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WATER SECURITY IN THE UK

A pilot model-based study of current and future water security in the UK

2012

NATURAL ENVIRONMENT RESEARCH COUNCIL

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1 Foreword

In its recent report on *Water resources in England and Wales – current state and future pressures*, the Environment Agency reminds readers that "*Compared to the rest of Europe, water resources* [in South East and Eastern England] *are under greater stress only in drier countries such as Cyprus, Malta, Spain and Italy*" (Environment Agency, 2008). While readers of this report will no doubt be aware of comparisons of this type, they can cause surprise to the general public. The general perception is that, unlike these countries that many UK residents visit for sunshine holidays, we live in a wet country within which any disruption to the public water supply is very rare. Furthermore there is limited recognition of the environmental consequence of our exploitation of water resources.

In attempts to make the facts and figures of water usage more relevant for the general public the media and industry have a love of non-traditional units, a particular favourite being the *Olympic-size swimming pool*, see for example, the websites of Thames Water[1] and the BBC[2], which tells us that the equivalent of five Olympic sized swimming pools are abstracted from the aquifer beneath the River Kennet every day. Even if this does manage to convey a volume of water, in itself, this gives no insight into the sustainability of such an abstraction.

The truth is that the UK's water environment is highly managed in an attempt to satisfy the multiple competing demands for water resources. Future pressures, notably changes to the climate and shifts in population, will change both the available water resources and the demands for water.

So, while a comparison with Italy or Spain draws attention to the challenge, it would help and inform to have simple but meaningful indicators of the water stress facing today's and tomorrow's water managers and policy makers. This is the challenge addressed in this report: can the security of our future water resources be described without reference to favourite holiday destinations, or Olympic-size swimming pools?

The approach adopted has been to use a UK-scale, model-based, assessment system that allows the consideration of a wide range of environmental (supply-side) and demand-side scenarios. This assessment system requires the integration and analysis of many large data sets, and has the potential to deliver an overwhelming variety of information. To meet the challenge presented above, this complexity has been encapsulated in a single indicator.

[1] http://www.thameswater.co.uk/cps/rde/xchg/corp/hs.xsl/8217.htm

[2] http://news.bbc.co.uk/panorama/hi/front_page/newsid_9560000/9560159.stm

2 Executive Summary

The map on the right shows the increased probability of there being a hosepipe ban in any year in the middle of this century as a consequence of possible changes in both climate and population. The range of values is from 0% to +90%. Zero values indicate no change in the risk of hosepipe bans compared with the present day, rather than a zero chance of such bans occurring. An increase of 90% means that almost all years would see such a ban since this is additional to the risk of such a ban occurring now. This existing risk varies regionally between water supply companies but a 1 in 20 year, or 5% risk, is typical.

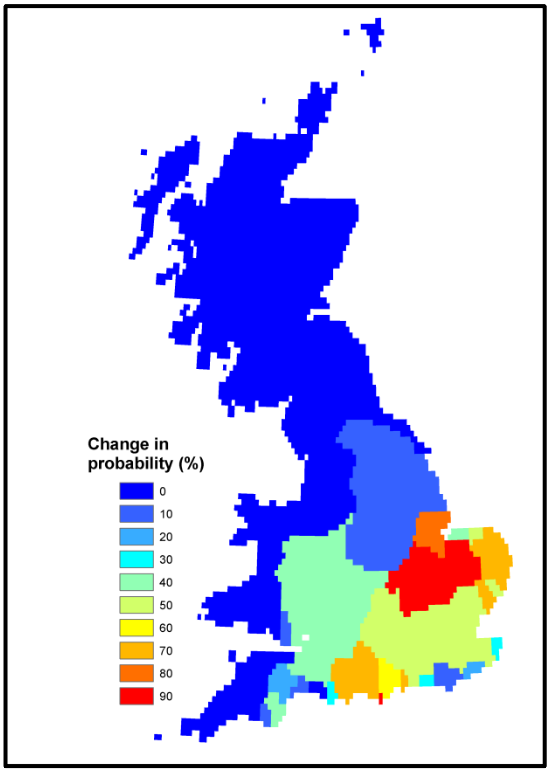


Figure 1: *The change in the probability of a hosepipe ban in the 2050s compared with the present day.*

The picture displayed in the map is somewhat alarming, with water use restrictions becoming more frequent across a swathe of south-east England, but is it believable? The provenance of the map is discussed in some detail below, but in brief it has been derived from a monthly comparison of simulated water availability and water demand, both for the present day and for a scenario representative of the 2050s. If demand exceeds availability, there must be some restriction on water use, perhaps a hosepipe ban. The map shows the increased probability of there being any one month in a calendar year in which demand cannot be met. There is no distinction between periods of deficit that last for a single month and those lasting for longer periods.

The map also fails to recognise that periods of deficit do not arise unexpectedly; water resources are stored both naturally and in constructed reservoirs. Monitoring of these resources as they are depleted enables measures to be taken that may avoid any actual restriction in use. Most obviously this will be an awareness campaign asking consumers to reduce their consumption. In this way many of the shorter duration hosepipe bans may be avoided.

However, at the other end of the scale, longer lasting periods of demand deficit may not be managed by either awareness campaigns, or minor measures such as hosepipe bans. So “hosepipe ban” is used as a convenient and all-embracing term to represent a water supply deficit event.

The analysis underpinning the map also assumes that nothing is done either to improve water resource capacity or change patterns of consumption. If the map represents a believable future, water companies and government have a duty to take action to avoid it becoming a reality. The map represents what may be the situation in 40 years’ time, giving sufficient warning for considered, long-term planning, and not immediate knee-jerk reactions.

But how much confidence should be placed in the map, and what uncertainties does it contain? The analysis represented in the map is based on the application of a water availability model to the UK. It is a model that has been widely applied to various regions of the world as part of many different studies. The model has three components: a hydrological component that represents the natural environment from rainfall to the flow of rivers into the sea; a water demand component that estimates water requirements for people, cattle, crops and industry; and a water infrastructure component that represents the artificial movement and storage of water required to match the natural availability with demand requirements. None of these components can be considered novel, unique, unconventional or untested, and indeed exist in similar formats in a number of other models.

What is new, however, is the application of this type of model to a relatively small country with a highly developed water infrastructure. For various reasons, which are explored in the report, the utility of such an application is open to question, and so as a pilot study an existing European scale model application has been further developed for the UK. This pilot was envisaged as a fast-track giving a rapid insight into whether a more detailed approach would be worthwhile, but in practice a great many issues were encountered which have been overcome pragmatically, or by-passed to produce the above map.

The nature of these issues and indeed the compromises involved in their resolution make the map at best only indicative of what the future might hold. But the map represents a consistent and valid, model-based approached to the review of present day and future water resources, and the experience gained in producing it would enable a more reliable and less compromised study in the future. The box below indicates some of the improvements that should be made in taking forward the pilot study.

This model-based approach represents an alternative methodology to that used by the Environment Agency (EA) and reported in the recently published document *The case for change – current and future water availability* (Environment Agency, 2011). The latter is based on a consideration of whether an index flow (the flow exceeded 70% of the time, Q_{70}) can meet all projected demands, including those of the environment. It, therefore, represents a combination of processed information from a number of sources. Despite the difference in approach there is a pleasing degree of similarity in the results.

Key developments to be made to the modelling framework used in the pilot study

- Improved representation of groundwater, notably the interaction of surface and groundwater and the combined exploitation of resources.
- Improved representation of water supply infrastructure, especially with respect to the use of Water Resource Zones and the representation of major storages and transfers.
- Better demand modelling (e.g. variations in per capita consumption, effects of metering etc.).
- Improved realism of management in times of developing water resource deficits.
- Better modelling of land use change under future climates.
- Replace latitude and longitude based grid with 1km grid based on UK National Grid.
- Extend spatially to represent UK/British Isles.
- Improved regionalisation of hydrological model parameters.
- Explore other climate scenarios and ensembles.

3 Introduction

This report describes a pilot project to assess water security in the United Kingdom. As will be seen, the approach adopted is not new. At its heart sits a conceptual model of water availability driven by rainfall and other meteorological data. The model simulates the flow of water in rivers, and the drainage of water into aquifers. These water resources are then exploited to meet the demands of agriculture, industry and public water supply. Characteristics of these simulations are then presented, mainly in the form of maps, to give an insight into whether there is sufficient water; this general scheme is illustrated in Figure 2). To give some credibility to the model it is first used to represent a historical period which contains episodes of known water stress, and its output compared with observations of the actual situation. The model is then used to simulate the conditions in an imagined future within which key features relating to both meteorological inputs and water demands have changed, thereby giving insight into the future challenges facing the management and exploitation of the UK's water environment.

The results from these simulations are presented in Chapter 7. The next four chapters describe how they have been produced, and, perhaps most importantly, the assumptions and short-cuts that have been made to produce them. These have been necessitated by the lack of data, understanding, time or resources available to this pilot project. In every instance it's straightforward to propose how improvements could be made, but to implement them would require a concerted effort by a number of organisations.

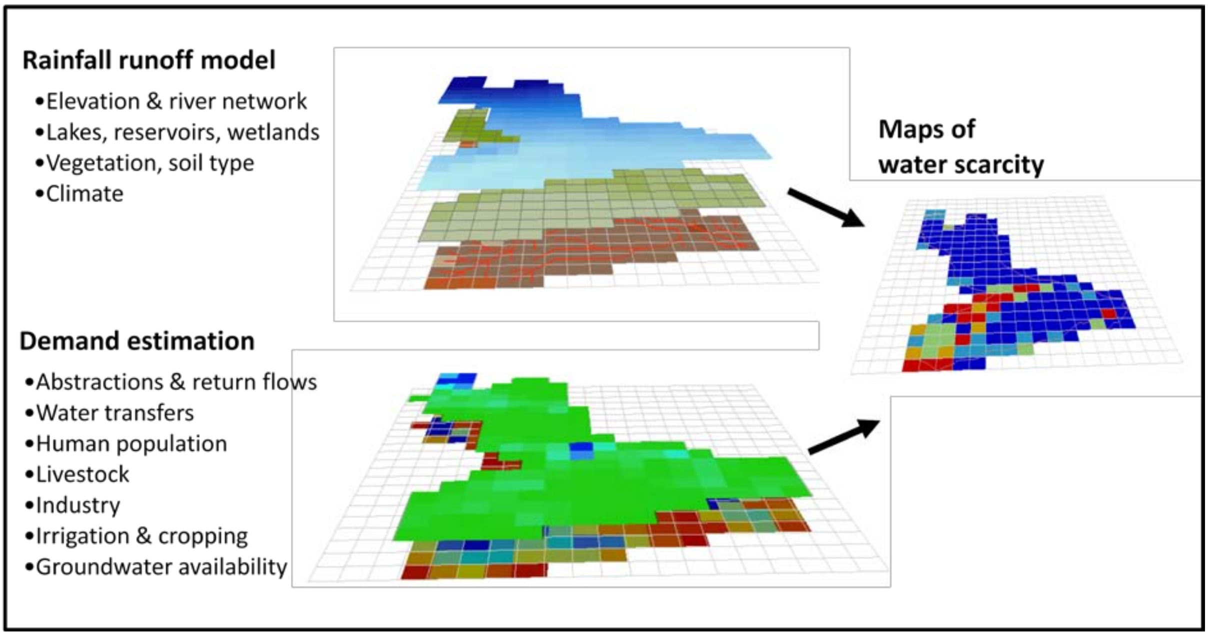


Figure 2: *Combining a hydrological model with demand estimation enables an assessment of water scarcity*

3.1 Background

The Living With Environmental Change (LWEC) partnership was established in 2007 “to provide decision makers with the best information to effectively manage and protect vital ecosystem services on the time and space scales on which the economy is managed”. Specifically LWEC addresses six challenges, the third of which, Challenge C, was “To promote human wellbeing, alleviate poverty and minimise waste through the sustainable provision of water, food and material resources in ways that mitigate or adapt to environmental change”.

Within the Natural Environment Research Council (NERC), the Centre for Ecology & Hydrology (CEH) and British Geological Survey (BGS) recognised that a number of recent activities and developments placed them in a strong position to deliver against the water component of LWEC Challenge C, and proposed a pilot project to develop a UK-scale scenario assessment framework that integrates future water resources and how they inter-relate, that would provide fundamental information to managers and policy makers.

This LWEC Challenge fits closely with NERC’s strategy under both the Sustainable Use of Natural Resources and Natural Hazards themes. It links to all three parts of the overall NERC strategic goals, regarding the capability of society to respond to increasing pressures on natural resources (understanding this key interface promises improved management of water resources, especially in areas of increased demand pressure e.g. in southern Britain), improved prediction of environmental change (particularly key impacts of land use change) and the potential to focus and integrate, drawing together terrestrial, ground and surface water science research communities.

As well as the strategic drivers for this research activity, CEH and BGS saw the opportunity to draw together their largely independent modelling activity of surface waters and groundwaters, at the regional or national scale. To date such linked modelling had only been achieved at local-scale associated with individual aquifer units.

With these common interests in mind, and in recognition of the shared strategic drivers, a pilot project was initiated in the summer of 2010.

3.2 Organisational and legislative framework

The NERC and its research centres, CEH and BGS, have no operational or strategic responsibility for the UK’s water resources, although they do undertake a number of specific activities on behalf of government. They are primarily research institutes with a remit in respect of natural resources. This activity is described in more detail in the Section 3.3.

Managing water resources is undertaken through a co-ordinated approach by government departments, agencies and water companies. Figure 3 shows the linkage between water resource strategy and plans for England and Wales, which is taken from *Managing water abstraction* (Environment Agency, 2010). This document contains succinct descriptions of the various plans listed in the figure. Because of the different government structures in England, Wales, Scotland and Northern Ireland, there are different arrangements in different parts of the UK. The summary below presents a highly simplified overview based on the position in England and Wales, so readers should be mindful of differences in other parts of the UK.

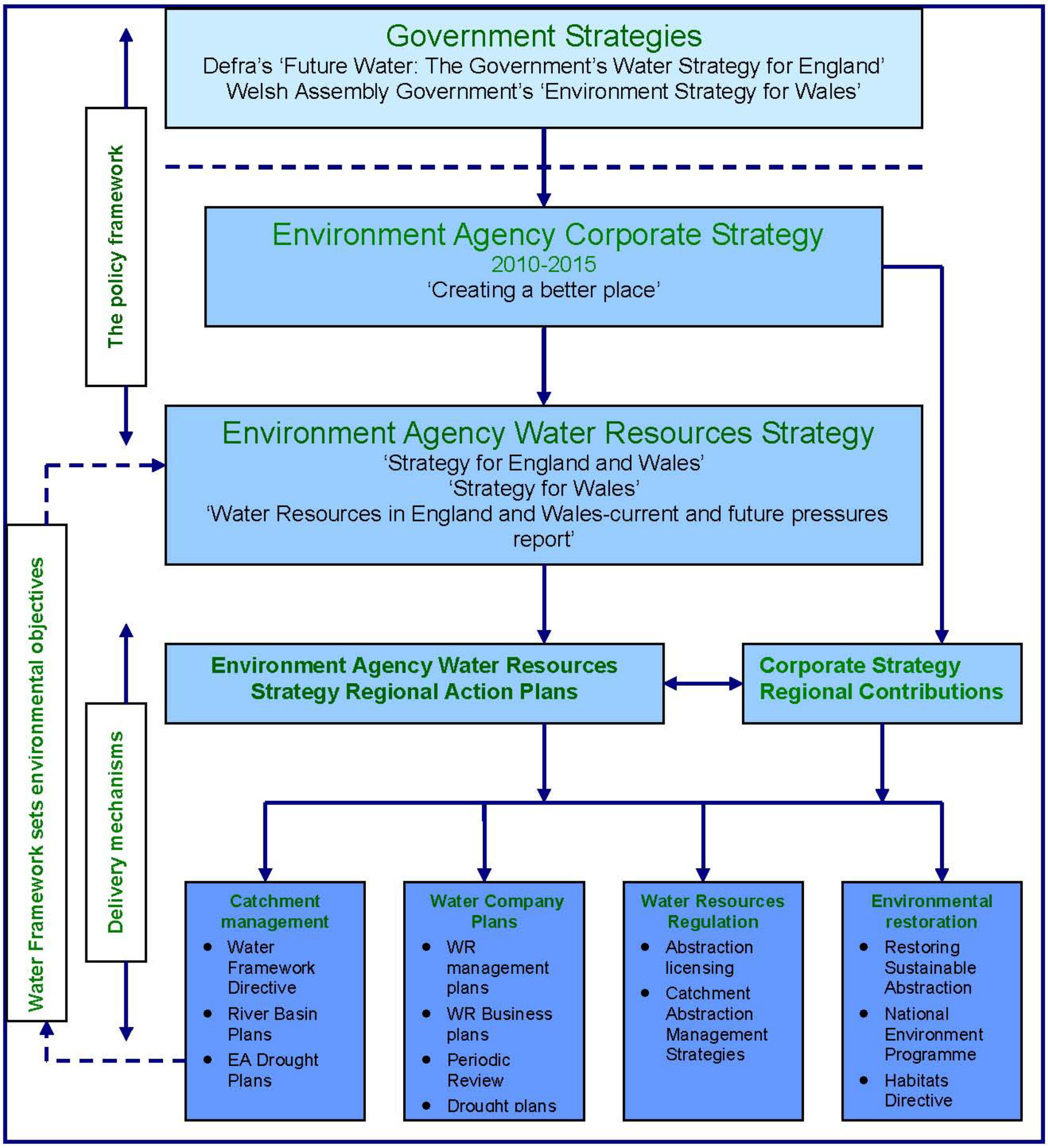


Figure 3: *Links between water resource strategies and plans (Reproduced without permission from Managing Water Abstraction, Environment Agency, 2010)*

What's important to understand is that the EA has responsibility for protecting the environment. Its role is to decide whether, and on what basis, the abstraction of water is permitted. The environmental objective derives from the Water Framework Directive (WFD) which requires that all water bodies reach either good ecological status by 2015, or an alternative justifiable objective, and additionally that groundwaters achieve good quantitative status. The EA's decision regarding individual abstractions is made in the context of River Basin Management Plans (RBMPs) and Catchment Abstraction Management Strategies (CAMS).

Water companies, who abstract nearly half of all the water abstracted, are required to produce and maintain plans to show how they will deliver the required water supply for the next 25 years. These plans consider both the demand during the period and sources of water that will be utilised. The plans will identify additional resource requirements and the costs associated with their development. The plans are published in draft for consultation and must be approved by Ofwat (the economic regulator of the water and sewerage industry in England and Wales).

The plans underpin the five-yearly water company Water Resource Business Plans (WRBPs) produced for the Periodic Review (plans produced in November 2009 are referred to as PR09). These five-year plans set the price limits for the service provided to customers by the companies, and again must be approved by Ofwat.

It should be noted that in their plans the water companies look at all aspects of water supply and demand. So, for example, demand might be managed through water metering, leakage reduction, home and commercial audits, and more general customer awareness and education campaigns.

The EA of course also takes a strategic look at water resources. The water resources strategy for England and Wales *Water for people and the environment* (Environment Agency, 2009) considers how water should be managed to 2050 and beyond. The conclusion is that a better integrated and planned approach will be required and that "society may also need to make bold choices". But beyond stating that the aim of the strategy is make sure that there's enough water, there's nothing to say that this can be achieved.

In addition to these longer-term plans and strategies, both the EA and water companies have drought plans which describe the actions they will take as drought conditions develop. These plans describe a progression through awareness campaigns and appeals to the public to use less water, through hosepipe bans ("temporary bans"), to drought orders.

3.3 Water resources research

During the 20th century water resource issues were largely dealt with through the construction of infrastructure in the form of dams and pipelines. Reservoir design required a proper understanding of the variability of the climate, together with an assessment of how demand was likely to change in the future, and was a significant area of hydrological research. There's no question that this research informed the construction of many projects that realised considerable benefits in terms of water supply, hydropower generation, and flood management.

Environmental costs associated with the impoundment and abstraction of water were often ignored or deemed acceptable. Arrangements for the release of waters below impoundments, known as compensations or guaranteed flows, were sometimes made, but often with regard to downstream users, rather than the environment. More recently, the modification to the natural ecosystem is being recognised as a loss in itself, and also that there is a loss in the service provided by the ecosystem. As a consequence there has been considerable research into the magnitude and timing of reservoir releases so as to minimise the environmental impact.

This need to consider environmental flow requirements coupled with ever greater demands for water abstraction led to a shift in water resources research towards an integrated approach that included all interests and stakeholders.

This more holistic approach to water resource development became practicable with the development of global and regional scale models that represent local uses of water within a wider setting of water availability and demand (e.g. GWAVA and WaterGap). The development of such models was only made possible by the availability of data sets at the same spatial scales; these included static data such as elevation, topography, hydrography, geology, and soils; data that describe characteristics that change through time such as population, vegetation, agriculture, and industry; and data that describe the highly dynamic drivers of hydrology, such as, precipitation and temperature.

In addition to consuming vast quantities of data, these models can also produce staggering volumes of output data. In an attempt to manage the possible information overload, results are often presented in the form of a map of a key indicator. Meigh *et al.* (1999), for example, use GWAVA to derive a set of 12 indices of water availability, which include a simple total annual runoff divided by total annual demand, and a more complex index that reflects the situation in the most critical month when the combined 90 percentile surface water runoff and groundwater yield, is compared with the water demand.

As well as allowing a holistic and large-scale assessment of current water resources, these modelling approaches also enable an exploration of future conditions. The complexity of those future conditions has changed markedly since the end of the 20th century. A hydrology text-book of the 1970s (Linsley *et al*., 1975, significantly entitled *Hydrology for Engineers*) invites a consideration of an increase in demand for water, but advises that "available evidence does not suggest significant climate change in the time scale... within which project-planning horizons normally fall". This was no doubt sound advice at the time, but an unthinkable approach now.

Today a wide range of sophisticated scenarios are readily available that couple a wide-range of socio-economic and environmental factors, see for example Global Environment Outlook GEO_4 (United Nations Environment Programme, 2007). Here is an exploration of how economic development can impact climate change (and hence water availability) and at the same time modify domestic water demand. But there's no need to use off-the-peg, global scenarios. Participatory involvement in scenario development can facilitate region specific scenarios that local stakeholders feel are more relevant to them and their situation (e.g. SCENES, see Kamari *et al.*, 2008).

Such ownership of the scenarios also allows the stakeholders to modify aspects of them in response to what emerges from the modelling process, and indeed to define the indicators that are most relevant to their interest. So for example, if their indicator is chosen to represent the state of the aquatic ecosystem and suggest an unacceptable level of degradation, they can decide what action to take and incorporate this in a revised scenario.

Finally, in setting the context of water resources research it is necessary to say something about drought. Water resources management concerns the balancing of water availability and water demand, in time and space. Drought presents a particular challenge to this activity, but is only one aspect of what needs to be considered in managing water resources.

The term drought refers to a limited availability of water, but this can be expressed in many different ways and have many different impacts. Four widely recognised types of drought are:

- meteorological drought - a period with no or low rainfall,
- agricultural drought - a period during which naturally available water limits crop growth,
- hydrological drought - river flows and groundwater levels are below normal values, and
- economic drought - a period with restricted access to water.

These different aspects of drought need not all occur at the same time, and their effects may be exacerbated by other factors, most obviously high temperatures. Because droughts and their impacts can be perceived in different ways, attempts to quantify drought severity can produce apparently contradictory statements. Recently, there has been an increased interest in describing and cataloguing drought episodes, see, for example, Hannaford *et al.* (2011).

3.4 UK Water Security Pilot Project

The Water Security pilot project takes what has been done at the global and continental (European) scales, and applies it to the UK. In doing so it's possible to add more detail, for example, relating to water supply infrastructure, but there will be challenges, mainly relating to temporal and spatial scales.

The objective is to explore the possibilities offered by an integrated, UK scale assessment system that allows the consideration of a wide range of environmental (supply-side) and demand-side scenarios.

It should be noted that the pilot project is only going to consider water quantity; whether the available water is of sufficient quality is not going to be addressed. Changes in water quality of abstracted water may make it more expensive to treat, or in extreme cases uneconomic to treat. There are also possible consequences of changes in flow volumes on the quality of water in rivers, the most obvious that effect being that lower flow volumes having less capacity to dilute effluent discharges. But there are other effects such as changes in water temperature and dissolved oxygen that could have significant ecological consequences. Large-scale modelling of the type adopted in this study has been used to study water quality (e.g. Dumont *et al.*, 2010) and could be taken forward in a follow-up to this pilot project.

Also out of scope of the pilot is any consideration of solutions. Where problems of future water security are revealed, how to deal with them, either in terms of increasing supply or reducing demand, is not explored.

4 Data and Methods

As noted above, the application of a water availability model at the national scale requires many large data sets and a modelling framework to bring them together. This section contains a description of the model, and the reasons behind its selection (Section 4.1), followed by details of the data set required (Section 4.2), and examples of existing indices of water availability (Section 4.3).

4.1 The GWAVA model

The GWAVA (Global Water AVailability Assessment) model developed at CEH (see, for example, Meigh *et al*., 1999) is a grid-based model. Within grid cells the key element is a rainfall-runoff model of the natural environment (described in Section 4.1.1), modifications to this natural state, including water demands, are generally introduced as the water is transferred between cells as described in Section 4.1.2.

The hydrological function of each cell is represented by a rainfall-runoff model; the particular model is an implementation the probability-distributed model (PDM) developed by Moore (1985). The choice of this model was informed by work at the Institute of Hydrology (now incorporated within CEH) and the University of Southampton examining the effects of climate change on river flows in Britain (Arnell and Reynard, 1996), Europe (Arnell, 1996a), and Southern Africa (Reynard, 1996). In each of these studies a number of models were investigated and they all decided to use the PDM. Note that the concept of a probability distributed model can be implemented in many different ways, and embedded within other model elements, e.g. other processes. What follows is therefore a description of the PDM as implemented within GWAVA.

4.1.1 The PDM rainfall-runoff model

The PDM is used to generate the runoff that occurs in response to the current, and historic, pattern of rainfall. Within the model the term “runoff” can be considered to be the volume of water that is generated within grid cell as surface water in a river channel. There’s no implication that the water is flowing over the surface of the grid cell (surface runoff). Whether this runoff is actually in a river channel will be discussed later.

At the heart of the PDM is the representation of the available storage volume of the soils within a grid cell by a probability distribution of the soil capacity (Figure 4). It’s possible for this distribution to have any form, so, for example, it could be a uniform distribution, with all locations in the cell having equal soil water storage capacity. Usually, and most efficaciously, the distribution goes from zero, to a maximum value for the entire cell (c_{max}), with the shape of the distribution being a key model parameter (b). Rain falling on the soil surface at any point in the cell will add to soil water storage, until the soil reaches its maximum capacity, and after which rainfall will contribute directly to runoff (since this only happens where the soil is saturated this can be termed “saturation-excess runoff”). Because the distribution starts from zero capacity, any rainfall will produce runoff for the cell as a whole, with the total runoff dependent on how much of the soil within the cell becomes saturated during the time interval. The model is shown schematically in Meigh *et al*. (1998) and in summary below.

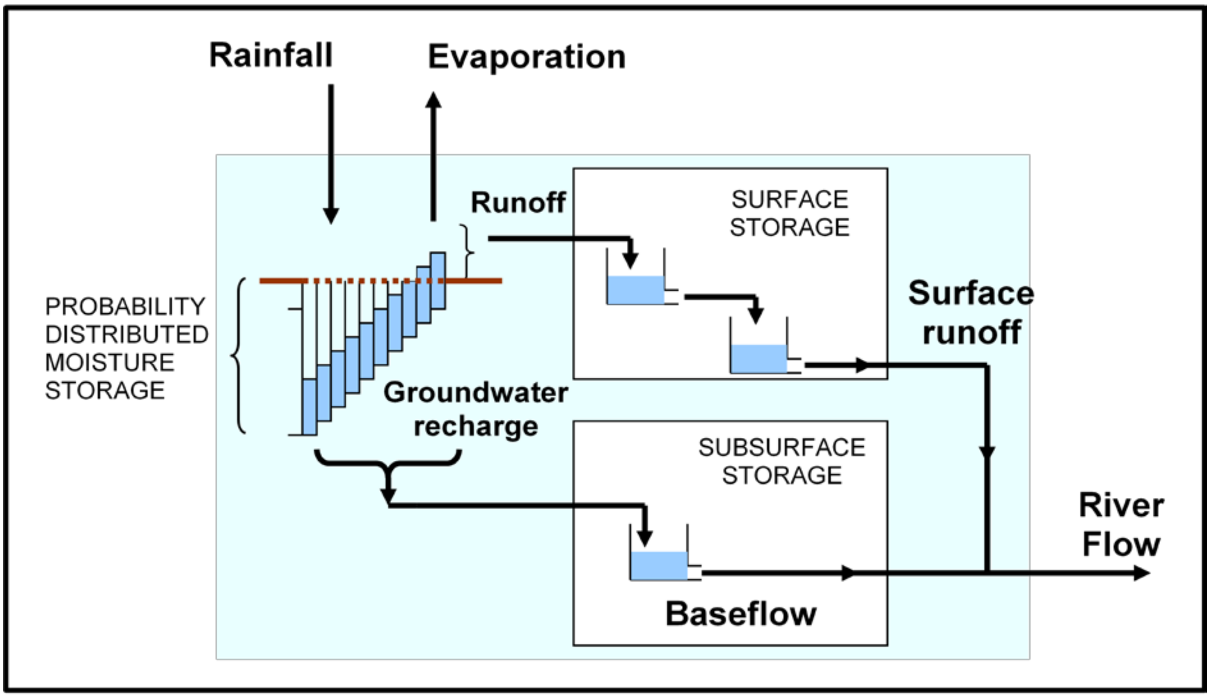


Figure 4: *The structure of the rainfall-runoff model*

This saturation-excess runoff is routed through a cascade of two linear reservoirs to represent the delay and dispersion that will occur as it travels across the grid cell. For each linear reservoir, the outflow, q_s, is a linear function of the surface storage, S_s:

$$q_s = S_{rout} S_s \quad \text{(Equation 1)}$$

where S_{rout} is the surface routing parameter.

Once the change in soil storage due to rainfall has been calculated, the soil storage is depleted by evaporation and drainage to groundwater. Actual evaporation is assumed to occur at the potential rate until field capacity (f_c, the volume of water that can be held in the soil by capillary forces) is reached, below which the ratio of actual evaporation to potential evaporation declines linearly to zero.

If the soil moisture is above a defined field capacity, groundwater recharge, *r*, takes place at a rate dependent on the current soil moisture storage.

An outflow from the groundwater store also contributes to runoff, in what can conceptually be considered to be baseflow runoff. This is computed by means of a non-linear reservoir which has the form:

$$q_b = G_{rout} S_b^3 \quad \text{(Equation 2)}$$

where q_b is the baseflow, S_b is the is the sub-surface water storage (i.e. the groundwater storage above a threshold), and G_{rout} is the baseflow routing parameter. This formulation for the groundwater storage means that there is only a baseflow contribution to runoff once the threshold value is exceeded, but, as will be seen later, it's still possible to abstract water when the storage is below threshold value. In some applications of GWAVA, notably in very dry areas of east Africa, it was also necessary to include a loss term, l, from the groundwater in order to achieve a water balance. Whether this is a real loss, an indication that other processes were not quantified correctly, or the effect of data error is not clear.

The water balance equation for S_b is therefore

$$S_b = S_b' + r - q_b - l \qquad \text{(Equation 3)}$$

Where the ʻ indicates the storage at the end of the previous time step.

The surface (saturation-excess) runoff and baseflow runoff components are then summed to calculate the total runoff from the grid cell, $q_t = q_s + q_b$.

The PDM, as described above, has five parameters:

c_{max}	–	maximum capacity of the soil moisture store (saturation capacity),
f_c	–	field capacity of the soil,
b	–	describes the shape of distribution of soil moisture stores,
S_{rout}	–	surface routing parameter,
G_{rout}	–	baseflow routing parameter.

While local observation and measurement can be used to help set these parameters, in practice the usual method of setting these parameters is calibration against observed flow data, combined with experience gained from previous applications. For example, it has been established through application of GWAVA that the two most sensitive parameters are c_{max} and f_c, and these are reliably related to estimates of the land cover and the soil type (Meigh *et al.,* 1998, based on Vörösmarty *et al.*, 1989). Thus in the application of GWAVA, the PDM parameters c_{max} and f_c are replaced by the single parameter *fact*.

It is recognised that the representation of groundwater in the current version of GWAVA is a gross simplification that fails to recognise the highly-variable and often complex hydrogeological conditions that exist in the UK. Therefore the development of an improved groundwater component has been investigated (see Appendix B) to enable different aquifer types to be represented in each of the GWAVA model grid cells.

In addition to the representation of soil and groundwater storage and routing elements as described above, the rainfall-runoff component represents interception storage, snowmelt, and glacier model elements.

Interception losses are important in areas with significant amounts of forest cover. Developed by Meigh *et al.* (1999) following Calder (1990), the intercepted precipitation, p_i, is calculated as:

$$p_i = g\,(1 - e^{-dp}) \qquad \text{(Equation 4)}$$

where p is the input precipitation, and g and d are the model parameters, universally set to 2 and 0.5 respectively. This interception model is only applied to the forested area in the cell (i.e. it's not applied to the other land cover types, unvegetated, grassland and shrub). GWAVA implements this, and other differences between the land cover type, by running the model separately for each land cover type and then combining the runoff according to the proportion of each class.

The snowmelt model included in GWAVA is derived from Bell and Moore (1999) and includes the following components:

- a model for partitioning precipitation into rainfall and snow, typically according to the air temperature relative to some user defined 'freezing' temperature;
- a snowmelt module assuming melt is proportional to air temperature above freezing;
- a one-dimensional snow-pack storage model with separate representation of the dry part of the snow-pack (snow which has not yet melted) and the wet part (snow which has melted but which is still in the pack). For the wet store, two drainage rate constants are also specified; allowing faster drainage to occur once a critical storage is exceeded;
- a component allowing for partial coverage of snow in the region of interest;
- allowance for the influence of elevation on temperature via elevation zones.

This model will simulate seasonal snowpack development typical of temperate maritime climates. A glacier module has also been developed but this has no relevance in the current context.

4.1.2 Routing flows through the grid cell network

The above description of how runoff is generated is applied separately to each modelled grid cell. Flows are routed between cells using a predefined topography that routes the outflow of one cell into one of its neighbours. This topography defines the order in which calculations are performed.

As well as defining the direction of flow from the cell, the topography also defines those cells that feed into the current cell. Since each grid cell has eight neighbours, and one of these must be the cell that receives the outflow, there can be a maximum of seven input grid cells. Considering only the natural aspects of this water movement, the total flow out of the current cell Q_S is given by

$$Q_S = Q_L + (1-L)\Sigma Q_U' \qquad \text{(Equation 5)}$$

where:

Q_L = runoff generated within the current cell,

Q_U = flow from each adjoining upstream cell flowing into the current cell,

L is a parameter that represents a transmission loss that occurs as water passes through the cell (set to zero for no such losses), and the *'* indicates that flows have been routed to represent the time delay and dispersion of the flood wave.

4.1.2.1 Effects of lakes, reservoirs and wetlands

Where there are storages (i.e. lakes, wetlands, or indeed, reservoirs,) there may be a considerable alteration to the flow regime. GWAVA incorporates this as a modification to the runoff as it moves between cells. Note that within GWAVA very small lakes, and those not on the river network, are usually ignored.

Where detailed data do not exist, the lake or wetland, it is modelled by a simple water balance procedure.

$$S_i = S_{i-1} + Q_{in} + (P_i - E_i) \cdot Area - Q_{out} \qquad \text{(Equation 6)}$$

where

S_i = storage at end of the period i;

S_{i-1} = storage at end of period i-1;
Q_{in} = inflow in period i;
Q_{out} = outflow in period i;
P_i = Precipitation in period i
E_i = Evaporation in period i
Area = lake, reservoir or wetland surface area

For lakes, open water evaporation is used, while wetlands are assumed to be covered in vegetation which tends to increase the rate of evaporation loss, and so a higher evaporation rate is used.

Currently GWAVA has two built in representations of the depth storage relationship, i.e. a constant area (rectangular cross section), or the area increasing linearly with depth (v-shaped cross section).

Q_{out} is estimated in two different ways depending on the type of storage. Firstly there are storages (normally direct supply reservoirs) in which there is only a discharge once the lake level exceeds a threshold value, and secondly there are storages (mostly natural lakes and wetlands) from which the flow is related to current water level or storage, and then possibly increased once a threshold level is reached. In the first case the natural variability of flows is decreased, while in the second case it is likely to be increased.

In the second case, Q_{out} is estimated from the long term average monthly inflow multiplied by a factor derived from the ratio of current storage to maximum storage;

$$Q_{out} = Q_{net\text{-}in} (S/S_{max})^{1.5} \qquad \text{(Equation 7)}$$

where $Q_{net\text{-}in}$ = long-term-average net inflow in month i (= {Q_{in}+(P-E)·Area} averaged over the period of the model run); S_{max} = the capacity of the reservoir; S is the storage in the previous month.

In both cases there is a contribution to the outfall if the storage exceeds the threshold in which case the volume of spill is calculated.

The description above applies to storages contained within a single grid cell. If the storage extends over more than one cell, the cells which do not include the lake outlet are treated as normal except that when calculating the local runoff only the area of land is used (i.e. the area of the cell less the area occupied by the lake). For those cells totally within storage, local runoff is zero and the precipitation contributes directly to the storage volume, and the routing model is applied to this cell, although this uses the total area and storage from all cells covered by the storage.

While this is the default representation of storages, it is also possible to include special case formulations; for example when representing large reservoirs, with detailed data on physical characteristics and operation, a more detailed sub-model can be used.

4.1.2.2 Water abstraction and return flows

The model as defined so far more or less describes the "natural" system; the exception being that the effects of reservoirs have been described, as these are represented in a very similar way to natural storages.

Water abstracted from and returned to the cell, Q_C, and Q_R respectively are also included as the water transfers between cells and are therefore added to Equation 4 above giving

$$Q_S \;=\; Q_L \;+\; \Sigma(1\text{-}L)(Q_U - Q_C + Q_R)' \;-\; Q_T \qquad \text{(Equation 8)}$$

Where:

Q_C = water abstracted in an adjoining upstream cell;

Q_R = return flow from an adjoining upstream cell;

Q_T = artificial transfer of flow out of or back to the current cell to account for canals and pipelines

L = proportional loss for flows out of the upstream cell to account for transmission losses due to seepage into river banks

Σ refers to the summation over those of the 8 adjoining cells which flow into the current one.

Water abstracted includes all uses (irrigation, water supply, etc.) in the cell. This is calculated from the demands in that cell (as discussed below), with the proviso that, if demands exceed the available supply, the water consumed is limited to the total available water. The available water is the sum of the runoff Q_s and a specified maximum yield; this yield can either be allowed even when the groundwater store falls below the threshold at which baseflow is generated (conceptually equivalent to mining a limitless groundwater resource) or set to zero when the groundwater storage falls below this threshold.

Water abstracted for irrigation will be lost to the river catchment as evaporation from the crop, and is known as a consumptive use. A large portion of the water abstracted for other purposes is likely to be returned, e.g. domestic water is returned to the river after appropriate water treatment. In some instances water is abstracted for use at a distant location, in another grid cell. This is the case in a traditional direct-supply reservoir and is represented by a net water transfer Q_T.

Demands can be supplied from either surface or groundwater or from a combination of the two.

The fluxes modelled in GWAVA are shown in Figure 5.

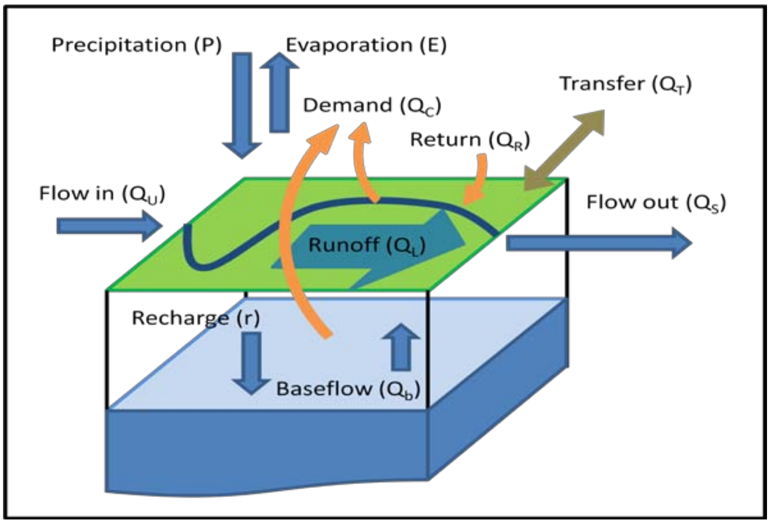


Figure 5: Fluxes modelled in GWAVA

4.2 GWAVA model of water demands

GWAVA categorises water demands into three components:

- Domestic: rural and urban water supply, all uses;
- Industrial;
- Agricultural: irrigation and livestock.

Domestic water supplies are mostly for consumption by people for drinking, cooking and washing, but small industrial demands may sometimes be included here as well. They are estimated from the population in each cell and data for water requirements per capita.

The domestic water use model in GWAVA includes features relevant to model applications in developing countries where, for example, an important distinction is between water use in cities, other urban areas, and rural areas. For the UK model application a uniform per capita consumption rate has been adopted. An obvious future enhancement of the model for application in the UK would be to allow for different water in metered and unmetered households.

Industrial demand refers to large-scale industrial and energy sector water users that are not included in the domestic water supply. There is often a lack of information on actual industrial water use, but where such demands are known they can be entered into the appropriate grid cell and added to the other demands. In this first phase of the project, industrial demands are not included.

In the UK the agricultural sector generally uses little water, but in contrast to the other types of demand, which can reasonably be assumed to be constant throughout the year, water for irrigation is required during periods of low rainfall when resources may be limited. The requirement for water for irrigation is a possible consequence of future climate change. Irrigation schemes vary widely in scale; the main areas need to be identified and, where possible, the following information should be assembled for each scheme: gross and net irrigated area, irrigation efficiency, main crops, and cropping pattern. As noted, irrigation demands vary through the year depending on the potential evaporation, precipitation, crop type, number of cropping seasons and time of planting of each. Estimates of the demands throughout the year are modelled in GWAVA following FAO guidelines for crop water requirements (Doorenbos and Pruitt, 1977) and taking account of effective precipitation (Dastane, 1974).

4.3 Data requirements

It is apparent from the above description, and indeed it has already been noted, that the application of GWAVA requires a great many data sets. In summary these are:

- Sub-grid elevation distribution
- Hydrography
- Soil texture
- Land cover
- *Climate*
- Lake, *reservoir* and wetland parameters
- *Water demand*
- *Water resource type (i.e. combination of surface and groundwater)*
- *Water transfers*
- *Distribution losses (leakage)*

In addition it has been noted that the flow generation model requires a degree of calibration which requires observed river flow data.

The above list of data requirements includes the overall water demand, and again it's already been noted that these are generally categorised as domestic, industrial and agricultural. While these can be provided as input data, GWAVA contains sub-models to estimate these demands based factors that influence the demands (these sub-models are described in Section 4.2.1). These factors are represented by data describing:

- *Population: urban, rural and city.*
- *Locations of irrigated crop types and the start and end of their growing season*
- *Crop characteristics and growth stage durations for 47 irrigated crop types*
- *Rural population*
- *Total population*
- *Livestock population*

Within the two lists above those in italics are time-varying and are therefore representative of a particular period. The model application (i.e. the combination of the model formulation or code, and a particular set of data) is generally demonstrated to have some degree of validity by simulating a baseline period during which some model outputs can be compared with observations. By changing all or some of the time-varying data the model can represent possible future conditions. Clearly the model can represent many such scenarios of possible future conditions. In this pilot project only two changes have been made, climate and population.

Many baseline inputs that were used in this project were prepared previously for GWAVA's application over the whole of Europe for the SCENES project (Kämäri *et al.,* 2008) as described in detail by Dumont *et al.* (submitted). Input data sets that were prepared specifically for this project are:

- Future climate parameters
- Population growth and migration within the UK
- Fraction of water extracted from groundwater
- Urban, rural, and industrial water demand per capita
- Transport water from resource to consumer (i.e. places connected by UK water supply infrastructure) and the average residence time of water during this transport

4.4 Indicators of water security

GWAVA has a number of built-in indices of water availability (Meigh *et al.,* 1999). Six of these indices describe the risk as the excess of water demand over water availability during the most demanding months in the simulated period (positive values mean that there is no risk and values around zero or negative indicate risk). An example of such a map is presented in Figure 6.

Indicators of this type were developed for regions such as Africa with little water supply infrastructure and the representation is based on the underlying model grid. In situations in which there is sharing of water between cells such maps are unrealistic as local differences in water availability are readily managed, through minor storage and redistribution of water. With greater water management and larger scale infrastructure it becomes more appropriate to consider larger water supply zones within which water can be transferred.

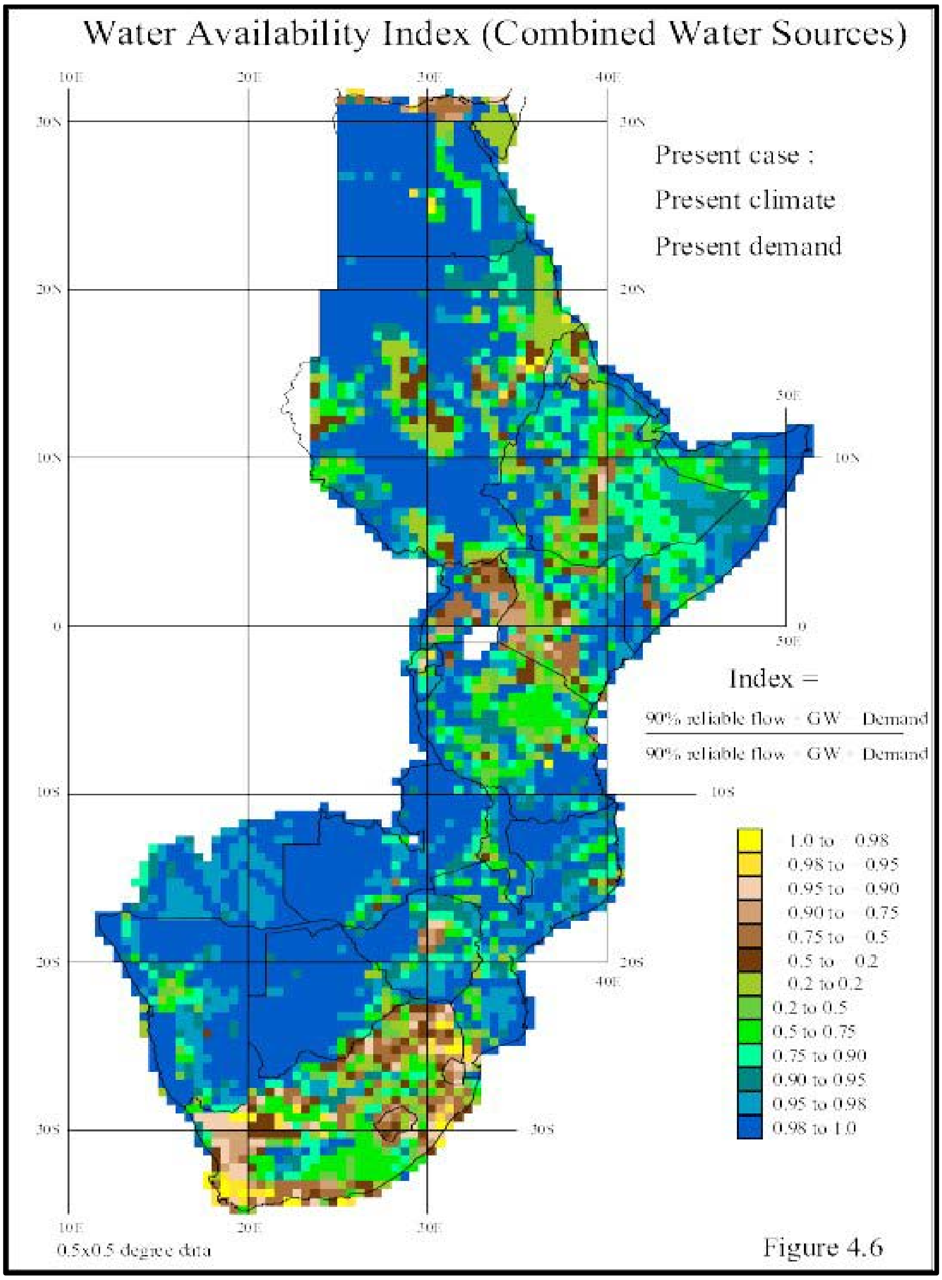


Figure 6: *An example of a regional map of water availability (from Meigh et al., 1998, without permission)*

5 Model Application

For the pilot study, the application of GWAVA has been based on the SCENES application to the greater Europe area. This used a grid resolution of 5 by 5 arc minutes (approximately 6 km by 9 km, increasing in area in the north and decreasing in the south). This represents a compromise between a high resolution, which would better represent spatial variability, and the coarser resolution of readily available data (e.g. many global data sets). Adopting a national grid-based representation is an obvious modification to make in taking this work forward.

The rainfall-runoff model parameters have been set by calibration as described in Appendix A.

A number of simplifying assumptions have been made in applying GWAVA:

- no hydraulic routing,
- lakes and wetlands use Equation 5,
- no transmission losses, i.e. term L in Equation 7 set to zero,
- No water transfers, i.e. term Q_T in Equation 7 set to zero,
- pipe leakage: 21.8% of abstraction (Environment Agency, 2007).

5.1 Scenarios

For the purpose of the pilot study it was decided to run scenarios representing just two factors: climate change and population change. Running these in combination means that there are four model runs:

i) Baseline
ii) Only climate change
iii) Only population change
iv) Climate change and population change.

The selected baseline was the 21 year period 1980-2000, with the projections being estimated for the period 2040-2060, these periods are referred to as the baseline and 2050s in the remainder of this report.

With these assumptions and data sets some sub-models within GWAVA produce data sets of water demands that remain fixed for all four model runs, e.g. the livestock demand. In contrast the Irrigation demand changes in response to a change in climate. In order to compare these two water demands, they are presented for the baseline period in Figure 7. It can be seen that the irrigation demand is lower than livestock water demand, but the impact of irrigation demands on water security risk is much larger because irrigation is required in the driest months when natural river flows are lowest.

Note that in these figures a border of lower demand is visible along some coastlines. This is caused by cells that have a large proportion of sea and therefore a reduced land area and water demand. Similar borders are visible in a number of the maps that follow and are caused by the same phenomenon.

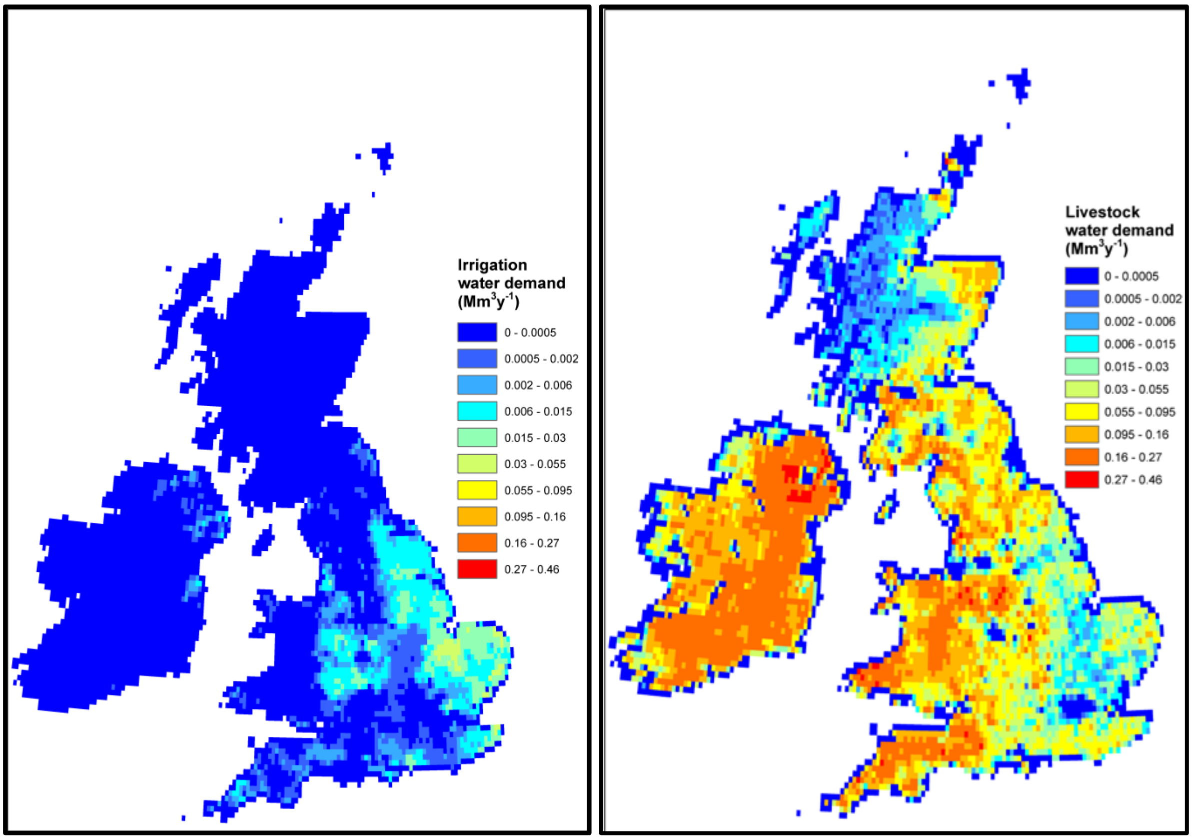


Figure 7: *Average irrigation water demand (left) and livestock demand (right) for the baseline period in the UK and Ireland*

All results are based on monthly model outputs; that is to say that that water availability and demands are assessed on a monthly basis. GWAVA could be run on a daily basis but for water resource assessment in situations with any degree of water management a monthly assessment is considered appropriate.

5.2 Climate

GWAVA requires data from a number of metrological variables in order to drive the hydrological simulations, including; precipitation, potential evapo-transpiration, temperature, and rain days. These data are supplied as a daily resolution time series for a specified period over which hydrological modelling will be conducted.

Modelling of predicted changes in regional climate allows assessments to be made concerning changes to the availability of water supplies across the water resource zones identified. The derivation of changes in climate data used within GWAVA has been based upon a selected scenario of future regional climate modelling (RCM) determined by recent work within the Future Flows programme, based in CEH. Further details concerning how these data were developed is included within the 'Future Flows and Groundwater Levels – Science Report/Project Note – SC090016/PN1' (Prudhomme, 2011).

Baseline climate data for the period 1980-1999 were obtained from Climatic Research Unit datasets representing interpolated observed data, while future climate data for the periods 2020-2039 and 2040-2059 were obtained from future scenario output derived from the climate change scenario named 'afgcx'. The chosen climate change scenario (afgcx) is one of a multitude of future scenarios based upon CEH modelling of HadRM3 future climate. It was selected at random and does not in any way reflect a particular type of future climate, merely one probabilistic future series of meteorological data. These data only covers Great Britain, thus all modelling of future climate on hydrological processes is limited to this geographical extent.

Climate data are formatted as a grid of equally spaced data across the area of interest, which in turn drive hydrological modelling at the same grid scale. GWAVA already contains baseline gridded time series of meteorological data, thus for the purposes of this pilot study it was decided that these would form the basis of the climate data used to drive the hydrological simulations. Rather than creating whole new time series of future climate meteorological data for these grids, a transformation of the available data according to changes observed in the climate data assessed was applied to simulate future climate. This involves assessing the average monthly change for each climate variable between the periods considered, and subsequently applying the calculated monthly change to the available GWAVA baseline data for that variable.

The process and data used to transform GWAVA gridded data are outlined in Appendix C.

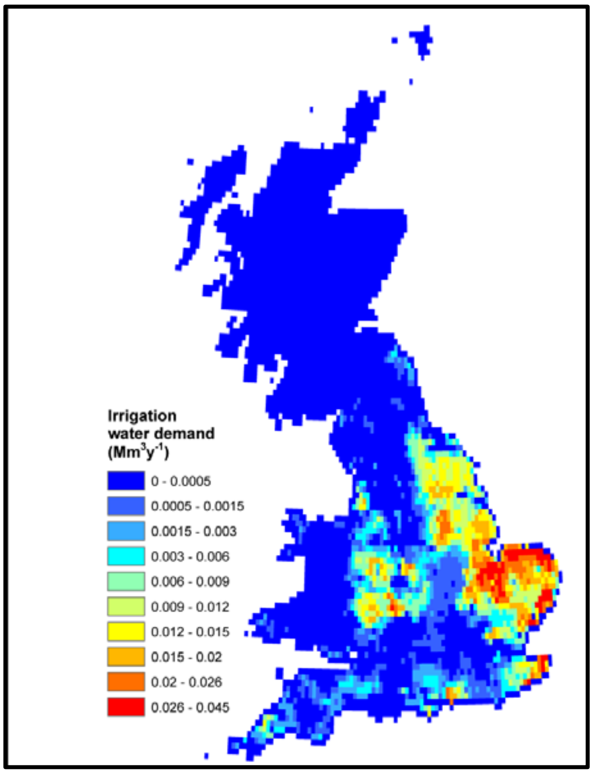


Figure 8: *Irrigation demand in the 2050s.*

5.3 Population

GWAVA has a built-in population grid for the United Kingdom for the year 2001. To determine how population numbers will change across the United Kingdom it is necessary to obtain reliable data on predicted growth, ensuring that predicted changes in migration and immigration are accounted for. As climate data are only available for those gridded areas of the UK that fall within the boundaries of Great Britain the population grids used within GWAVA modelling are limited to the same areas. The population in 2050 is taken to represent the entire period 2040-2060.

Population data for Great Britain have been obtained from the Office of National Statistics (ONS), the executive office of the UK Statistics Authority, a non-ministerial department responsible for providing national statistics. The ONS produce population growth forecasts based on the most up-to-date census and emigration/migration data. The most recent population projections were published in 2008 and form the basis for data on GB population changes included in this study. This study has selected to model the changes between 2001-2030 across the discrete regions of Scotland, Wales and the Government Office Regions of England. In this way the data will represent some of the broad changes in UK migration and regional differences in growth that are expected. There are no regional projections available for 2050, but national projections of change are available and have been applied to the population grids of 2030.

ArcGIS has been employed to determine which GWAVA grids fall within the regional boundaries discussed, employing a nearest neighbour approach to encompass those grids that do not directly fit within the ONS national shape-files. Original data within the GWAVA grids has been adjusted to reflect the slight differences in total population in the year 2001 between GWAVA and ONS data. These data have then been adjusted by a regional growth factor for the year 2030, and subsequently a national growth factor for the year 2050. Ascii files of gridded GB population were created and used within GWAVA (see Figure 9)

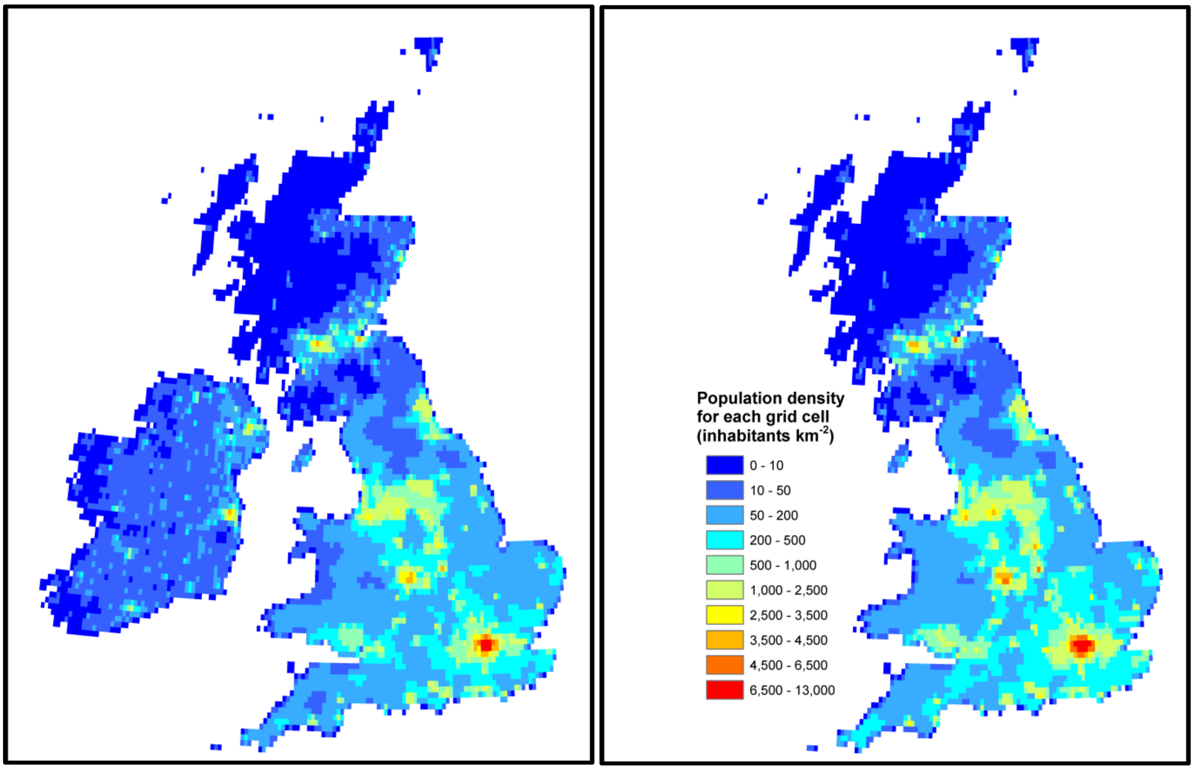


Figure 9: *Gridded population in Great Britain in 2000 (left) and 2050 (right)*

As noted above, GWAVA has a built-in model of domestic water use that can allow different uses in different settings (e.g. rural, peri-urban and urban). For the pilot all of these have been set to the same value of 155 l/head/day (Environment Agency, 2007). Applying these figures results in the two water demand maps shown below (Figure 10).

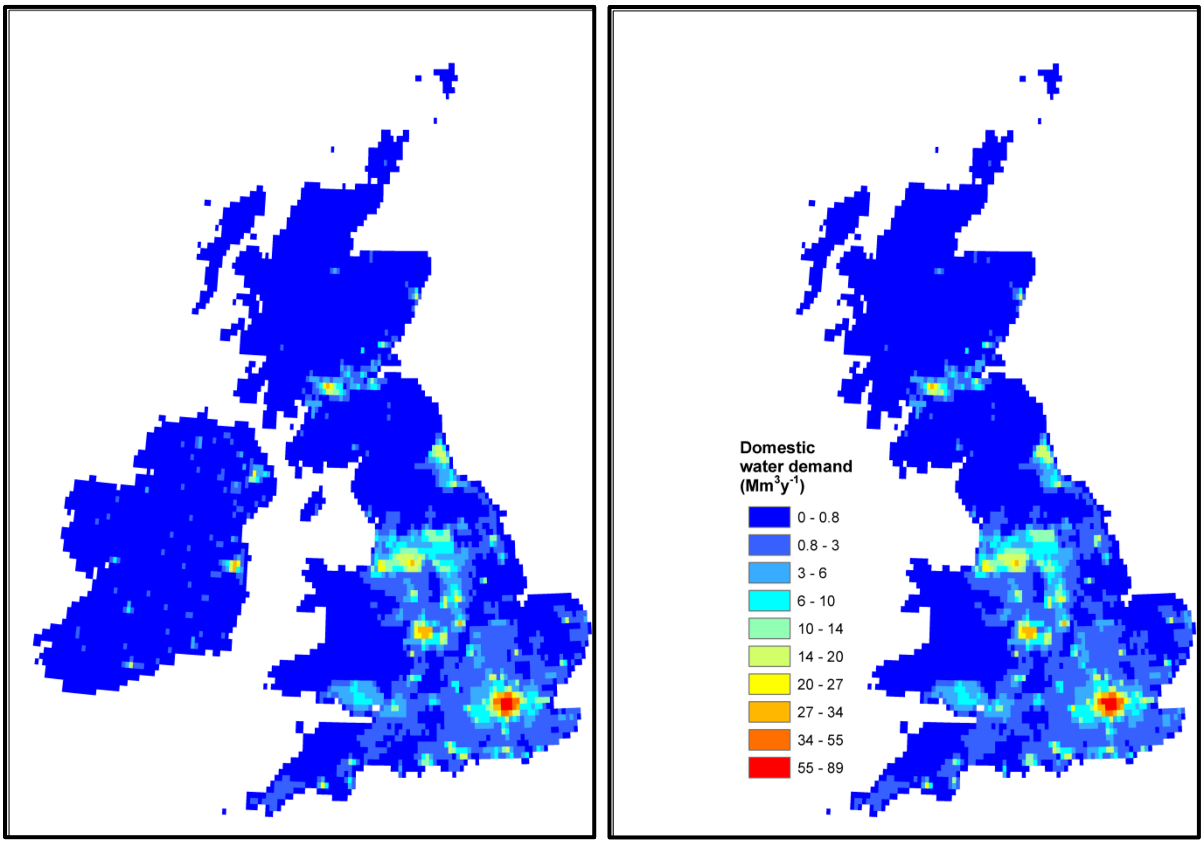


Figure 10: *Modelled domestic water demand for the baseline period (left) and 2050s (right)*

6 Assessing water availability and security

Runoff has been calculated for the baseline period and the 2050s using the climate change scenario as shown in Figure 11.

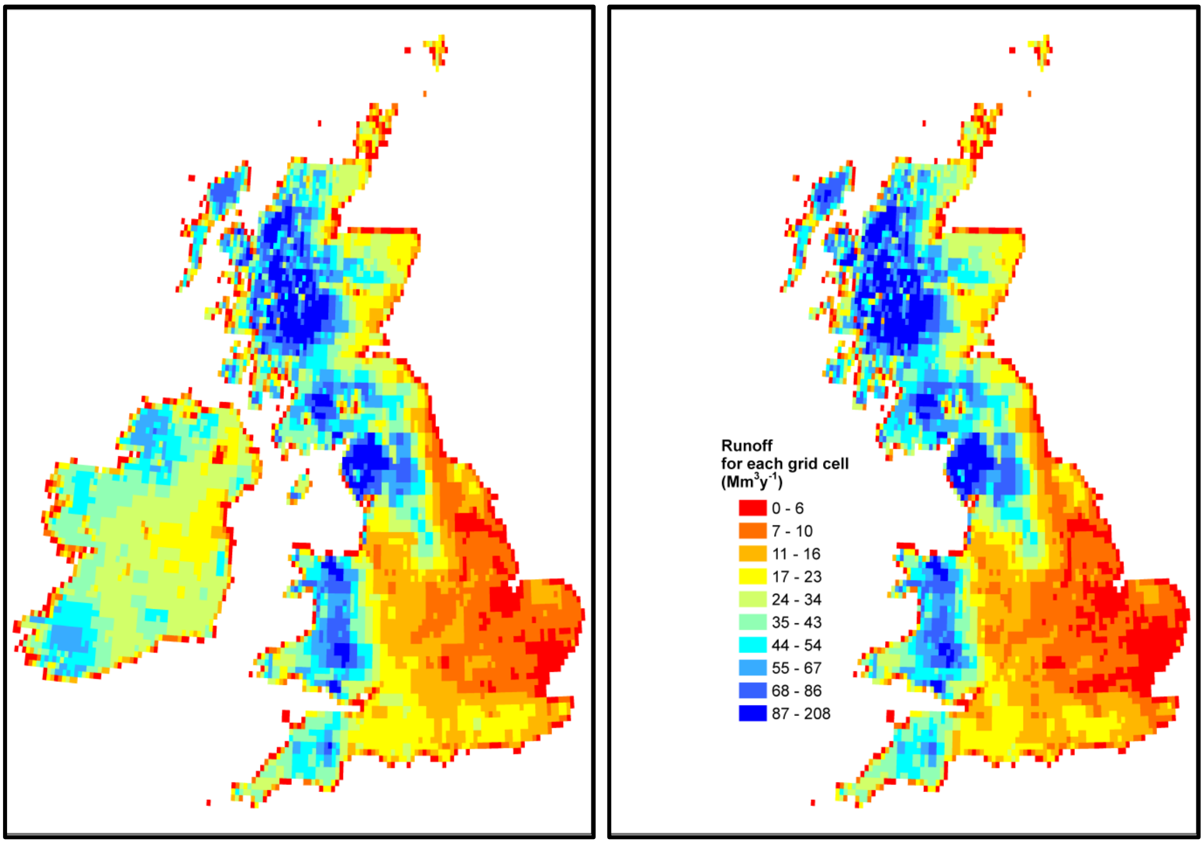


Figure 11: *Runoff from the land fraction of each grid cell in the baseline period (left) and2050s (right). Note that runoff of 50Mm^{3}y^{-1} in a grid cell is roughly equal to a depth of 0.9m.*

A very simplistic view of whether the available water (runoff) can meet the demands is obtained by subtracting the sum of the demands (i.e. irrigation and livestock demands, Figure 7, and domestic demand, Figure 10) from runoff for individual grid cells. The result of this for the baseline period is presented in Figure 12. Three factors limit the usefulness of this map.

i) There is long-term averaging of both the water resource and the demand within each cell (i.e. this is equivalent to storing all water for possible future use).
ii) There's no restriction on consuming all of the available water, i.e. there's nothing to stop all of the water being abstracted and leaving nothing in terms of an environmental flow.
iii) Water not consumed in a cell is not made available in neighbouring or downstream cells.

So while on this basis most of the UK has enough locally available water to meet the demand this is not a useful indicator of water resources.

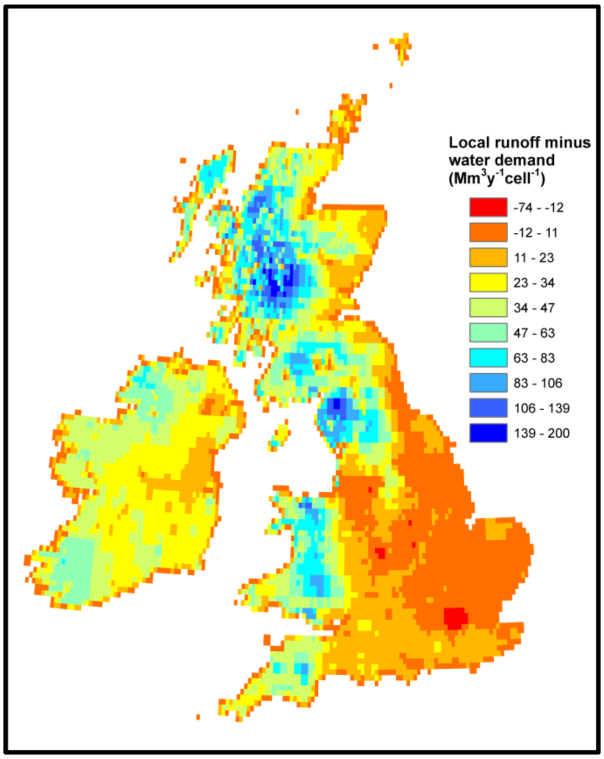


Figure 12 *Local grid cell runoff minus total water demand in the same grid cell (Mm^3y^{-1}) averaged over the baseline period.*

A different presentation of the balance between water availability and demand is given using the index of Meigh *et al.* (1999) described in Section 4.4. This index is presented for the baseline period in Figure 13a. This index is based on flow rather than runoff, so water unused in an upstream grid cell is available in downstream cells. For this reason the major rivers of the UK can be seen as dark blue bands of high availability. There are many situations where cells of high availability are bordered by cells with large negative values for availability; these areas correspond to cities and towns, although some urban areas in wetter parts of the UK have sufficient water.

Note that few red specks of unsatisfied demand appear in wet regions away from urban areas. Investigation shows that these result in cells with very little land area, and therefore very little runoff. More generally such maps shouldn't be used to look at the values in individual cells, or even small groups of cells, but rather to give an impression on a region scale.

The same indicator is also presented in Figure 13b for the period 2040-2060 under both climate and population change. The most obvious change is the development of a large water stressed area to the north of London extending as far as the Wash. Exploring the various datasets feeding into this suggests no single causative factor, but a number of changes combining to increase stress.

Of course what this map does not include is any water infrastructure to store and transfer water. How such infrastructure is represented is the subject of the next section.

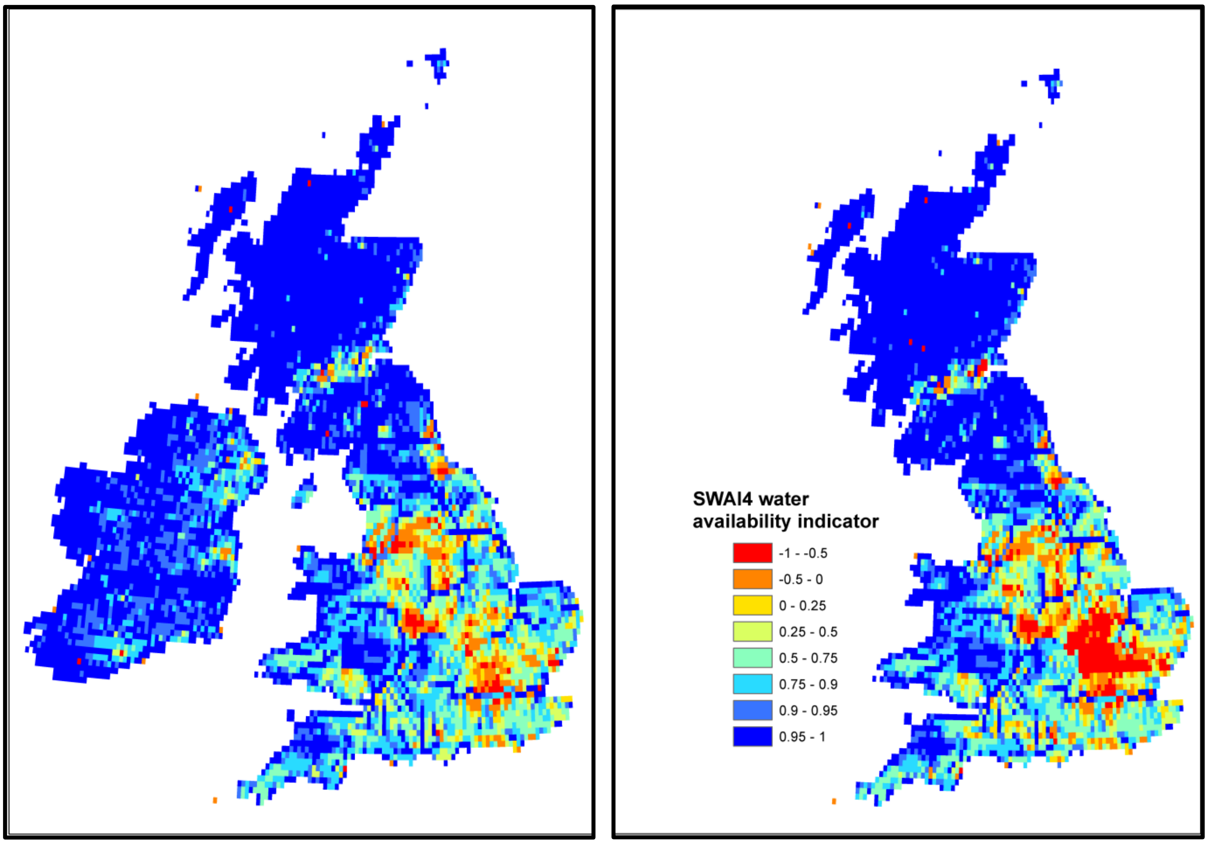


Figure 13: *Water availability indicator SWAI4 (Meigh et al., 1999) for (a) the baseline period (left), and (b) 2050s (right)*

6.1.1 Water supply infrastructure

Water supply infrastructure has been developed to make water available at times and locations at which there would otherwise be a water shortage. There are pipe networks and pumping stations to transport water over a range of scales from the local to regional. Artificial storage also comes in a wide variety of forms, perhaps most notably direct supply and regulating reservoirs.

GWAVA's capability to represent reservoirs and water transfers has been described in Section 4.1.2.1. Unfortunately, the information required to implement these was not available to this project.

An attempt to overcome this gap was made using the water resource zones defined by the water companies. The 110 resource zones in England and Wales are shown in Figure 14(a) and their representation using the 5' by 5' spatial resolution in the GWAVA application in Figure 14(b). This representation is based solely on their spatial extent. Comparing these zones with the river basins as defined by the flow grid in GWAVA revealed a number of mismatches where close agreement was expected, i.e. between major river basins.

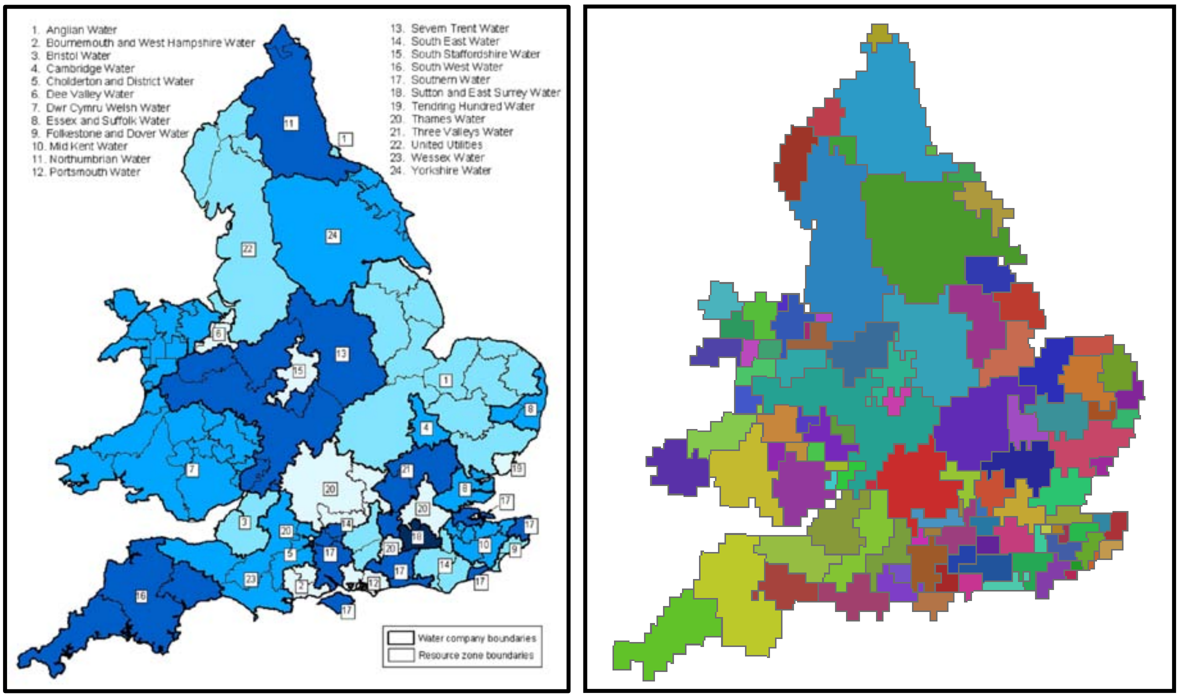


Figure 14: *Resource zones in England and Wales: a (left) as defined by the Environment Agency © Crown Copyright [all rights reserved. Environment Agency, 100026380, 2007] and b (right) as represented in the model application.*

On investigation the cause of the mismatch was found to be the poor quality of the underlying flow grid. This grid was a European-wide grid and appropriate for the model application at that scale, but not suitable for more detailed analysis at the UK scale. The nature of the problem is seen clearly at the watershed between the Thames and Severn as seen in Figure 15.

The option of realigning the water supply zones to align with the flow direction grid was considered, but dismissed as water supply zones would then not correspond accurately with the population data which are also on a European-wide grid.

In retrospect the decision to build the pilot on the existing European GWAVA application was possibly a poor one; starting a new application might have been a better option in the long-term.

However, to overcome this mismatch, resource availability was assessed within the river basins as modelled in GWAVA. This is actually about the same number of units as for the water resource zones, but overcomes the problem of the water resource zone representation as the majority of the UK is represented by relatively few, large, basins.

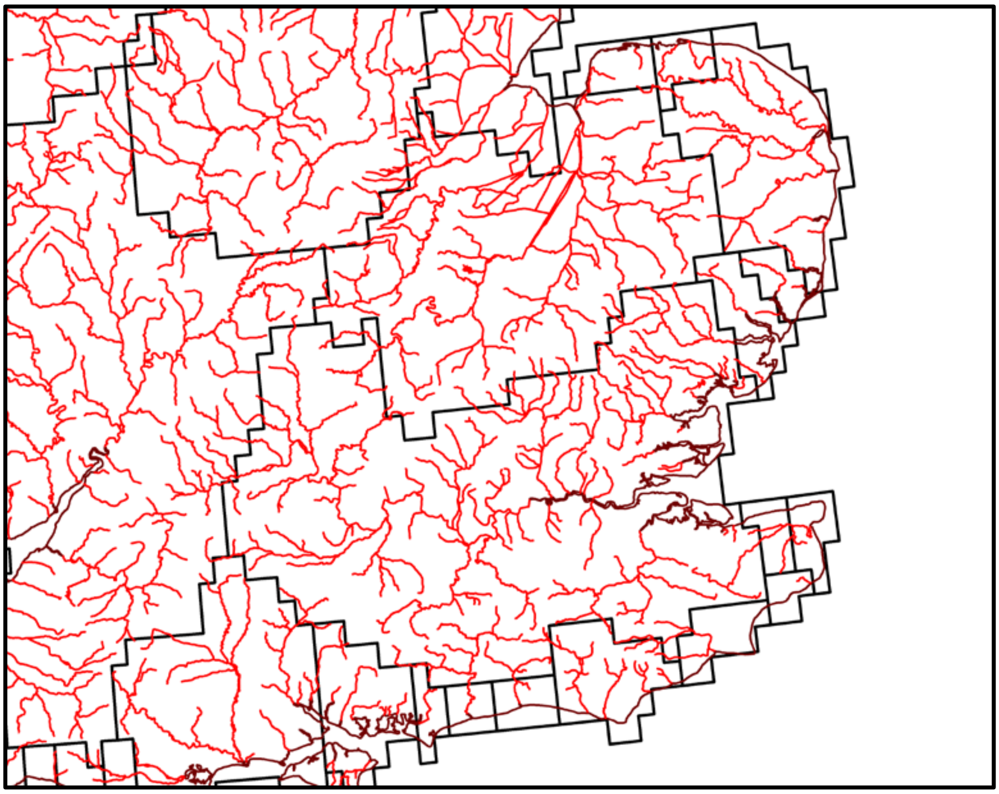


Figure 15: The black lines represent the basins as defined in the European scale application of GWAVA, the red lines are from a more accurate UK river network. In the middle left of the map the black boundary clearly allocates a significant part of the upper Thames catchment to the basin of the River Severn.

6.1.2 River basin resource analysis

For each river basin, monthly time series of flow and demands were available which could be compared over a range of durations. As has already been noted at any longer duration and larger scale there is always sufficient water because, as a long term average, the UK's water demand is only a few percent of what runs off into the surround seas. In the vast majority of basins the long-term average demand is less than ten percent of the runoff. And yet in cases where the long term average demand is less than 5% of the runoff there can be many months in which demand exceeds runoff.

However, it is not true that if flow exceeds demand all is well as there is also a need to maintain an environmental flow in the river, and allowing for this greatly increases the number of months in which flow cannot meet the demand.

This environmental flow is usually specified as a percentage of index low flow, e.g. the 95 percentile flow, or the flow that is exceeded for 95 percent of the time (Q_{95}). If the environmental flow was in fact Q_{95} then it follows that that during the 5% of the time flow is below this level, no demand (D) can be met and that while the flow is less than (Q_{95}+D) the demand can only be partially met. This would imply a failure rate greater than 5%, possible considerably greater where demands are high. Yet such a failure rate is unrealistic as water companies typically manage resources to prevent any disruption to supply, a "hosepipe ban", occurring more frequently than once in 20 years (i.e. only in 5% of years).

To represent this water conservation a small storage was included in each basin with a maximum capacity of 2% of the annual basin runoff and a maximum withdrawal from flow of 2% of the monthly basin total. These storages could be drawn down to meet demands and environmental flow requirements during extreme low flows.

For the vast majority of basins, 223 out of 236, this storage was sufficient to ensure supplies were maintained in line with the objectives of the water companies, i.e. a failure rate equivalent to what is expected from a planned 1 year in 20 failure. In those some basins this was not true, and so in these basins the demand was reduced to be compatible with this failure rate. Note that this doesn't mean a single occurrence in the modelling period; from a statistical perspective it is to be expected that some basins will see no 1-in-20 year events in a 20 year period, many basins will experience one such event, but in other basins 2, 3 or more such events will occur.

This adjustment of demand can be considered to include two effects. Firstly, in some basins water is reused many times as it travels through a catchment. Of the water abstracted by water companies over 70% is returned to rivers as treated effluent, and can be abstracted again further downstream. Secondly, the factor can be compensating for the mismatch between the flow grid used in this study and the actual catchment areas. Of course, this adjustment probably includes an element of both of these.

As a check that sufficient water was available, it was noted that the increases in abstraction from other basins to withdraw the correct amount from the UK as whole were only slightly greater than one.

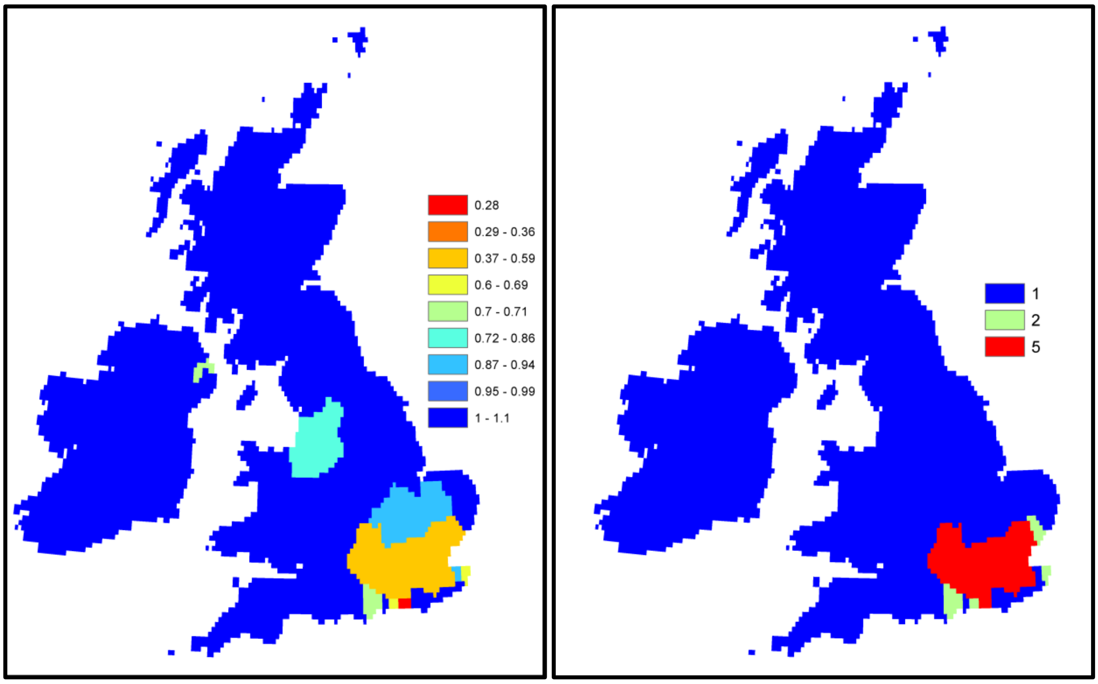


Figure 16: *Factors applied to demand to reduce failure rates (left) and an interpretation of these to represent the number of time water is reused within each basin (right).*

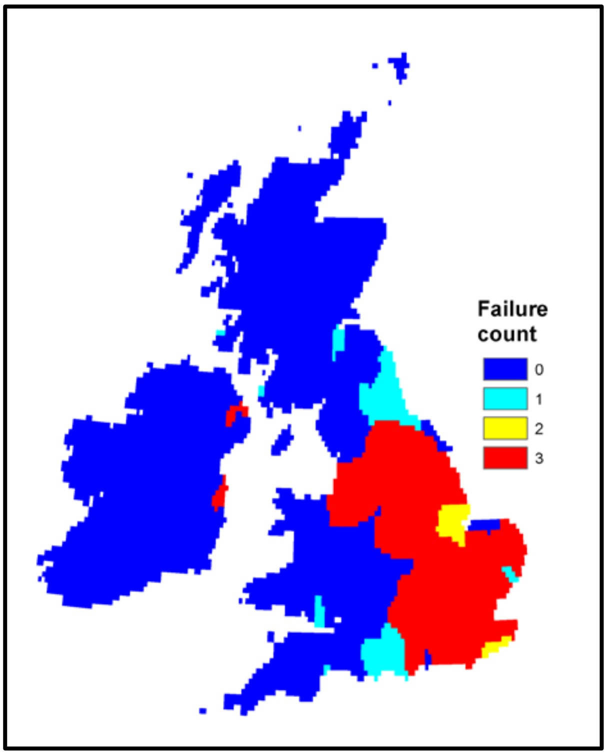


Figure 17: *Number of failure events in the simulated 21 year baseline period*

Figure 17 shows the number of failure events occurring in the modelled baseline period. The map shows large areas having three such failures, and it should be noted that these are probably individual months with insufficient supply where minimal management intervention (e.g. a public awareness campaign) would be sufficient to prevent any actual disruption to supply. Additionally, while it might be expected that the area experiencing three failure events is located to the south and east, it is perhaps surprising that is largely contiguous. This is probably attributable to the high degree of spatial correlation in weather patterns between basins.

7 Results

In the previous sections descriptions have been given of:

- The hydrological model
- The water demand model
- The water resource infrastructure model
- Data preparation for climate and population scenarios

Combining all of these allows results to be prepared describing the water resource situation in the scenarios.

The indicator used is based on the map presented in Figure 17, but expressed as the change in probability of there being a hosepipe ban in any year as a consequence of the scenario of possible changes in climate and population. These scenarios have been run both separately and together, and the results are shown in Figures 18, 19 and 20. Note that in all of the scenarios it appears that there is always either no change or an increase in probability; in fact there were some decreases in probability but these were less than 5% and these appear in the band labelled zero in the maps.

As might be expected the greatest impact is in the south and east of England. Climate change is seen to have a greater impact than the change in population. The combined impact of climate and population change indicates a region in which the probability of a hosepipe ban in any year is close to 100%. This of course assumes no action is taken is manage demand or improve resource availability as will be discussed in the next section.

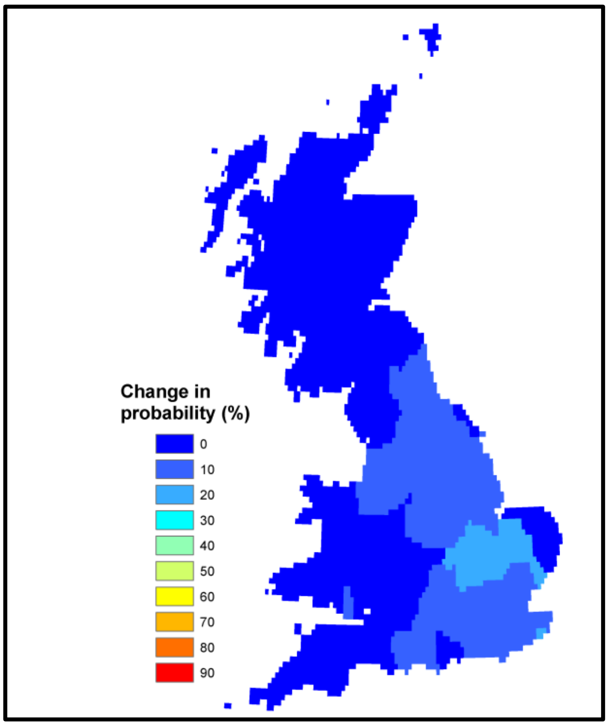


Figure 18: *The change in the probability of a hosepipe ban in the 2050s compared with the baseline based on population change. Note bands represent a 10% range centred on the number given in the key.*

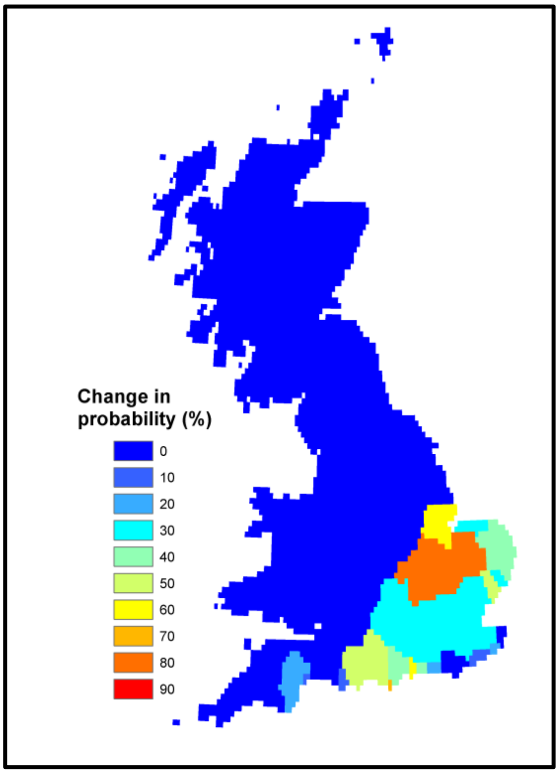


Figure 19: *The change in the probability of a hosepipe ban in the 2050s compared with the baseline based on climate change.*

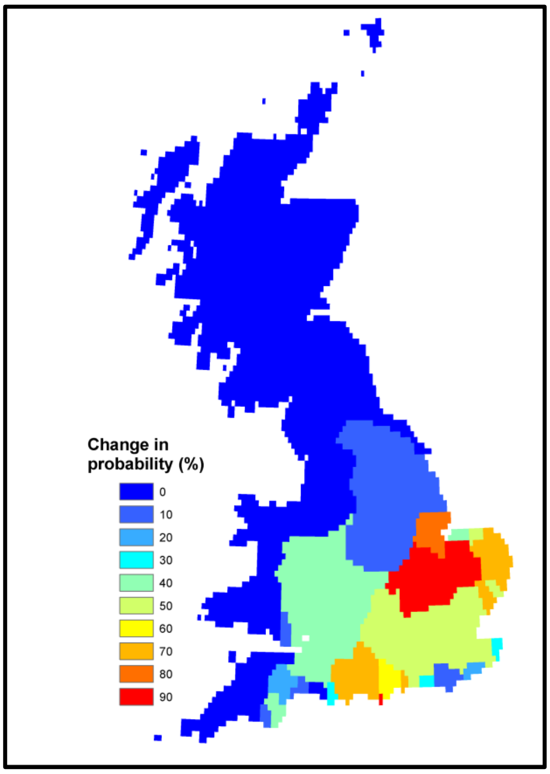


Figure 20: *The change in the probability of a hosepipe ban in the 2050s compared with the baseline based on climate change and population change.*

8 Discussion and conclusions

The results described in this report are based on the application of a water availability model to the UK. It is a model that has been widely applied to various regions of the world as part of many different studies. The model has three components: a hydrological component that represents the natural environment from rainfall to the flow of rivers into the sea; a water demand component that estimates water requirements for people, cattle, crops and industry; and a water infrastructure component that represents the artificial movement and storage of water required to match the natural availability with demand requirements. None of these components can be considered novel, unique, unconventional or untested, and indeed exist in similar formats in a number of other models.

What is new, however, is the application of this type of model to a relatively small country with a highly developed water infrastructure. This model application was conceived as a pilot study that would provide a rapid insight into whether a more detailed approach would be worthwhile, but in practice a great many issues were encountered which have been overcome pragmatically, or by-passed altogether in order to reach a conclusion.

The challenge posed in the foreword was to develop a sophisticated and realistic modelling approach to water security that could generate results that are readily accessible and meaningful to a non-expert audience. The index adopted represents the change, almost always the increase, in the probability of a hosepipe ban occurring during any calendar year in the 2050 based on changes in population and climate. There is of course much scope for misinterpreting what this means.

The index fails to recognise that periods of deficit do not arise unexpectedly; water resources are stored both naturally and in constructed reservoirs. Monitoring of these resources as they are depleted enables measures to be taken that may avoid any actual restriction in use. Most obviously this will be an awareness campaign asking consumers to reduce their consumption. In this way many of the shorter duration hosepipe bans may be avoided.

However, at the other end of the scale, longer lasting periods of demand deficit may not be managed by either awareness campaigns, or minor measures such as hosepipe bans. So “hosepipe ban” is used as a convenient and all-embracing term to represent a water supply deficit event.

The use of a single indicator to present the scenario results in Section 7 was deliberate. It will be clear from the many other maps presented in other parts of the report that many other presentations would be possible. Each of these would be different and possibly more relevant to particular readers. But overall more indicators just confuse. The best way to overcome this confusion is by agreeing with users what indicator is most appropriate for them, and proving it. This requires full stakeholder engagement throughout the project.

It must be acknowledged that the analysis underpinning the results also assumes that nothing is done either to improve water resource capacity or change patterns of consumption. If the results represent a believable future, water companies and government have a duty to take action to avoid it becoming a reality. The results represent what may be the situation in 40 years’ time, giving sufficient warning for considered, long-term planning, and not immediate knee-jerk reactions.

This model-based approach represents an alternative methodology to that used by the Environment Agency (EA) and reported in the recently published document *The case for change – current and future water availability* (Environment Agency, 2011). The later is based on a consideration of whether an index flow (the flow exceeded 70% of the time, Q_{70}) can meet all projected demands, including those of the environment. It, therefore, represents a combination of processed information from a number of sources. Despite the difference in approach there is a pleasing degree of similarity in the results.

So the results from the pilot study are interesting and accessible, compatible with the EA's alternative approach, and indicative of challenging times ahead. But too many issues and uncertainties have arisen for the results to be considered definitive or authoritative. Having undertaken the pilot there is significantly increased confidence in the underpinning methodology to suggest that the approach is valid.

The following section outlines the issues identified in this pilot project and how they might be addressed in a follow-up study. Many of these issues are technical in nature, but there is also the need to secure access to real data describing the UK's use of water. A cooperative approach that involves the LWEC partnership and the UK Water Industry is required.

9 Next steps

Improved representation of groundwater, notably the interaction of surface and groundwater and the combined exploitation of resources.

- Appendix B expands on this issue.

Improved representation of water supply infrastructure, especially with respect to the use of Water Resource Zones and the representation of major storages and transfers.

- The representative of water infrastructure is a significant weakness of the current study. Working with water companies major storages and transfers should be represented explicitly.

Better demand modelling (e.g. variations in per capita consumption, effects of metering etc.).

- The domestic demand model used in the pilot study was a single per capita usage figure. It would be straightforward to include known regional variations in usage, the uptake and impact of domestic water usage, domestic water harvesting, and technological developments likely to change patterns of water usage.

Improved realism of management in times of developing water resource deficits.

- The hosepipe ban indicator used in the pilot was not subtle or representative of the way in which developing water shortages are handled. Again this would be straightforward to implement. It would also be possible to distinguish between shortages that are minor and localised, from those that are major and regional in their extent.

Better modelling of land use change under future climates.

- The climate change scenario included the effect of a change in the crop water requirement, but not how land use itself might change in response to a change climate. Or indeed how land use may change in response to other drivers.

Replace latitude and longitude based grid with 1km grid based on UK National Grid.

- This straightforward adjustment would make it far simpler to make use of other UK specific data sets.

Extend spatially to represent UK/British Isles.

- While the intention of the pilot had been for a consistent UK-wide approach that wasn't possible given the time and resource constraints.

Improved regionalisation of hydrological model parameters.

- The regionalisation of the rainfall-runoff model was generally disappointing. That this wasn't more damaging to the project as a whole demonstrates the importance of rainfall in driving hydrological response especially over longer durations.

Explore other climate scenarios and ensembles.

- The range of available scenarios and ensembles makes it possible to explore the wide variety in possible future climates.

Explore uncertainty and confidence.

- Uncertainty and confidence have not been addressed, and indeed need to be considered in all of the above issues.

Engage with stakeholders during the model application.

- Even in an extended follow-up study it may not be possible to address the issues raised above rigorously. It is therefore important to engage with stakeholders during model development and refinement so that all stakeholders are aware of the compromises and assumptions that have been made. Similarly stakeholders need to state requirements with respect to indicators. Early and full engagement with stakeholders will be essential to the success of a follow-on study.

APPENDIX A: Setting rainfall-runoff model parameters in GWAVA

Determining parameter values for the rainfall-runoff model in GWAVA was a three stage process:

i) calibration against observed flow data;
ii) generalisation by relating values to catchment descriptors;
iii) checking flow and runoff simulations using these parameters.

These are described in the following sections.

A.1 Calibration against observed flow data

The four parameters requiring calibration are:

- *b*: PDM parameter characterising the distribution of storage capacity within the grid cell
- *fact*: multiplication factor modifying the modelled field capacities and saturated capacities
- S_{rout}: parameter of the linear reservoir to characterise surface routing
- G_{rout}: parameter of the non-linear reservoir to characterise groundwater routing

Calibration is achieved by seeking to minimise the difference between observed and simulated flows. This difference is represented by a so-called objective function; the function itself is objective, but many different possible functions can be chosen and selecting one is a subjective decision. For this study the mean relative error objective function was chosen:

(Equation A.1)

Where obs_t and mod_t the observed and modelled flows and time step *t* and the summations are over the period t_{start} to t_{end}. This function gives weights towards low flows which are of course the most critical periods for water security.

Since the parameters represent the natural part of the water environment, calibration was against flow data either largely unaffected by anthropogenic factors (natural) or data corrected for such factors (naturalised).

The optimisation algorithm used was the Downhill Simplex method in Multidimensions (Nelder and Mead, 1965). The time taken by this algorithm can be reduced by defining maximum and minimum values (bounds) for the parameters. The bounds are given in Table A.2 and are based on previous experience with the model.

Calibration was against flows from 36 UK catchments; 23 naturalised flows and 13 observed flow records from benchmark catchments (Bradford and Marsh, 2003). These 36 records are all of the natural or naturalised records held by the NRFA from catchments with areas above 300 km^2 (>5 grid cells), and with continuous observed record of at least two calendar years. The catchments are listed in Table A.1 and shown on the map in Figure A.1.

Note that as GWAVA estimates the catchment area as a number of cells this can be significantly different from the actual catchment area. To correct for this error, the measured discharge was multiplied with the ratio of modelled to measured catchment area.

Table A.1: Catchments used for calibration

NRFA ID	Gauge type	River	Location	Catchment area (km^2)	Error (Equation 1)
8004	Benchmark	Avon	Delnashaugh	542.8	0.36
12001	Benchmark	Dee	Woodend	1370.0	0.26
21006	Benchmark	Tweed	Boleside	1500.0	0.32
23001	Naturalised	Tyne	Bywell	2175.6	0.37
23004	Benchmark	South Tyne	Haydon Bridge	751.1	0.36
25001	Naturalised	Tees	Broken Scar	818.4	0.26
25008	Naturalised	Tees	Barnard Castle	509.2	0.39
26002	Naturalised	Hull	Hempholme Lock	378.1	0.40
27009	Naturalised	Ouse	Skelton	3315.0	0.34
27015	Naturalised	Derwent	Stamford Bridge	1634.3	0.28
27071	Benchmark	Swale	Crakehill	1363.0	1.14
27079	Naturalised	Calder	Methley	930.0	0.17
28012	Naturalised	Trent	Yoxall	1229.0	0.14
33002	Naturalised	Bedford Ouse	Bedford	1460.0	0.35
33019	Benchmark	Thet	Melford Bridge	316.0	0.29
33026	Naturalised	Bedford Ouse	Bedford	2570.0	0.33
36015	Naturalised	Stour	Lamarsh	480.7	1.03
39001	Naturalised	Thames	Kingston	9948.0	0.21
39002	Naturalised	Thames	Days Weir	3444.7	0.27
39034	Benchmark	Evenlode	Cassington Mill	430.0	0.28
39046	Naturalised	Thames	Sutton Courtenay	3414.0	0.82
42010	Benchmark	Itchen	Highbridge+Allbrook	360.0	0.18
50001	Naturalised	Taw	Umberleigh	826.2	0.32
50006	Naturalised	Mole	Woodleigh	327.5	0.30
54001	Naturalised	Severn	Bewdley	4325.0	0.23
54005	Naturalised	Severn	Montford	2025.0	0.40
54014	Naturalised	Severn	Abermule	580.0	0.42
55002	Naturalised	Wye	Belmont	1895.9	0.43
55007	Naturalised	Wye	Erwood	1282.1	0.53
55023	Naturalised	Wye	Redbrook	4010.0	0.52
64001	Benchmark	Dyfi	Dyfi Bridge	471.3	0.31
66011	Naturalised	Conwy	Cwm Lanerch	344.5	0.22
79002	Benchmark	Nith	Friars Carse	799.0	0.32
81002	Benchmark	Cree	Newton Steward	368.0	0.41
94001	Benchmark	Ewe	Poolewe	441.1	0.25
96002	Benchmark	Naver	Apigill	477.0	0.27

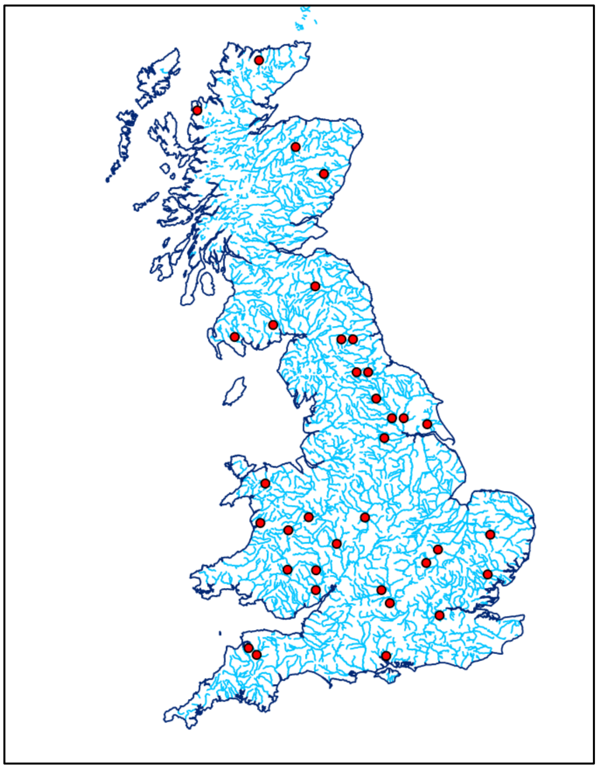


Figure A.1 *Location of catchments used in model calibration*

Table A.2: *Bounds of calibrated parameters*

Calibrated parameter	*b*	*fact*	S_{rout}	G_{rout}
upper bound	4	4	1^2	100
expected value	1	1	-	
lower bound	0.25	0.25	0	0^1

1: *A negative value of G_{rout} is allowed. However, this means that there is no routing, i.e. all water that drains from the soil store becomes baseflow immediately without being temporarily stored in the groundwater store.*

2: *S_{rout} values above 1 are allowed, however then surface routing is modelled as if S_{rout} is 1*

A.2 Extrapolation of calibrated parameters to ungauged catchments

This section describes how the optimal parameter values found for the four parameters in gauged catchments are extrapolated to the rest of the UK. This was done by relating the spatial distribution of calibrated parameters to catchment descriptors that are available nationally, e.g. elevation. Note that it is not necessary to estimate *fact* as this parameter adjusts observed data to aid calibration.

A.2.1 Correlations used in the parameter extrapolation

It was found that the natural logarithm of calibrated parameter G_{rout} (Groundwater routing coefficient) was weakly correlated with mean catchment elevation, as shown in Figure A.1.
A possible physical explanation for this is that aquifers are generally larger in lowland locations.

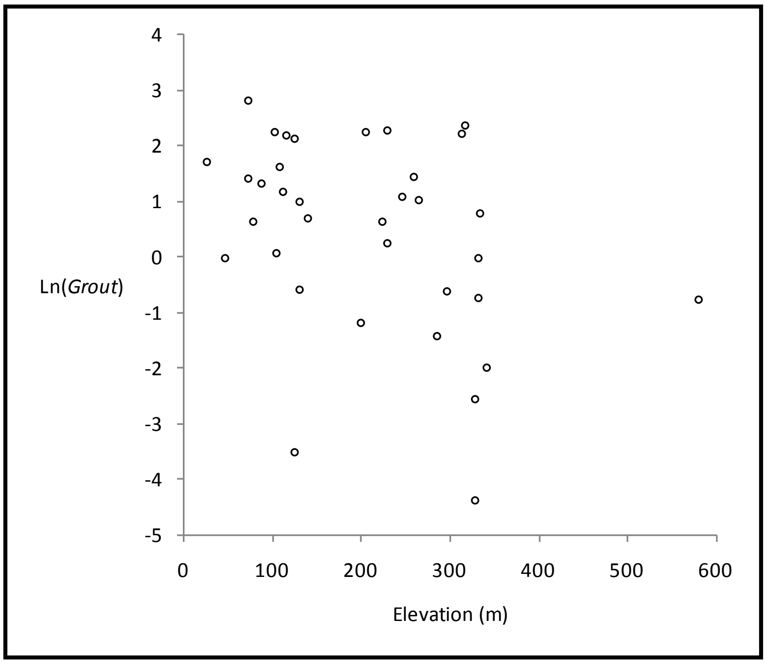


Figure A.2: *Calibrated values of the natural logarithm of parameter G_{rout} versus average catchment elevation*

There was a similar weak relationship between the natural logarithm of calibrated parameter S_{rout} (surface water routing coefficient) and the baseflow index derived from the BFIHOST map contained in Hydrology of Soil Types report (Boorman et al., 1995), as shown in Figure A.3. This may be explained by the fact there is generally less overland flow if the percentage baseflow is higher, thus leading to longer surface residence times (i.e. smaller S_{rout}).

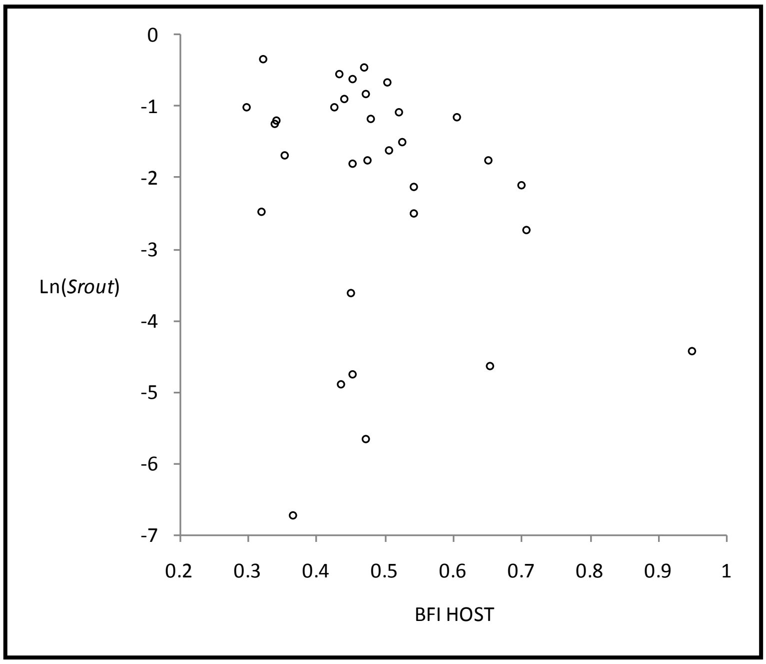


Figure A.3: *The natural logarithm of the calibrated values of parameter S_{rout} versus the average BFI index in the corresponding calibration catchments*

Parameter *b* is weakly correlated to the calibrated parameter S_{rout} (surface water routing coefficient), as shown in Figure A.3. This may be explained physically as a smaller soil moisture store (i.e. a large b) is generally associated with lower surface storage (large S_{rout}).

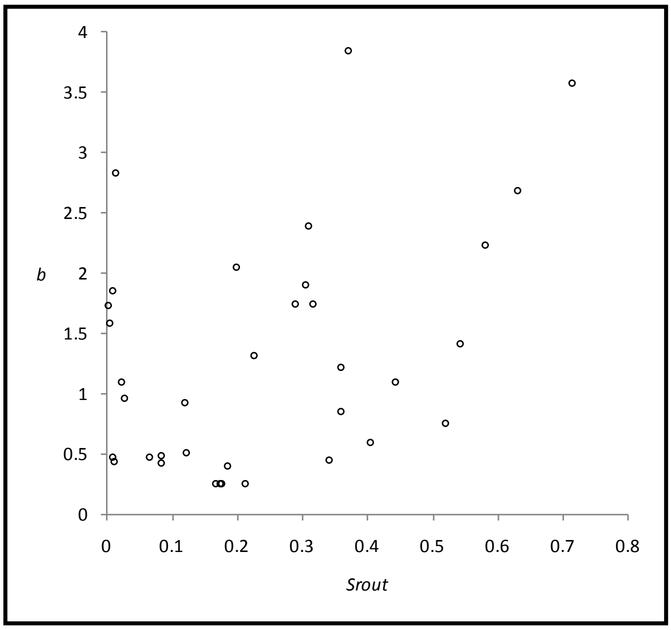


Figure A.4: *Calibrated values of parameter b versus the calibrated values of parameter S_{rout}.*

A.2.2 Derived functions

From these admittedly weak correlations, the following functions have been derived.

$G_{rout} = 9.025 \cdot e^{-0.008 \cdot Elev}$		(Equation A.2)
$S_{rout} = 6.686 \cdot e^{-7 \cdot BFIHOST}$	if $0.271 < BFIHOST$	(Equation A.3)
$S_{rout} = 1$	if $0.271 > BFIHOST$	(Equation A.4)
$b = 0.125 + 3.469\ S_{rout}$	if $0.12 < S_{rout}$	(Equation A.5)
$b = 0.54$	if $0.12 > S_{rout}$	(Equation A.6)

The range in which the function for S_{rout} can be applied corresponds to the physical limit if the possible values of S_{rout}. In the case of *b*, the lower bound of the range is based on the scatter plot shown in Figure A.4.

A.3 Validation modelled runoff and discharge

The weak nature of the correlations presented above, and the resulting uncertainty associated with the developed relationships might imply that simulations using them would be highly unreliable. This can be tested by comparing the model simulations with independent data. This is done in three ways at three different scales.

Firstly, such a comparison has been made at the UK scale on the basis of long-term (average) runoff. GWAVA's modelled average runoff for the period 1980-2000 is presented in Figure A.5. This can be compared visually with the map of long-term average composite runoff (Fekete *et al.* 2002); and a map of estimated runoff provided by the Nation Hydrological monitoring programme (Marsh, personal communication). While the patterns and magnitude of all three datasets are similar, the different periods and resolutions allow only a general comparison to be made.

In fact this comparison introduces an interesting point about what a map of runoff actually represents. It's only in exception circumstances that an observer would actually see "runoff" even in the wettest areas; in the drier areas there would never be observable runoff. Runoff must be interpreted as an excess of rainfall over evaporation; this excess is only likely to become available at the larger scale and when aggregated into river channels.

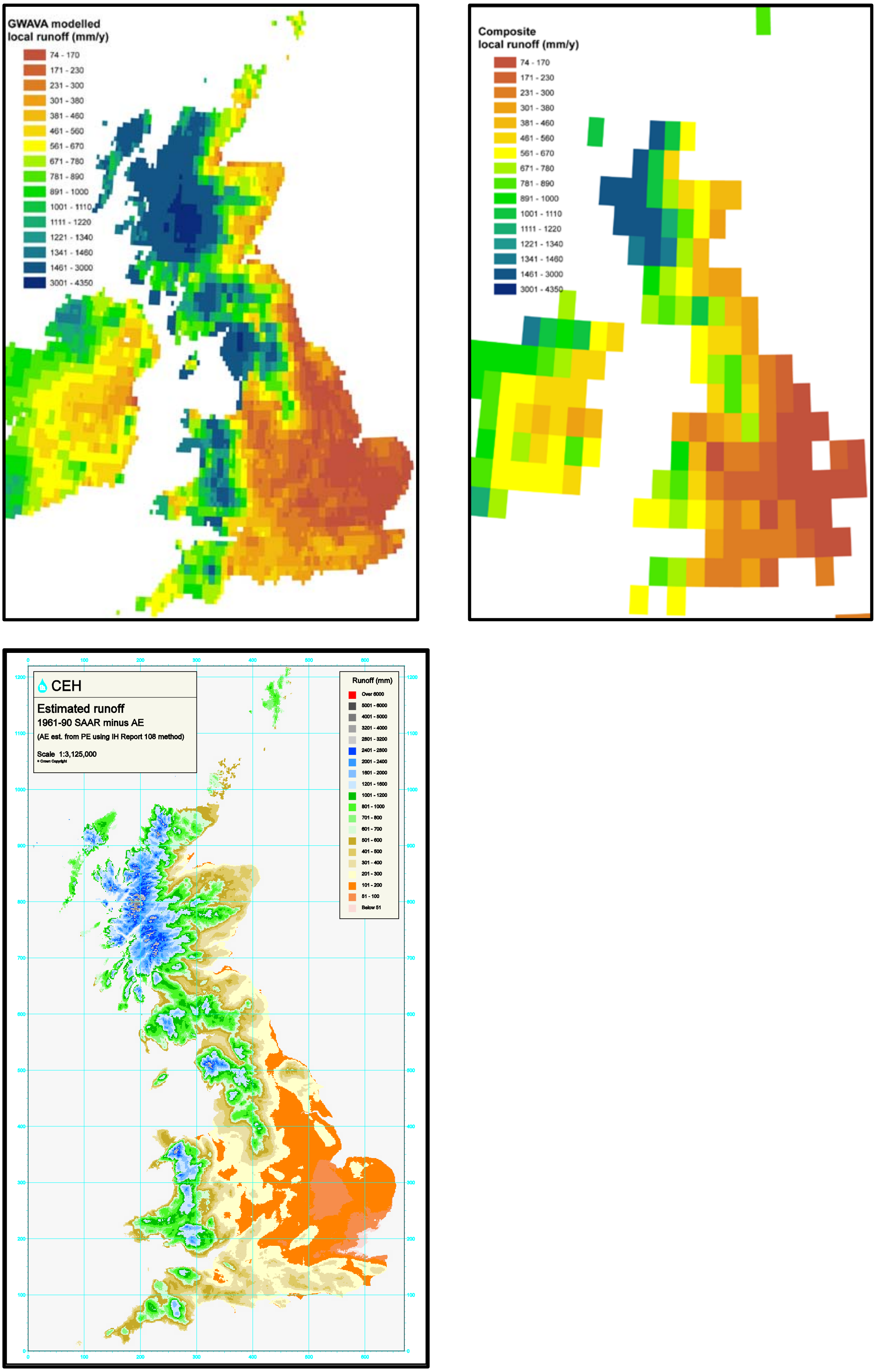


Figure A.5: *GWAVA modelled 1980-2000 average runoff (mm/y) left, Long-term average composite runoff (mm/y) (Fekete et al. 2002) right, Long-term average runoff estimated by the Centre for Ecology & Hydrology (mm/y)(bottom).*

Secondly, a comparison can be made between the modelled and measured, or naturalised, hydrographs of river discharge. Using the same measure of goodness-of-fit as used in the optimisation, but now using model parameters estimated using the equation constructed in section, a set of error values can be derived for the 35 catchments used previously. These are plotted in Figure A.6 and show that for 86% of these catchments the error is below 0.44. Remember that with this statistic zero represents a perfect fit and that 1.0 represents the situation in which the magnitude of the cumulative absolute difference between modelled and observed flows is the same as the magnitude of the observed flow, and represents a very poor simulation.

The calibration process was largely automatic and on investigation it was found that these sites were somewhat compromised by short records for which the warm-up period of the model was likely to have an undue influence. This calibration should be revisited in any follow-up study.

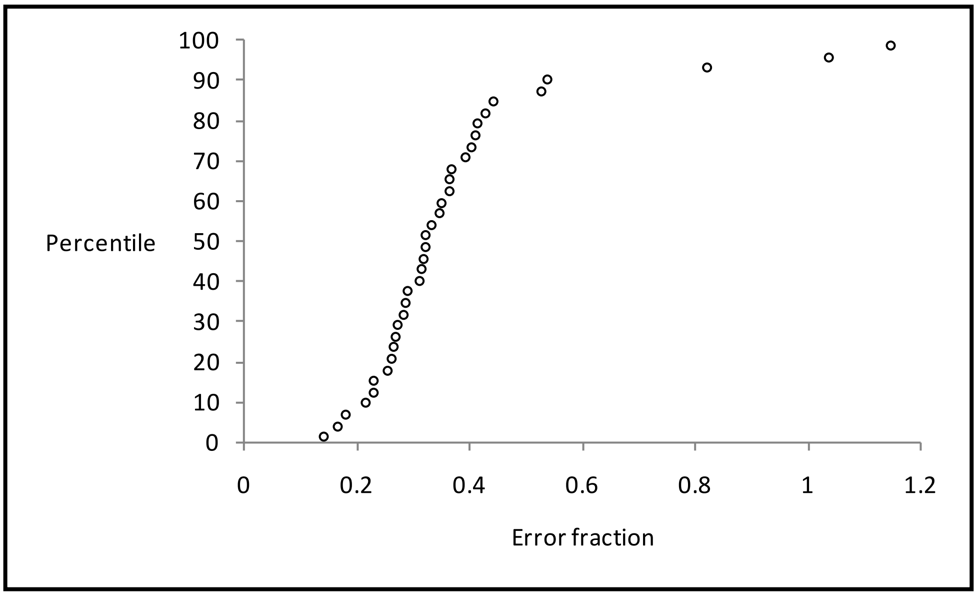


Figure A.6: *Error fraction for each modelled natural or naturalised river versus the percentile of the error fraction.*

Thirdly, the model simulations can be compared as time series of flows on individual rivers. Figure A.6 gives an example of GWAVA's ability to model the naturalised discharge of the Thames at Kingston, this being largest gauged river basin with naturalized discharge. As can be seen the simulations are generally good.

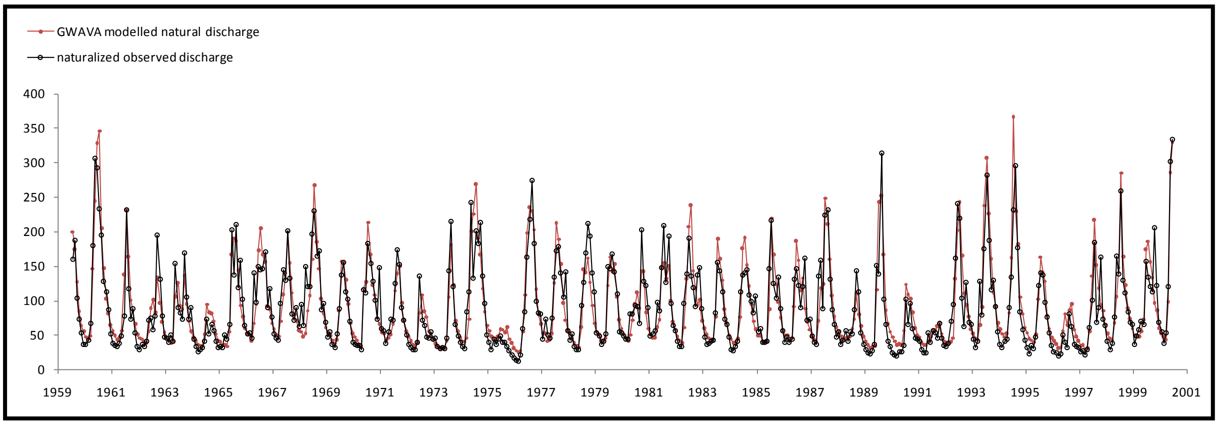


Figure A.7: *GWAVA modelled natural discharge ($m^3\ s^{-1}$) versus naturalised observed discharge in the Thames at Kingston gauge (source: NRFA)*

Finally, a similar comparison is made, but this time using observed flows, i.e. uncorrected for abstractions and returns. Figure A.7 again shows this comparison for the River Thames. The simulation here is less satisfactory. This is because demands have not been met in the very many cells that comprise the Thames catchment. For example, a town like Swindon not on a major river will not have its demand met. In practice such demands are met by transferring water within water supply zones. Note that the periods presented in Figure A.7 and A.8 are different, in the latter the baseline period is used, whereas the former uses an extended period intended to represent model performance over a wider range of conditions.

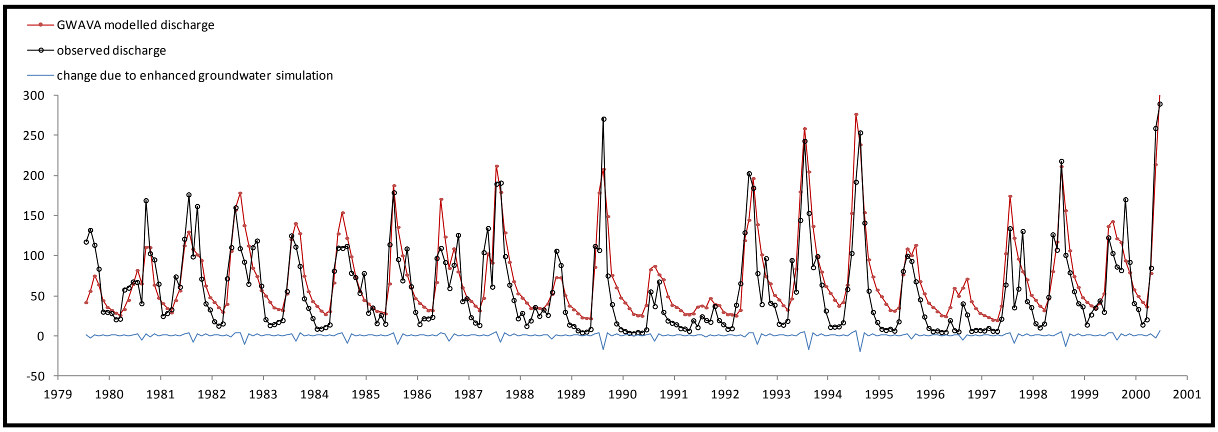


Figure A.8: *GWAVA modelled human-influenced discharge ($m^3\ s^{-1}$) versus observed discharge in the Thames at Kingston gauge (source: NRFA). The change in GWAVA modelled river discharge due to the enhancement of GWAVA's groundwater simulation is also shown.*

APPENDIX B: Improving the Groundwater model

The description of the rainfall-runoff model within GWAVA presented in Section 4.1.1 includes an element termed a groundwater store. This store provides long term storage of water in the way in which an aquifer might, but is in several ways over-simplistic. This Appendix describes the development of an improved groundwater model.

B.1 Data and Methods

B.1.1 Enhancements to GWAVA's groundwater simulation

A groundwater model has been developed for GWAVA which retains the original mathematical solution as described by Moore (2007). This uses two parameters: the storage rate coefficient (K) and the initial storage per unit area (S_{init}) to iteratively simulate storage and baseflow over time and space from recharge and abstraction driving datasets. A number of modifications have been made, however, in an attempt to build a more hydrogeologically informed groundwater modelling component.

Instead of formulating one analytical solution over the entire GWAVA grid domain, the model area has been divided into multiple classes based on hydrogeological properties of the sub-surface. Separate models can then be calibrated for each unique class in an attempt to account for the variable behaviour of contrasting geological formations. Five aquifer classes have been chosen in total using a 625km geological map of the UK. These include the Chalk, Permo-Triassic, Inferior Oolite, Middle Old Red Sandstone (MORS) and Scottish Midland Valley Aquifers (SMVA) (Figure B.1). The areas that are not covered by these five classes are assumed to be either 'non-aquifers' i.e. they do not receive recharge, provide water for abstraction or produce baseflow, or 'poor-aquifers' in which case they contribute relatively insignificant baseflows.

Importantly, the detail provided by the aquifer classification map is much greater than the resolution of the GWAVA model grid. In order to incorporate this detail, the resolution of the groundwater model has also been enhanced so that for every GWAVA node there are now nine groundwater model nodes on a 3x3 grid. When the groundwater model is run, each node is realised using its associated aquifer model (as defined from by the aquifer class map), producing distributed estimates of baseflow over time. Baseflows are also aggregated back up to the GWAVA grid resolution to produce time series data that is comparable to the surface water outputs of the GWAVA model.

Finally, flexibility has also been introduced into the groundwater model so that it can be calibrated using catchments that are independent from the catchments used to calibrate the surface water component of GWAVA. This allows the user to delineate independent groundwater catchments which is important as groundwater catchments often differ greatly from the surface water catchment for a particular flow gauge. For this initial report, this aspect of the groundwater model has not been tested, but nonetheless, the option is now available.

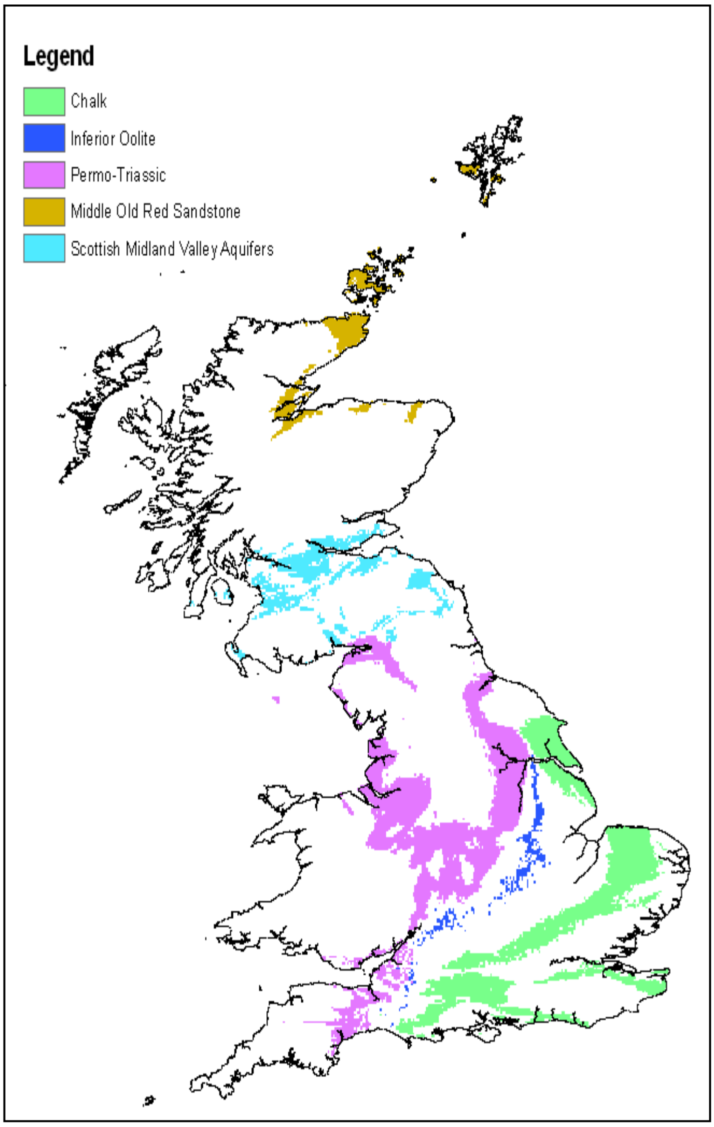


Figure B.1: *Map of the five aquifer classes chosen for the groundwater model.*

In summary the main enhancements are listed as follows:

- Model grid can now be divided into multiple aquifer classes with the option of calibrating a unique model for each classification.
- The model now works on a higher resolution to incorporate detailed datasets as well a produce high resolution baseflow and water security outputs.
- Groundwater catchments can now be defined independently of surface water catchments for model calibration.

Whilst the groundwater model has been subject to considerable development, a number of key assumptions have been made that will be addressed later. These are detailed in Table B.1.

Table B.1: List of assumptions made during development of the GWAVA groundwater model along with potential implications and limitations of these assumptions.

Assumption	Implications and limitations
All geological units can be lumped into five unique aquifer classes or a sixth non-aquifer class.	Groundwater systems are known to be extremely complex. Even within a single geological unit, there are likely to be considerable heterogeneities in hydrogeological properties which are not considered here.
Groundwater catchments are identical to surface water catchments. Note, this assumption can be avoided by delineating separate groundwater catchments.	Total recharge input and abstraction outputs are inaccurate when estimating baseflow at gauged catchments. This could be detrimental to model performance.
Groundwater abstractions can only occur if there is sufficient water available. Demand does not need to be met (For baseline scenario only).	This is incorrect and a major flaw in water security estimates for the baseline simulation.
Baseflow generated at a model node within a catchment reaches the corresponding flow gauge instantaneously.	This flow routing method is simplistic in that it does not consider flow times based on distance from gauge for example. This could be detrimental to model performance.
The Nash-Sutcliffe Efficiency (NSE) is an adequate measure of model performance.	The NSE is known to preferentially fit higher flows over the low flows (troughs in the hydrograph). This skews the model parameters during calibration and can lead to overestimation of low flows (therefore missing important indicators of water security).
Those areas covered by open water bodies (lakes, marshes, wetlands) do not contribute any recharge	There could be significant interaction between surface water bodies and groundwater systems and therefore this assumption is incorrect.

B.1.2 Model Calibration

Each of the aquifer models have been calibrated against observed baseflow for a selection of catchments. The observed baseflows were obtained using the Institute of Hydrology low flow estimation technique (Gustard *et al.,* 1992). The model produces baseflow simulations by summing the estimated baseflows at each model node within a given catchment.

Initially, a selection of catchments from the 37 used to calibrate the surface water component of GWAVA have been chosen for calibration of the groundwater model based on a simple quantitative analysis. Specifically, the percentage aquifer coverage has been calculated for each catchment along with the total number of aquifer model nodes. An initial criterion of at least 55% aquifer coverage and/or at least 150 aquifer model nodes has been used, resulting in 11 catchments in total. However, aquifer classes four and five are not represented in these 11 catchments. As such, two additional catchments have been delineated resulting in 13 calibration catchments in total.

Preliminary calibration results using the 13 catchments have shown to be poor. In particular, catchments with the same aquifer classes often converge on contrasting analytical solutions or parameters show little or no sensitivity. In response, one catchment has been chosen to represent each aquifer class. These catchments are highlighted in TableB.2 and shown in Figure B.2.

Table B.2: Summary of statistics for five catchments chosen for model calibration.

Catchment	1	2	3	4	5
Total number of nodes	216	567	333	99	342
Total number of model nodes	151	154	235	47	125
Percentage aquifer coverage	69.91	27.16	70.57	47.47	36.55
Chalk Nodes	151	82	0	0	0
Inferior Oolite nodes	0	72	0	0	0
Permo-Triassic Nodes	0	0	235	0	0
MORS nodes	0	0	0	47	0
SMVA nodes	0	0	0	0	125

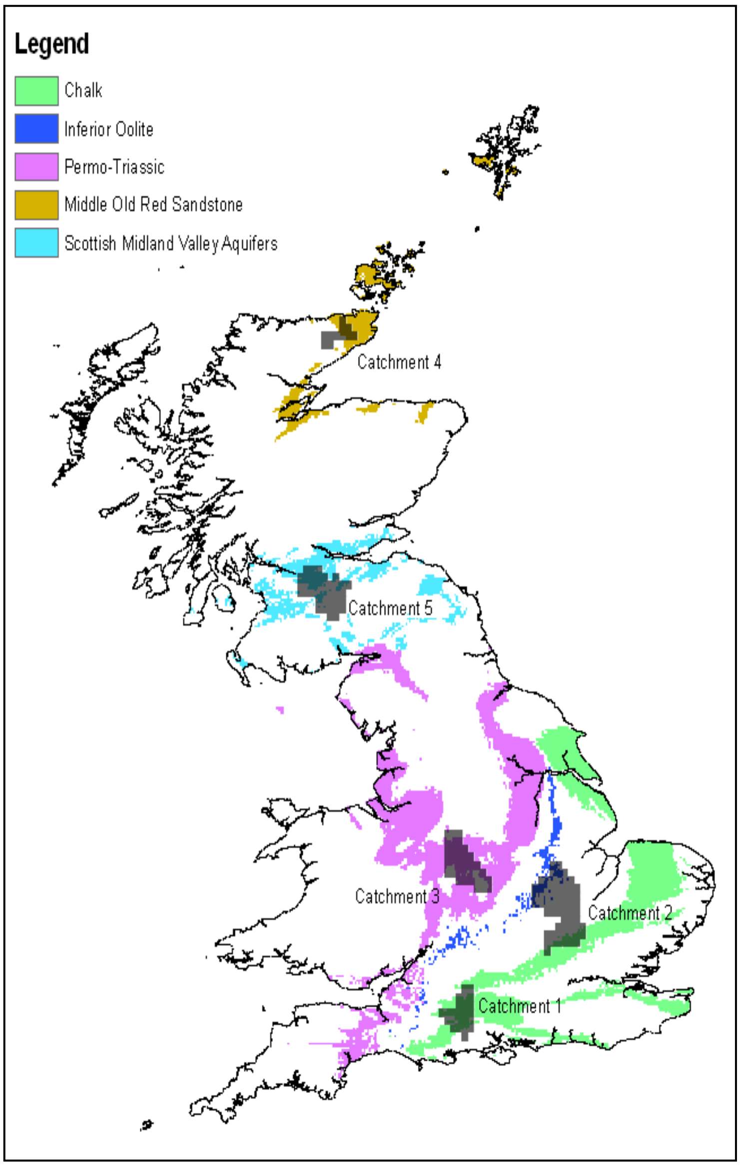


Figure B.2: Map of the five aquifer classes chosen for the groundwater model along with five catchments chosen to calibrate each class model.

A Monte Carlo calibration approach has been used to calibrate each of the aquifer models simultaneously. For each Monte Carlo calibration run, parameter values are drawn randomly from a uniform distribution within a defined range; the model is run and then evaluated. The Nash-Sutcliffe Efficiency (NSE) is used as a measure of model fit which ranges from 1 (perfect fit) to $-\infty$. A value of zero is equal to taking the mean of the observations and a negative value is worse than this. To allow for the model to 'warm up' and avoid the effects of initial conditions, the NSE has only been calculated on the last 90% of data.

The calibration method can be summarised in the following steps:

1. Define appropriate initial parameter values for S_{init} and K (0 to 10 for S and 0 to 200 for K).
2. Run 10000 Monte Carlo Simulations
3. Analyse parameter 'dotty' plots for parameter sensitivity
4. Analyse time series data for model behaviour
5. If best possible fit has been achieved, stop calibration, else continue to step 6.
6. Re-adjust parameter bounds based on steps 3 and 4 and return to step 2.

B.1.3 Extrapolation to un-gauged catchments

Once a mathematical solution has been calibrated for each of the aquifer classes, the solution is then extrapolated from the calibration catchments over all classified aquifers. By doing this, baseflow can be estimated at high resolution on a national scale.

B.2 Results

B.2.1 Calibration

Initial results from calibration show that the groundwater model performs poorly with an overall NSE of -0.545. Closer analysis of the time series reveals that all aquifer models struggle to reproduce the peak flows (Figure B.3). The Permo-Triassic and SMWA models also consistently underestimate low flows suggesting an overall lack of recharge input in their corresponding catchments. The Inferior Oolite model shows to be especially bad with an individual NSE of -0.79908 (Table B.3). Indeed, the time series reveals that this model shows little or no recognition of peak flows. This is also reflected in the optimum K value of 200,000; at least four orders of magnitude higher than the other aquifer models. Such a high K value demonstrates that the model needs to compensate by introducing unrealistic parameters.

Table B.3: Summary of optimum parameter values and performance of each aquifer model in the GWAVA groundwater model.

Catchment/Model	S_{init}	K	NSE
C1: Chalk	0.928	0.116	0.755
C2: Inferior Oolite	0.656	200000	-0.799
C3: Permo-Triassic	0.197	35.080	-0.149
C4: MORS	0.993	33.545	0.216
C5: SMVA	0.394	480.600	-0.507

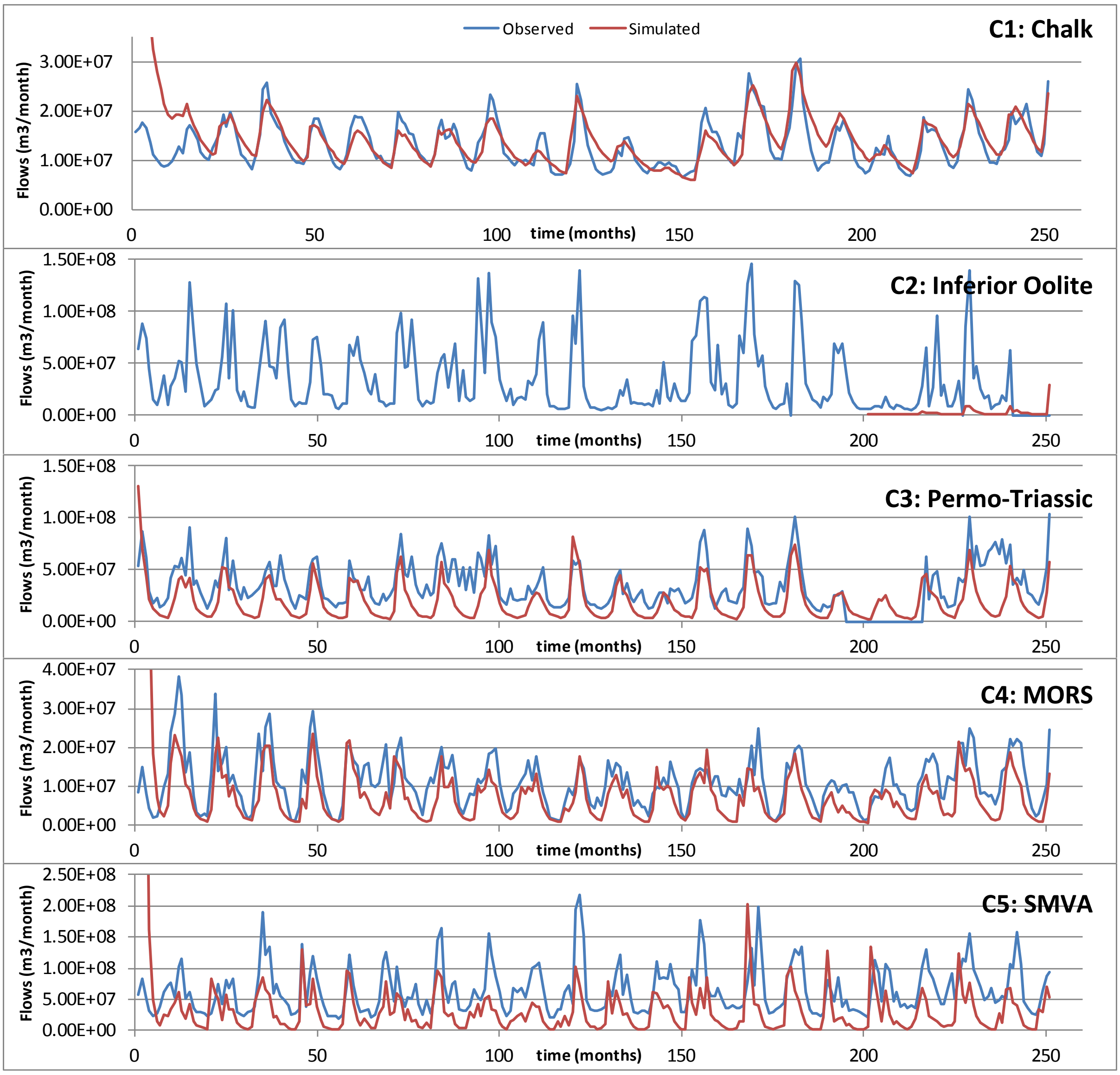


Figure B.3: *Time series plots of observed baseflows against simulated baseflows for each catchment / aquifer model.*

It should be noted that it is catchment two that has the biggest portion of non aquifer of 72.84%. Furthermore, the rest of the catchments have ~44% of their sub-surface classed as non – aquifer. Importantly, this means that an equivalent percentage of the recharge and abstractions are ignored and never end up as baseflow at the catchment outlets. This phenomenon in conjunction with the recurring problem of underestimating flows suggest that the non aquifer may in fact receive recharge and contribute to baseflow.

In response, a second groundwater model has been calibrated. This time, instead of assuming that all of the sub-surface that falls outside of the original five aquifer classes does not conduct water, it has now been designated as a ‘poorly conducting aquifer’. In contrast to the previous model, the calibration procedure uses constrained values of K and S (0 to 1 and 0 to 5 respectively) to allow this poor aquifer portion of the UK to contribute small amounts of baseflow.

Results from this second groundwater model show to be more promising with an overall NSE of 0.251. There is a noticeable jump in simulated baseflow for all catchments, highlighting the impact of including extra nodes, and thus extra recharge on the overall catchment water balances (Figure B.4). This increase improves model efficiency for the Inferior Oolite, Permo-Triassic and SMVA aquifer models by 63%, 293% and 206% respectively (Table B.4). In contrast, the inclusion of the poor aquifer has a detrimental effect on the performance of the Chalk and MORS models with a respective loss in efficiency of 146% and 68%.

Certainly, this is reflected in the sensitivity of each model with respect to the K parameter chosen for the 'poor aquifer'. While a relatively low value of K is preferable for all models, the Inferior Oolite, Permo-Triassic and SMVA models are most efficient when K is near to 0.02 whilst the Chalk and MORS models perform best when K is near zero (Figure B.5). This could be an artefact of using surface water catchments as opposed to groundwater catchments which may have a detrimental effect on the total recharge and abstraction rates which comprise each catchment's water balance. However, the sensitivity analysis suggests that the behaviour of the poor aquifer in one catchment is not necessarily comparable to its behaviour in another and may in fact highlight the inherent problem of lumping together what is known to be a heterogeneous sub-surface into one single class.

Even, with the apparent improvement in model efficiency, the Inferior Oolite model still shows to be poor at reproducing the observed baseflow hydrograph where it consistently underestimates peak flows. Analysis of the driving data demonstrates that of all the catchments, catchment two is the only one where the long term average net inflow is smaller than the corresponding observed baseflow (Figure B.6). In other words, there is insufficient water in catchment two to produce the required baseflow. To counteract this problem, the Inferior Oolite model converges on an unrealistically high value of K.

On the contrary, the chalk model has a relatively low value of K. Analysis of the simulated hydrograph reveals that the model appears to struggle by overestimating the peak flows. Thus, a smaller K is optimum as it reduces flashiness and hence hydrograph peaks. However, this also results in larger low flows at the troughs of the hydrograph which in conjunction with overestimating the peaks, results in a poor NSE.

The Permo-Triassic, MORS and SMVA model all converge on values of K between 23 and 36 and demonstrate the best model efficiencies.

All models have an optimum S_{init} between 0 and 1. Interestingly the poor aquifer has the highest initial storage. This is counterintuitive, although it should be stressed that this parameter shows little sensitivity (if any) for all aquifer classes (Figure B.7). This is understandable as its effect is lost through time (and potentially within the warm up period of the model). As such these parameter values cannot be expected to be representative of a particular aquifer class.

Table B.4: *Summary of optimum parameter values and performance of each aquifer model in the GWAVA groundwater model when the non aquifer is changed to a poor aquifer.*

Model/Catchment	S_{init}	K	NSE
C1: Chalk	0.770	0.074	-0.345
C2: Inferior Oolite	0.301	988300	-0.299
C3: Permo-Triassic	0.351	35.680	0.287
C4: MORS	0.610	23.416	0.069
C5: SMVA	0.790	28.095	0.639
Poor Aquifer	1	0.017	NA

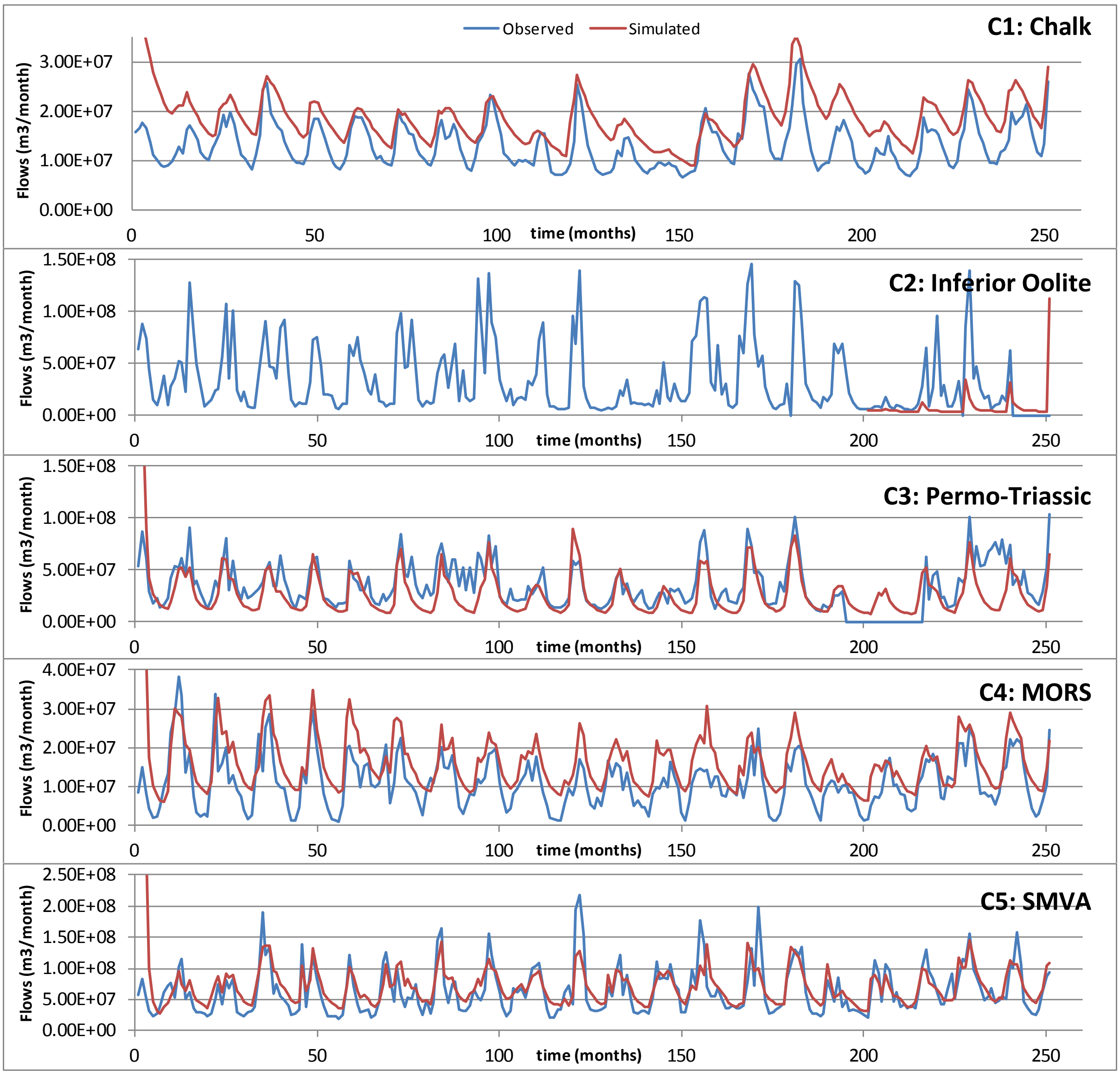


Figure B.4: *Time series plots of observed baseflows against simulated baseflows for each catchment / aquifer model after 'non aquifer' class has been changed to 'poor aquifer' class.*

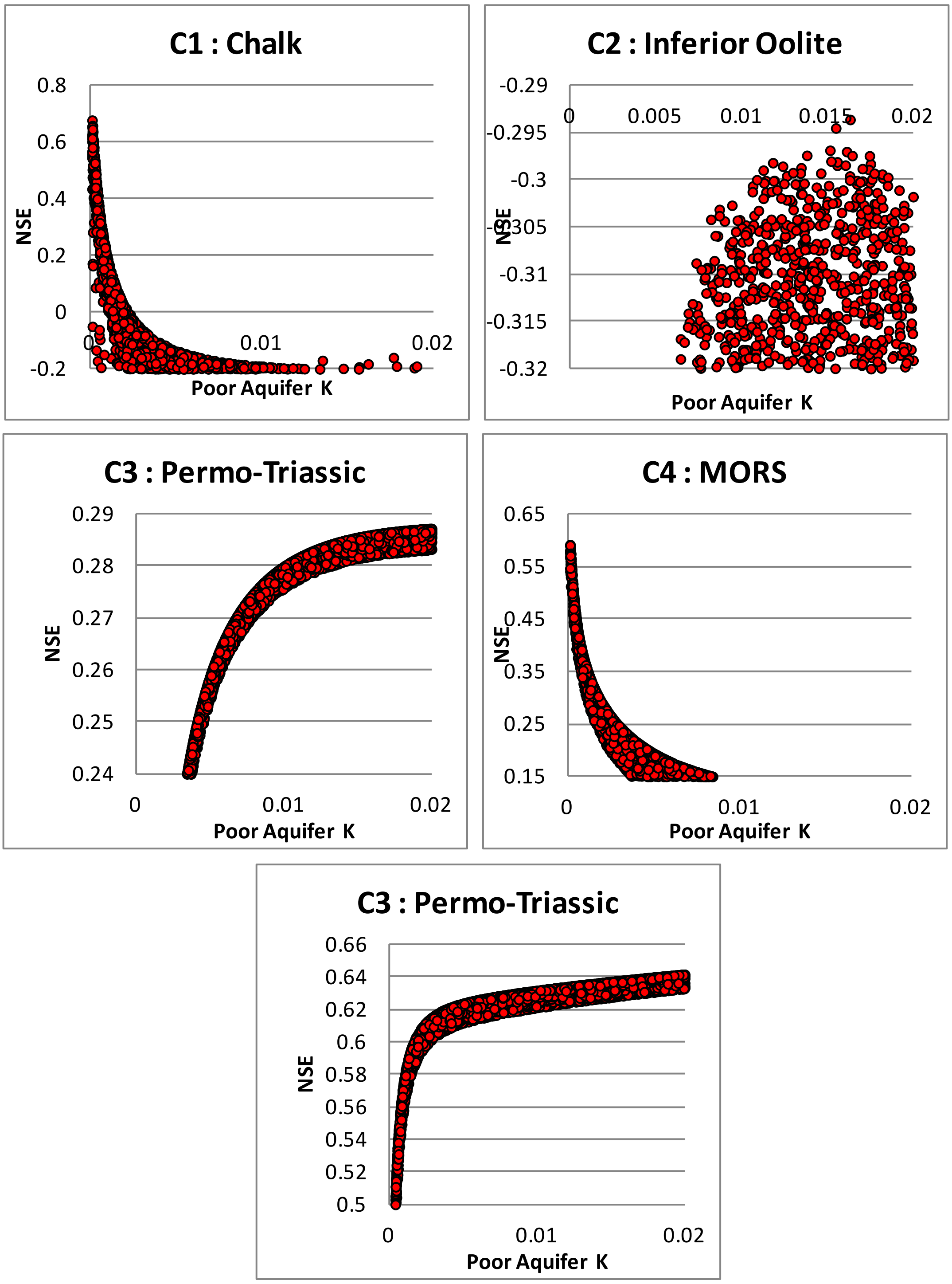


Figure B.5: *Dotty plots of poor aquifer K parameter value against NSE for each calibration catchment used.*

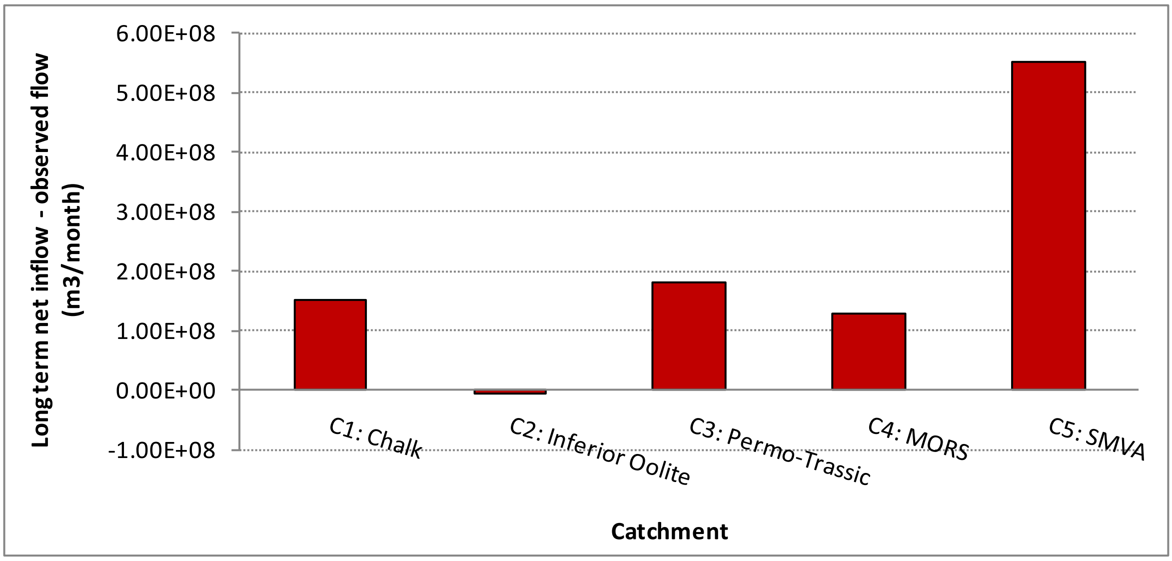


Figure B.6: Comparison of long term average net inflow minus the long term average baseflow for each catchment.

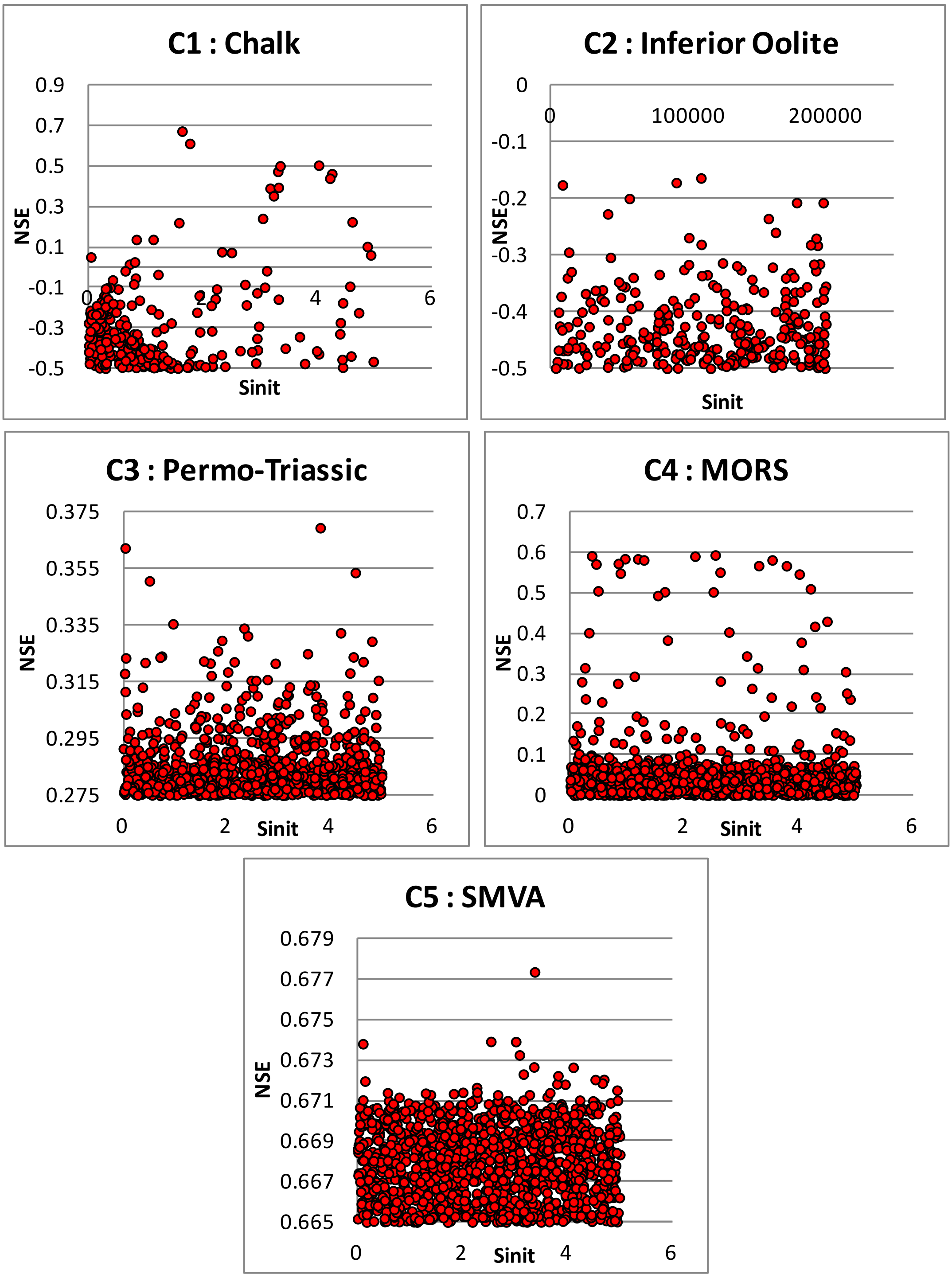


Figure B.7: *Dotty plots of S_{init} parameter values against NSE for each catchment.*

The overall baseflow distribution produced by the calibrated model largely reflects the recharge distribution, although there are some exceptions to this (Figure B.8). For example the baseflows along the coast of the British Isles tend to be small; most probably due to the small land cover for the grid cells here. The Inferior Oolite generates by far the largest baseflows, some of which are three orders of magnitude larger than anywhere else in the UK. These exceedingly high flows are induced by the high K value calibrated for the Inferior Oolite model, making it very flashy in response to recharge. This allows any stored to water to flow quickly and in large volumes. The flows are unrealistic and highlight the potential for errors when extrapolating predictions in space. In this case the Inferior Oolite model has already shown to perform badly, resulting in unrealistic and erroneous parameters. These errors have been extrapolated over the entire aquifer resulting in unrealistic baseflow predictions. The remainder of the aquifer classes show to have much less influence over the baseflows and instead the flows are more heavily influenced by the recharge input.

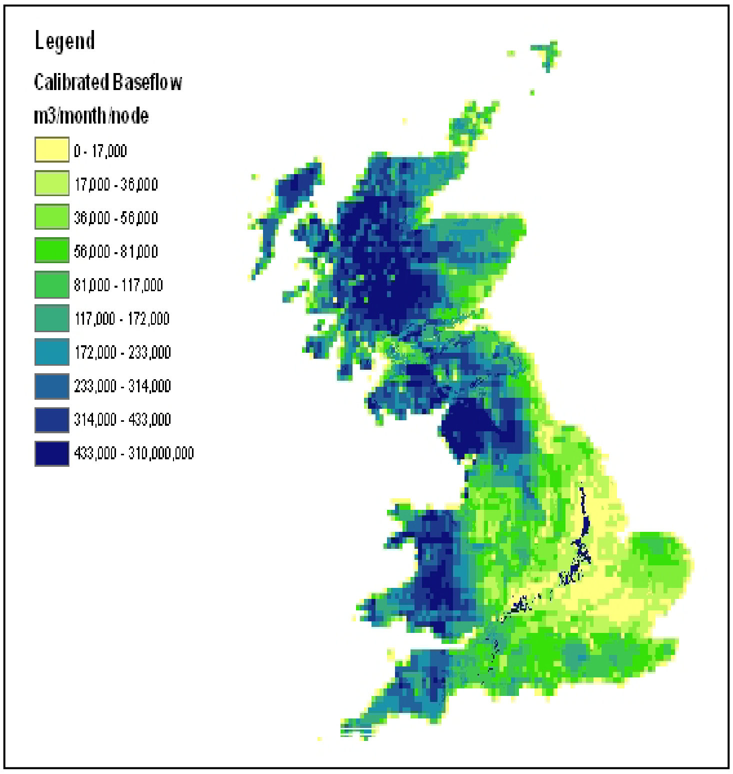


Figure B.8: *Distributed baseflow output from groundwater model over the UK in m^3/month/node.*

B.3 Assessment of recharge produced by GWAVA

Results from calibration have shown that the correct calculation of recharge values is of paramount importance to the refinement of the groundwater model. As such, a quantitative assessment of the recharge estimates produced by GWAVA has been undertaken by comparing them to the recharge values calculated by the BGS recharge model: ZOODRM (ref). It is important to note that the ZOODRM recharge output is by no means definitive or exact, and as such this exercise will highlight deficiencies and uncertainties in the results produced by both models.

Figures B.9 and B.10 display the distributed long term average recharge values calculated by GWAVA and ZOODRM respectively. Both models produce similar distributions of recharge, with the maximum values produced along the western coast of the British Isles. That the models show similar results is as expected because recharge is mainly driven by the rainfall and evaporation data which are similar in both models. More importantly, the range of the recharge values for both models are very similar; starting at zero and reaching just under 8 mm/day in both cases.

Nevertheless, there are still some notable differences between the two model outputs. In particular, the GWAVA recharge values calculated over South-East England and the majority of Scotland have more limited spatial variations than those calculated by ZOODRM. In fact, the smallest recharge estimates by GWAVA are all focussed in central and south-east England and the eastern coast of the British Isles, while ZOODRM has areas of minimal recharge distributed over the whole of Great Britain. This lack of spatial variability could have a detrimental effect on the recharge estimates by GWAVA. For example, over the chalk the range of recharge rates predicted by ZOODRM is between 0.3 and 1.6 mm/day. For GWAVA however, the majority of recharge rates fall between 0 and 0.6 mm/day. This is known to be much smaller than previous estimates of recharge in the chalk and therefore it is likely that GWAVA is underestimating the recharge rate of what is known to be an important aquifer.

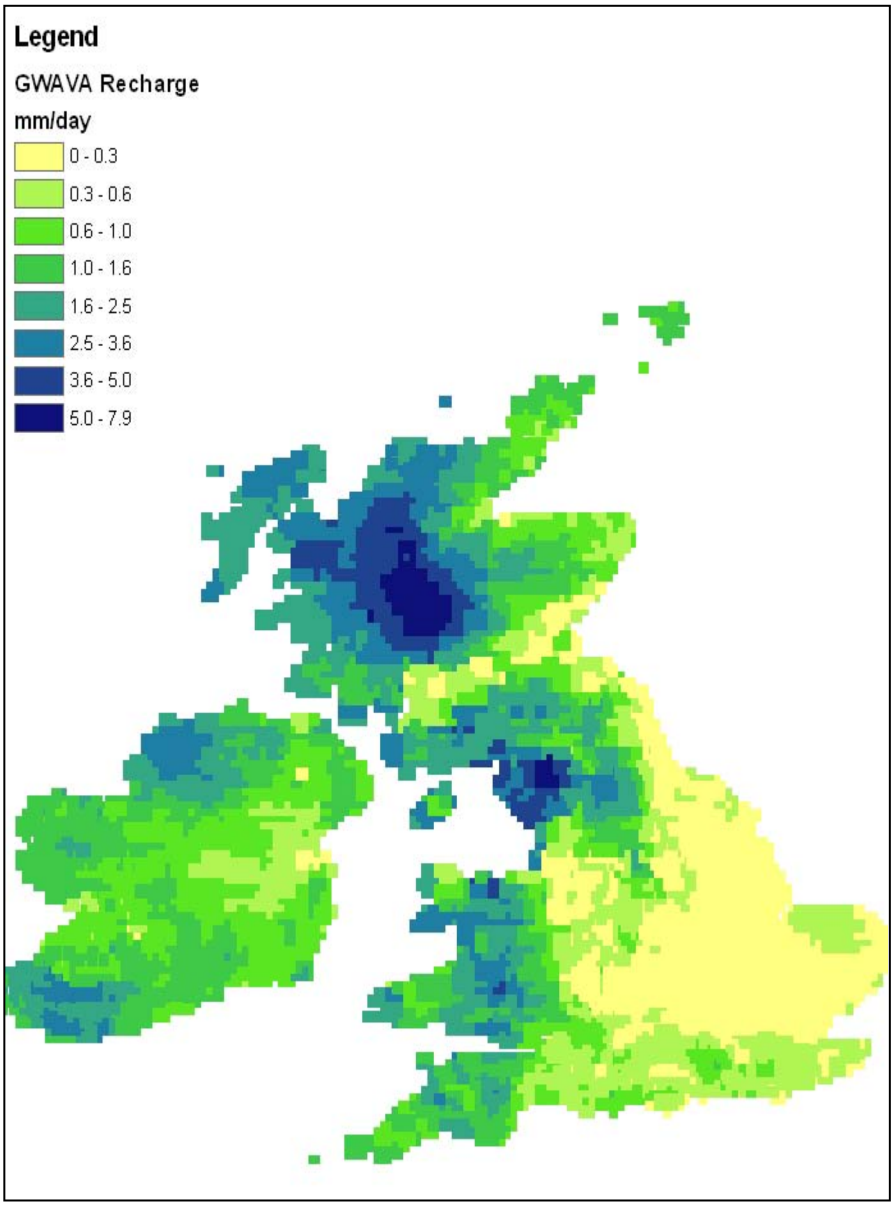


Figure B.9: *Distributed recharge output from GWAVA over the UK in mm/day.*

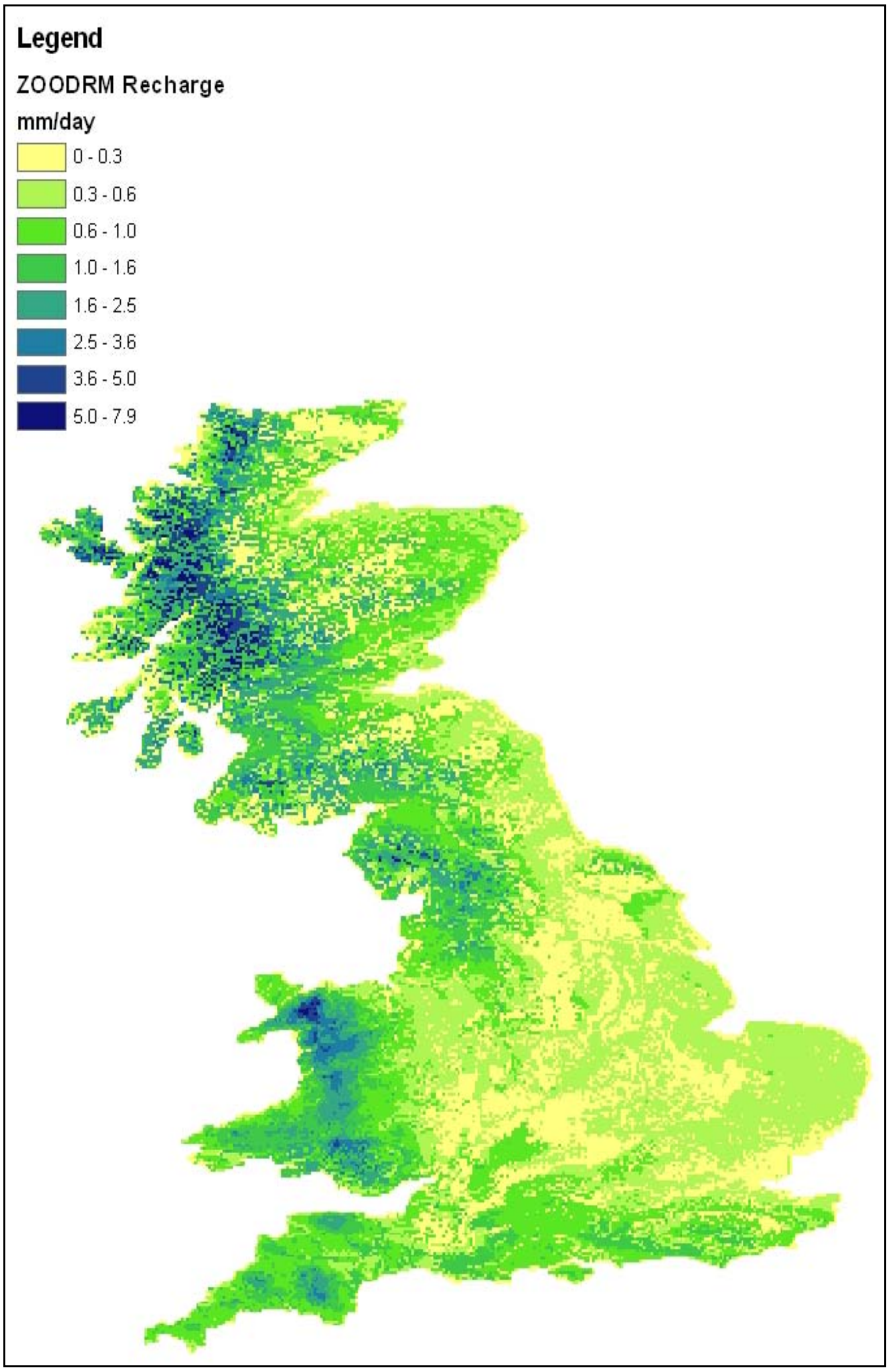


Figure B.10: Distributed recharge output from ZOODRM in mm/day.

To aid the comparison, a percentage difference map was created and this reinforces this point, demonstrating a consistent under-estimation of recharge in the central and eastern England by over 75% with respect to ZOODRM (Figure B.11). Furthermore, catchment two lies directly over this area which could explain the reason that long term average recharge is smaller than its associated baseflow as shown in Figure B.7.

Further North, and in particular in the North of Scotland, GWAVA shows a tendency to overestimate recharge with respect to ZOODRM by hundreds or even thousands of percent. Again, that does not mean that the GWAVA estimation is incorrect, however it may explain at least partially why catchment 4 overlying the MORS aquifer tends to overestimate baseflow. In fact, GWAVA recharge estimates for this catchment exceed those made by ZOODRM by over 1000% at some grid nodes.

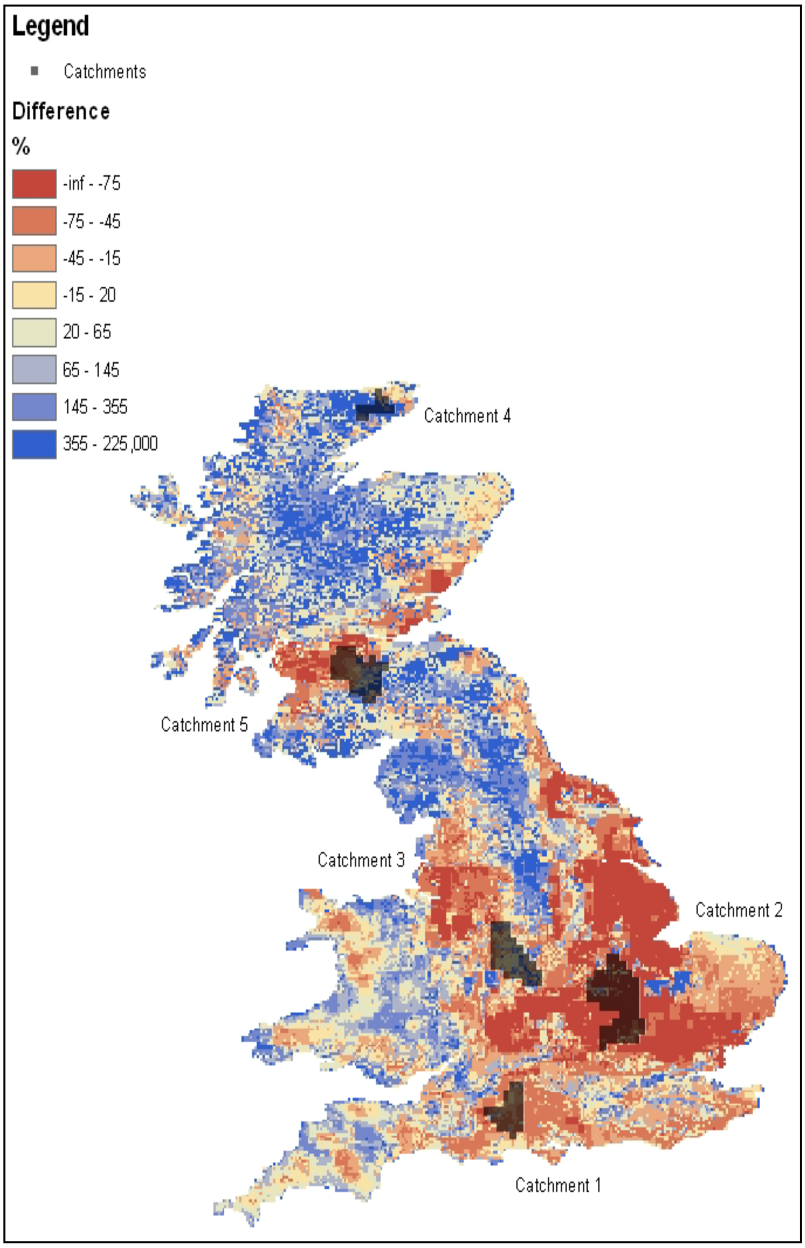


Figure B.11: Percentage difference between GWAVA and ZOODRM recharge estimates with five catchments superimposed. Note, a negative value indicates that the GWAVA estimate is lower than the ZOODRM estimate.

This comparison serves to highlight the uncertainties in recharge estimations over the UK, and possibly an explanation for some of the poorer results produced by the groundwater model. It should also be emphasised that whilst the calibration of the K and S_{init} parameters can serve to counteract inaccuracies in recharge input data to some degree, they cannot generate or reject recharge to/from the groundwater system i.e. modifying the water balance. Accurate recharge data are thus vital to producing a groundwater model that reproduces the observed baseflow.

B.4 Groundwater Security in the UK

B.4.1 Introduction

GWAVA produced recharge and abstraction data to feed into the groundwater model to undertake the scenarios. These data were run through the groundwater models to produce the scenarios. These scenarios have been analysed for water security in terms of the groundwater system. This analysis was undertaken independently from the assessment of the surface water systems. Seven future scenarios were run through the groundwater model.

B.4.2 Projected driving data

Two sets of driving data are used for the scenarios: recharge and abstraction data. Before describing the results, the driving data need to be described, in particular the differences between the baseline and the future projected. The overall distribution of the recharge data for the baseline simulation and under climate change remains the same with the largest recharge rates seen along the western side of the UK and in particular in north-west Scotland and the smallest recharge rates focussed in central and south-east England (Table B.5). On average, the recharge rates are predicted to increase by 0.055 mm/day. Furthermore, the difference plot indicates that the wetter regions to the west will get wetter and drier regions in the south of England, drier. This is reinforced by the standard deviation which shows to increase for the projected recharge under climate change.

The projected abstraction rates under population growth demonstrate an overall reduction in rates from an average of 0.099 mm/day to 0.072 mm/day. Generally it is assumed that population growth would result in an overall increase in abstractions, however the results here suggest the opposite. A possible reason for this is the method used to project the abstraction rates. More specifically, the baseline abstraction distribution exhibit large areas with rates < 0.01 mm/day, but also small localized areas (often a single GWAVA node in size) where rates can be as high as 144 mm/day, as indicated by the blue spots on the baseline abstraction map. On the contrary, the projected abstraction data shows a more gradual change in rates over the UK with a range of only 4.34 mm/day and this is emphasized by the spread of the baseline data which is more than an order of magnitude larger than the corresponding projected dataset. The majority of the UK shows an increase in abstraction under population growth as demonstrated by the difference map, but the loss of the localised high abstractions contained in the baseline dataset (signified by red spots in the difference map) results in an average reduction of abstraction rates of 0.027 mm/day.

The reduction of groundwater abstraction for the future projection may highlight a weakness in the method used for projecting abstraction rates and will be considered when interpreting these results. It should also be noted that the abstraction rates are assumed to be zero for the whole of Scotland for the baseline simulation. This is incorrect and will be considered in the scenario evaluation.

B.4.3 Water Security

The water security for the UK has been evaluated using a water stress index (WSI). This is calculated as the number of months in a given simulation in which the recharge exceeds abstraction. The maximum number of months equal to the simulation period, which is 251. This measure of water security is relative and cannot be used to quantify potential for water resource use, but can simply be used as a relative indicator of the effects that climate change and population growth will have on the UK's water resources.

As groundwater abstraction in Scotland is zero for the baseline, it cannot be represented in the percentage difference plots.

B.4.3.1 Baseline

The baseline water security map is understandably well correlated with the recharge data due to the nature of the WSI where central and south-east England show the highest water stresses (Table B.6). In fact some regions in the south-east have a WSI of 251 i.e. abstraction exceeds recharge for the entire modelling period. Scotland shows an ideal WSI of zero, but this is due to the zero abstraction assumption and should not be considered accurate.

There are also notable 'specks' of red along the coast of the UK which correlate with the exceedingly large abstraction rates reported in the driving data.

B.4.3.2 Scenario 1 – Projection under climate change

Climate change shows to increase the WSI on average by 3.8, suggesting that it will put the UK's water resources under more stress in the future. It is important to emphasize however, that a proportion of this increase can be attributed to the fact that Scotland's abstractions are assumed to be zero for this scenario resulting in a WSI of zero. It is also Scotland that shows that shows the greatest increase in recharge, but because the WSI is already zero throughout, there is no room for improvement. Instead, the WSI is more heavily influenced by the drying occurring in south of England; in particular along the English-Welsh boarder and in the south-west of England which show an increase in WSI of up to 83.8%. Regions north of Wales show a reduction in WSI by up to 23.5%.

B.4.3.3 Scenario 2 – Projection under population growth

The projected abstractions have a significant detrimental effect on the water resources of the UK with an average increase in WSI of 40.7. However, a large proportion of this increase can be attributed to Scotland with major abstractions occurring in and around Edinburgh and Glasgow which was otherwise assumed to be zero.

South of Scotland, the most affected areas are major industrial and economic hubs including London, Birmingham, Manchester and Newcastle which demonstrate rises in the WSI of up to 149%. The average percentage rise in WSI is 11.4%; more than that of scenario one.

Only very localised areas show an improved WSI, and these are highlighted in green in the difference maps. Actually, these relate to the exceptionally high abstraction rates observed in the baseline scenario which have been lost in the projected abstractions. Improvements here are as high as 100%.

B.4.3.4 Scenario 3 – Inclusion of water supply infrastructure

Interestingly, by including the water supply infrastructure, the overall effect in the WSI is negative with a mean increase of 12.7. This is not to be expected, as including an infrastructure should help to manage the resources more intelligently and reduce stress on the supply. This finding can be explained by the way in which the infrastructure works. It takes all the abstractions within a given resource zone and then redistributed it based on the storage at each model node. By doing so, it spreads the localised high abstractions used for the baseline simulation over space. This also spreads the stress over space so that now, rather than have all the stress focussed at a few localised nodes, the majority of nodes are now subject to more stress resulting in a larger WSI for the UK.

This may highlight a weakness in the methodology used to represent water supply infrastructure in the groundwater model.

The effect of including the water supply infrastructure can be seen especially in the south-east of England where some areas indicate a 176.3% increase in WSI. In contrast, the areas which had localised high abstractions for the baseline model run show a decrease in the WSI by as much as 89.2%.

B.4.3.5 Scenarios 4 to 7 – Combined effects

So far it has been demonstrated that by introducing the effects of climate change, population growth and water supply infrastructure to the baseline simulation, they all have an overall negative effect on the UK's WSI.

Indeed, by combining the effects of different scenarios, the negative effect is amplified in all cases. For example, scenario four combines climate change – which showed greatest detriment to water security in the south-west of England and the English-Welsh border – and population growth which showed to have even larger negative impacts in and around the major cities of the UK. The resultant percentage difference map shows an aggregation of the two with a mean percentage increase in the WSI of 18.5% relative to the baseline scenario. Scenarios five and six also show this aggregation of water supply infrastructure impacts.

Scenario seven combines all three water resource stresses and as such has overall the worst WSI with a mean percentage increase of 18.9%. The largest impacts are seen in south-east and south-west England, in and around major UK cities and along the English-Welsh Boarder. The WSI increases by as much as 268.4% in these areas.

The results demonstrate that climate change, population growth and water supply all have a negative impact on the security of groundwater resources in the UK. However there are some important details that should be considered when evaluating the certainty in these results. In particular:

- Abstraction rates are assumed to be zero throughout Scotland for the baseline simulation.
- The method to project abstractions results in the loss of localised high abstraction rates as shown in the baseline dataset.
- The method used to represent water supply infrastructure should be re-evaluated as it has a negative effect on the water security of the UK.

B.5. Future Research

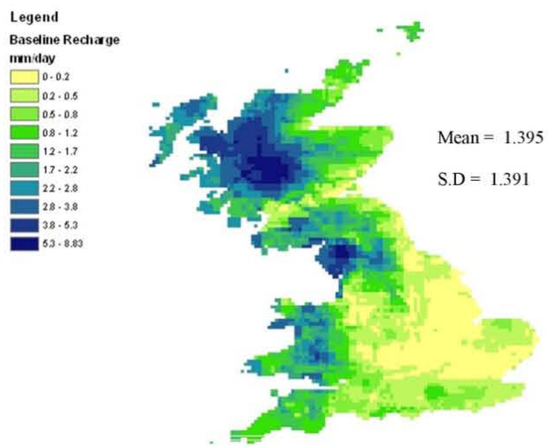
A major assumption of the groundwater model developed for this study is that all geological units can be lumped into five unique aquifer classes along with a poor aquifer class. This assumption that UK hydrogeology can be represented in this way has not been tested. For example, it would be useful to investigate the effect of using different classes. Undoubtedly, the classification process is subjective, where one hydrogeologist is likely to come up with a different set of classes to the next. Instead, a quantitative method could be developed using known hydrogeological parameters such as hydraulic conductivity and storage coefficients as the basis for dividing the geology of Britain.

The ability to delineate separate groundwater catchments for model calibration has been coded into the model, but was not utilized in this study. Using groundwater catchments rather than surface water catchments is likely to improve model results considerably as it will delineate the area contributing to baseflow for each catchment. Indeed, the driving data has been shown to be of considerable importance for model performance. There is evidence of uncertainty and perhaps inaccuracy in the GWAVA model recharge estimates which should be investigated before continuing to use the data for groundwater modelling purposes.

Groundwater abstraction is another complication that needs to be looked at carefully. Abstraction rates are currently averaged over space within the GWAVA grid. In reality however, abstractions are at point. Abstractions from confined aquifers overlain by less permeable deposits or even other, shallower aquifers can be especially complex: The pumping borehole could be located within the extent of a surface water catchment area and yet drawing groundwater from another.

The calibration procedure for the groundwater model also needs some revision. In particular, the NSE objective function used to optimize the model parameters is known to preferentially fit high flows over low ones, as these are the flows that generate the largest residual errors. On the contrary, this study's focus is water security, and thus we are most interested in low flows. A multiple objective function approach is a potential alternative to that used here. There also appears to be difficulty with finding a solution to satisfy all catchments when multiple calibration catchments are used with the same aquifer model. Problems of non-sensitive parameters or parameter interaction are common in conceptual parameter models; however this case showed to be especially problematic when more than the five catchments chosen were used. This may be overcome with improved driving data, catchment delineation and aquifer classification.

Finally, the groundwater model itself may require some development. In particular, the routing method currently used assumes that all baseflow produced at a node within a calibration catchment instantaneously flows to the corresponding flow gauges. This is known not to occur in reality. Improvements should result from implementing a more sophisticated routing technique that uses a "time to concentration" parameter for example to determine flow pathway times as a function of node position in space.

<table>
<tr><th>Variable</th><th>Forcing</th><th>Baseline (1980 -2000)</th><th>Projection (2040 – 2060)</th><th>Difference</th></tr>
<tr>
<td>Recharge</td>
<td>Climate Change</td>
<td>


Mean = 1.395
S.D = 1.391
</td>
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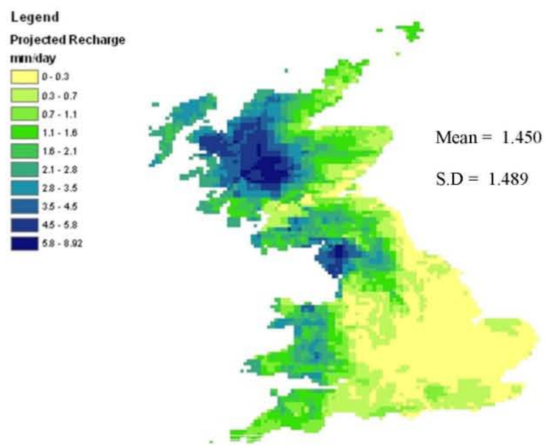

Mean = 1.450
S.D = 1.489
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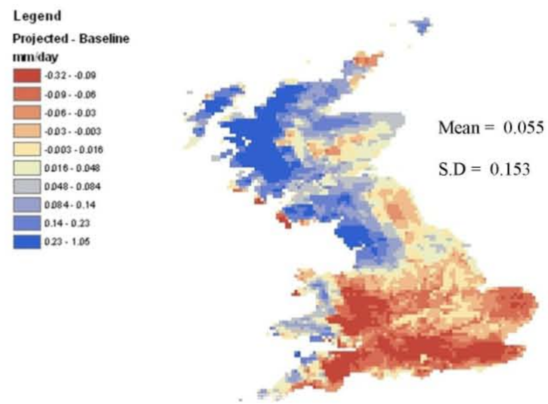
<td>


Mean = 0.055
S.D = 0.153
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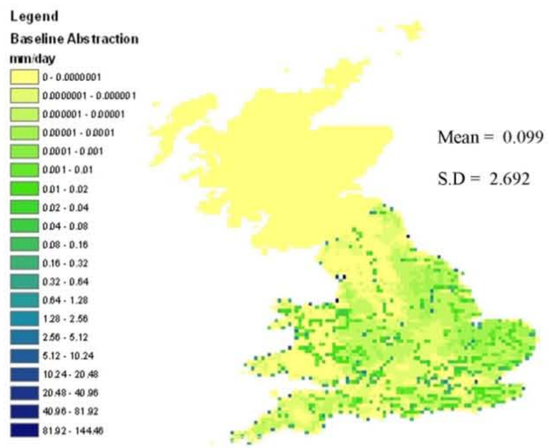
</tr>
<tr>
<td>Abstractions</td>
<td>Population Growth</td>
<td>


Mean = 0.099
S.D = 2.692
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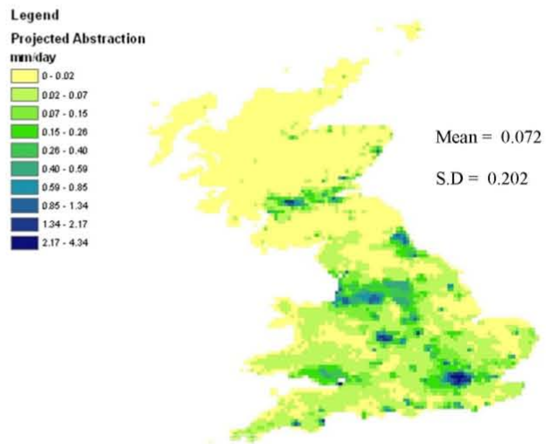
<td>


Mean = 0.072
S.D = 0.202
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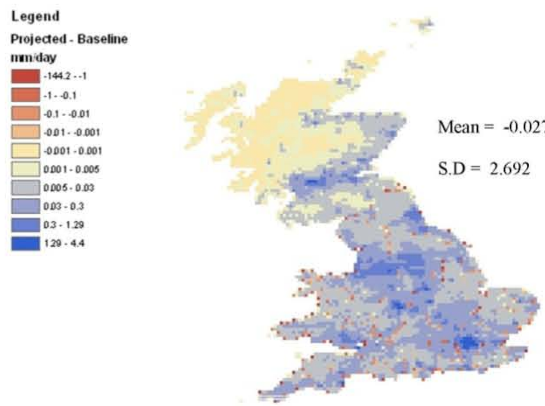

Mean = -0.027
S.D = 2.692
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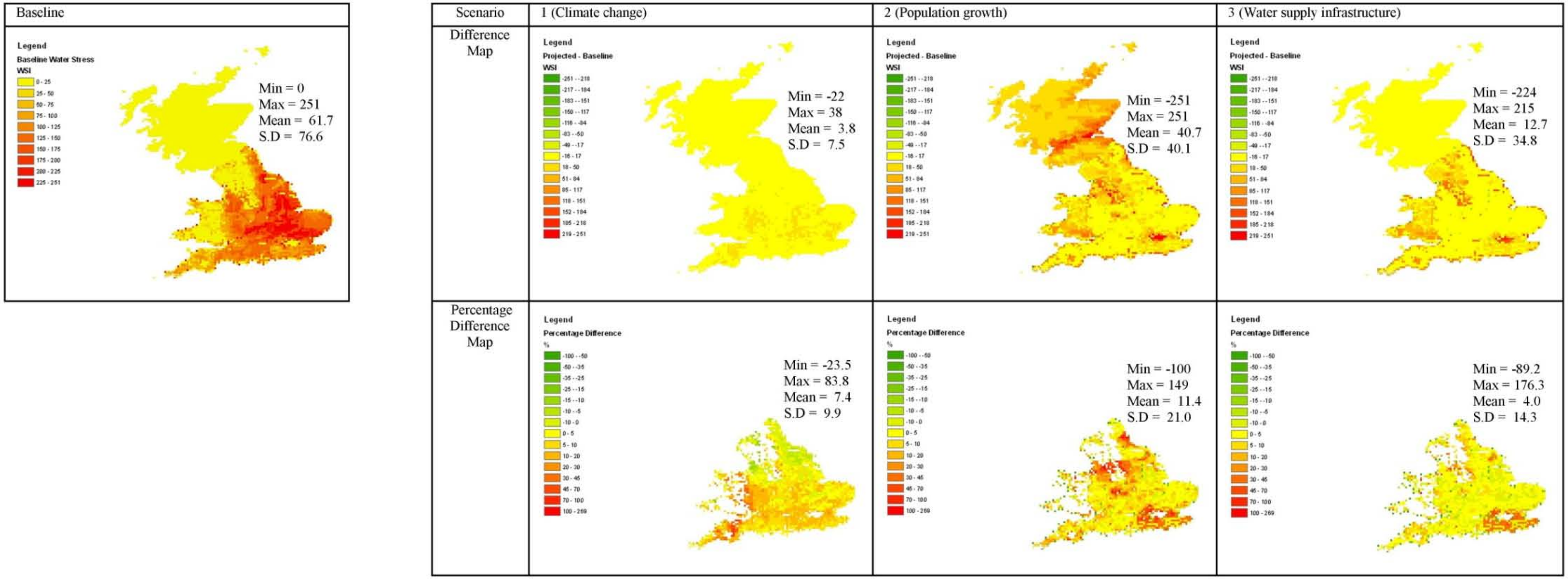
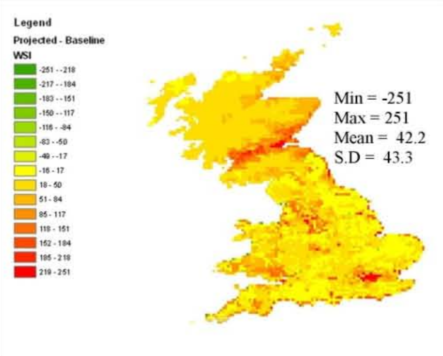
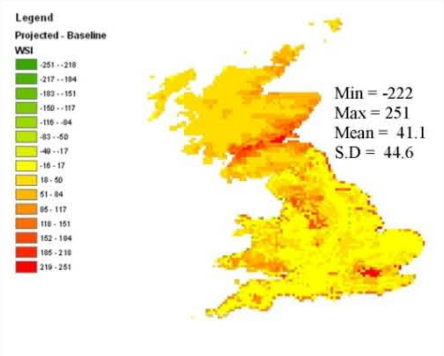
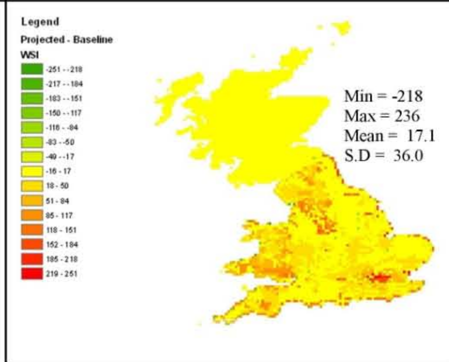
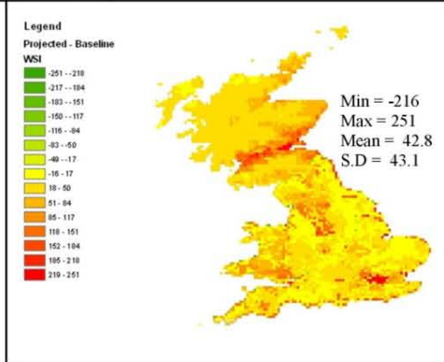
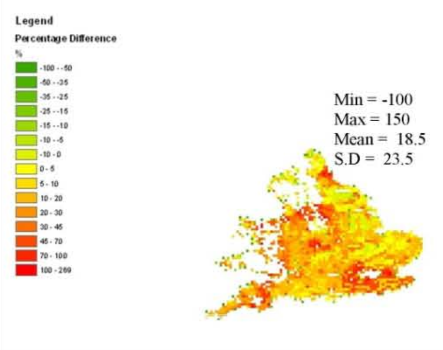
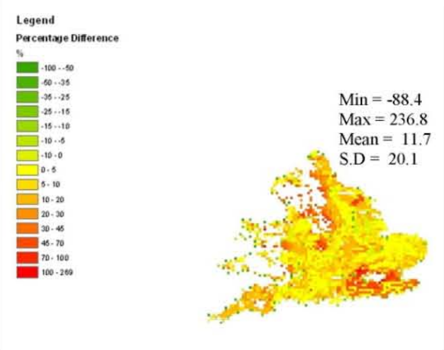
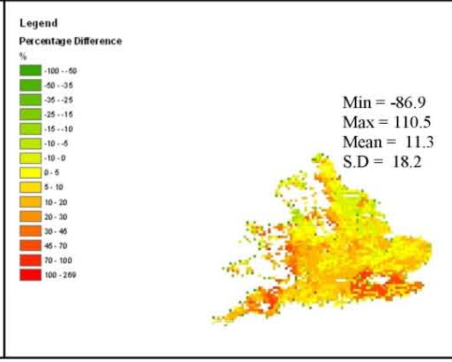
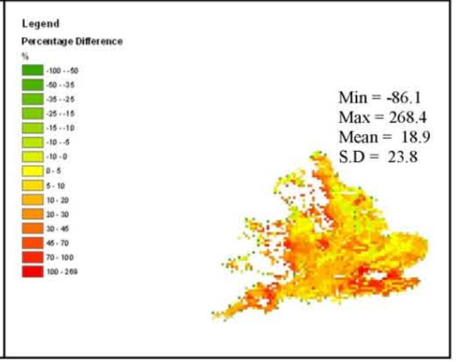


Baseline
Legend
Baseline Water Stress
WSI
Min = 0
Max = 251
Mean = 61.7
S.D = 76.6
Scenario
1 (Climate change)
2 (Population growth)
3 (Water supply infrastructure)
Difference Map
Legend
Projected - Baseline
WSI
Min = -22
Max = 38
Mean = 3.8
S.D = 7.5
Min = -251
Max = 251
Mean = 40.7
S.D = 40.1
Min = -224
Max = 215
Mean = 12.7
S.D = 34.8
Percentage Difference Map
Legend
Percentage Difference
Min = -23.5
Max = 83.8
Mean = 7.4
S.D = 9.9
Min = -100
Max = 149
Mean = 11.4
S.D = 21.0
Min = -89.2
Max = 176.3
Mean = 4.0
S.D = 14.3

Scenario	4 (Climate change and population growth)	5 (Population growth and water supply infrastructure)	6 (Climate change and water supply infrastructure)	7 (Climate change, population growth and water supply infrastructure)
Difference Map	 Min = -251 Max = 251 Mean = 42.2 S.D = 43.3	 Min = -222 Max = 251 Mean = 41.1 S.D = 44.6	 Min = -218 Max = 236 Mean = 17.1 S.D = 36.0	 Min = -216 Max = 251 Mean = 42.8 S.D = 43.1
Percentage Difference Map	 Min = -100 Max = 150 Mean = 18.5 S.D = 23.5	 Min = -88.4 Max = 236.8 Mean = 11.7 S.D = 20.1	 Min = -86.9 Max = 110.5 Mean = 11.3 S.D = 18.2	 Min = -86.1 Max = 268.4 Mean = 18.9 S.D = 23.8

APPENDIX C: Derivation of Climate Scenarios

In order to derive gridded future climate data a series of processes were undertaken that would enable transformation of available gridded data according to changes predicted. These were undertaken by developing a FORTRAN based programme that would be able to read in data from various formats, process these data, and provide data in a suitable format for GWAVA to transform the available gridded data. The steps followed include;

1. Transformation of climate data

Data made available from the Future Flows project exist as netCDF files in either a 1 km^2 or 5 km^2 (according to data type) array of data points according to data type, covering the geographical region encompassing Great Britain. This array is defined geographically according the coordinate system applied to mapping of Great Britain. GWAVA gridded data are based upon a 5' (i.e. 5 arc minutes) resolution coordinate system defined by latitude and longitude. As such, the primary task involved developing programmes to undertake this transformation of data from netCDF files and then from one coordinate system to the other.

2. Locate points within GWAVA grids and calculate the average of these points climate data

Once Future Flows point data are given latitude and longitude geographical coordinates it is possible to determine those points falling within GWAVA 5' grids. From this an average monthly value for each climate variable can be calculated. First a running total of monthly data for each climate variable is calculated, which is then averaged over the number of years within the period considered. Thus for each of the GWAVA grids a single monthly average for each of the twelve months of the year is provided.

3. Calculate the ratio or absolute difference in climate variable between baseline and future periods

Two measures of change are required for transformation of GWAVA climate data: for precipitation and potential evapotranspiration climate variables it is the percentage change in mean monthly values between baseline and future periods, for temperature and rain-days it is the absolute change in mean monthly values between baseline and future periods. For the purposes of this study this is the change between the baseline period that encompasses years 1980-1999, and the future periods encompassing 2020-2039 and 2040-2059.

4. Write gridded data to direct access format for reading by GWAVA

Finally the gridded data held within programme arrays are written into a format recognisable by the GWAVA program.

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