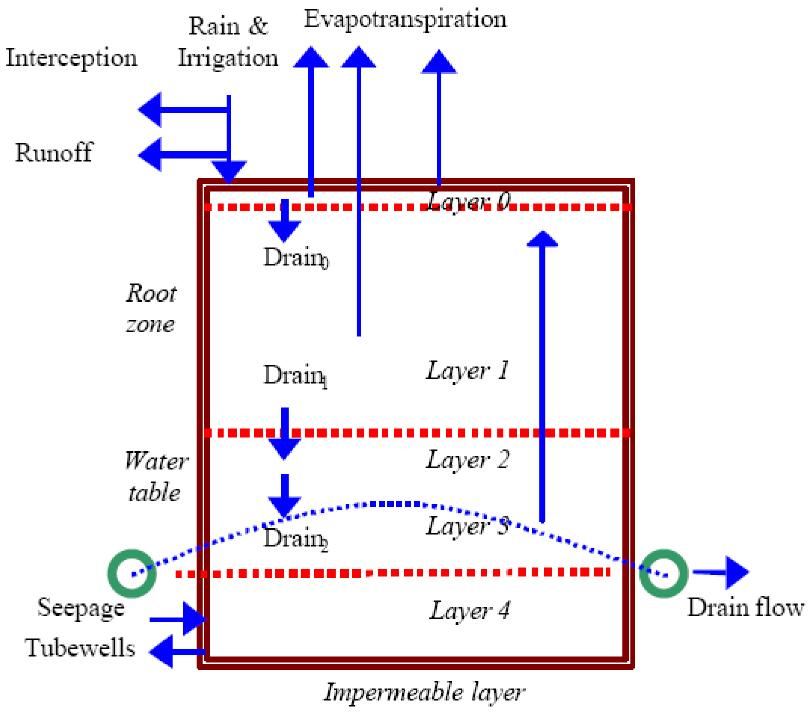


Figure 2.2 A schematic illustrating the WaSim Water Balance Model

Surface runoff comprises two components; runoff due to intense rainfall (infiltration excess) and runoff due to saturated soil. As the rainfall data used to drive the water balance model is only available on a daily time step, daily surface runoff due to the intensity of rainfall is estimated using the CN method, and any rain falling on saturated soil is assumed to run off. Any precipitation that does not run off is assumed to infiltrate. The storage, S, is recalculated using the method of Hawkins *et al*. (1985).

2.3 Model data requirements

The WaSim simulations require a range of input data, namely:

- Weather – daily rainfall and reference evapotranspiration (ET_o);
- Soil properties and condition;
- Land use;
- Curve Number.

However, because of the large number of potential combinations of climate/weather, soil type, field condition, land use and curve number, methods to simplify the data were applied.

2.3.1 Weather

Daily precipitation and Reference Evapotranspiration (ET_o) are required by WaSim. To achieve an acceptable compromise between an adequate representation of the spatial variability of the climate across England and Wales and the number of model runs to be undertaken, WaSim was run using catchment average daily climate transient projections for the Future Flows project's 261 river catchments (Figure 2.3), derived from Future Flows Climate (FF-HadRM3-PPE-CatID dataset). These represented projections from the ensemble of 11 variants of the Met Office Regional Climate

Model (HadRM3-PPE) as continuous time series of climate variables from 1950 to 2099 using the A1B emissions scenario.

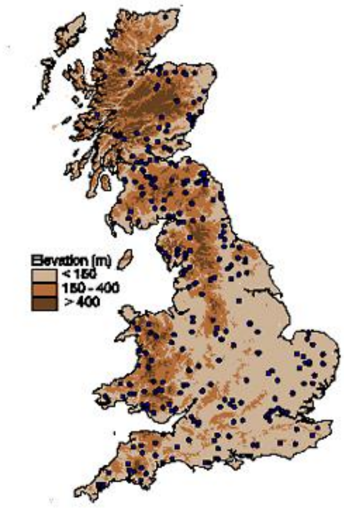


Figure 2.3 Outlet of river catchments where Future Flows Hydrology time series are generated

2.3.2 Soil

Each Hydrology of Soil Type (HOST) class, as defined by Boorman *et al.* (1995), includes a large number of individual soil series (soil types) which share the same conceptual model that describes the dominant pathways of water movement through the soil and, where appropriate, substrate. The most-extensive soil series within a HOST class (based upon analysis of the National Soil Map for England and Wales (Hodge *et al.* 1984)) was selected to represent the HOST class. Each of the identified soil series was classified into a Soil Hydrological Group based on its HOST class (J.M. Hollis, unpublished data).

Saturated hydraulic conductivity and volumetric water contents at saturation, field capacity and permanent wilting point for the selected soil series were provided by data in the Land Information System (LandIS) maintained by the National Soil Resources Institute (NSRI) at Cranfield University.

2.3.3 Land cover

Six representative vegetation types were considered (Table 2.1). NRCS (2002) provides values of Curve Number for a limited range of land cover types and these have been linked to, and parameterised for, the representative vegetation types.

Table 2.1 Representative vegetation types based on land cover types for the SCS Curve Number method

Representative vegetation type	Curve Number land cover type
Spring beans	Row crops
Winter barley	Small grains
Grass	Managed grassland
Grass (shallow rooting)	Largely unmanaged / semi-natural
Forest	Woodland

Parameters describing the vegetation growth cycle, rooting depth and crop coefficients (which represents the ratio of crop potential evapotranspiration to ET_o) were based on the values for the agroclimatic regions of Knox and Holman (2004), given in Holman *et al.* (2004). Key parameter values are given in Table 2.2

Table 2.2 Key vegetation input parameters

Vegetation	Emergence Date	Harvest Date	Maximum Root Depth (m)	Crop Coefficient	Growing season length (days)***
Permanent grass	01-Jan	31-Dec	0.7	100	365
Woodland	14-Apr	19-Nov	1.5	114	219
Semi-natural	01-Jan	30-Dec	0.35	100	364
Winter barley	13-Sep*	31-Jul**	1.5	110	293
Spring beans	14-Mar	31-Aug	0.75	110	170

* Varies from 13th September to 11th October depending on agroclimatic regions of Knox and Holman (2004)

** Varies from 3rd July to 31st July depending on agroclimatic regions of Knox and Holman (2004)

*** Calculated as days between ‘emergence’ and ‘harvest’

2.3.4 Descriptive classes of soil-field conditions

The impacts of differing land management on runoff have been simulated by linking the curve number with a descriptive class of soil-field condition. Five descriptive classes of soil-field condition have been used, from Excellent to Very Poor, which encapsulate both the condition of the soil (as it affects runoff generation) and the presence of land management practices which increase or decrease the risk of runoff from the field (affecting runoff transmission). For a given land cover and soil hydrological group, the lowest and highest curve numbers from NRCS (2002) have been used for Excellent (or Good for woodland) and Poor classes, respectively. The curve number for Very Poor condition represents a soil whose hydrological response has been altered to an extent that it behaves as though it belongs to a soil hydrological group of higher runoff potential e.g. a sandy soil of Very Poor condition would have a curve number from Soil Hydrological Group B, rather than Soil Hydrological Group A. In the case Soil Hydrological Group D in Very Poor condition, the curve number is not increased beyond the highest value given in NRCS (2002), in the same way that Packman *et al.* (2004) did not increase the degraded Standard Percentage Runoff (SPR) beyond the highest value in Boorman *et al.* (1995).

2.4 Model outputs

To cover a representative range of soil types, we have focussed on the model outputs for four contrasting soils (Table 2.3 and Figure 2.4). The WaSim model produces a range of hydrological outputs and indicators for each day of the simulation. For the purposes of this report, only a selection of the hydrological model outputs have been analysed.

For each soil and land use combination, we have analysed:

- Average annual Hydrologically Effective Rainfall (AAHER): this is the average annual amount of precipitation that has not been used by the crop or evaporated and which contributes to either streamflow or groundwater.
- Potential Baseflow: this is taken as that component of the Average Annual Hydrologically Effective Rainfall that moves along slow pathways and supports either river abstraction during non-storm periods or groundwater abstraction.

For the freely draining soils (Rivington and Andover) we have estimated “Potential Baseflow” as the potential recharge (i.e. water draining from the modelled root zone) and “Average Annual Hydrologically Effective Rainfall (AAHER)” as the sum of surface runoff and potential recharge.

Soil/land cover combinations in which artificial drainage would be required have been modelled with a representative drainage system design of pipe drains at 0.5m depth and 30m spacing. For these soils (Blacktoft and Wicham), we have estimated “Potential Baseflow” as the drain flow and AAHER as the sum of surface runoff and drain flow.

Table 1.3 Summary of the modelled soils

Series	HOST Class	Description
Rivington	4	A permeable, freely draining soil with a low water holding capacity
Andover	1	A permeable, freely draining soil with a medium water holding capacity
Blacktoft	8	A low permeability soil with a high water holding capacity that has impeded drainage causing seasonal waterlogging
Wickham	25	A low permeability soil with impeded drainage causing seasonal waterlogging. Lower available water and a higher propensity to generate runoff than Blacktoft

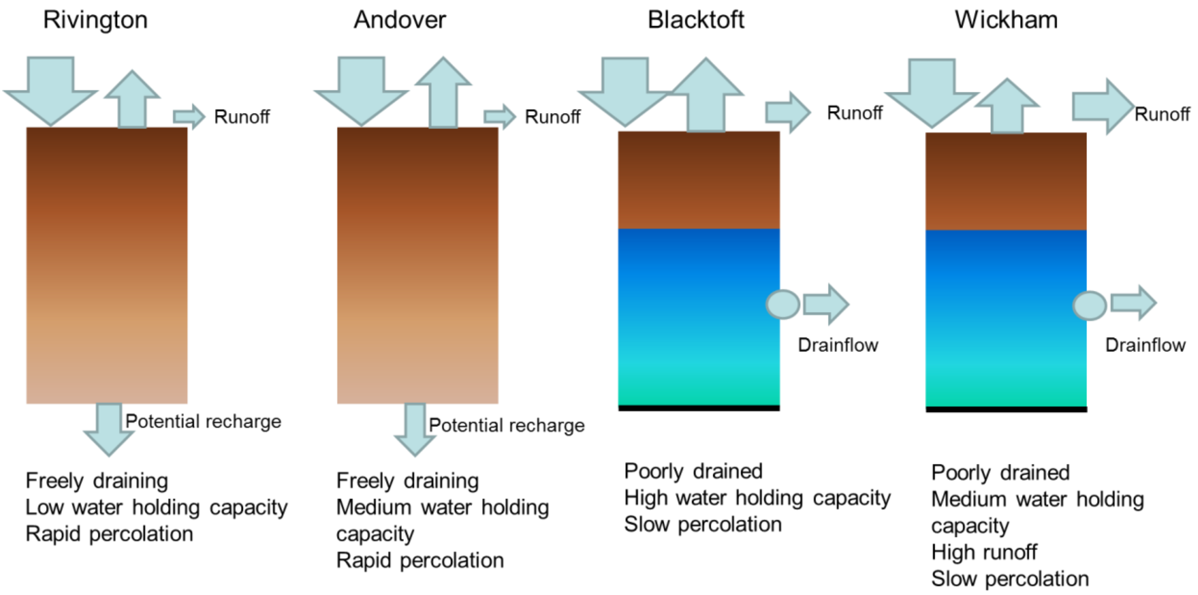


Figure 2.4 Schematic of the hydrological behaviour of the selected soil series

All simulation results have been expressed as a proportion of the model results for a ‘reference’ run (described at the beginning of each sub-section). A value of 1 indicates no change compared to this reference (Figure 2.5). To facilitate easy comparison of the results, and therefore the significance of the changes simulated, most graphs have been given the same y-axis range.

We have classified each catchment according to its baseline Potential Soil Moisture Deficit (PSMD), a measure of the climatological wetness (or dryness) of the catchment based on precipitation and reference evapotranspiration. A PSMD value of zero would mean than a summer soil moisture deficit would not develop in most years and would be indicative of a catchment in the wetter uplands. A PSMD of greater than 175 mm would be typical of East Anglia where the combination of relatively low annual precipitation and warmer weather produces high summer soil moisture deficits.

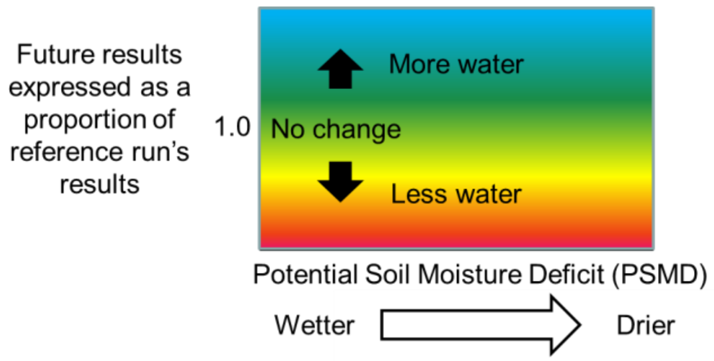
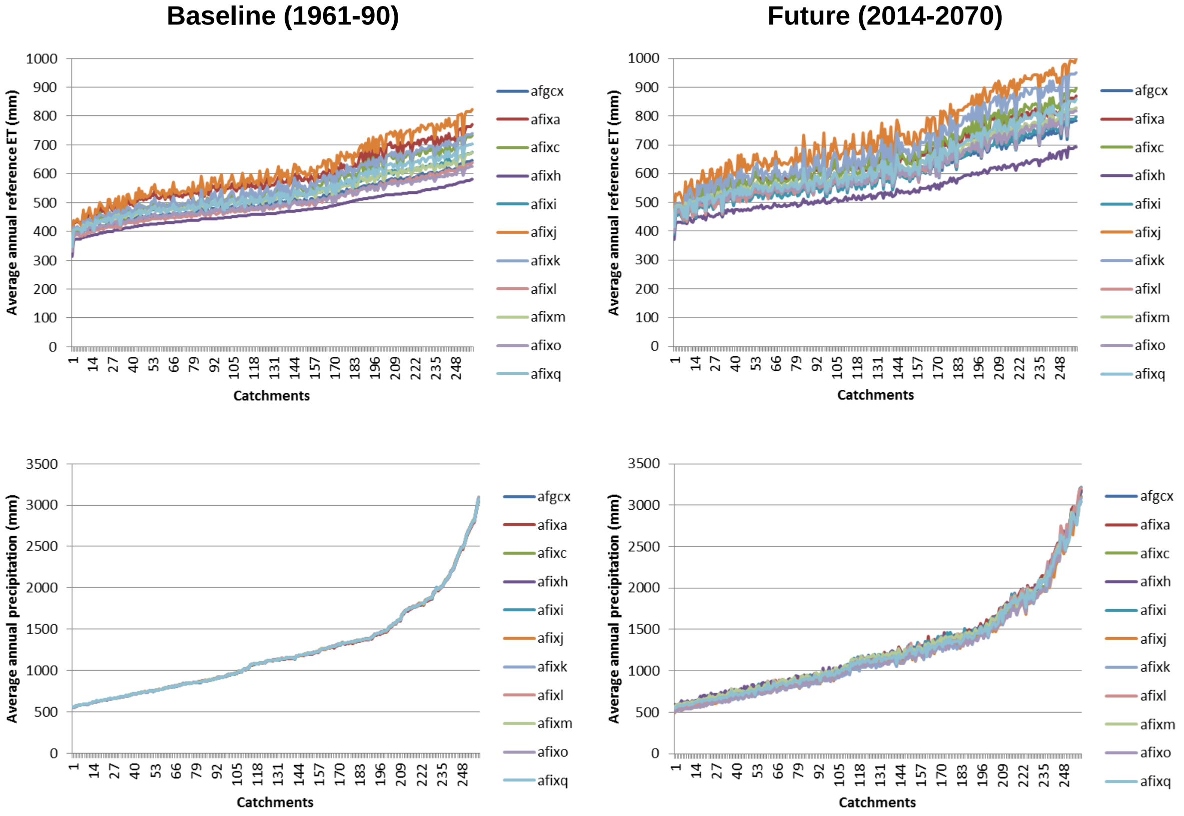


Figure 2.5 Explanation of the form of the presentation of WaSim results

2.5 FutureFlows projections

Average annual baseline and future precipitation and ET_o were calculated in order to select a FutureFlows projection for the modelling. Whilst there was little change in average annual precipitation across the ensemble members, there was greater variability in average annual ET_o (Figure 2.6).

Two contrasting ensemble members were selected for study. The "afixh" ensemble member was selected as a best-case, having some of the smaller increases in ET_o, whilst the afixj" ensemble member was selected as a worst-case, having some of the largest increases in ET_o.


Baseline (1961-90)

Future (2014-2070)

Figure 2.6 Comparison of the baseline and future average annual reference evapotranspiration and precipitation for FutureFlows ensemble members (ranked according to baseline afixh values)

2.6 Model validation

To confirm the applicability of the FutureFlows baseline climate data and the Curve Number approach, the Baseflow Index (BFI) has been calculated from the average annual Potential Baseflow divided by the average annual Hydrologically Effective Rainfall). Figure 2.7 shows the average simulated BFI for all of the vegetation types across the 28 HOST classes, averaged across all of the Future Flows catchments, along with the published UK-average BFI (across uncertain proportions of each vegetation type) for each HOST class and the 95% confidence intervals based on Boorman et al. (1995). This shows that the simulated BFI for most of the soil/vegetation combinations is within the 95% confidence interval of the UK-average measured BFI.

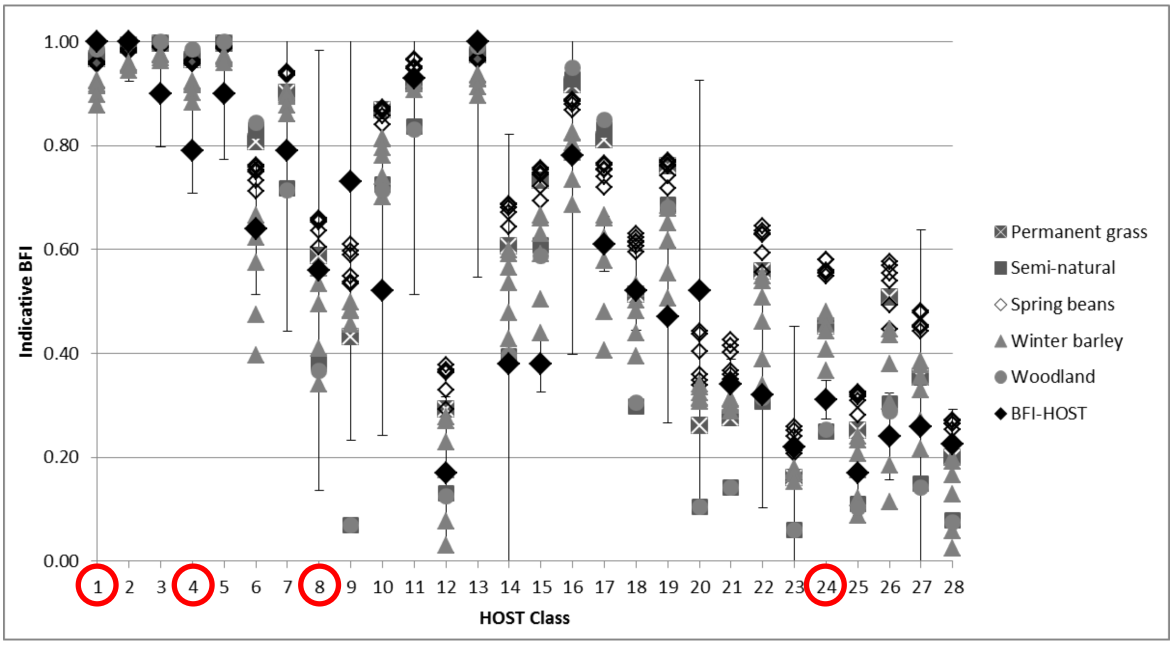


Figure 2.7 Baseline evaluation of the modelling system [*Circled HOST classes numbers are those reported*]. There are more than one data point for the spring beans and winter barley because of the multiple cropping calendars used across England and Wales.

3. RESULTS

Based upon the insights gained from Tasks A and B, the modelling has sought to provide initial insights into the effects of the following changes on AAHER and Potential Baseflow:

- Changes in vegetation type (under baseline climate) – between permanent grass, autumn and spring sown crops, woodland, and semi-natural vegetation;
- Changes in climate in the 2050s (without land-use change);
- Changes vegetation type with climate change ;
- Changes in land management affecting soil conditions only, and propensity for generating runoff, with climate change;
- Changes in the crop timings (with climate change).

3.1 Effect of changes in vegetation type only (under baseline climate)

This series of model runs assesses the effects of different vegetation types on baseline AAHER and Potential Baseflow, expressed as a ratio of the results with permanent grass.

Reference run:

- Baseline (1961-90) FutureFlows (afixh) weather
- Permanent grass
- Medium soil condition.

3.1.1 Average Annual Hydrologically Effective Rainfall (AAHER)

Under the baseline climate, the different vegetation types have a large effect on AAHER (compared to permanent grass), with the modelled ratio ranging from 0.04 to 2.54, or 4 – 254% of the baseline AAHER under grassland (Figure 3.1), indicating that land-use change can lead to either increases or decreases in AAHER depending on the nature of the change.

In wet catchments (low PSMD) there are only small differences in AAHER between vegetation types. With increasing dryness (increasing PSMD), the differences in AAHER compared to permanent grass between the vegetation types become more evident, as soil water availability and rooting depth become increasingly important in determining the evapotranspiration. The greater rooting depth of the modelled woodland allows this vegetation type to maintain higher rates of evapotranspiration in drier regions (compared to grass); in contrast to the semi-natural vegetation which is significantly impacted by soil moisture stress in the low AWC soils in the drier catchments.

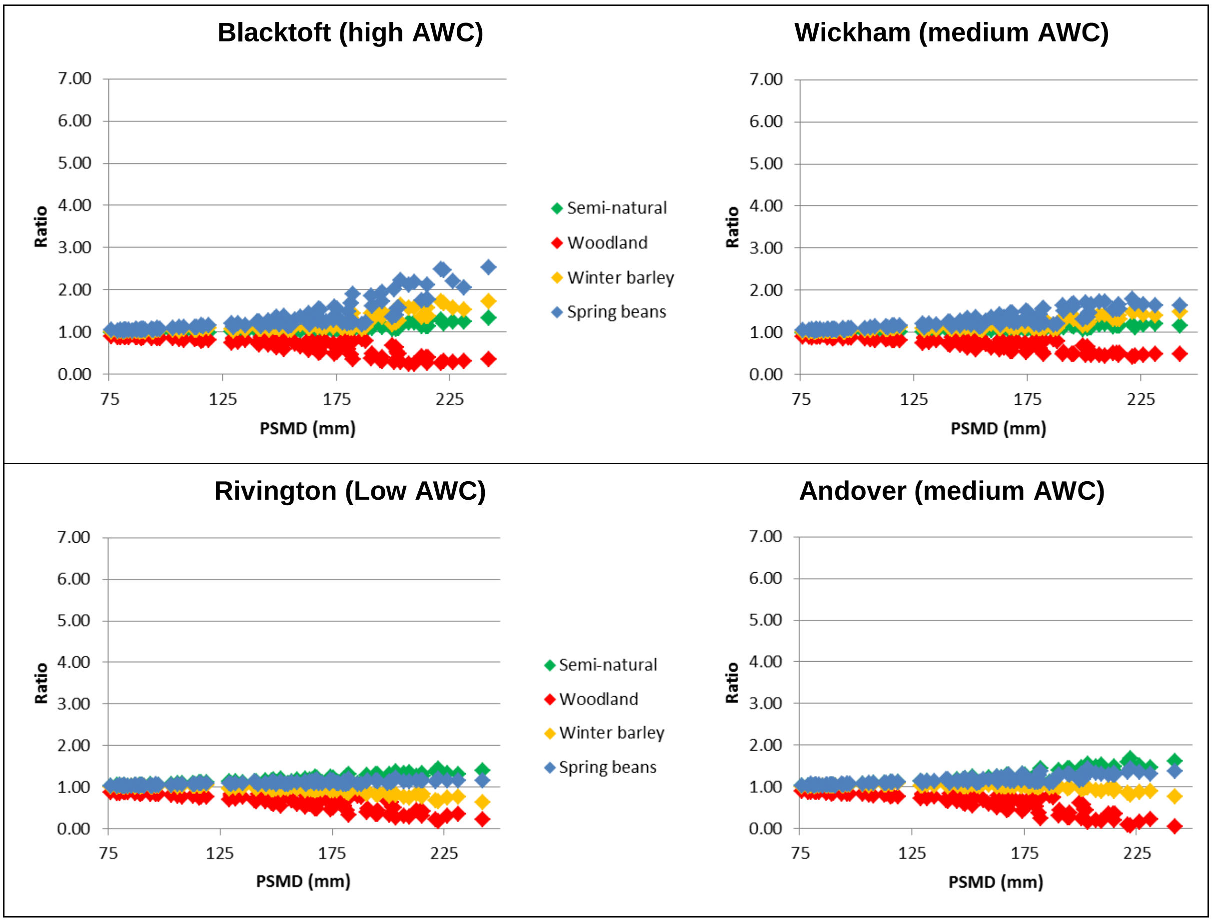


Figure 3.1 Changes in baseline average annual Hydrologically Effective Rainfall (AAHER) under different vegetation types, expressed as a ratio of the AAHER under permanent grassland (a value of 1 indicates no difference)

In soils with low available water, short-rooted vegetation with a long growing season (e.g. semi-natural) “uses” less water than deeper rooted vegetation with a shorter growing season (e.g. spring beans), as the effects of higher soil water stress within the shallow root zone offsets the effect of the longer growing season. The opposite is found in high available water soils, where evapotranspiration was greater due to lower soil water stress.

3.1.2 Potential Baseflow

Similar patterns are seen with Potential Baseflow (Figure 3.2), although the spread across the vegetation types increases to 0 – 600% of the baseline Potential Baseflow under grassland. Deeper rooted vegetation (e.g. woodland) is able to use all the water that infiltrates into the soil in the drier catchments (as indicated by ratios approaching zero). This arises as their high summer evapotranspiration creates sufficiently high soil moisture deficits that the soils do not return field capacity in the winter and consequently, deep drainage does not occur.

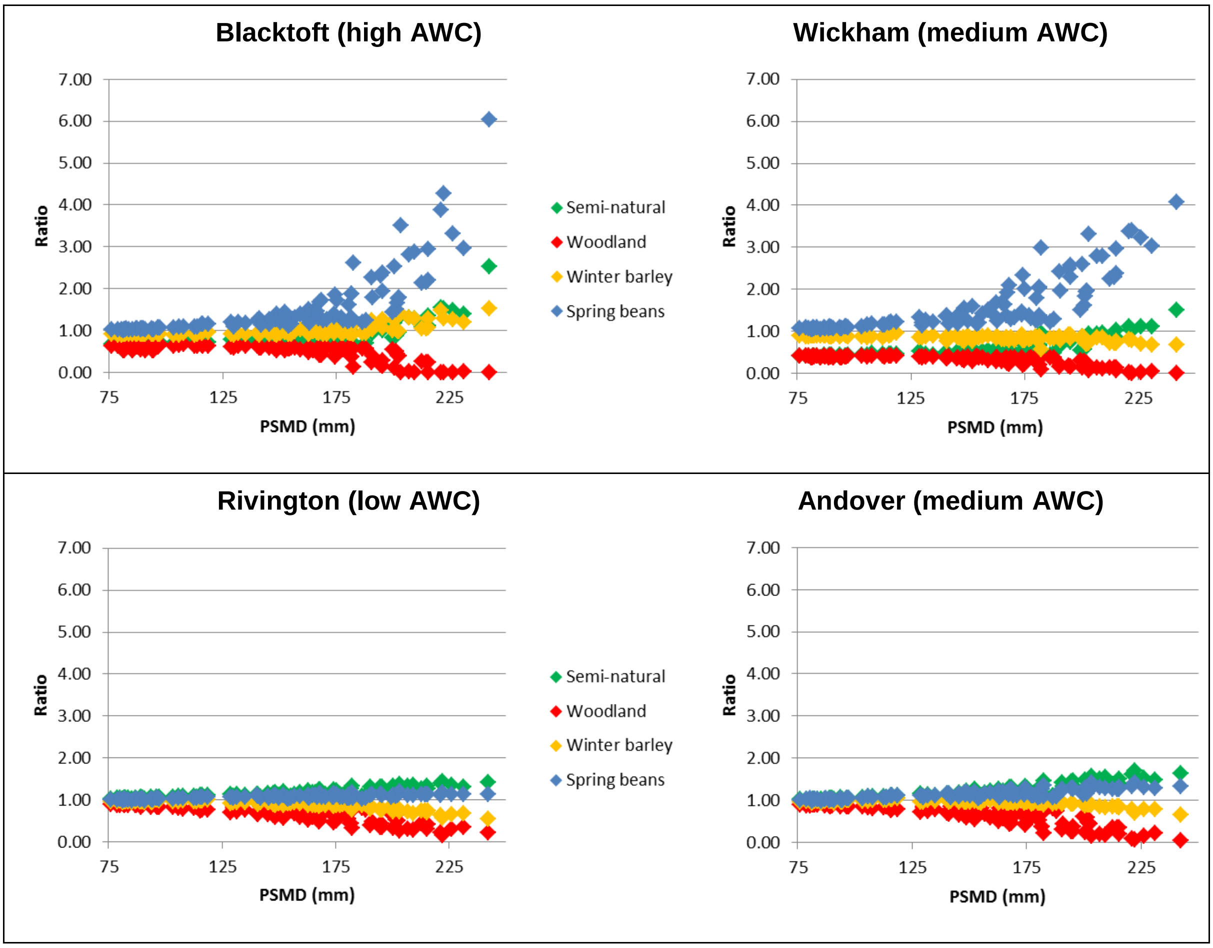


Figure 3.2 Changes in baseline average annual Potential Baseflow under different vegetation types, expressed as a ratio of the annual average Potential Baseflow under permanent grassland (a value of 1 indicates no difference)

<u>Key points</u>:

- There is little difference in average annual HER or Potential Baseflow in wetter catchments
- Land-use change can have a large effect on AAHER and Potential Baseflow, leading to either increases or decreases in both depending on the nature of the vegetation change.
- Deep rooted vegetation has higher annual evapotranspiration leading to reduced AAHER and Potential Baseflow, compared to permanent grassland in all of the soil types.

- In soils with low available water, short-rooted vegetation with a long growing season (e.g. semi-natural) “uses” less water than deeper rooting vegetation with a shorter growing season (e.g. spring beans) due to higher soil water stress. The opposite is found in high available water soils, where evapotranspiration is greater.

3.2 Effect of climate change only (grassland)

It is widely understood that there is considerable uncertainty in climate change scenarios, so a series of permanent grass simulations were performed with two contrasting climate change ensemble members for the 2050s (Afixh – lower ET^o; and Afixj – higher ET^o – see Fig. 2.6) and compared to a baseline 'reference' run under the same ensemble member. Changes in the ratio reflects the effect of climate change uncertainty.

Reference run:

- Baseline (1961-90) FutureFlows (afixh or afixj) weather
- Permanent grass
- Medium soil condition.

3.2.1 Average Annual Hydrologically Effective Rainfall (AAHER)

The two contrasting climate change scenarios generally lead to modest changes in AAHER, with the ratio changing from 0.51 to 1.45 (i.e. from 51% of the baseline amount to 145%) across the catchments and two climate scenarios (Figure 3.3).

In the wetter areas (low PSMD) where soil water availability does not limit evapotranspiration, increases in ET_o led to increases in evapotranspiration and a small reduction in AAHER (except where precipitation increased by more than the increase in evapotranspiration). The effect is slightly larger in the Afixj scenario given its higher ET_o.

In the drier areas (with a baseline PSMD of above 125mm), soil moisture stress starts to limit for evapotranspiration, so that the effect of changes in the seasonal distribution of precipitation (primarily increased winter precipitation) outweigh the effects of increased ET_o leading to ratios of greater than 1 under the afixh scenario. Under the higher ET_o of the Afixj scenarios, this doesn't occur and ratios remain <1.

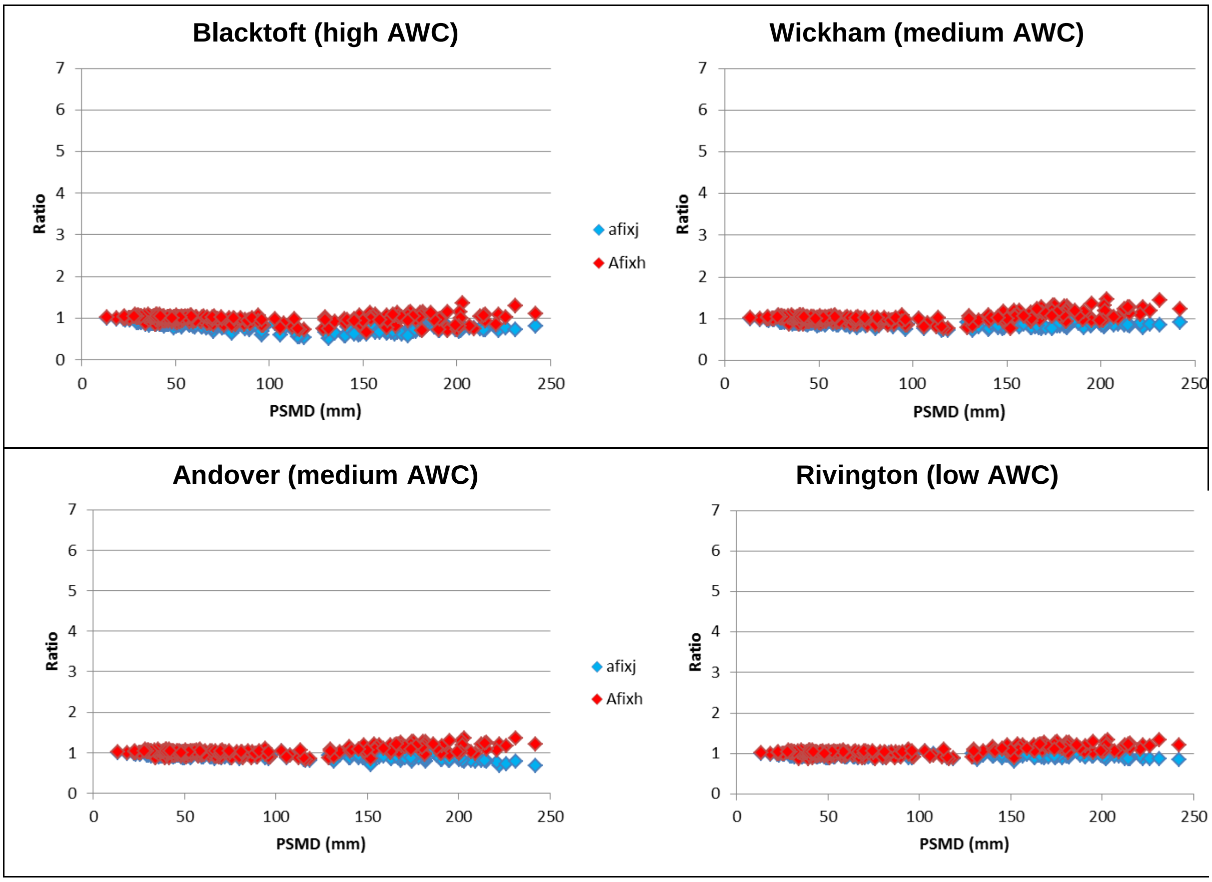


Figure 3.3 The effect of two contrasting climate change scenarios (Afixh with a lower ET$_o$ increase and Afixj with a higher ET$_o$ increase) on the ratio of future to baseline Average Annual Hydrologically Effective Rainfall under permanent grassland

3.2.2 Potential Baseflow

Although the apparent response of the four soils to climate change for the AAHER was similar, there are important differences for the Potential Baseflow, with the ratio varying from 0 – 1.57 (0 to 157%) of the baseline amount across the catchments and climate change scenarios (allowing for a single outlier):

- Low permeability soils – the much higher available water capacity of Blacktoft allows a large summer soil moisture deficit to develop and hence a much later return to field capacity. This leads to a shorter field capacity period and reduced percolation and drainflow. Within Wickham, the behaviour is similar up to a baseline PSMD of around 150 mm, at which point soil moisture limitations prevent further increases in summer soil moisture deficit. Therefore the field capacity period is not further shortened, so that the effect of increased winter precipitation becomes dominant, leading to the ratio being >1.

- Freely draining soils – in the wetter (low PSMD catchments), the effect of increased evapotranspiration and increased winter precipitation balance each other such that the ratio is around 1. The Potential Baseflow from Andover is slightly lower than from Rivington, as the higher available water leads to the build-up of greater summer soil moisture deficits and hence later return to field capacity and a shorter recharge season (field capacity period). The lower runoff potential of these soils means that a greater proportion of precipitation infiltrates into the soil helping to counteract the increased reference evapotranspiration. In drier catchments (baseline PSMD of >125mm), the increased winter precipitation outweighs the effect of increased evapotranspiration leading to a net increase in Potential Baseflow. Under the higher ETo of the afixj scenario, the ratio remains below 1.

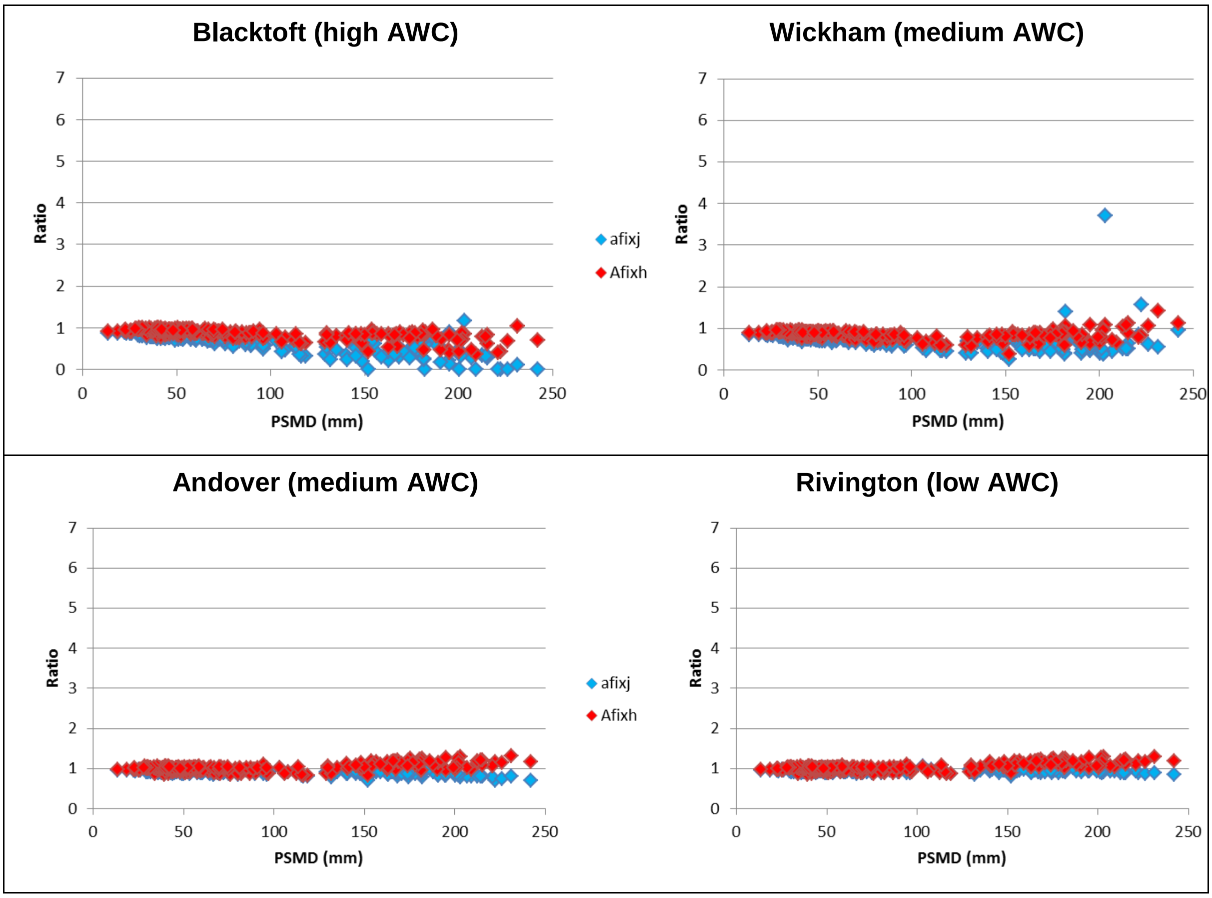


Figure 3.4 The effect of two contrasting climate change scenarios (Afixh with a lower ETo increase and Afixj with a higher ETo increase) on the ratio of future to baseline average annual Potential Baseflowunder permanent grassland

Key points:

- Uncertainty in future climate projections means that there is uncertainty in the direction of change in Average Annual Hydrologically Effective Rainfall (AAHER) and Potential Baseflow in the drier catchments.
- Climatologically wetter areas will have similar or slightly reduced AAHER as increased reference ET leads to higher ET.
- In climatologically drier areas, the climate uncertainty (particularly ET_o projections) and the role of the soil is key in determining the magnitude and direction of the impacts of climate change. Soils with low available water impose drought limitations on future evapotranspiration increases, so that summer soil moisture deficits do not increase further. Increased winter precipitation may lead to increased AAHER and Potential Baseflow under some climate scenarios

3.3 Effect of climate change (only) under different land uses

In this series of runs, the impacts of climate change (using the Afixh ensemble member) on the different vegetation types was assessed by comparing the 2050s results for each vegetation type with that vegetation type's baseline results. Within figures 3.5 and 3.6, the results for grassland will be the same as in the Afixh results in Figs. 3.3 and 3.4, respectively.

Reference run:

- Baseline (1961-90) FutureFlows (afixh) weather
- Medium soil condition.

3.3.1 Average Annual Hydrologically Effective Rainfall (AAHER)

Climate change alone has a modest impact on the AAHER for the different vegetation types (Figure 3.5), with the ratio varying across the catchments from 0.37 – 1.95 (37 to 195% of their baseline AAHER values).

The changes in AAHER across the vegetation types are broadly similar. Within the wetter areas (baseline PSMD of less than around 125mm), the AAHER ratios slightly reduces, suggesting that increases in evapotranspiration are greater than the increases in precipitation. Above a baseline PSMD of 125mm, AAHER ratios can be below or above 1 depending on the vegetation and climate. With the exception of the low AWC Rivington soil, woodland generally has the greatest reduction in AAHER compared to the other vegetation types, reflecting the effect of a lower propensity to generate runoff and the greater rooting depth to enable increased evapotranspiration

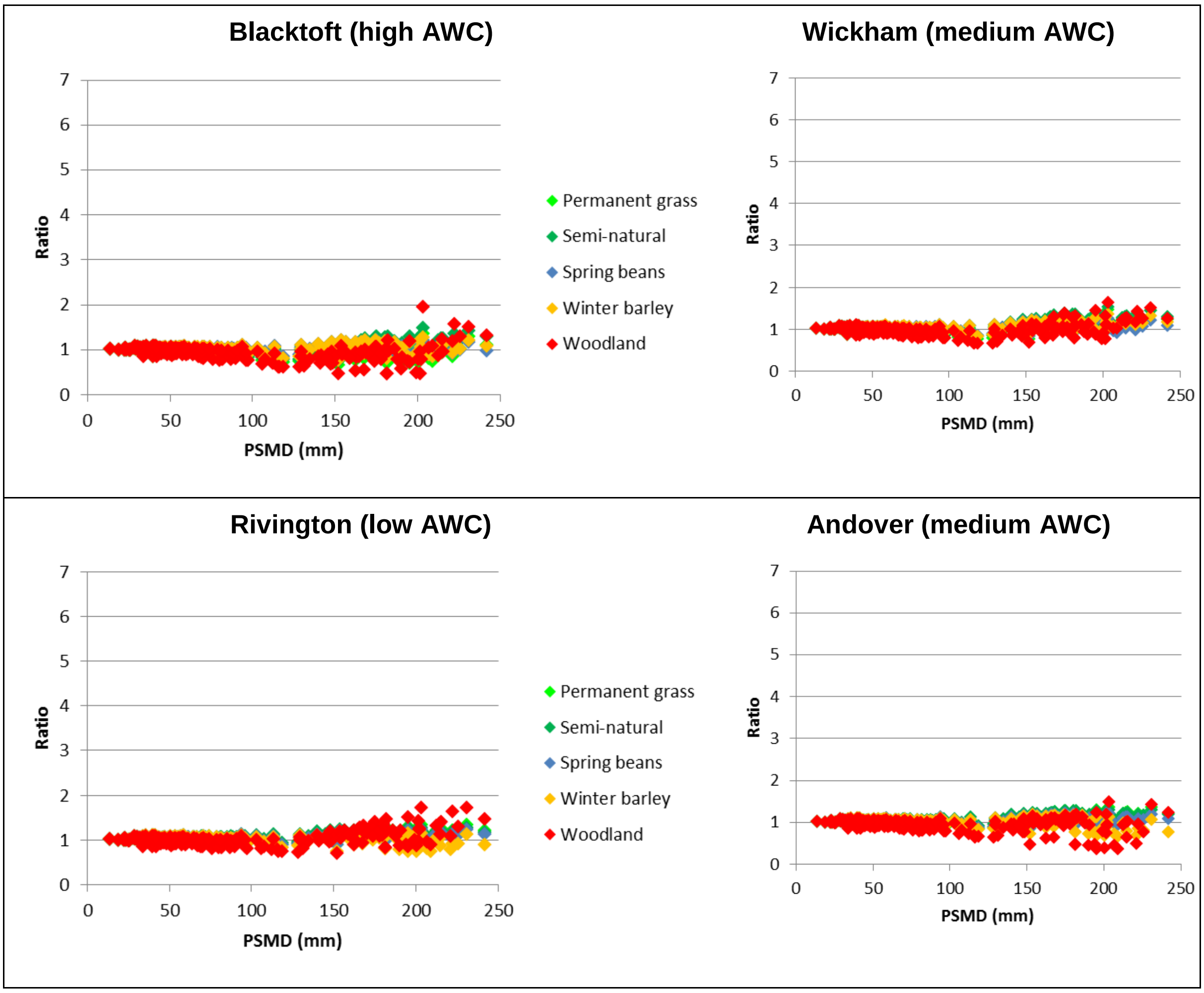


Figure 3.5 Changes in future Average Annual Hydrologically Effective Rainfall (AAHER) due to climate change, expressed as a ratio of the baseline AAHER for the vegetation type (a value of 1 indicates no change for the vegetation type)

3.3.2 Potential Baseflow

The effects of climate change on Potential Baseflow across the vegetation types are similar to those of climate change alone, with future Potential Baseflow ratios of 0 – 1.48 (0 to 1.48%) of the baseline values for that land use (Figure 3.6), excluding a single outlier. This compares to a range of 0.37-1.43 (37-143 %) for permanent grassland alone under the same climate change scenario (Figure 3.4). Comparison of Figures 3.6 and 3.2 indicate that the differences in Potential Baseflow between the vegetation types is greater than the effect of climate change, suggesting that land-use change will have a greater impact than climate change alone.

Deeper rooted vegetation (e.g. woodland) is able to transpire sufficiently to develop soil moisture deficits in the high and medium available water soils that prevent Potential Baseflow in the drier catchments (as indicated by ratios approaching zero).

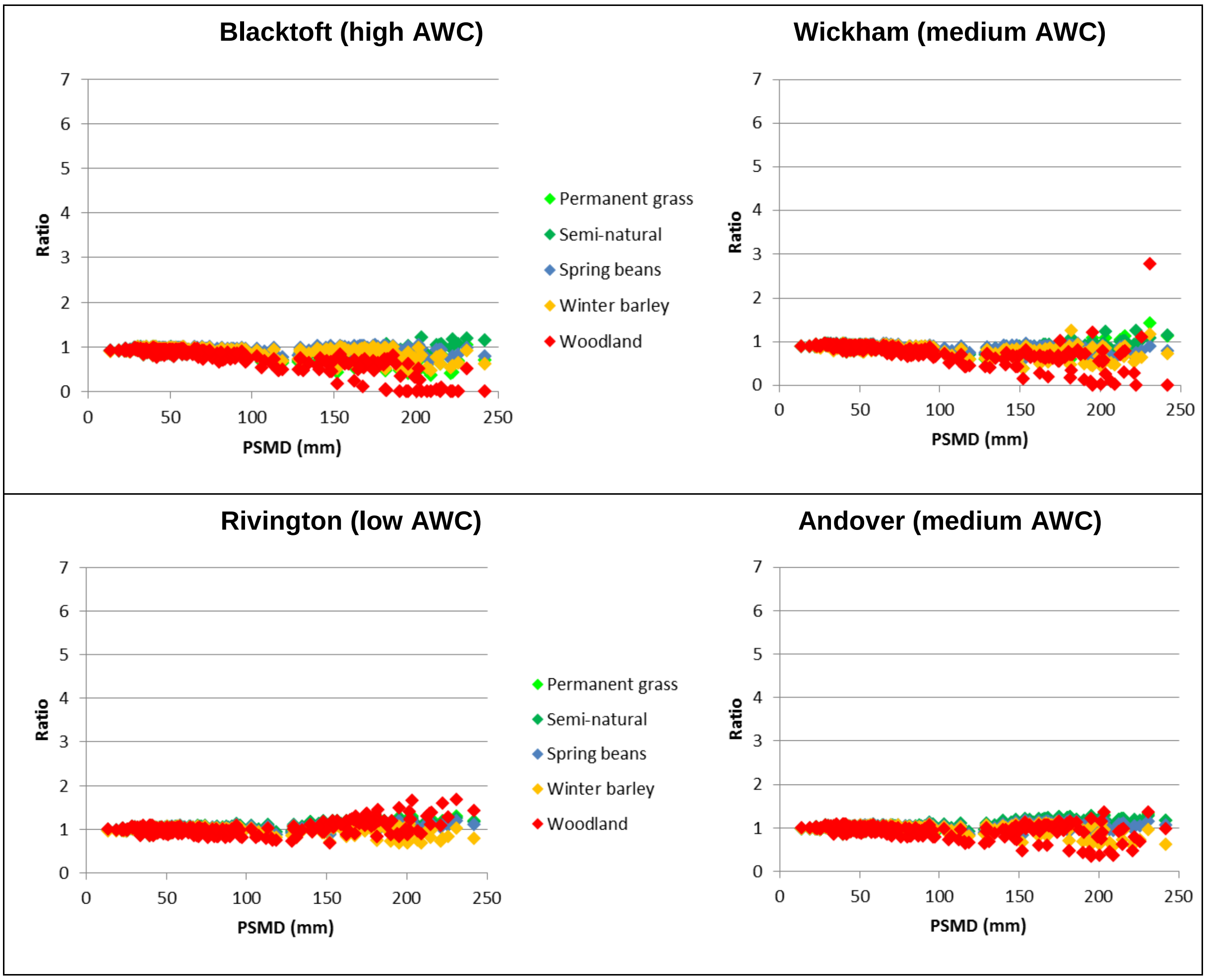


Figure 3.6 Changes in future average annual Potential Baseflow under different land uses under climate change, expressed as a ratio of the baseline annual average Potential Baseflow for the vegetation type (a value of 1 indicates no difference)

Key points:

- The effects of climate change on the AAHER and Potential Baseflow are similar across the vegetation types within the wetter catchments
- Taller and/or deeper rooted vegetation or crops are better connected to both the atmosphere and soil moisture stores, leading to higher evapotranspiration, reduced AAHER and reduced Potential Baseflow
- The effects of climate change (in the absence of land-use change) on AAHER and Potential Baseflow are generally much less than the effects of land-use change.

3.4 Effect of changes in vegetation type under climate change

In this series of runs, the impacts of climate change (using the Afixh ensemble member) on the five vegetation types was assessed by comparing the 2050s results for each vegetation type with the baseline results for permanent grass i.e. the same model run as used in Section 3.1.

Reference run:

- Baseline (1961-90) FutureFlows (afixh) weather
- Permanent grass
- Medium soil condition.

3.4.1 Average Annual Hydrologically Effective Rainfall (AAHER)

The combined effects of climate change and land-use change (Figure 3.7) is to slightly modify the spread of changes in AAHER due to land-use change under the baseline climate (Fig. 3.1), with the ratio varying across the catchments from 0.05 – 2.70 (5 to 270% of the baseline AAHER under permanent grass). This compares to the range of ratios observed under the baseline climate of 0.05 to 2.54, or 4 – 254%.

The changes in AAHER across the vegetation types are similar within the wetter areas, but start to diverge in drier catchments (with a baseline PSMD of around 100 mm, compared to at around 125mm under the baseline climate simulations). This reflects both the increasing spatial influence of soil moisture limitations on the evapotranspiration of short rooted vegetation (e.g. semi-natural) and the increased evapotranspiration of the deep rooting vegetation (e.g. woodland and, to a lesser extent, winter barley) under the warmer future. There is also evidence of the AAHER ratio starting to increase above a baseline PSMD of around 200 mm for woodland on the Blacktoft and Wickham soils, as soil moisture stress in the medium to high available water content soils begins to limit evapotranspiration under these deep rooted vegetation.

Whilst the high ratios under the Blacktoft and Wickham soils are little changed compared to Figure 3.2 (indicating little change in land-use change effect on AAHER for the short growing season (spring beans) and shallow rooting (semi-natural) vegetation types), there is a slight increase in the ratio under semi-natural vegetation indicating a longer period of soil moisture stress limitations on evapotranspiration.

3.4.2 Potential Baseflow

The effects of land use and climate change on average annual Potential Baseflow across the vegetation types are broadly similar to those of land-use change alone, with future Potential Baseflow ratios of 0 - 4.76 (0 to 476 % of the baseline Potential Baseflow under permanent grass). This compares to the range of ratios observed under the baseline climate of 0 – 600% of the baseline Potential Baseflow under grassland. There is, however, an increase in the number of catchments with very low ratios, as shown by ratios approaching zero being evident in catchments with baseline PSMDs of around 150mm compared to about 175 mm under the baseline climate simulations (Figure 3.2).

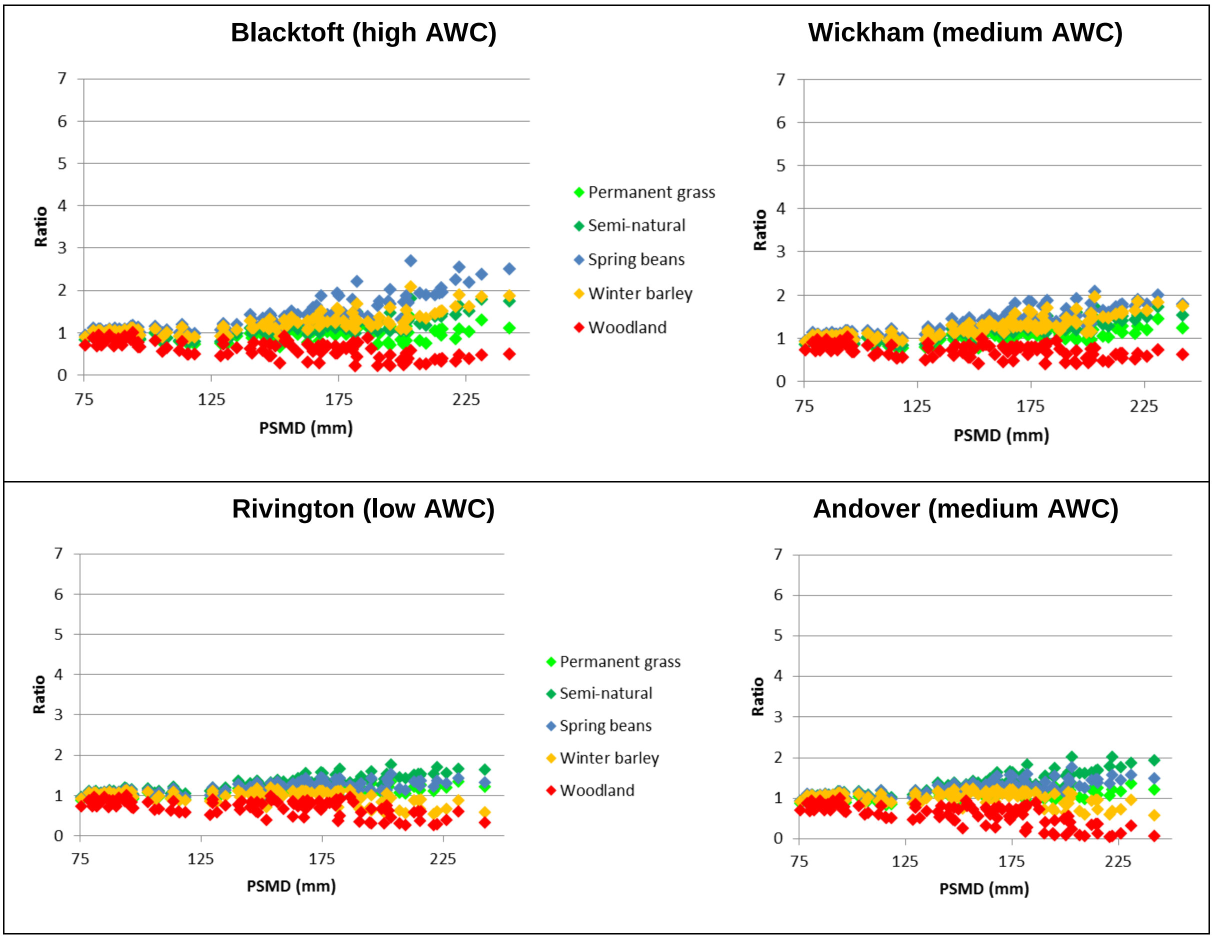


Figure 3.7 Changes in future Average Annual Hydrologically Effective Rainfall (AAHER) for different land uses under climate change, expressed as a ratio of the baseline AAHER under permanent grassland (a value of 1 indicates no difference)

Key points:

● Climate change has a small impact on the changes in both AAHER and Potential Baseflow due to land-use change only (i.e. under the baseline climate)

● The additional effect of climate change, compared to land-use change alone, is to allow the differences in AAHER and Baseflow caused by land-use change to become apparent in more catchments due to increasing future PSMD. This reflects both the increasing spatial influence of soil moisture limitations on the evapotranspiration of short rooted vegetation and the increased evapotranspiration of the deep rooting vegetation under the warmer future.

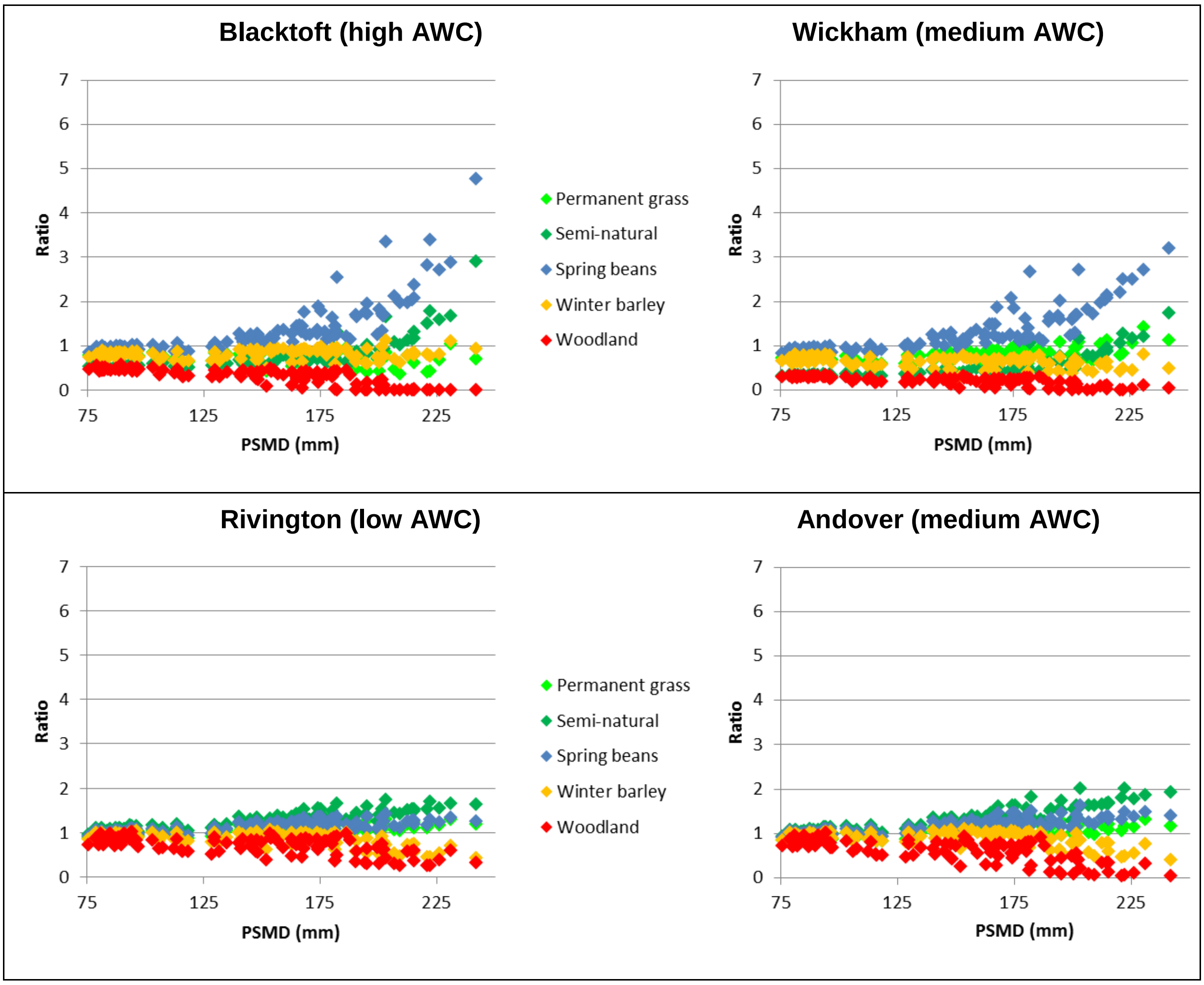


Figure 3.6 Changes in future Potential Baseflow for different land uses under climate change, expressed as a ratio of the baseline annual average Potential Baseflow under permanent grassland (a value of 1 indicates no difference)

3.4 Effect of climate change and changed soil conditions

In this series of runs, the impacts of land management changes which might affect the propensity to generate runoff (from Very Poor to Excellent soil-field condition) under climate change (using the Afixh ensemble member) was assessed by comparing the 2050s results with baseline results for a soil in medium condition. NB there is no Very Poor class for Wickham series (as explained in Section 2.3.4)

Reference run:

- Baseline (1961-90) FutureFlows (afixh) weather
- Permanent grass
- Medium soil condition.

3.4.1 Average Annual Hydrologically Effective Rainfall (AAHER)

The combined effects of climate change and changed soil conditions (Figure 3.7) leads to an increase the spread of changes in AAHER, with the ratio varying across the catchments from 0.58 – 2.43 (58 to 243% of the baseline AAHER under permanent grass). This compares to a range of ratios for the permanent grassland under medium soil condition with climate change only of 0.65 to 1.45 (65 – 45%) in Figure 3.3.

Within the permeable soils, detrimental changes to the soil condition lead to very small increases in AAHER, compared to the effects of climate change alone. This arises because the increased contribution of runoff to AAHER due to deteriorating soil condition produces increased soil water deficits (due to less rainfall infiltrating into the soil profile) which leads to reduced recharge.

On lower permeability soils (Blacktoft and Wickham), increasing soil degradation appears to increase AAHER. This arises as a consequence of the increased runoff and the decreased evapotranspiration because of increased soil water deficits (due to less rainfall infiltrating into the soil profile). This should not be taken as a perverse incentive to damage soils, as the increased soil degradation leads to decreased soil water availability to support vegetation and crop growth, and potentially increased flood risk.

3.4.2 Potential Baseflow

The effect of changing soil condition on Potential Baseflow is highly significant in the low permeability soils (Figure 3.8), with the ratio varying across the catchments from 0 – 2.25 (0 to 2225% of the baseline AAHER under permanent grass). The increase in runoff associated with moving from Excellent to Very Poor (or Poor in the case of Wickham) leads to reduced soil moisture availability (as less rainfall infiltrates into the rootzone) and higher soil moisture deficits. As a result, Potential Baseflow reduces and can lead to zero in the drier catchments (with baseline PSMD of >175mm) as a soil moisture deficit persists throughout the winter

With the more permeable soils, which naturally produce less runoff, deteriorating soil condition leads to a small increase in surface runoff that produces a proportional reduction in the amount of baseflow.

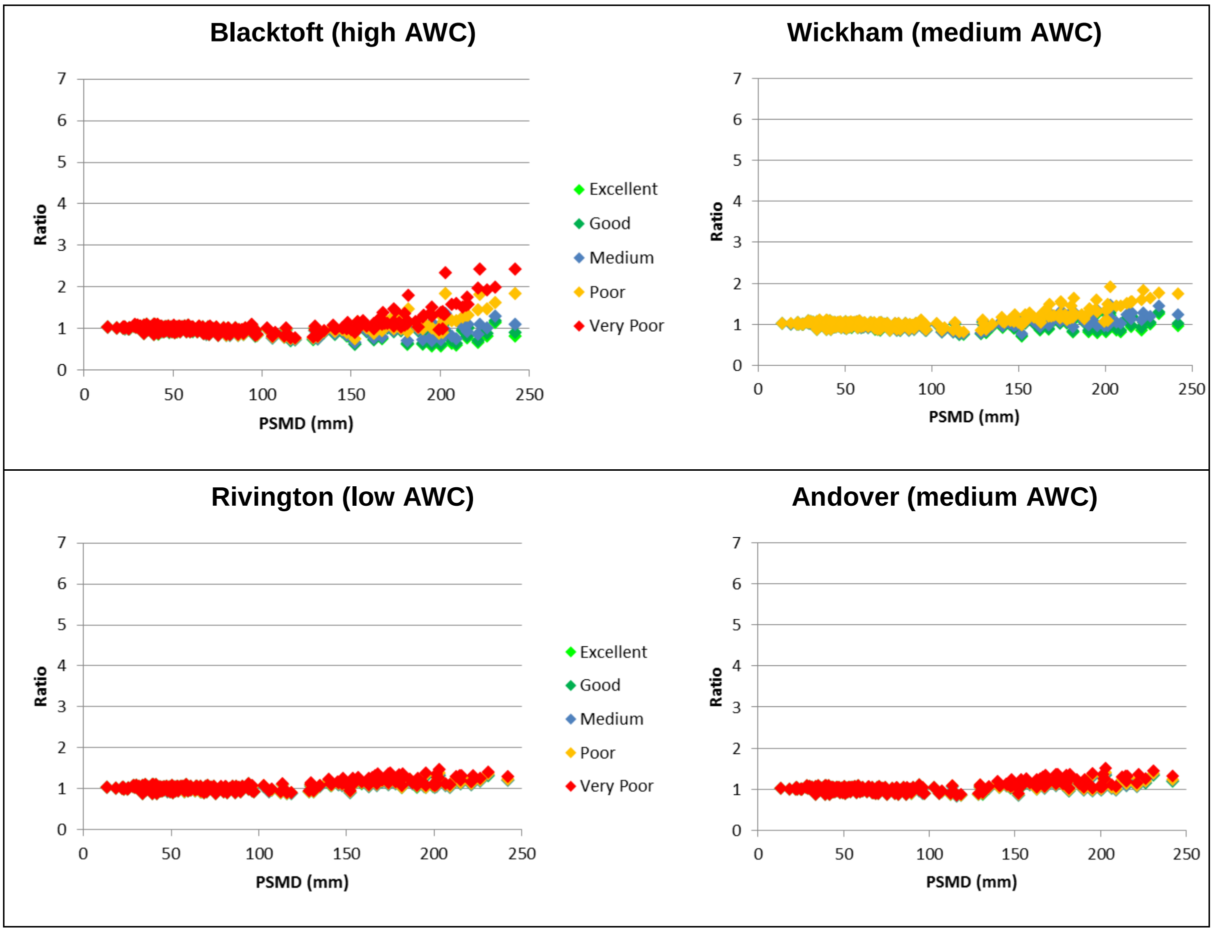
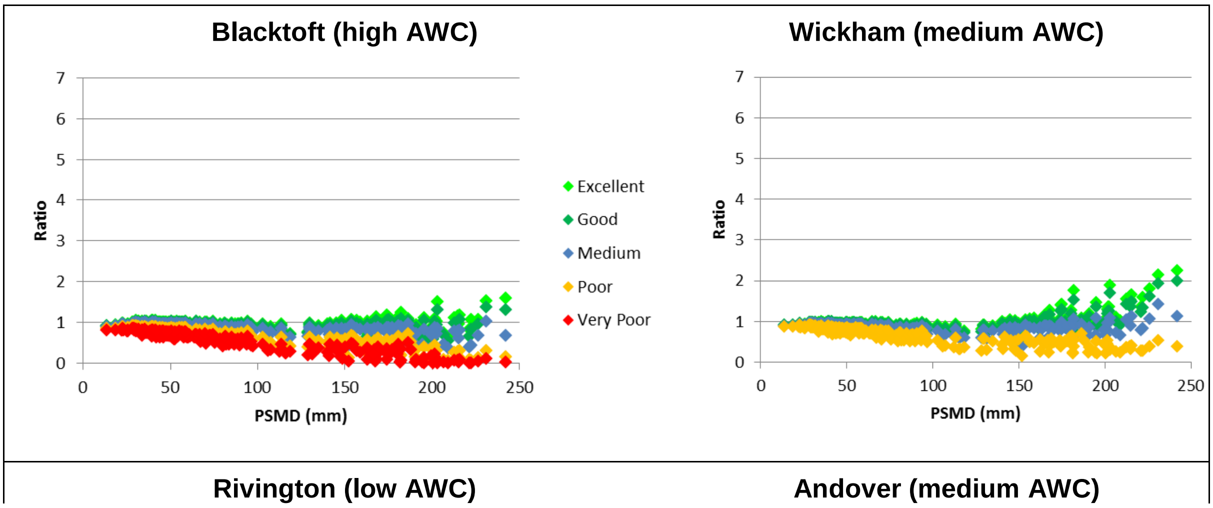


Figure 3.7 Changes in 2050s water availability under permanent grassland with changing soil condition, expressed as a ratio of the baseline annual average water availability under permanent grassland with medium soil condition (a value of 1 indicates no difference)



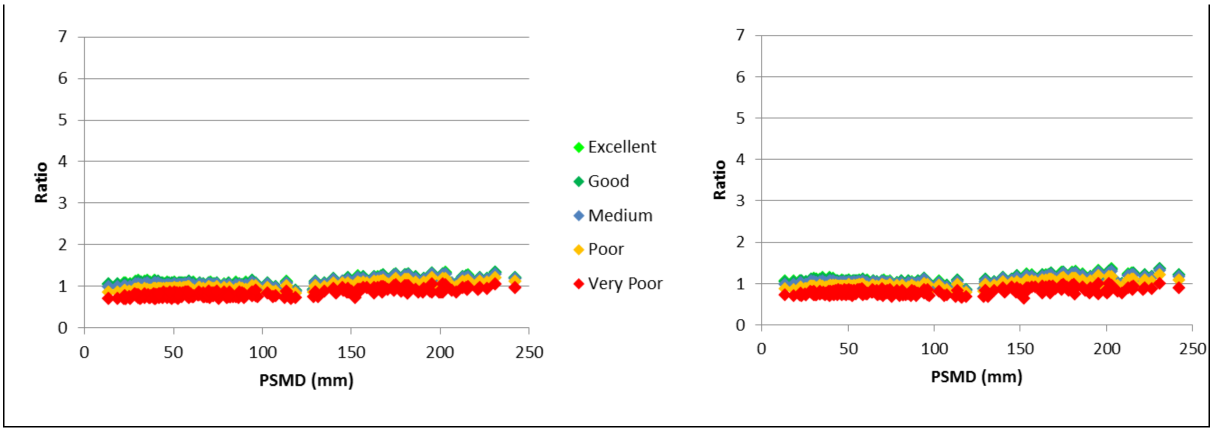


Figure 3.8 Changes in 2050s baseflow under permanent grassland with changing soil condition, expressed as a ratio of the baseline annual average baseflow under permanent grassland with medium soil condition (a value of 1 indicates no difference)

Key points:

- Low permeability soils are more prone to significant hydrological impacts of soil degradation than permeable soils. Increased degradation of permeable soils leads to increased available water (and runoff), due to reduced soil water content and increased soil moisture stress, but reduced baseflow.
- On low permeability soils, increased soil degradation leads to apparent increases in Average Annual Hydrologically Effective Rainfall, due to increased runoff and decreased evapotranspiration. This should not be taken as a perverse incentive to damage soils, as the increased soil degradation leads to decreased soil water availability to support vegetation and crop growth, reduced Potential Baseflow and potentially increased flood risk.

3.5 Effect of climate change-induced changes to crop timings

Within these simulations the effect of changes to the crop establishment (earlier planting) and crop development (earlier harvest) have been investigated for spring beans. In contrast to the previous sections, the results are compared to the spring beans with unaltered timings under the climate change.

Reference run:

- 2050s FutureFlows (afixh) weather
- Spring beans with baseline crop timings
- Medium soil condition.

3.5.1 Average Annual Hydrologically Effective Rainfall (AAHER)

Changes in planting and/or harvesting dates have only minor effects on AAHER. Earlier harvesting is associated with earlier and more rapid crop development, so that there is a shortened growing season. As a result there is less evapotranspiration leading to increased AAHER (Figure 3.9). The effect is less pronounced in the permeable soils. Earlier planting produces marginal differences.

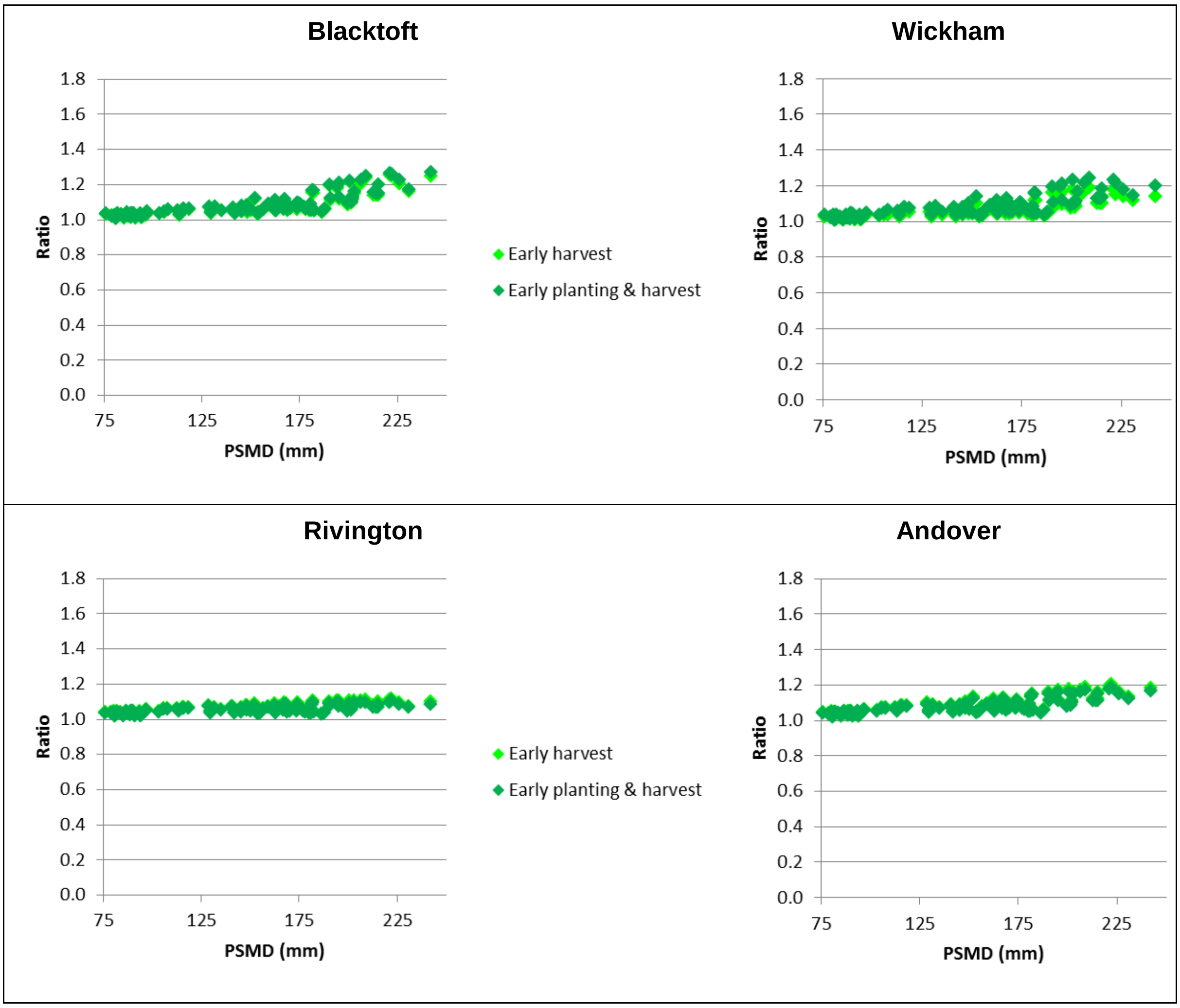


Figure 3.9 Changes in 2050s Average Annual Hydrologically Effective Rainfall (AAHER) under spring beans associated with changing planting and harvesting dates, expressed as a ratio of the 2050s AAHER under spring beans with unchanged dates (a value of 1 indicates no difference)

3.5.2 Potential Baseflow

There are slightly greater simulated effects of changed dates on Potential Baseflow (Figure 3.10), although the ratio across the catchments is only 0.95 – 1.61 (or 95 – 161 % of the AAHER under climate change with unchanged crop timings). The reduced growing season evapotranspiration associated with earlier crop development (and harvesting) leads to a reduced summer soil moisture deficit so that the soils reach field capacity sooner in the autumn/winter allowing greater Potential Baseflow. Earlier planting partially offsets some of the gains as it allows a slightly increased maximum soil moisture deficit to develop and thereby shortening the field capacity period.

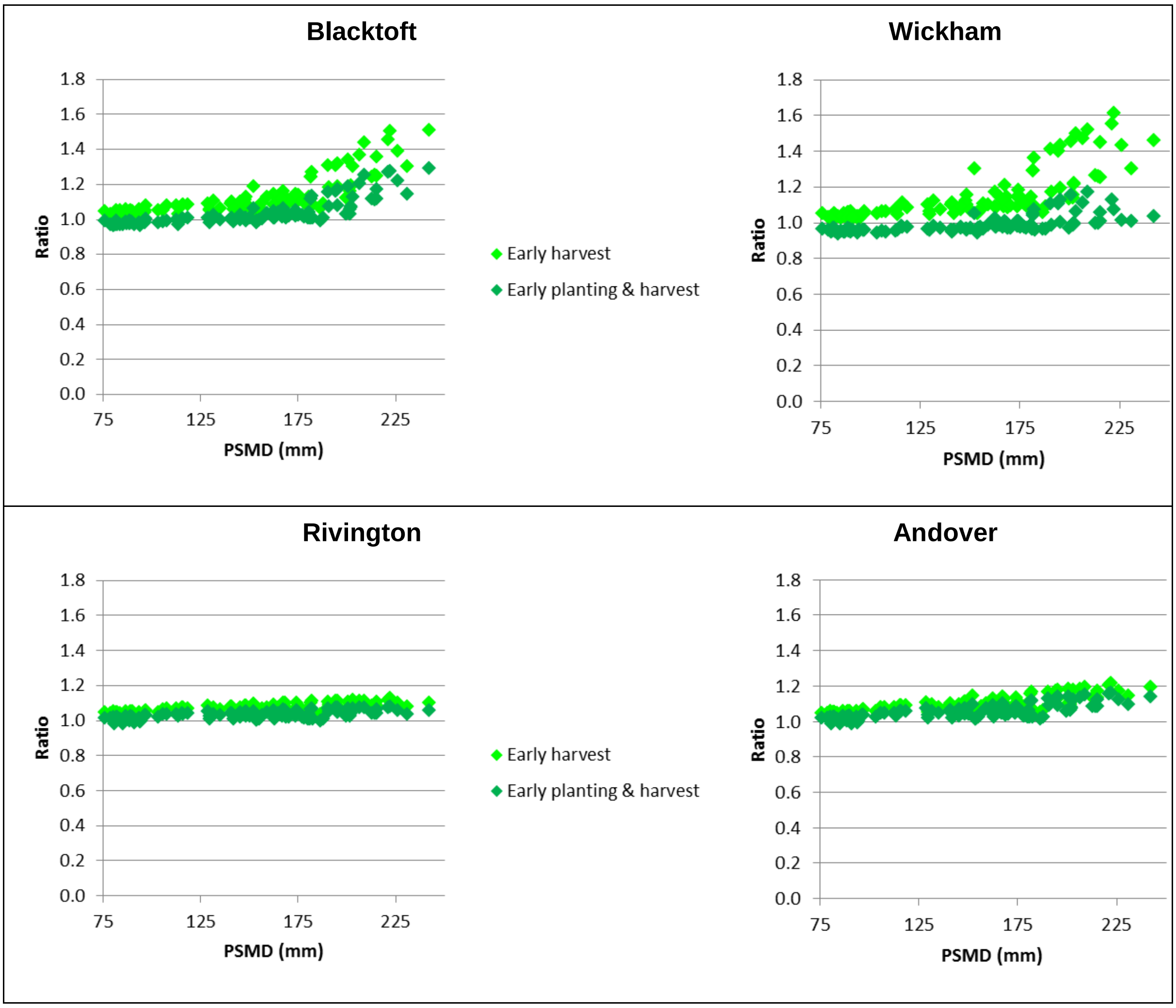


Figure 3.10 Changes in 2050s Potential Baseflow under spring beans associated with changing planting and harvesting dates, expressed as a ratio of the 2050s annual average Potential Baseflow under spring beans with unchanged dates (a value of 1 indicates no difference)

Key points:

- Changes to the crop growth calendars, whether associated with autonomous responses by the crop or agronomic changes to planting/harvesting dates have the potential to produce modest increases in Average Annual Hydrologically Effective Rainfall and Potential Baseflow.
- The effects are greater within the drier regions and in the higher available water soils

4. OVERALL CONCLUSIONS

The modelling described in the report has tested the sensitivity of average annual Hydrologically Effective Rainfall (AAHER) and Potential Baseflow from contrasting soil types to a number of key potential shifts in land use and cropping, climate, soil conditions, and agronomic timings. This preliminary modelling has identified a number of key issues with regard to the impact of land use and land management change on Average Annual Hydrologically Effective Rainfall (AAHER) and Potential Baseflow under current and future climates:

1. Climate change and land-use / land management change, in isolation or combination, can have potentially significant positive or negative impacts on average annual Hydrologically Effective Rainfall and Potential Baseflow, depending on the nature of the change (Table 4.1).
2. Land-use change tends to have a greater positive or negative impact on average annual Hydrologically Effective Rainfall and Potential Baseflow than climate change alone. In combination with land use change, Climate change leads to a slightly greater range of impacts in AAHER and either a slightly reduced or slightly increased range for Potential Baseflow for the low permeability soils and free draining, respectively (Table 4.1).
3. However, the FutureFlows climate change scenarios used are only for a single emissions scenario (A1B) so that future changes in climate may be greater or less;
4. Generally the range of impacts is proportionally greater for Potential Baseflow (infiltration and slower flows) than for AAHER (which includes more rapid runoff responses) (Table 4.1)
5. The modelled impacts of future change result from complex interactions between the weather (rainfall and ET_o), vegetation / crop properties (affecting ET demand and rooting depth) and soil properties (affecting soil moisture availability for evapotranspiration and flow partitioning between runoff and infiltration);
6. The modelled results suggest that the magnitude and direction of the impacts of future changes in land use and management on AAHER and Potential Baseflow will depend on:
    - Type of land use – the greatest modelled impacts are associated with changes in the vegetation type, given their differences in rooting depth, crop coefficients and growing seasons. Taller and deeper rooted vegetation or crops are better connected to both the atmosphere and soil moisture stores, leading to higher evapotranspiration and reduced AAHER.
    - Agroclimate – impacts generally increase with increasing Potential Soil Moisture Deficits (PSMD), with wetter areas (with low PSMD) being less sensitive to land use characteristics than drier areas due to the lack of soil moisture limitations. However, climate change leads to a general increase in PSMD and therefore increased sensitivity to land use and land management change;
    - Soil type – impacts of land use and management change differ among soil types because of the influence of their properties on runoff generation, water holding capacity and drainage rate. Generally the range of future impacts on AAHER and Potential Baseflow are greatest on the lower permeability drained soils and least on the freely draining soils with low available water capacity;
    - Soil condition – improving soil conditions may reduce AAHER by reducing runoff, increasing infiltration and the soil water content, and therefore enabling greater evapotranspiration. However, improving soil conditions is generally beneficial for Potential Baseflow as the higher soil water contents lead to a longer field capacity period;

7. Impacts of future change on AAHER and Potential Baseflow across England and Wales will therefore differ spatially according to agroclimate, soil type, soil condition and land use type / vegetation. However, the overall magnitude and direction of changes at a catchment scale will depend on the spatial extent and type of changes to the rural landscape and to the magnitude and spatial patterns of future climate change.

Table 4.1 Summary of the effects of the modelled changes on average annual Hydrological Effective Rainfall (AAHER) and Potential Baseflow, expressed as minimum and maximum ratios of reference runs without the change [ratios of <1 indicate less AAHER or Potential Baseline than in the reference simulations]. Colour cells indicate the future changes which produce the greatest (adverse or beneficial) impacts.

	Drained soils				Freely draining soils			
	AAHER (minimum and maximum ratios)							
	Blacktoft		Wickham		Andover		Rivington	
Land-use change only (relative to baseline grass)	0.24	2.54	0.43	1.78	0.05	1.69	0.17	1.44
Climate change uncertainty (relative to baseline grass)	0.51	1.36	0.72	1.45	0.68	1.36	0.81	1.33
Climate change only (relative to baseline vegetation)	0.47	1.95	0.66	1.63	0.37	1.49	0.69	1.72
Land use and climate change (relative to baseline grass)	0.22	2.70	0.41	2.07	0.05	2.02	0.25	1.75
Soil management	0.58	2.43	0.70	1.92	0.84	1.51	0.87	1.46
Changed timings (relative to unchanged timings with climate change)	1.00	1.27	1.00	1.24	1.00	1.20	1.00	1.12
	Potential Baseflow (minimum and maximum ratios)							
	Blacktoft		Wickham		Andover		Rivington	
Land-use change	0.00	6.04	0.00	4.07	0.04	1.71	0.17	1.45
Climate change uncertainty (relative to baseline grass)	0.00	1.17	0.25	1.57*	0.69	1.31	0.81	1.30
Climate change (relative to baseline vegetation)	0.00	1.21	0.01	1.43*	0.35	1.36	0.68	1.69
Land use and climate change (relative to baseline grass)	0.00	4.76	0.00	3.20	0.04	2.02	0.25	1.73
Soil management (relative to baseline grass)	0.00	1.60	0.15	2.25	0.63	1.36	0.69	1.34
Changed timings (relative to unchanged timings with climate change)	0.96	1.51	0.94	1.61	0.95	1.22	0.95	1.13

* excludes single outlier

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APPENDIX 1

Table A1.1 Runoff Curve Numbers for antecedent rainfall condition II (average) (from NRCS, 2002)

Land use or cover	Treatment or practice	Hydrologic condition	Soil Group			
			A	B	C	D
Row crops	Straight row	Poor	72	81	88	91
		Good	67	78	85	89
	Contoured	Poor	70	79	84	88
		Good	65	75	82	86
	Terraced	Poor	66	74	80	82
		Good	62	71	78	81
Small grains	Straight row	Poor	65	76	84	88
		Good	63	75	83	87
	Contoured	Poor	63	74	82	85
		Good	61	73	81	84
	Terraced	Poor	61	72	79	82
		Good	59	70	78	81
Pasture or range		Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
	Contoured	Poor	47	67	81	88
		Fair	25	59	75	83
		Good	6	35	70	79