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How might climate change affect river flows across the Thames Basin? An area-wide analysis using the UKCP09 Regional Climate Model ensemble

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Abstract

The Thames Basin drains an area of over 10,000km^2 through London to the North Sea. It encompasses both rural and heavily urbanised areas overlying a spatially-varied and complex geology. Historically, the lower Thames has proved resilient to climate variability, and careful river management in recent years has helped protect the region from flooding. However, recent climate projections for the region indicate that over the next century winter rainfall might increase by 10-15%, potentially leading to higher flows than the Thames can accommodate. This study uses a distributed hydrological model, the Grid-to-Grid (G2G), to assess future changes in peak river flows for a range of catchments across the Thames Basin. The G2G model has used as input an ensemble from the UK Climate Projections (UKCP09) Regional Climate Model (RCM), under the A1B emissions scenario, to analyse changes in flood frequency between two 30-year time-slices (Oct 1960-Sep 1990 and Oct 2069-Sep 2099). The RCM ensemble uses a perturbed-parameter approach to address uncertainty in climate projections.

Results indicate considerable spatial variation in projected changes in peak flows. Towards the downstream end of the fluvial Thames, the average estimated change in modelled 20-year return period flood peaks by the 2080s is 36% with a range of -11% to +68%, which is broadly in line with recent government guidance for the Thames Basin. A key question that arises is whether these estimated changes fall within the range of natural variability and would therefore be indistinguishable from the effects of typical weather patterns in the current climate. Comparison of the modelled changes in flood frequency with an RCM-based estimate of current natural variability shows that, whilst for some rivers (or parts of rivers) there are few changes outside the range of current natural variability, for other rivers there are more changes outside of this range. The latter locations could be considered as sites where further monitoring/modelling may provide early warning of statistically significant changes in observed flows, due to climate change.

Keywords

Rainfall-runoff, flood frequency, climate change, RCM ensemble, UK Climate Projections 2009

1 Introduction

Since the 1960s, daily precipitation in the UK has tended to be more intense in winter and less intense in summer (Osborn and Hulme, 2002; Maraun et al., 2008). The impact of changes in rainfall on river flows will depend on both the nature of the rainfall and the physical characteristics of the catchment draining to the river. For fast-responding catchments, such as those in impermeable or high relief areas, the characteristics of the specific rainfall event are critical. These fast-responding catchments tend not to have the deep soils or permeable geology that lead to the long-term hydrological "memory" of larger lowland catchments. Catchments across the Thames Basin in England are typical of these lowland catchments, where the longer-term balance between rainfall and evaporation is particularly important. The River Thames is of particular strategic importance as it drains an area of over 10,000 km^2 through central London, much of which was developed on low-lying marshland close to the Thames Estuary (Fig. 1). The Thames Barrier provides flood protection from tidal surges which are the main threat, but extremes of fluvial flow will also have an impact on thousands of properties situated in the flood plain.

Fig. 1

Historically, the lower Thames has proved resilient to climate variability. There is no long-term trend in annual maximum flows over the 126 year record for the Thames (Marsh 2004), despite increases in temperature and a major change in the seasonal partitioning of rainfall. River management in recent times (for example channel straightening, bed re-profiling, and improvements to the efficiency of weirs) has led to greater channel storage and conveyance. This has resulted in fewer floods in the lower Thames. At Kingston, for example, an increase of around 30% in the channel capacity over the last 70 years means that flows that would have caused significant flooding in the 1930s can now be accommodated within-bank.

In the recent IPCC assessment (IPCC 2007) of projected climate change over Europe a wide range of changes in precipitation is seen over the UK. By the 2080s under the A1B (medium) emissions scenario, this includes winter rainfall increases of up to 15% and summer rainfall decreases of up to 20% over England. The UK Climate Projections (UKCP09) incorporate information assessed by the IPCC along with projections from a larger ensemble of Hadley Centre global and regional models and estimate, for the same emissions scenario and future time period, a 50% probability of winter rainfall increasing by 19% and summer rainfall decreasing by 22% for the London area (Jenkins et al., 2009). It should also be noted that both sets of projections include much smaller increases in winter precipitation and increases in summer precipitation. Coupled with projected increases in mean temperature of 3-4K which could affect evaporation, the overall impact of these changes on river flows is unclear.

Most research into the effects of climate change on UK river flows has used catchment hydrological models to provide estimates of changes in flow at single locations or a small set of locations (e.g. Kay et al., 2009; New et al., 2007; Fowler and Kilsby, 2007; Wilby and Harris, 2006; Wilby et al., 2006; Nawaz and Adeloye, 2006; Cameron, 2006; Kay et al., 2006; Arnell, 2003; Reynard et al., 2001). Normally, the hydrological model is calibrated to catchment conditions, using model parameters to adjust the modelled catchment response to rainfall, in order to reproduce the controlling effects of spatial heterogeneity of soil/geology/topography. The model parameters can also be adjusted to take into account artificial influences on flows, such as abstraction. Using this approach, Kay et al. (2006) examined the effect of projected climate change on river flows for 15 catchments across the UK using a simplified form of the PDM catchment model whose parameters were estimated using derived regression relationships with catchment properties provided by digital datasets (e.g. land cover, soil-type). An RCM assuming a UKCIP02 climate scenario (Hulme et al., 2002) provided the atmospheric inputs to the PDM and, despite decreases in average annual rainfall in most catchments, eight catchments showed an increase in flood frequency at most return periods while two showed substantial decreases (one of which was located in the Thames Basin). The increases in flood frequency, despite decreased annual rainfall, were attributed to the UKCIP02 projection of increased seasonality in future rainfall with more rainfall falling in winter.

Distributed grid-based models provide another approach to understanding the spatial effects of projected climate change on river flows, and can potentially provide flow estimates for all locations on a spatial grid including ungauged sites. An important strength is their use of digital datasets of terrain/soil/geology/land-cover properties to underpin the model response to rainfall and potential evaporation (PE). Land-surface models are of this type; their development was motivated by Global Climate Models (GCMs) which required estimates of fluxes of heat and water vapour between the land-surface and atmosphere. These models can provide estimates of soil-moisture, runoff and river flow, but often on a coarse grid and at a monthly time-step (although the resolution is increasing), with global coverage. In recent years, the hydrological modelling community has in turn moved to larger scales with the development of gridded hydrological models which rely on now widely-available spatial datasets on landscape properties to control spatial heterogeneity of catchment response. Often using as inputs climate model outputs, these hydrological models provide a means to estimate the impact of regional climate change on river flow response at a regional or large-catchment scale. National-scale hydrological models are now emerging: for example Henriksen et al., (2003) present and assess a hydrological model for Denmark based on the MIKE SHE model (Abbott et al., 1986). Another grid-based model, LISFLOOD, has been developed and applied to simulate river flow, soil-moisture and flood inundation in large European river basins (De Roo et al., 2000, 2003).

The work presented here uses a single model (Grid-to-Grid, or G2G) and set of parameters for the whole of the Thames Basin (~13600 km^2), employing digital datasets to provide the spatial information needed to simulate spatial differences in the flow response to rainfall across the river basin. G2G output consists of a (1km) grid of river flow estimates across the region of application. The G2G can either be used as an area-wide model providing flow estimates over a large region, or as a catchment model which may be calibrated to obtain the best possible agreement between modelled and observed flows. As an area-wide model, the G2G can be less accurate for a particular catchment than a model specifically calibrated to the catchment, but is well suited to support river flow simulation at any set of locations within a region. Bell et al., (2009) assessed the G2G model performance for 43 catchments across Britain using daily rainfall and river flow observations, finding that it provided reasonably good daily flow estimates. For the smaller Thames Basin area examined here, model parameters which govern the temporal development of flow peaks have been determined through recalibration using 15-minute time-series of rainfalls and river flows, while taking care not to over-calibrate the model to individual catchments. Model performance has been assessed with reference to quality-controlled river flow records for 34 locations across the area.

To estimate projected future changes in peak river flows, the calibrated Thames G2G model employs as its input rainfall and PE estimates derived from outputs from a 25 km resolution RCM, for a Current (Oct 1960 to Sep 1990) and a Future (Oct 2069 to Sep 2099) time-slice. The RCM used here consists of the Met Office Hadley Centre perturbed-physics ensemble of 11 variants of the RCM (HadRM3), run from 1950-2099 and used to dynamically downscale GCM results as part of the latest UK Climate Projections report (Jenkins et al., 2009). The broader aim of this study was to produce estimates of spatial changes in return period flows on a continuous 1 km grid across the Thames Basin, to support future flood defence planning. Estimating changes to the inflows to the tidal Thames via the main river and 13 major tributaries is of particular interest to future planning in relation to the Thames Barrier.

A key question that arises is whether these estimated flow changes fall within the range of natural variability and would therefore be indistinguishable from changes arising from typical weather pattern variation. Here an RCM ensemble representative of “present climate” has been used to provide an estimate of natural variability with which modelled changes in flood frequency can be compared. Areas within the Thames Basin where projected climate change impacts on river flows fall outside this estimated range of natural variability will be investigated and highlighted.

2 Hydrological Modelling

2.1 The Grid-to-Grid model

The hydrological model used here is a distributed model of runoff production and flow routing - called the Grid-to-Grid (or G2G) - formulated to employ terrain, soil/geology and land-cover datasets, presented as the “Soil-G2G” in Bell et al., (2009). The model formulation contains enhancements to the prototype G2G formulation previously trialled in the Upper Thames catchments (Moore et al., 2006, 2007), which was in turn a development of the elevation-dependent formulation presented in Bell et al., (2007a,b) and extended by Cole and Moore (2009). The model formulation is presented briefly here and further detail is provided by Bell et al., (2008, 2009), together with an assessment for a large range of UK catchments.

The G2G model is modular in form and distinguishes between runoff-production and lateral routing of runoff to form river flow. The runoff-production scheme divides the terrain into a square grid of vertical soil columns which are subject to precipitation and evaporation. Some of the rainwater entering the soil column can drain laterally to adjacent grid-squares, while saturation-excess flow contributes to surface runoff. Water also moves downwards via percolation and drainage which eventually contributes to groundwater (sub-surface) flow. In order to ensure that a grid-square generates realistic quantities of saturation-excess surface runoff even when it is not fully saturated, a probability-distributed soil moisture store formulation (Moore, 1985, 2007; Zhao et al., 1980) has been invoked within each grid-square. This conceptualisation represents the spatial variation in water absorption capacity with soil, geology, land-cover and topography across the grid-square.

Digital datasets are used to provide estimates of soil hydraulic properties required by the runoff-production scheme. These soil properties are specified where possible through a relationship between the HOST (Hydrology of Soil Types) classification of soils (Boorman et al., 1995) and highly derived soil attributes. For each of the 29 HOST soil classes (of which only nine classes have a significant presence in the Thames Basin), an association table provides indicative estimates of the saturation and residual water contents, the vertical saturated hydraulic conductivity, and the depth of the soil column. These soil property estimates offer only a coarse approximation for use at the model scale (1km and depth integrated) and cannot reflect the true spatial complexity of soil water control. However, the modest number of soil classes involved has the advantage of easing exploration of how soil properties impact on the timing and volume of runoff-production across the Thames Basin.

Digital datasets are also used to configure and parameterise lateral routing of runoff across the landscape to form estimates of river flow. Flow-routing is undertaken in two parallel planes representing sub-surface and surface pathways with a return flow term representing the contribution of groundwater to river flow. The gridded flow-directions which define the lateral pathways of water movement constitute a critical component of the model configuration as they determine the water-balance contributing to flow at every location. The network-derivation scheme of Paz et al. (2006) has been used to identify 1km-resolution flow directions from hydrologically-corrected 50m river networks, following the recommendations of Davies and Bell (2008) who found that use of this scheme resulted in the smallest errors in derived catchment area when compared to other methods. For the set of Thames catchments examined here, errors in derived area are usually less than 5%, and less than 1% for more than half the catchments.

Schemes that invoke the kinematic wave approximation in their development form the basis of the routing component of G2G. Routing along surface land pathways and subsurface land and river pathways employs kinematic wave equations, applied in 1-dimension over a 2-dimensional river network and approximated by a finite-difference scheme (Bell et al., 2007a,b). The wave speed can vary with the pathway (surface or subsurface) and surface-type (land or river) combination. Routing along surface river pathways employs the Horton–Izzard nonlinear storage approach (Dooge, 1973; Moore and Bell, 2001) applied to a varying width channel network (Ciarapica and Todini, 2002; Moore et al., 2007) and exploits geomorphological relations developed by Bell and Moore (2004). In urban and sub-urban areas - identified through the LCM2000 spatial dataset of land-cover (Fuller et al., 2002) - responsiveness has been increased through the use of an enhanced routing speed and reduced soil storage, leading to a faster response to rainfall.

2.2 The Thames Basin

Both soil and geology influence the hydrological response of catchments to rainfall. The geology of the Thames Basin is particularly complex with many catchments comprising a

Fig. 2

Table 1

mixture of geological types, as shown in Fig. 2(a). A main feature of the region is the chalk escarpment of the Chilterns running southwest to northeast, also evident in the relief map of Fig. 2(b). The escarpment is broken in places by valleys, in particular by the Thames at Goring Gap (situated south of gauging station 39139). The remainder of the Thames Basin is made up of newer rocks with superficial deposits. London is situated to the eastern side of the basin, in a depression in the underlying chalk over which sand and London Clay have been deposited. The north-western catchments are underlain by Liassic formations, with a majority being clay, in particular Lias Clay to the north of Banbury (39026). A band of Great Oolite, a sedimentary rock, sometimes called clayey limestone, underlies catchments such as the Windrush (39006), the Evenlode (39034) and the Northern part of the Thames to Farmoor (39129). The underlying geology influences both the relief and the soils in the catchment above: areas of higher relief tend to correspond to chalk and marlstone geology. Soil consists of a mixture of weathered rock and organic matter, both of which influence its properties.

The relationship between catchment response and geology is highlighted in Table 1 which lists the 34 study catchments in decreasing order of baseflow index (BFI) which is closely associated with soil and geology, with deeper soils (or permeable bedrock) resulting in a larger baseflow response (Gustard et al., 1992). The table indicates that in this region, catchments with low BFI (<0.4) tend to overlay London Clay. These catchments tend to have shallower soils above an impermeable or "gleyed layer" and respond relatively quickly to rainfall events. High BFI (>0.7) is associated with chalk/Lias geological formations which tend to have deeper soil-stores or aquifers and a slower response to rainfall. The Lias group of rocks generate a surprisingly large range of overlying soil properties with effective soil depths ranging from 0.31m in the Ray at Grendon (39017) to 0.54m in the Cherwell at Enslow Mill (39021). This variation can be attributed to the further classification of Lias group rocks into Lower and Middle Lias formations which have very different properties: the Middle Lias group consists of deep silts and fine sandstones overlain by the relatively thin sandstone and ironstone of the Marlstone Rock Formation, while the Lower Lias group, consists predominantly of mudstones over an impervious layer of limestone.

The spatially-distributed nature of the G2G model allows for river flow simulation to be undertaken for an entire region or for individual catchments for which observations of river flows are available for calibration and assessment. Here, the G2G has been applied at a regional scale in order to give consistent, area-wide estimates of the effects of projected climate change on river flows across the Thames Basin. Many centuries of development in the Thames Basin makes it difficult to find catchments entirely free from anthropogenic changes to the flow regime: thus a high proportion of artificially-influenced catchments are included here in the model assessment. These influences are taken into consideration during model calibration and assessment, noting that the G2G formulation used here will perform best in natural river basins.

In their study of high-flow trends in undisturbed UK catchments, Hannaford and Marsh (2008) note that "very few UK rivers are pristine", but are able to identify a number of catchments for which the net influence of artificial disturbance is modest. This list is subject to ongoing revision and Table 1 highlights that six of the 34 study catchments are at present considered to be relatively undisturbed. Thus for these catchments a more accurate simulation of observed flows may be achievable with the simple model formulation used here. The flow regimes of the other 28 catchments are more heavily influenced, with factors ranging from a reduction in flow from groundwater abstraction (39026, 39129, 39046, 39005, 39010, 39056, 39001, 40016, 40012), to increases in measured flows from effluent returns (39034, 39021, 39046, 39010, 39069, 39005, 39007, 39003) or augmented low-flows (39049, 40012). However, many catchments are affected by abstraction to a lesser degree, whilst the variable accuracy of gauged river flows beyond bankfull capacity affects estimation of high flow peaks in others. Further model development to include (at least) abstractions could significantly improve simulation accuracy in the Thames Basin.

2.3 Model calibration and assessment

Previous work has examined the performance of the G2G for catchments across the UK using daily rainfall and river flow records (Bell et al., 2009). For a country-wide analysis, daily records are more readily available than those at 15 minute resolution, but for the Thames Basin it has been possible to assemble concurrent flow and rainfall data at the finer resolution. These data derive from 15 minute rainfall accumulations, obtained from a dense network of 103 tipping-bucket raingauges, and interpolated onto a 1km grid using a multi-quadric surface fitting technique (Cole and Moore, 2008, 2009). Gridded estimates of potential evaporation from a short grass vegetated surface are provided by MORECS (Met Office Rainfall and Evaporation Calculation System), a monthly climatological dataset for 201 (40 by 40 km) squares across the UK (Thompson et al., 1982; Hough et al., 1997). The combined potential evaporation from land and vegetation is sometimes referred to as ‘‘potential evapotranspiration’’ (PET), but here the abbreviation PE will be used in preference. Model performance has been assessed with reference to quality-controlled river levels/flows provided by the Environment Agency for 34 locations in the Thames Basin at a 15 minute resolution. A complete list of the gauging stations and the area draining to them is presented in Table 1.

Five years of records (January 1997 to December 2001) were used for split sample calibration and assessment, although periods of missing data have reduced the record-length in places. For calibration, the G2G model was initialised from 1 January to 21 July 1999 and then run from 21 July 1999 to 18 June 2001; for assessment, the model was initialised from 1 January to 21 July 1997 and then run from 21 July 1997 to 18 June 1999. To maximise use of good quality records there is an overlap in the two datasets during initialisation of the calibration period. Model performance over this initialisation period is ignored by the calibration process so these data are considered to be available for the independent model assessment.

The G2G was designed to rely on digital datasets to determine the response of the landscape to rainfall. However, many aspects of sub-surface hydrology are ill-defined, leading to the need to adjust or "calibrate" some model parameters to gain better agreement between observed and modelled river flows. Here, the seven routing parameters which govern the temporal development of flow peaks are set at a regional level (in this case the whole of the Thames Basin) while the heterogeneity of runoff production is specified primarily through the spatial datasets of slope, urban land-cover and soil properties, leaving only two regional parameters relating to runoff requiring adjustment. These two runoff parameters provide regional estimates of the vertical saturated hydraulic conductivity and the groundwater drainage rate constant, while the routing parameters comprise four lateral routing parameters (for surface and sub-surface, land and river routing), land and river return flow factors, and a critical drainage area beyond which flow in a 1km grid-cell is assumed to be river. In practice, accurate flow simulation is most dependent on the two runoff parameters: the return flow term and the surface river flow routing parameter. Values for all the parameters are determined by manual calibration to river flow records for locations across the Thames Basin. Future developments using improved spatial datasets will aim to strengthen the underpinning physical basis of the model, reducing reliance upon model calibration.

The G2G model is designed for area-wide use, so care has been taken not to over-calibrate the model to individual catchments. Instead, river flow records for catchments with a predominant soil-type have been used to determine whether the soil hydraulic properties associated with the HOST soil-type provide realistic estimates of the relative volumes of surface- and sub-surface runoff. Where required, manual adjustment of soil hydraulic properties (usually effective soil depths) is applied recursively to different catchments and sub-catchments until a good estimate of downstream surface- and base-flow volumes across a range of soil-types is achieved. In the Thames Basin nine HOST soil types have a significant presence, of which four classes - 1 and 18 (soils overlying chalk), 25 (clay) and 2 (limestone/marlstone) - are most dominant. It is these soil types for which some adjustment has been made with respect to the effective soil depth. In chalk areas, the baseflow component of river flow depends on the volume of water stored in both the soil and the aquifer. On account of the lack of data on groundwater hydraulic properties, storage in these areas has been augmented by increasing the effective soil depth to a value larger than is typically observed and assuming that the soil hydraulic properties apply at all depths. This procedure results in depths of 3.0m and 2.0m for HOST classes 1 and 18 respectively (previously 0.73m and 0.91m respectively). Similarly, the soil depth (to a gleyed layer) in clay soils has been decreased from 0.25m to 0.15m to speed up the hydrological response in clay soils; however, since much urban development has taken place on London Clay it has been hard to separate the two factors.

Calibration and assessment results for 34 catchments are presented in Fig. 3, displayed in descending order of BFI for both undisturbed and anthropogenically-influenced catchments. Model performance is evaluated for 15-minute flows and summarised in terms of R^2 Efficiency, as defined by Nash and Sutcliffe (1970); this provides a relative measure of model simulation accuracy permitting some comparison across the different catchments. A value of 1 indicates perfect agreement, 0 indicates the model simulation is only as good as using the mean flow value for the whole period, whilst negative values arise if the flow simulations are worse than that provided by the mean flow. Negative R^2 values are indicated with a value of -0.1 in Fig. 3 for clarity of display, but can be as poor as -8.0 for catchments subject to anthropogenic influences (e.g. the Darent, which is subject to groundwater abstraction, augmented low flows and an erroneous sub-surface contributing area).

Fig. 3

The G2G model has the best performance statistics when applied to catchments for which (a) the response to rainfall is relatively free from artificial influences, (b) the gauge is considered to be reasonably accurate and (c) there are no significant data problems (flow and rainfall). In these areas, R^2 Efficiency ranges from 0.59 to 0.84 (median 0.77) for the calibration period and from 0.40 to 0.77 (median 0.75) for the assessment period. For catchments with greater levels of anthropogenic disturbance, G2G model simulation accuracy is more variable, usually in line with the degree of disturbance. For these catchments, R^2 Efficiency ranges from -2.89 to 0.85(median 0.55) for the calibration period, and from -8.0 to 0.84 (median 0.33) for the assessment period. Example hydrographs for four catchments over the two-year assessment period are presented in Fig. 4. Hydrograph (a) for the Ock at Abingdon (39081) provides an example of a catchment where the G2G is performing reasonably well, although some peaks are overestimated. The hydrograph for the Lambourn at Shaw (39019) shows how the G2G performs for a groundwater-dominated chalk catchment with only limited net

Fig. 4

artificial disturbance to the natural flow regime. Here, observed and modelled flows are not co-incident but they are similar, and the configuration of the G2G model has enabled its response in this catchment to be very different to (say) the Ock at Abingdon. The G2G model simulates natural rather than influenced flows and thus can appear to over- or under-estimate flows for heavily influenced catchments (e.g. those affected by effluent returns or abstractions for public water supply). Hydrograph (c) for the Darent at Hawley (40012) provides an example of where the G2G struggles to simulate observed flows because of anthropogenic influences discussed earlier. Hydrograph (d) presents simulated and observed flows for the Thames to Kingston (39001) alongside naturalised flows which are adjusted to take account of net abstractions and discharges upstream of the gauging station. The flows are shown as daily mean values (naturalised flows are not available at a 15-minute resolution) and the graph indicates that naturalised flows are generally higher for this catchment than observed flows particularly during the summer months. As expected, flows simulated by the G2G are much closer to naturalised flows than observed. For the Thames to Kingston, daily R^2 Efficiency values increase from 0.78 to 0.84 for the calibration period and from 0.20 to 0.51 for the assessment period when modelled flows are compared to naturalised rather than observed flows. Overall, these hydrographs indicate that the G2G model is able to broadly reproduce a wide range of hydrological behaviour in catchments which have very different responses to rainfall.

Against the background of this assessment of G2G model performance for historical periods, the model is used here with some confidence to investigate the impact of projected climate change on flood frequency for naturalised flows across the Thames Basin. Although for a particular catchment the G2G does not perform as well as a model specifically calibrated to flows gauged at its outlet, the G2G has been shown to be able to reflect the heterogeneity of response to rainfall from different landscapes in a consistent way across the whole region. Climate change impacts on river flows for a particular catchment should however be considered indicative only: they do not reflect current (or future) flood defences, flood inundation or anthropogenic influences. Importantly, this analysis can serve to highlight areas that may be particularly sensitive to projected changes in the rainfall regime and that deserve further investigation in support of flood defence planning.

3 Use of Regional Climate Model (RCM) data

3.1 The Hadley Centre RCM

Gridded rainfall and potential evaporation estimates from a system consisting of the Met Office Hadley Centre GCM, HadCM3, dynamically downscaled to 25km using the HadRM3

RCM are used to as input to the G2G hydrological model. HadCM3 (Gordon et al., 2000; Pope et al., 2000) has previously been shown to have considerable skill at simulating the global climate. Furthermore, when combined with the regional atmospheric climate model HadRM3, a higher resolution version of the atmospheric component of HadCM3, the modelling system is able to reproduce many of the observed features of the United Kingdom and European climate (see e.g. Jones et al., 2004; Buonomo et al., 2007).

The HadRM3 perturbed physics experiment (HadRM3-PPE-UK)was designed to simulate the regional climate for the UK in the period 1950-2100 using historical emissions and a medium (SRES A1B) emissions scenario, and is a key UK Climate Projections dataset (UKCP09; Murphy et al., 2009). This RCM ensemble is the dynamical downscaling component of an 11-member ensemble of global and regional models where the global model provides boundary conditions to the RCM whose formulation matches that of its driving GCM. One member of the ensemble comprises the GCM/RCM pair HadCM3/HadRM3 and the other 10 members are formed of GCM/RCM pairs incorporating a range of perturbations to important parameters in the physical formulation of the HadCM3/HadRM3 models. The same historical (1950-2000) and future (2000-2100) climate forcings from the SRES A1B scenario (IPCC, 2000) were used in each of the GCM/RCM pairs. The standard forcings include historical levels of greenhouse gases (including methane), sulphur (direct and first indirect forcing, sulphur chemistry without natural DMS and SO2 background emissions; anthropogenic SO2 emissions from surface and high level only) and tropospheric/stratospheric ozone.

RCM output data are available on a 0.22˚ (~25km) rotated lat-long grid, shown in Fig. 1. The data comprise hourly precipitation and daily PE data, which are then downscaled to a 1 km UK national grid as required by the G2G model. Since rainfall is highly spatially variable, the Standard Average Annual Rainfall (SAAR) 1km dataset for the UK for the period 1961-1990 has been used for downscaling using the approach outlined in Bell et al. (2007a). For each time-step, the rainfall for each RCM grid-square is multiplied by the ratio of RCM grid-square SAAR to the1 km grid-square SAAR to provide rainfall on a 1 km grid. This determines whether some areas generally receive more or less rainfall than others, for instance as a consequence of topography, but makes no attempt to adjust overall rainfall amounts in line with observations. The same SAAR weighting is used for both the Current and Future time-slices of the RCM precipitation data (with an assumption that there will be no major changes in the track of weather systems). Note that although the RCM precipitation is available at an hourly time-step, it is applied within the G2G at a 15-minute time-step by dividing each hourly value by four.

The G2G requires as input an estimate of PE for a short grass land-cover. Currently, where an estimate of PE from vegetation is required for use in impact studies, it is common hydrological practice to use climate model outputs of atmospheric variables as input to a standard PE estimation scheme. These schemes vary in complexity and data requirements, ranging from temperature-only methods such as those used by Thornthwaite (1948) and Oudin et al. (2005) to the full Penman-Monteith formulation (Monteith, 1965) requiring estimates of air temperature, relative humidity, wind-speed and net downward short- and long-wave radiation. The more complex schemes are often preferred for climate impact studies as their physical basis is likely to be more responsive to climate effects on a range of atmospheric variables. One of the climate model parameter perturbations of particular relevance to hydrological applications is the dependence of stomatal conductance on atmospheric CO_2 levels. This effect has been included in six of the 11 ensemble members and may be an important consideration for climate impact and modelling studies as increased CO_2 is thought to lead to leaf stomatal closure and a reduction in evaporation from vegetated surfaces. Recent studies, such as Gedney et al. (2006), indicate that elevated levels of atmospheric CO_2 can reduce evaporation from vegetation which could result in river flow increasing under projected climate change. The method of Bell et al. (2011) has been used here to estimate PE from vegetated surfaces using a scheme which emulates that of Penman-Monteith and can take advantage of RCM estimates of the effect of projected future change in CO_2 levels on plant stomata. Note that although the PE estimates derived from the RCM data are available at a daily time-step, they are used within the G2G at a 15-minute time-step by spreading each daily total equally throughout the day.

For each ensemble member, data for two time-slices were chosen out of the full 150-year RCM run. The first (Current) time-slice runs from 1 October 1960 to 30 September 1990 and the second (Future) time-slice runs from 1 October 2069 to 30 September 2099. Note that both time-slices have been chosen so as to cover exactly 30 water-years, although it should be noted that the length of an RCM year is only 360 days, comprising of twelve 30-day months (which is applied in the climate modelling system to simplify the run-time calculation of monthly and seasonal statistics). The G2G model was run for each time-slice *including* a 9-month run-in period before each (i.e. from 1 January 1960 and 1 January 2069 for Current and Future respectively).

3.2 Comparison between RCM estimates and observations

3.2.1 Rainfall and PE

It is useful to compare the ensemble RCM precipitation and PE both between the Current and Future time-slices for each ensemble member, to assess how the G2G model inputs are changing between the two time-slices, and with observational series, to aid an assessment of the performance of each member individually and of the ensemble as a whole. However, it should be noted that any comparison of RCM data with observational data needs to be interpreted with care, as the Current run of each ensemble member is not meant to reproduce exactly what happened in that period, but is simply one possible representation of what *could* have happened in that period, given the existence of stochasticity and natural variability. In addition, differences in resolution between RCM grids and observational grids could cause discrepancies, particularly for rainfall and especially in regions with high topographic variability.

Fig. 5

Fig. 5 shows, for one RCM grid-box located in the north of the Thames Basin (indicated by the highlighted box in Fig. 1), the monthly mean rainfall and PE over each time-slice, and the difference between the two time-slices, for each ensemble-member. The unperturbed ensemble member is shown with a bold black line and the dashed black line indicates observed rainfall and PE for the period 1961 to 1990. The observed rainfall has been taken from a corresponding box within the dataset of Met Office 5km grid-interpolated daily rainfall. The 'observed' PE has been taken from a corresponding location within the MORECS dataset of 40km gridded monthly mean PE. The graphs highlight the variability between the 11 ensemble members but also show how these estimates differ from observations. For this particular grid box, the 11 RCMs tend to produce more rainfall than observed between October and July, but less in the warmer months between July and October, and estimates of PE tend to be higher than those from MORECS. Under future projected climate change conditions the tendency for less late summer rainfall is more pronounced and there is an overall shift in the occurrence of rainfall from summer (April to September) to winter (October to March). It is assumed that any bias in the PE and rainfall estimates used to drive the G2G model will be present in both Current and Future time-slices, and thus will not be important when looking at relative changes in peak flows.

The RCM projections lie within the range of GCM projections presented in the IPCC Fourth Assessment Report (Christensen et al., 2007) which indicate that in much of Europe precipitation is likely to increase in winter but the signal in summer, especially in central and western regions is less clear (see also Rowell, 2006; Rowell and Jones, 2006; Kendon et al., 2010). Similarly, the UKCP09 report (Murphy et al., 2009) central estimates (50% probability level) indicate an increase in winter rainfall of 20 to 30% and a decrease in summer rainfall of 20 to 30% but with an increase in summer rainfall indicated at the 10% level.

3.2.2 Flood frequency

In order to be able to estimate flood frequency for each river point modelled by the G2G, annual maximum (AM) flows are stored for each point by UK water-year (1 October to 30 September). The AM are then ordered and their Gringorten plotting positions determined (Gringorten, 1963). A generalised logistic distribution - recommended for UK catchments by Robson and Reed (1999) - is then fitted to the AM at each point using L-moments. The fitted flood peaks can then be plotted against their return period, which is the average interval between peaks exceeding a given magnitude, to give a flood frequency curve. This method assumes stationarity over the data period, and the fitted curve should not be used for extrapolation much beyond the length of the data period.

Fig. 6

Flood frequency curves arising from use of RCM data as input to the G2G are presented in Fig. 6 for the four example catchments for which hydrographs were shown in Fig. 4. These curves are derived from simulations using the Current time-slice of each RCM ensemble member as input to the G2G. Also shown for each catchment is the median observed flood frequency (and its 95% bounds), derived by resampling any 30 observed (non-missing) AM daily mean flows available for the catchment between 1961 and 2005. For the Thames to Kingston the observed flood frequency curve shown is for naturalised flows, which is similar to the curve for observed flows but slightly higher, particularly at lower return periods. The comparison of observed flood frequency with RCM-derived flood frequencies (which have also been estimated using daily mean flows in this case) suggests that the flood frequency is modelled well for some catchments using (some versions of) the RCM outputs for input to G2G; but there is a tendency to over-estimate flood frequencies even for catchments for which the G2G generally performs reasonably well (such as the Ock and the Lambourne). The Darent (Fig. 4c) provides an example of a catchment for which anthropogenic influences reduce flows so significantly that the G2G overestimates, a tendency which is exacerbated through the use of RCM rainfall. It should be noted that, as for the comparison of RCM and observed rainfall and PE, the comparison of flows simulated using RCM-derived inputs with observed flows needs to be interpreted with care: the Current run of each ensemble member is not meant to reproduce exactly what happened in that period, but is simply one possible representation of what *could* have happened in that period, given the existence of stochasticity and natural variability.

4 Results

4.1 Climate change impacts on flood frequency

Flood frequency curves are derived from both Current and Future time-series of 15-minute G2G-modelled river flows at each 1km river pixel, and the percentage change in peak flow at different return periods is determined. There is considerable variation in the estimated percentage change in flood frequency for different locations within the Thames Basin, between ensemble members and for different return periods. Results averaged over the 11 ensemble members are presented in Fig. 7(a): this shows the mean impact of projected climate change on peak flows at two return periods. Here it has been assumed that no ensemble member is more or less likely than any other, and so a non-weighted mean has been calculated (at each return period) from the percentage changes in flood frequency for each of the 11 ensemble members. The maps show significant variation for different parts of the Thames Basin, again highlighting the dependence of the impact on soil/geology, as areas overlying chalk (highlighted in Fig. 2) have much lower percentage changes than elsewhere. Percentage change in peak flows estimated for individual river pixels reflect the properties of the catchment draining to that location which will not necessarily be of one particular soil/geology type. However, small headwater catchments can be relatively spatially homogeneous, and it is from these that some inference can be made between catchment properties and projected future change. Specifically, examination of Fig. 7(a) indicates that percentage changes in peak flow at the 20-year return period range from -10 to 15% increase in chalk areas, from 15 to 40% in areas to the west underlain by Liassic/Oolite formations, and from 15 to 50% for London Clay. At the tidal limit of the Thames at Kingston (39001), which drains an area of mixed soil/geology/land-cover, the percentage changes in peak flow are 21% and 18% at the 5-and 20-year return periods respectively.

Fig. 7

The pattern of change across the Thames Basin is broadly in line with results obtained by Bell et al. (2009) using the G2G Model, therein denoted "Soil-G2G", with inputs derived from a single RCM (HadRM3H) assuming UKCIP02 scenarios for the period 2070 to 2100. The differences in the two maps of projected change in peak flows across the Thames are mainly due to use of different RCM data (the UKCP09 perturbed-physics ensemble vs. a single UKCIP02 RCM run), and the emphasis here on 15-minute flows (instead of daily) for G2G model calibration and assessment. A water-balance analysis reported in Bell et al. (2009) concluded that while areas with deeper effective stores (e.g. chalk) produced similar volumes of evaporation and runoff to areas with shallower ones (e.g. London Clay), differential timing of release and partitioning of runoff between surface and sub-surface stores lead to a different response. Specifically, under a possible future climate scenario of warmer drier summers and wetter winters (indicated for the 11 RCM ensemble members in Fig. 5), slowly-responding areas such as chalk will tend not to respond immediately to intense autumn/winter rainfall with high flows, but will instead replenish water in sub-surface storage. The length of the autumn/winter period required for deep stores to become replenished to field capacity would be extended further following projected increases in future evaporation. However, catchments with shallower soils, such as upland, urban and clay areas, are less affected by seasonal changes in rainfall and PE and would respond more immediately to high autumn/winter rainfall with high river flows, resulting in projected increases in future flow peaks in these areas.

One advantage of using PE and rainfall derived from a climate model with an embedded land-surface model is the ability to include climate-related processes that may be absent from simpler representations of land-atmosphere interactions. For example, the effect of projected future atmospheric CO_2 levels on plant stomatal conductance impacts on future estimates of PE. This effect may be an important consideration for climate impact and modelling studies since increased CO_2 is thought to lead to a reduction in evaporation from vegetated surfaces and a possible increase in flooding. However, most hydrological impact studies to date have neglected this effect. Six of the 11 ensemble members used here take this into account. The effect on changes in flood frequency has been determined by examining two subsets of the 11-member ensemble. These subsets are:

(i) dependence of stomatal conductance on CO_2 ‘on’ (*6 members*);
(ii) dependence of stomatal conductance on CO_2 ‘off’ (*5 members*);

Fig. 7(c) and (d) presents maps of projected change in flood frequency for subsets (i) and (ii) respectively. When stomatal conductance of moisture flux is assumed to be dependent upon future CO_2 levels (subset (i)), then projected change in flood frequency is often twice as high as that for subset (ii), where independence is assumed. For subset (ii), future PE tends to be higher, particularly for summer months, resulting in drier antecedent conditions which reduce the likelihood of floods arising from autumn/winter frontal rainfall systems. For example, for the Thames at Kingston (39001), the percentage changes in 5-year return period peak flows are 20% and 10% for subsets (i) and (ii) respectively. It should be noted that detailed conclusions on the effect of specific parameter perturbations on flood frequency impacts is difficult, as multiple parameters are varied between ensemble members. However, an examination of the range of results from all 11 ensemble members allows such different possible future effects of CO_2 on PE to be taken into account.

In order to be able to better compare changes in flood frequency arising from all ensemble members, results have been extracted for each member, for each point down the main Thames and for eighteen of its principal tributaries. These have been plotted together in Fig. 8 for the 20-year return period. The bottom row shows the results for the main Thames, 'flowing' from left to right. Each other row includes two tributaries, which also 'flow' from left to right, with the right-most plotted point for each tributary being that at which it joins the main Thames (whose outlet is plotted at the far right, at position zero). The tributaries are ordered by the point at which they join the main Thames. As well as showing the results for all 11 ensemble members together, these graphs illustrate how the percentage change in peak flow varies as one moves down the rivers, and at the points where tributaries join the main Thames. In particular, this highlights the dependence of the impact on soil type, as rivers that start on chalk before flowing into clay regions have a sudden change in impact as they cross from chalk to clay (e.g. half way down the Pang, three-quarters of the way down the Kennet and one-third of the way down the Colne). Variation in the modelled flow response to rainfall and PE from different RCM ensemble members is greatest in the clay/Lias areas of the Thames Basin, and least in the chalk headwaters for which larger sub-surface stores provide some resilience to change. For all river tributaries one RCM ensemble member consistently yields unusually high PE values leading to a projected decrease in peak flows. Although PE values for this RCM are higher than for other ensemble members in both Current and Future periods, the increase in future PE coupled with relatively unchanged future annual rainfall totals leads to lower net precipitation input to catchments and projected future decreases in peak river flows.

Fig. 8

The relationship between projected climate change impacts on peak flows and underlying soil/geology is indicated in Fig. 9, where the ensemble mean percentage change in 20-year return period peak flows is plotted against the BFI of the contributing catchment for every pixel along the main river channels in the Thames Basin. Although Fig. 9 shows considerable scatter, there is a tendency for catchments with BFI<0.4 (quickly responding catchments with shallower stores) to experience increases in peak flow of 40-60% while catchments with higher BFI (>0.7) experience lower projected changes (5-50%). The high spatial variability in catchment soil/geology would account for the wide scatter. However, the results broadly support the conjecture that catchments with shallower soils (low BFI) would respond more immediately to high autumn/winter rainfall, yielding high river flows and resulting in high projected increases in future flow peaks for these areas. Conversely, areas with high BFI and deeper stores, such as chalk, will replenish deficits in sub-surface stores before responding to autumn/winter rainfall with increased runoff/flows.

Fig. 9

4.2 Comparison with an RCM-based estimate of current natural variability

An RCM ensemble for the Current time-slice can be used as input to the G2G to gain an RCM-based estimate of current natural variability in river flow, by pooling data from the ensemble. For this case, a perturbed parameter ensemble is used rather than an initial condition ensemble. The estimation has to be done with care as the simulated variables of interest from the ensemble members used need to represent samples from the same population. That is, for flood modelling they should not include any members with parameter perturbations that give very different behaviours of precipitation (or PE) metrics.

An analysis carried out by the Met Office Hadley Centre (Elizabeth Kendon pers. comm.) suggested that a five-member subset of the original ensemble members could be pooled, as these have essentially the same settings for a number of key parameters, the perturbation of which leads to significant changes in certain precipitation characteristics. Originally six members were considered suitable for pooling, but the subset was subsequently reduced to five for the present application by excluding one member which had a different setting for the dependence of stomatal conductance on CO_2 to the other five ('off' versus 'on'; Fig. 7(c) and (d)). An RCM-based estimate of current natural variability has been obtained for each river point using the procedure described below.

The AM data for the Current time-slice from the selected five-member subset are pooled. The pooled dataset is resampled with replacement into 200,002 sets of 30 AM (from the 5 by 30 AM for each river point) and a flood frequency curve is fitted to each set. The differences (at specific return periods) between 100001 pairs of fitted flood frequency curves are calculated, and the bounds delineating the middle 50% and 95% are then calculated from the set of differences.

These bounds are shown using bands of grey shading on the graphs in Fig. 8 for the 20-year return period. The modelled changes in flood frequency between the Current and Future time-slices can then be seen in the context of this estimate of the natural variability that might be expected without the presence of climate change. It can be seen that some rivers, or parts of rivers, show few changes outside the range of current natural climate variability (e.g. the Mole and the Wandle), whereas others show many changes outside the range of natural variability (e.g. the Thame and the Wey). This alters according to the return period being considered, as well as location, as is shown on the maps in Fig. 7(b): darker colours indicate areas where more of the modelled changes in peak flows are outside the range of the RCM-based estimate of natural variability. These tend to be the more hydrologically responsive areas (e.g. clay and Lias formations) which have less sub-surface storage and saturate quickly during heavy rainfall.

Locations which consistently show modelled changes outside the range of natural variability are candidates for so-called ‘early-bird’ sites, where further monitoring could be expected to show evidence of statistically significant changes in observed flows before many other sites (Wilby, 2006). However, just because a location shows few, if any, modelled changes outside the range of natural variability does not mean that it is safe from flooding in the future, as the 11-member ensemble does not necessarily capture the full range of possible changes and because current flood defences may not accommodate the full range of natural variability in river flow. Also, it should be remembered that an RCM-based estimate of current natural variability has been used here as input to the G2G, and this estimate may not fully represent real variability. Natural variability could also alter under climate change.

5 Conclusions

5.1 Summary

The River Thames drains an area of over 10000 km^2 in the southeast part of England. Land-cover, soil and geology in the basin are particularly complex with a mixture of lithologies and variable land-cover including significant urban areas such as Oxford and London. The Grid-to-Grid (G2G) distributed hydrological model - formulated to employ terrain, soil and urban land-cover datasets - has been used to model river flows on a 1km grid across the Thames Basin. Model performance has been assessed with reference to high-resolution (15-minute) quality-controlled river levels/flows and using 15-minute gridded estimates of rainfall as input. The G2G model produces a realistic response to rainfall in catchments where (a) the response to rainfall is relatively free from artificial influences, (b) the river gauging station is considered to be reasonably accurate and (c) there are no significant problems with the flow and rainfall records. For these catchments, R^2 Efficiency ranges from 0.59 to 0.84 (median 0.77) for the calibration period and from 0.40 to 0.77 (median 0.75) for the assessment period. As the G2G primarily simulates “natural” flows, model performance can be variable for catchments with greater levels of anthropogenic disturbance.

Following calibration and assessment on historical periods, the G2G model has been used with inputs of rainfall and PE, - estimated from the UKCP09 perturbed-parameter RCM ensemble - to simulate flood frequency across the Thames Basin. This has been done for two 30-year time-slices: Current (October 1960 to September 1990) and Future (October 2069 to September 2099, under the A1B emissions scenario). Comparison of observed flood frequency with RCM-derived flood frequencies for the Current period suggests that flood frequency is modelled well by most RCM ensemble members in some catchments, but over-estimates in others. However, other factors need to be borne in mind when making such a comparison, including: G2G model error, river gauging station error, the consequences of artificial influences like abstraction (not included in the G2G) on river flow records, and that the RCM Current simulations do not aim to be reproductions of the 1961-1990 period but only possible scenarios.

The changes in flood frequency between Current and Future time-slices were then analysed on a 1km river grid across the Thames Basin. Considerable variation is evident, by ensemble member, by return period and by location, with areas underlain by chalk generally showing lower percentage changes than other regions. Almost all changes are increases, generally averaging between 5-10% in chalk areas and 30-50% elsewhere, for peak flows with up to a 20-year return period. However, for one particular RCM ensemble member many changes are negative (indicating decreases in peak flow), probably due to large increases in PE. For other ensemble members changes are much higher than average, with increases of over 80% in some areas.

It is important to recognise that projected changes in both rainfall and PE influence future changes in river flows, and that a range of methods with varying degrees of complexity are available for estimating projected future PE. In the RCM ensemble used here to estimate PE input to the hydrological model, one of the climate model parameter-perturbations of particular relevance is the dependence of stomatal conductance on atmospheric CO_2 levels. This effect may be an important consideration for studies of climate impact on water management as increased CO_2 is thought to lead to a reduction in evaporation from vegetated surfaces and a possible increase in river flow. However, most hydrological impact studies to date have neglected this effect. Six of the 11 ensemble members used here take this into account. The effect on changes in flood frequency has been determined by examining two subsets of the 11-member ensemble. If the effect of increased CO_2 on stomata is not taken into account, future levels of PE from vegetation are much higher and projected future change in flood frequency is lower than for the CO_2-dependent subset. These differences demonstrate that it is important to consider the effect of future CO_2 emissions on plant physiology in addition to the effect of emissions on physical atmospheric variables such as temperature and humidity. However, it is important to note that making precise conclusions concerning the effect of specific RCM parameter-perturbations is difficult, as multiple parameters are varied between ensemble members.

Comparison of the modelled changes in flood frequency with an RCM-based estimate of current natural variability reveals that, whilst some rivers (or parts of rivers) show few changes outside of the range of current natural variability, others show many changes outside of this range. The latter locations could be considered as sites where further monitoring may provide early warning of statistically significant changes in observed flows, due to climate change. It should be remembered that an RCM-based estimate of current natural variability has been used here, which may not fully represent real natural variability. Natural variability could also alter under climate change.

5.2 Discussion

Towards the downstream end of the fluvial Thames (for example near Kingston in the vicinity of Teddington Weir), the average estimated change in modelled flood peaks for a 20-year return period is 36% with a range of -11% to +68%. These estimated changes are broadly in line with the latest guidance for England (Environment Agency, 2011), which indicates that sensitivity analyses of river flood alleviation schemes in the Thames Basin should take account of potential increases in river flood flows of 25% (median) by the 2080s, with a range of -5% to 70%. This recent guidance updates earlier FCDPAG guidance (Defra, 2006) which indicated potential increases in UK peak flows of 20% for the period 2025-2115, and was a precautionary response to the research findings of projects FD0424-C (Reynard et al., 1999) and W5-032 (Reynard et al., 2004). The Thames modelling work presented here provides further evidence of changes in peak flows that exceed 20% by the 2080s, and additionally includes the effect of increases in atmospheric CO_2 levels on stomatal conductance, which can result in smaller increases in PE and lead to larger increases in peak river flows.

The large estimated increase in future peak flows should ideally be considered in a wider historical context than a modelling study over two 30-year time-slices might provide. Over the past thirty to forty years there has been some evidence of a positive trend in high river flow indicators (Hannaford and Marsh, 2008), generally thought to be linked to changes in winter precipitation arising from changes in atmospheric circulation patterns. However no such recent trend is evident for the lower Thames, and trend analyses of flow records throughout the 20^{th} century (Black, 1996; Robson, 2002; Hannaford and Marsh, 2008) have so far detected no apparent *long-term* trend in UK flood magnitude. The modelling of current and future river flows undertaken here has relied on observations and climate model output from 1960 onwards (a period over which increases in high river flows have been detected in some areas). It is important to note that the 1961-1990 period is considered to be notably 'flood poor' (Hannaford and Marsh, 2008); historically flood frequencies have varied substantially, a phenomenon normally assumed to be a natural consequence of the UK's inherent climatic variability. River management in recent times has led to greater channel storage and conveyance which has resulted in fewer floods in the lower Thames. The relatively low frequency of major flood events on the Thames during the 1961-1990 period indicates that the changes in return periods predicted for the 2080s should be treated with some caution, although this would be more likely to affect estimates of percentage changes from a baseline of observed flows (rather than a modelled baseline using RCM data, as applied here). Until the 1960s, snowmelt and frozen ground were major contributing factors in a significant proportion of major floods on the Thames (Griffiths, 1983) but, more recently, rising winter temperatures have resulted in a decline in snowmelt-induced flood risk in the Thames Basin (Marsh and Harvey, 2012), with significant snowfall occurring on relatively few occasions during 1961-1990. Compelling evidence for continuing temperature increases strongly suggests that snowmelt-induced flood events will continue to decline in both frequency and magnitude. The hydrological modelling undertaken here excludes the influence of snowmelt on high river flows as its impact on flood frequencies derived for the 1961-1990 period in the Thames Basin is expected to be minor.

Further development of the G2G hydrological model is ongoing, for instance through the inclusion of a snowmelt component to improve model performance, particularly for catchments located in Wales and Northern Britain. Improvements to the nature and availability of spatial datasets for soil, geology and land-cover properties will be expected to strengthen the G2G's underpinning by physical properties, and reduce reliance upon calibration of model parameters. The G2G model presented here simulates naturalised river flows and there is currently no allowance made for flood defences, or for the effect of out-of-bank flows on flood attenuation, which would in-practice lead to a reduction in high flood peaks during flood events. The introduction of a discharge-dependent wave speed and spatially variable estimates of bankfull capacity would therefore be beneficial. Such model enhancements are likely to lead to improved confidence in estimates of river flows and, in turn, improved assessment of climate change impacts on flood frequency. The inclusion of changing land-use patterns, particularly increased urbanisation, and changing patterns of abstraction could also be considered.

Uncertainty in model estimates of the hydrological impact of climate change can arise from a range of sources including emissions scenario, model structure (for both the climate and hydrological models) and parameterisation (again for both the climate and hydrological models). For catchments considered to be particularly susceptible to increases in future flood risk, additional analysis using a catchment model (such as the PDM) adjusted for local conditions is recommended. However, several studies have suggested that the greatest uncertainty comes from sources related to the modelling of the future climate, particularly the choice of GCM, rather than from emissions or hydrological modelling (Kay et al., 2008; Prudhomme and Davies, 2008; Wilby and Harris, 2006). The RCM perturbed-parameter ensemble applied in this study represents the first attempt at deriving fine-scale information consistent with a range of large-scale regional changes which result from this global modelling uncertainty. It demonstrates how these large-scale uncertainties translate into uncertainty in future flood risk. More work is required to determine how representative these assessments are of the implications of the full range of climate modelling uncertainty.

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Fig. 8. Percentage change in 20-year return period peak flows plotted against distance from the main Thames outlet (~km), for each of the 11 ensemble members. Plots show the main Thames (bottom graph) and eighteen of its principal tributaries (left and right of other graphs). Each river 'flows' from left to right, with the right-most plotted point for each tributary being that at which it joins the main Thames (whose outlet is plotted at the far right, at position zero). The tributaries are ordered according to where they join the main Thames (shown in the river network map). Bands of light and dark grey shading show the extent of an RCM-based estimate of current natural variability (middle 95% and 50% respectively).

Fig. 9. Percentage change in 20-year return peak flows (ensemble mean) plotted against the BFI for the contributing catchment, for every pixel along the main river channels in the Thames Basin (black circles).

Catchment	Station ID	Area (km^2)	BFI	Geology	Catchment relatively undisturbed ?	Gauge accuracy ?
Cray at Crayford	40016	119.7	0.86	Chalk/clay		Y
Lambourn at Shaw	39019	234.1	0.84	Chalk	Y	Y*
Darent at Hawley	40012	191.4	0.83	Chalk/clay		Y
Wandle at Connollys Mill	39003	176.1	0.81	Chalk/clay		
Wey at Tilford	39011	396.3	0.79	Oolite/Lias		
Windrush at Newbridge	39006	362.6	0.79	London Clay/chalk		Y
Kennet at Theale	39016	1033.4	0.76	Chalk	Y	Y*
Cherwell at Banbury	39026	199.4	0.73	Lias		
Sor Brook at Bodicote	39144	87.7	0.73	Lias	Y	Y
Wey at Weybridge	39079	1008	0.73	London Clay/chalk		N[1]
Mimram at Panshanger Park	38003	133.9	0.72	Chalk		Y
Ravensbourne at Catford Hill	39056	120.4	0.71	Chalk/clay		Y
Evenlode at Cassington	39034	430	0.70	Great Oolite	Y	Y
Thames at Farmoor	39129	1608.6	0.69	Oolite/Lias		Y*
Thames at Sutton Courtenay	39046	3414	0.65	Lias/Oolite/chalk		Y*
Thames at Kingston	39001	9948	0.65	Chalk/clay/etc.		Y
Ock at Abingdon	39081	234	0.64	Clay/chalk		Y*
Thames at Reading	39130	4633.7	0.64	Chalk/clay/etc.		Y
Blackwater at Swallowfield	39007	354.8	0.63	Sand/gravel/clay		Y
Colne at Denham	39010	743	0.62	Chalk/clay		
Cherwell at Enslow Mill	39021	551.7	0.59	Lias		
Cherwell at Oxford	39139	906.8	0.56	Lias /Oolite		Y
Lee at Feildes Weir	38001	1036	0.55	Chalk/clay		
Mole at Esher	39104	469.6	0.52	London Clay/sand	Y	Y
Ray at Islip	39140	290.1	0.49	Clay/Sand/Gravel		Y
Enborne at Brimpton	39025	147.6	0.49	Lias /Oolite		Y
Beverley Brook at Wimbledon Common	39005	43.5	0.47	London Clay/chalk		
Mole at Kinnersley Manor	39069	142	0.45	London Clay/sand		
Roding at Redbridge	37001	303.3	0.33	London Clay		
Mar Dyke at Stifford	37034	90.7	0.31	London Clay		
Ray at Grendon	39017	18.8	0.23	Lias	Y	Y
Cobbins Brook at Sewardstone Road	38020	38.4	0.22	London Clay		
Silkstream at Colindeep Lane	39049	29	0.18	London Clay		
Pinn at Uxbridge	39098	33.3	0.17	London Clay		

Table 1.

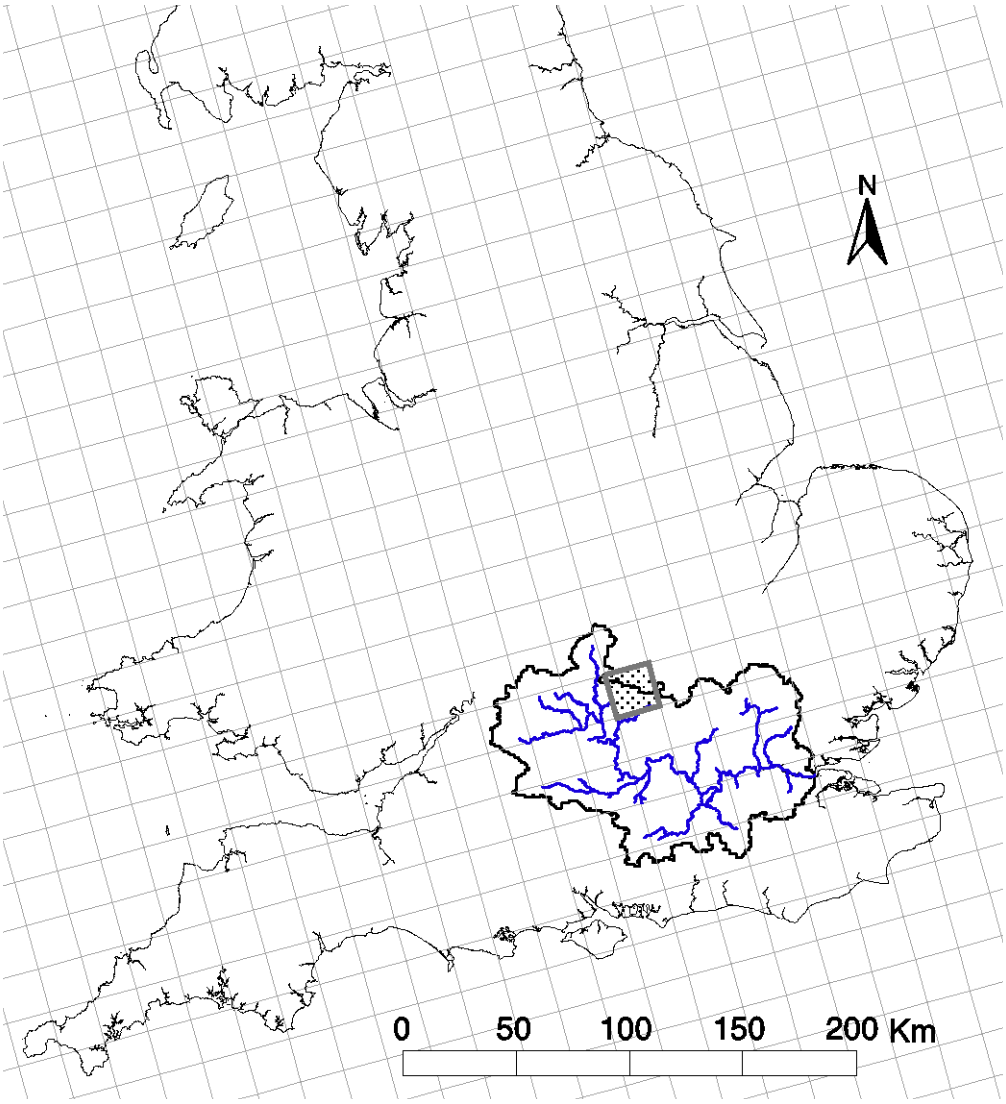
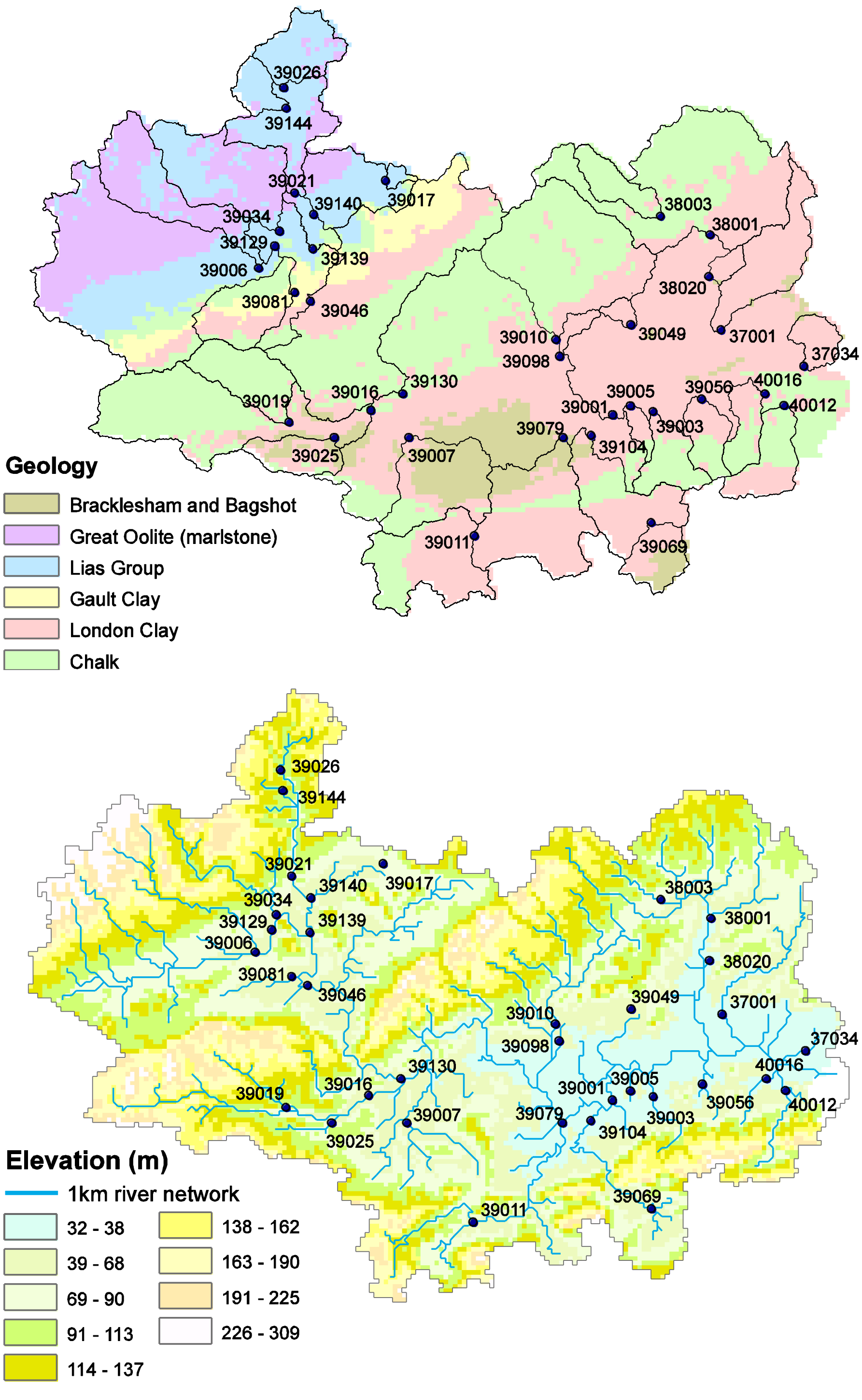


Fig. 1.


39026
39144
39021
39140
39017
39034
39129
39139
39006
39081
39046
38003
38001
38020
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37001
37034
39010
39098
39130
39016
39019
39005
39056
40016
40012
39001
39003
39079
39104
39025
39007
39011
39069
Geology
Bracklesham and Bagshot
Great Oolite (marlstone)
Lias Group
Gault Clay
London Clay
Chalk
Elevation (m)
1km river network
32 - 38
39 - 68
69 - 90
91 - 113
114 - 137
138 - 162
163 - 190
191 - 225
226 - 309

Fig. 2.

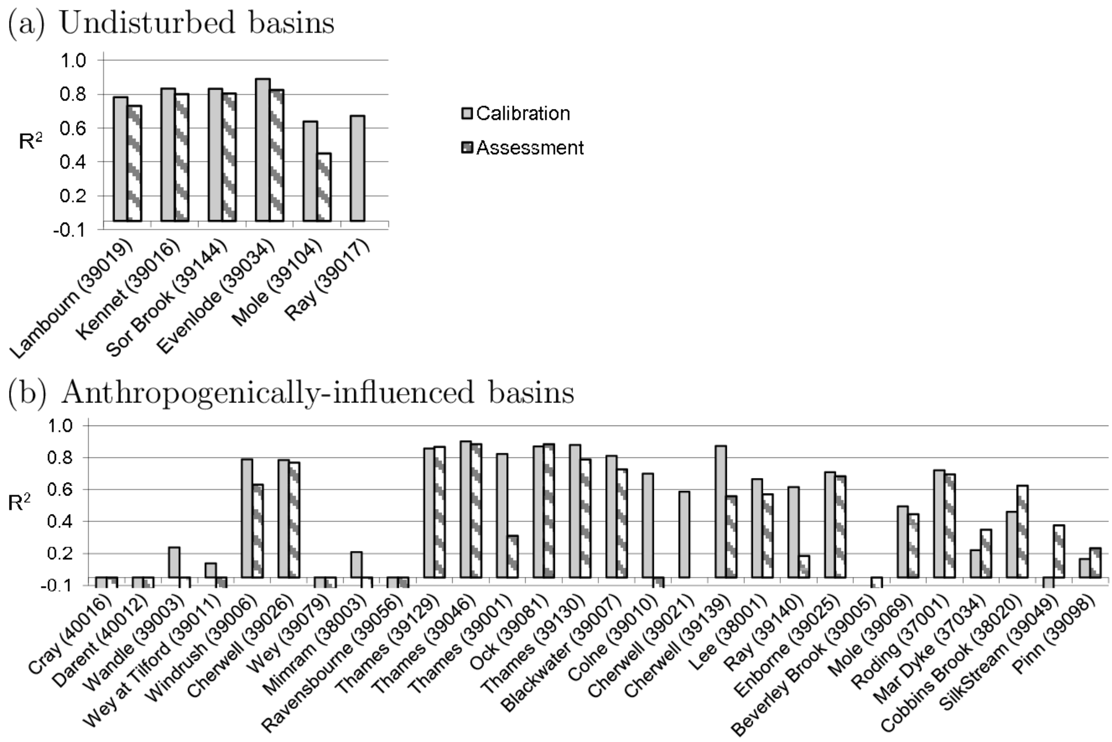
(a) Undisturbed basins
1.0
0.8
0.6
0.4
0.2
-0.1
R²
Calibration
Assessment
Lambourn (39019)
Kennet (39016)
Sor Brook (39144)
Evenlode (39034)
Mole (39104)
Ray (39017)
(b) Anthropogenically-influenced basins
1.0
0.8
0.6
0.4
0.2
-0.1
R²
Cray (40016)
Darent (40012)
Wandle (39003)
Wey at Tilford (39011)
Windrush (39006)
Cherwell (39026)
Wey (39079)
Mimram (38003)
Ravensbourne (39056)
Thames (39129)
Thames (39046)
Thames (39001)
Ock (39081)
Thames (39130)
Blackwater (39007)
Colne (39010)
Cherwell (39021)
Cherwell (39139)
Lee (38001)
Ray (39140)
Enborne (39025)
Beverley Brook (39005)
Mole (39069)
Roding (37001)
Mar Dyke (37034)
Cobbins Brook (38020)
SilkStream (39049)
Pinn (39098)

Fig. 3.

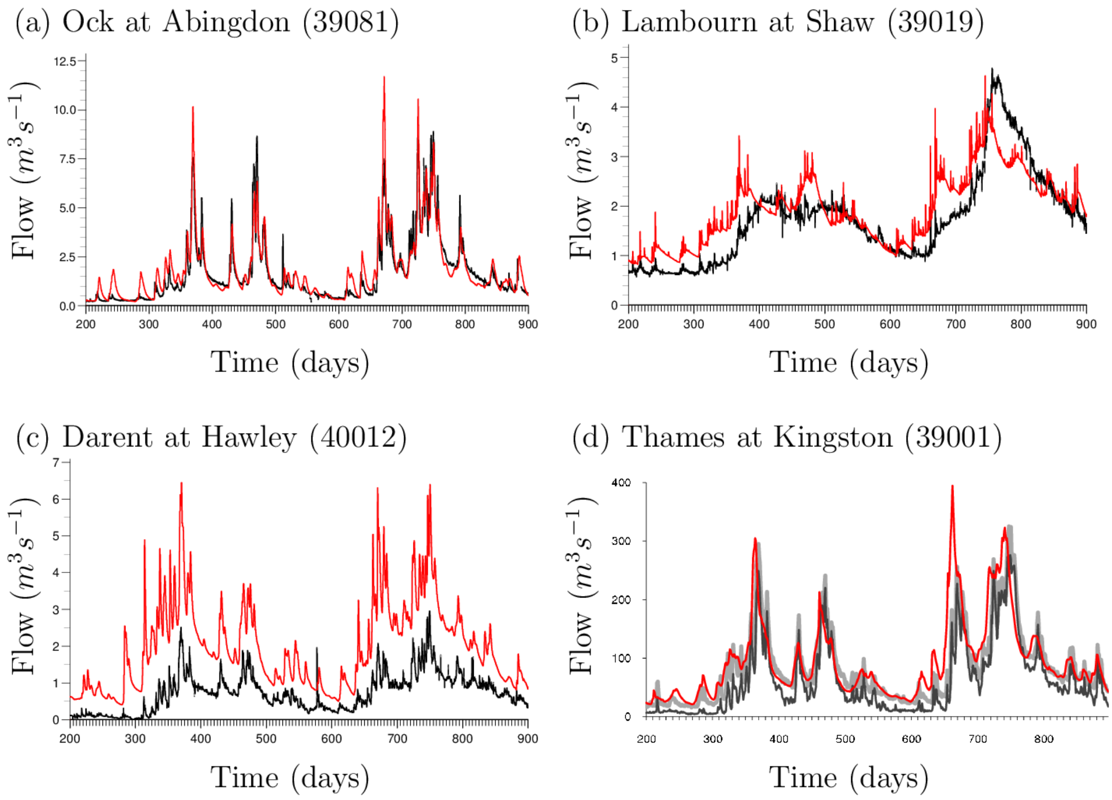
(a) Ock at Abingdon (39081)
(b) Lambourn at Shaw (39019)
(c) Darent at Hawley (40012)
(d) Thames at Kingston (39001)
Flow (m^3s^{-1})
Time (days)

Fig.4.

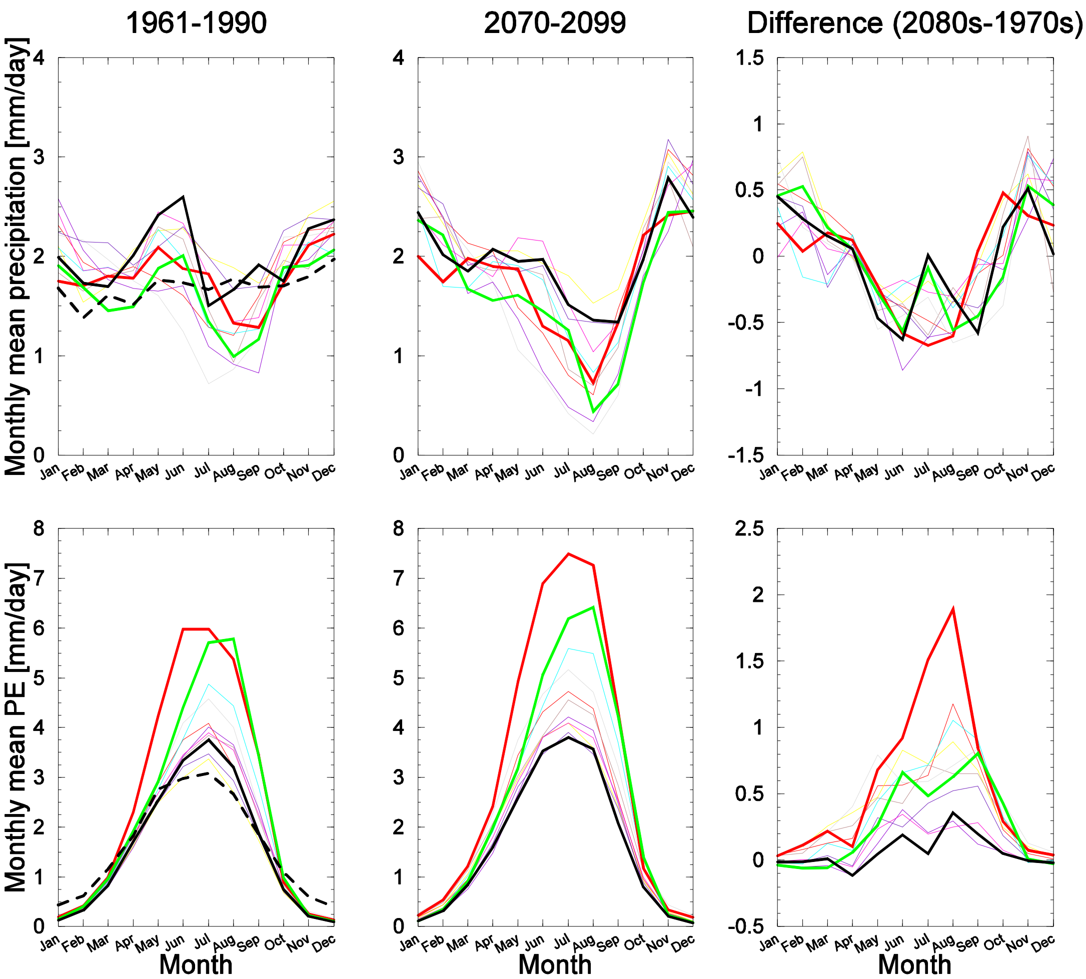
1961-1990
2070-2099
Difference (2080s-1970s)
Monthly mean precipitation [mm/day]
Monthly mean PE [mm/day]
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Month

Fig. 5.

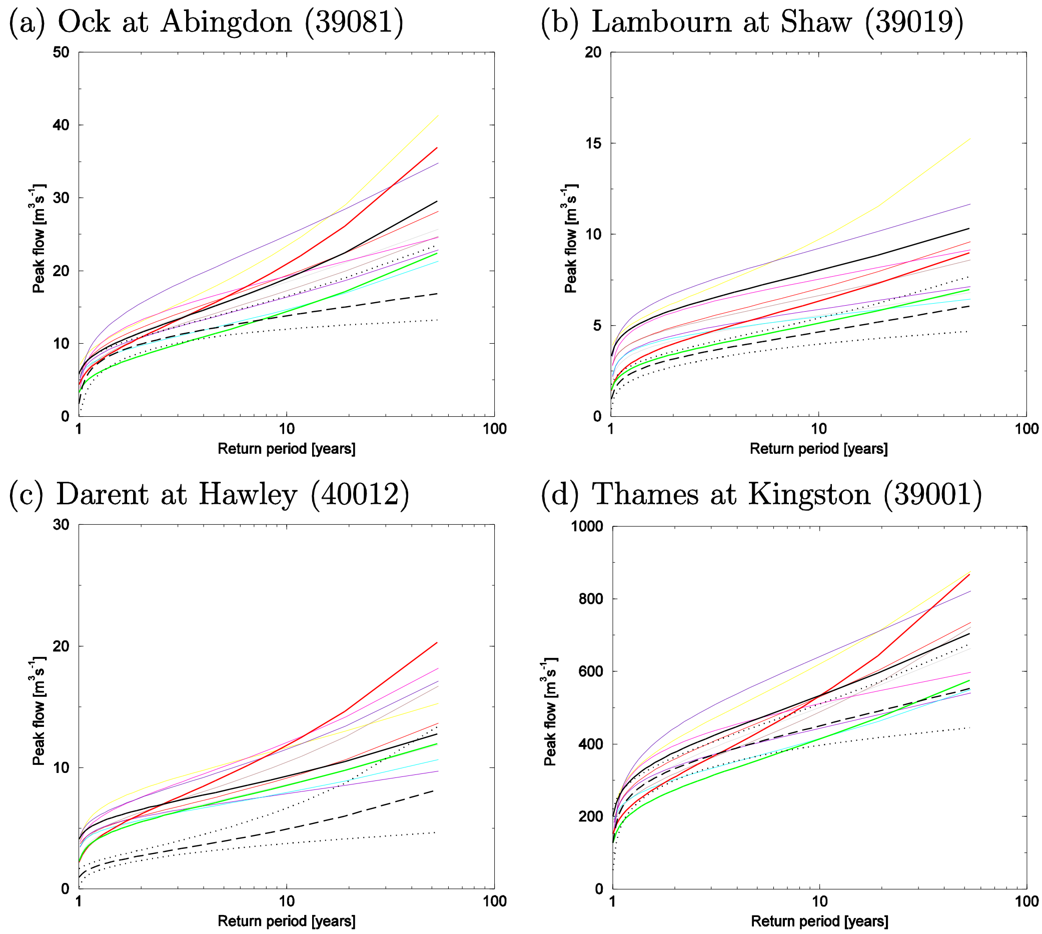
(a) Ock at Abingdon (39081)
(b) Lambourn at Shaw (39019)
(c) Darent at Hawley (40012)
(d) Thames at Kingston (39001)
Peak flow [m3 s-1]
Return period [years]
1
10
100
0
5
10
15
20
30
40
50
200
400
600
800
1000

Fig. 6.

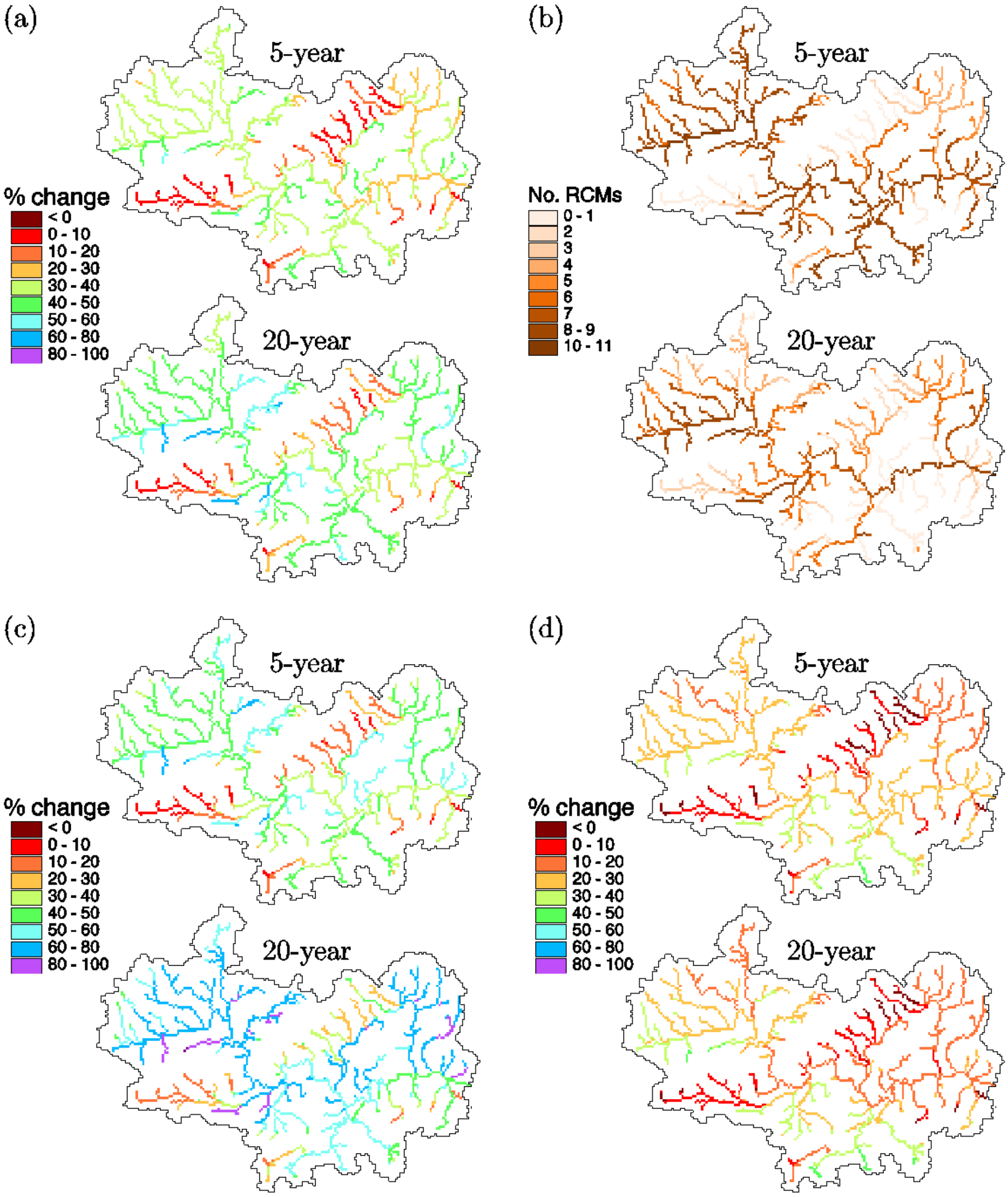
(a)
5-year
20-year
% change
< 0
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 80
80 - 100
(b)
5-year
20-year
No. RCMs
0 - 1
2
3
4
5
6
7
8 - 9
10 - 11
(c)
5-year
20-year
% change
< 0
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 80
80 - 100
(d)
5-year
20-year
% change
< 0
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 80
80 - 100

Fig. 7.

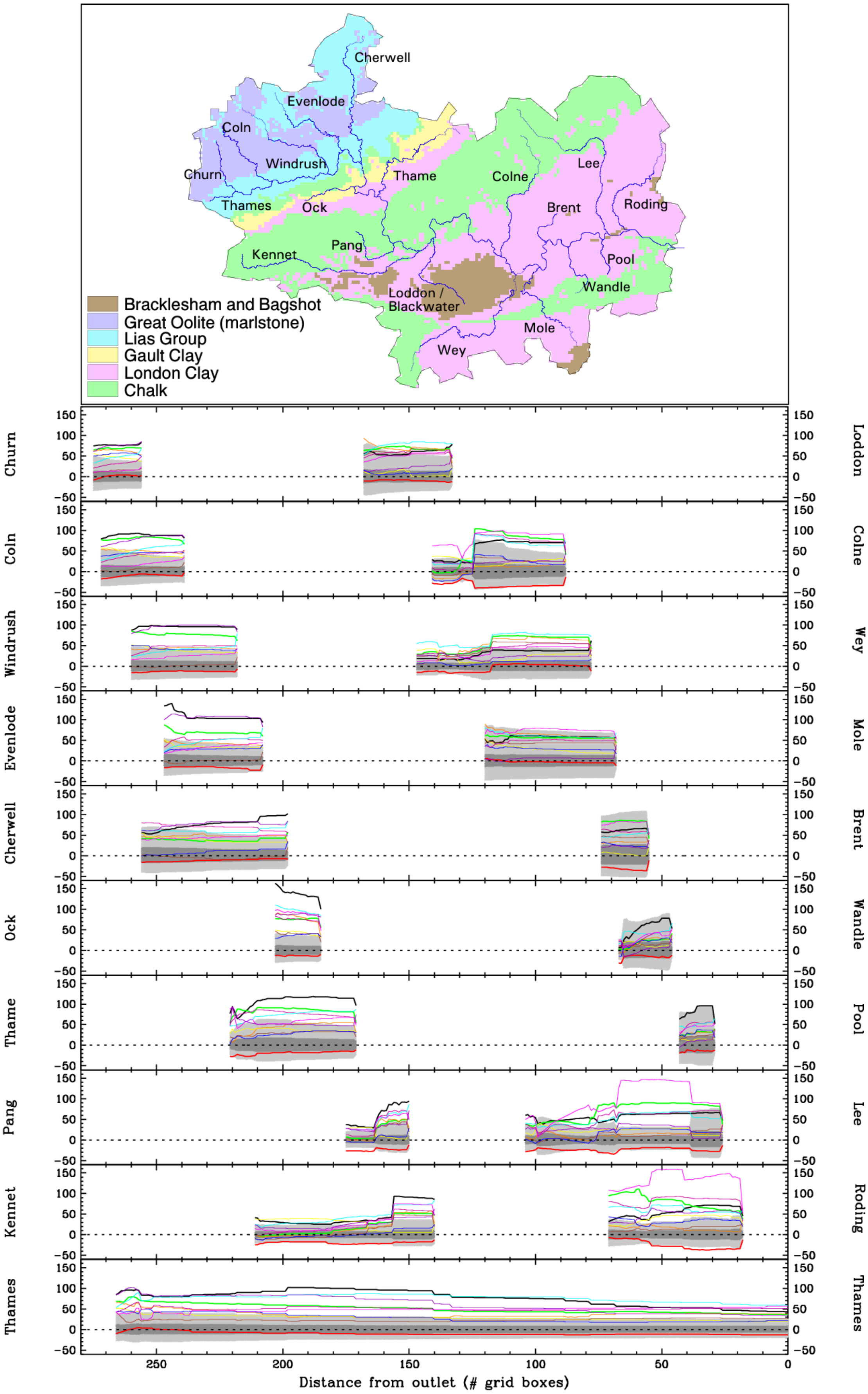
Cherwell
Evenlode
Coln
Windrush
Churn
Thame
Colne
Lee
Thames
Ock
Brent
Roding
Pang
Kennet
Pool
Wandle
Loddon / Blackwater
Mole
Wey
Bracklesham and Bagshot
Great Oolite (marlstone)
Lias Group
Gault Clay
London Clay
Chalk
Churn
Loddon
Coln
Colne
Windrush
Wey
Evenlode
Mole
Cherwell
Brent
Ock
Wandle
Thame
Pool
Pang
Lee
Kennet
Roding
Thames
Thames
Distance from outlet (# grid boxes)

Fig.8.

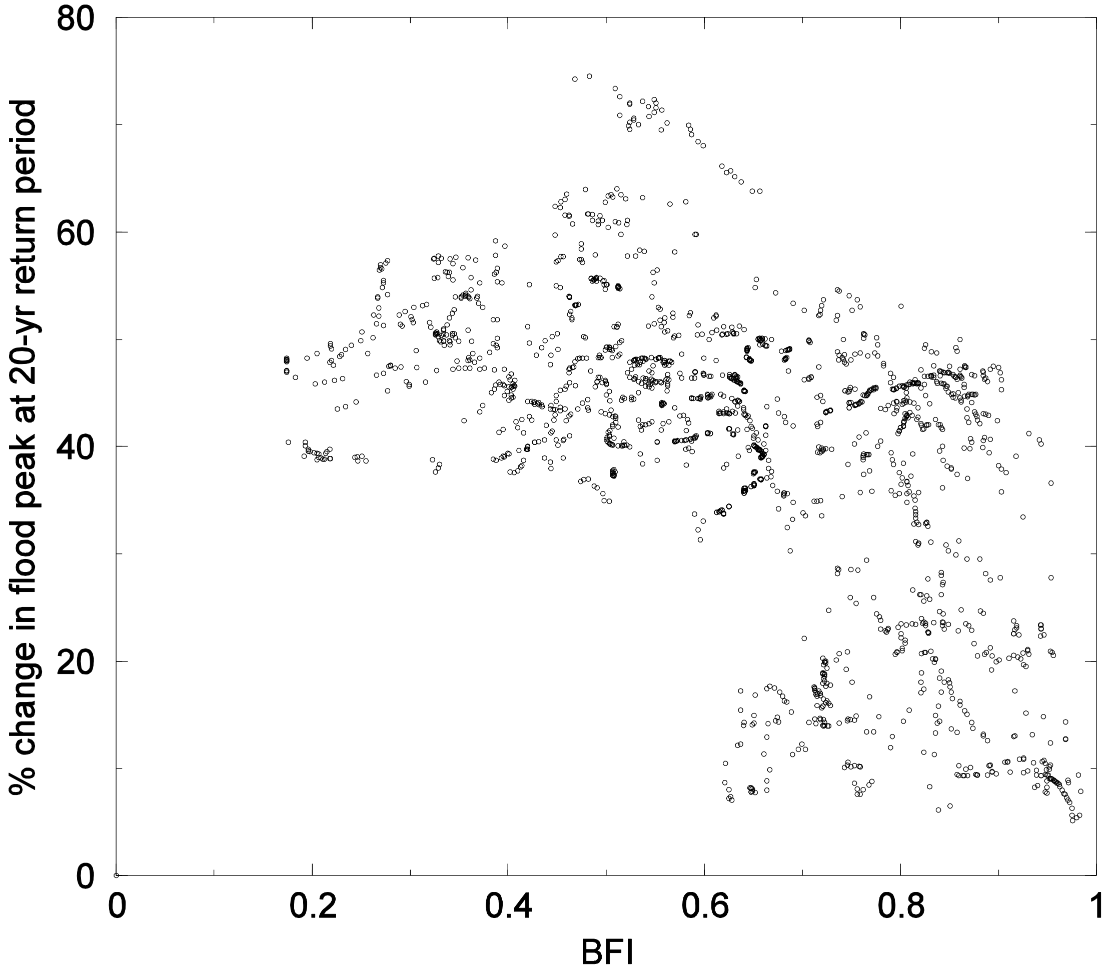
% change in flood peak at 20-yr return period
80
60
40
20
0
0
0.2
0.4
0.6
0.8
1
BFI

Fig.9.