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Combined impacts of future land-use and climate stressors on water resources and quality in groundwater and surface waterbodies of the upper Thames river basin, UK

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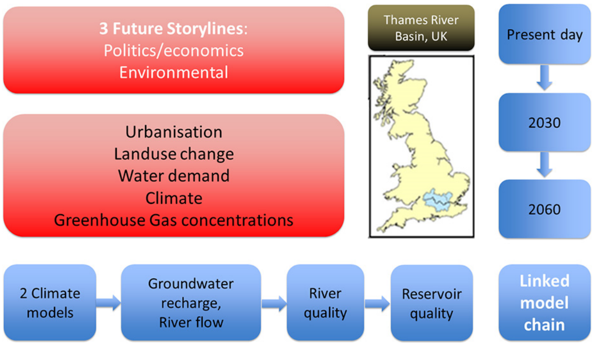
HIGHLIGHTS

- Future climate and human activity threaten water resources in the Thames Basin UK.
- A linked model approach was used and included groundwater, river and lake domains.
- Flow and quality modelled for three future policy and management scenarios.
- Continuation of current economic development reduces flow and impairs river quality.
- Water imports needed in less sustainable futures partly preserve freshwater status.

GRAPHICAL ABSTRACT



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ABSTRACT

It is widely acknowledged that waterbodies are becoming increasingly affected by a wide range of drivers of change arising from human activity. To illustrate how this can be quantified a linked modelling approach was applied in the Thames river basin in southern UK. Changes to river flows, water temperature, river and reservoir quality were predicted under three contrasting future "storylines"; one an extension of present day rates of economic development, the others representing more extreme and less sustainable visions. Modelling revealed that lower baseflow conditions will arise under all storylines. For the less extreme storyline river water quality is likely to deteriorate but reservoir quality will improve slightly. The two more extreme futures could not be supported by current management strategies to meet water demand. To satisfy these scenarios, transfer of river water from outside the Thames river basin would be necessary. Consequently, some improvement over present day water quality in the river may be seen, and for most indicators conditions would be better than in the less extreme storyline. However, because phosphorus concentrations will rise, the invoked changes in water demand management would not be of a form suitable to prevent a marked deterioration in reservoir water quality.

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1. Introduction

1.1. Background

With the global population continuing to increase, water resources are becoming ever more threatened by drivers of change, such as urbanisation, agricultural intensification or climate change, that can be directly or indirectly attributed to human activity (Vörösmarty et al., 2010; Wen et al., 2017). The impacts of these drivers of change in freshwater bodies, e.g. on flows, water storage and water chemistry, are here defined as stressors. Due to the increasingly complex nature of the drivers of change and their nonlinear interactions, freshwater bodies are exhibiting an increasingly diverse assemblage of multi-stressors rather than single stressors, (Schinegger et al., 2012; Hering et al., 2015). Consequently, there is a fundamental need to provide regulators, catchment managers and other stakeholders with an understanding of the links between drivers of change, multi-stressor waterbody responses to such changes, and the impacts of those multi-stressor combinations, i.e. effects on ecosystem services, which can be incorporated into programmes of measures to improve the status of water resources.

Whilst there is much well-founded evidence of effects on water resources of single stressors such as nutrient and sediment loads (e.g. Wagenhoff et al., 2012), in particular from monitoring programmes and controlled experiments, effects of stressors in combination are less tractable (Harris and Heathwaite, 2012). Multiple stressors can be hard to distinguish particularly in monitoring studies as they are often manifested in terms of the same indicator variable (Dafforn et al., 2016), they often act simultaneously (Floury et al., 2013) and their effects may be seen at different spatial scales (Hipsey et al., 2015; Villeneuve et al., 2015). To summarise by way of example, nutrient concentrations depend upon pollutant loads from a variety of sources (e.g. sewage, agriculture, industry) and are mediated by climatic factors (e.g. Neal et al., 2010). Nevertheless, at local scale insights on the interplay between pairs of stressors and their impacts on water resources have been gained, primarily through experimental work (e.g. Townsend et al., 2008). Syntheses of monitoring evidence on whether or not multiple-stressor effects are synergistic or merely additive have been compiled, for example in the case of biotic (phytoplankton, macroinvertebrate) responses (Jackson et al., 2016). Often however, due to circumstances and practicalities, the definition of these stressors and the mechanisms of their impacts are specific and restricted both in concept and in spatial scale. For example, impacts of the intensification of agricultural activity or the mitigation of its polluting effects in specific localities may be apparent in waterbodies only for short distances downstream. Detection of changes in downstream water quality in response to land management is likely to be moderated by other sources to river flow and by in-stream processes (Kirchner et al., 2000; Lloyd et al., 2014; Rode et al., 2016). River systems are often significant sinks of nutrient nitrogen and phosphorus (e.g. Mulholland et al., 2008 and Jarvie et al., 2012 respectively). Moreover, the nature of these impacts may be highly dependent on local conditions and be time-variant, for example bed sediments potentially act as sources as well as sinks of phosphorus (Withers and Jarvie, 2008). For these reasons, to evaluate impacts on river basin-wide water resources a statistical or deterministic modelling approach that incorporates the effect of climate drivers is essential. Moreover, the combined impacts of more than two stressors are much harder to identify without the application of modelling techniques (Hipsey et al., 2015).

1.2. Objectives

The objectives of the present paper are to evaluate how water resources in the Thames river basin will be affected by each of three future climate and planning scenarios. The Thames, (described in Section 2.1) is subject to a wide variety of stressors and the magnitude and interactions of these will inevitably change in the future.

A process-based modelling approach is used. Whilst integrated catchment models are well-suited to quantifying water resource impacts in different domains (soils, groundwater, flowing and standing water bodies) and in terms of hydrological, chemical and biological metrics (Abbaspour et al., 2015), an approach linking separate deterministic model applications is often favoured (Hipsey et al., 2015). A linked approach retains flexibility to choose model structures of a level of complexity sufficient to cover the issues being addressed and appropriate for the availability of data. Adopting a relatively simple approach where possible is appealing as it helps prevent model uncertainty from escalating (Lindenschmidt, 2006), for example when representing soil hydrology and chemistry. Conversely, the known complexity in the dynamic inter-relationships between aquifers can be captured more realistically using river basin-specific configurations of recharge and groundwater models. Therefore to achieve study objectives, a linked modelling approach using three tools was adopted here, comprising (i) catchment hydrology encompassing river flows and groundwater levels, (ii) river flow routing and water quality, and (iii) reservoir quality. The chosen modelling approaches and their performance under calibration and testing is described in Section 2.2.

The future climate and planning scenarios (termed “storylines”) are outlined in detail in Section 2.3. In Section 2.4 the technical process of linking the models together and applying the storylines is described. The results of the storylines are reported systematically in Section 3 for each of the three modelling tools in turn. These results are brought together in Section 4 and discussed in terms of the relative vulnerability of future water resources to the different storylines and to climate. Later in Section 4 the utility of the approach as a means for stakeholders to identify dominant stressors is reviewed. Overall in terms of the wider nature of the storylines themselves, the analysis comprises two elements. Firstly, the impact on water resources of future climate and socio-economics under an extension of present day rates of economic development is assessed and compared to present conditions. Secondly, the results from this assessment are further compared with two more extreme and less sustainable visions of future development.

2. Method

2.1. Water resources in the Thames river basin

The Thames river basin (Fig. 1) is situated in the south east of the United Kingdom and covers an area of ~16,000 km^2 (Environment Agency, 2016). It consists of a mixture of rural areas, primarily grassland, arable, and woodland in the east and south of the region, and urban areas, dominated by Greater London but also including numerous other towns and cities, with a total population of ~15 million. The river basin is underlain by two major aquifers, the Chalk and the Oolitic Limestones which provide the majority of public water supply in the river basin (Bloomfield et al., 2011). The River Thames, the principal water course, has a mean flow of ~78 $m^3\ s^{-1}$ at the lowest gauge in the river basin, and the mean annual rainfall is ~750 mm (Marsh and Hannaford, 2008).

As is common in regions of intensive agriculture and large urban populations, the Thames river basin is subject to a variety of drivers of change and of resulting stresses, many linked to land-use, to which water body failures may be attributed (Environment Agency, 2009). These include:

- abstraction and artificial flow regulation;
- physical modification of water bodies, for example for flood defence purposes;

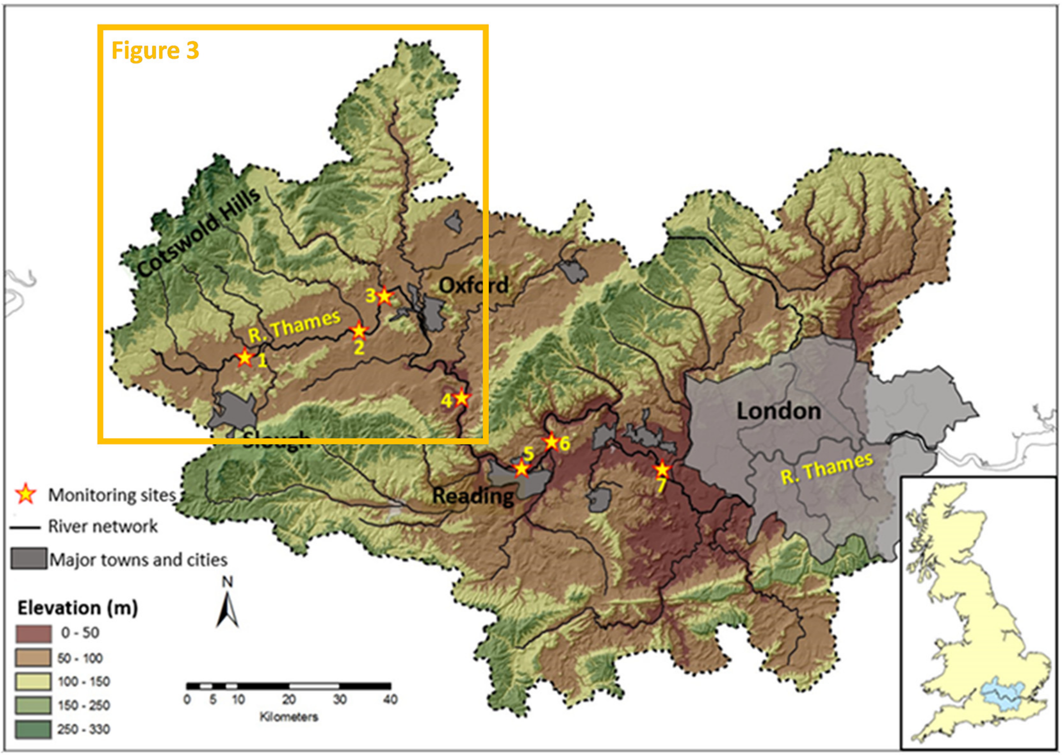


Fig. 1. Map of Thames river basin, showing location of key water quality monitoring sites. Site 1 = Hannington Wick; Site 2 = Newbridge; Site 3 = Eynsham; Site 4 = Wallingford; Site 5 = Reading; Site 6 = Sonning; Site 7 = Runnymede/Egham. Source: Bowes et al. (2016). The "Figure 3" orange box indicates the extent of modelling undertaken. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

- loading of organic pollutants (contributing to incidences of eutrophication) and faecal organisms, from sources such as manure or sewage;
- loading from agricultural nutrients, primarily nitrate and phosphate, and loading from pesticides;
- loading of other chemical pollutants, for example related to urban areas and the transport network, including a growing range of personal care products and hazardous substances;
- increased rates of, or changes in patterns of soil erosion from land-based activities resulting in changes in sediment regimes; and,
- introduction of invasive non-native species that impact on native wildlife.

These stresses have resulted in a number of significant water management issues as documented in the Thames River Basin Management Plan (Environment Agency, 2016). Water bodies have been affected by physical modification; pollution from waste water, agricultural sources and from towns, cities and transport. Some have had changes to their natural flows and levels and others have been affected by non-native species. The river basin comprises 489 surface water bodies and 47 groundwater bodies. Because of the stresses within the river basin, the ecological status of 27 of the surface water bodies has been assessed as bad, 112 as poor, 320 as moderate, 39 as good, but none as high. 493 of the surface water bodies have good chemical status and 5 have a failed status. Of the 47 groundwater bodies, 22 have been assessed as having poor quantitative status and 18 have poor chemical status. A programme of measures is in place in the river basin to address each of the water management issues at both the river basin and local (catchment) scales; however, none of the measures explicitly recognise or take into account that there may be significant interactions between different environmental stressors. Importantly, although the Management Plan recognises that climate change needs to be taken into account when planning measures to improve the environment, it notes that there is currently significant uncertainty on the likely impacts of climate change across the river basin on river flows, water quality and ecosystems (Environment Agency, 2016).

In order to facilitate design of a linked model application to evaluate impacts of multiple stressor combinations on water resources in the Thames river basin, the MARS modelling framework (Hering et al., 2015) was used to identify links in the Driver-Pressure-State-Impact-Response (DPSIR) scheme. A conceptual framework for modelling of the D-P-S elements for the Thames river basin (Fig. 2) identifies and links drivers and pressures (equivalent to stressors, Hering et al., 2015) that could be possible causes for water body failures.

2.2. Modelling techniques, including model performance

Three modelling tools were chosen. The models of recharge and groundwater were linked into a single integrated tool. The other two tools used were QUESTOR and PROTECH. The links between them are outlined in Fig. 4. Individual models are described below and the technical linkages described in Section 2.4.

The input data requirements of the models are as follows. Climate data are taken from ISI-MIP (available via https://www.pik-potsdam.de/research/climate-impacts-and-vulnerabilities/research/rd2-cross-cutting-activities). The recharge model used distributed data on rainfall and evaporation (CEH-GEAR rainfall data (Tanguy et al., 2014) and MORECS evaporation data (Hough and Jones, 1997)). Data used to define tributary inputs to the QUESTOR river network (Table A1) are accessible via spatial or placename searches of EA and CEH online databases. EA water quality data available at. http://environment.data.gov.uk/water-quality/view/landing. CEH "Thames Initiative" water quality data available at the CEH Environmental Information Data Centre (doi:https://doi.org/10.5285/e4c300b1-8bc3-4df2-b23a-e72e67eef2fd). Fo calibration of QUESTOR daily river flow data were also used as accessed via NRFA: http://nrfa.ceh.ac.uk/data/search. Meteorological observations were accessed at the British Atmospheric Data

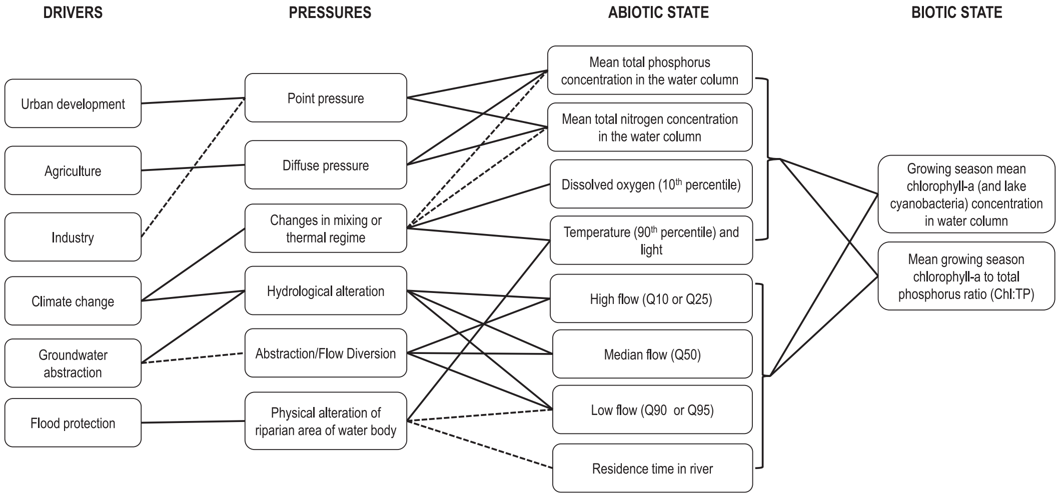


Fig. 2. Thames river basin DPS (IR) conceptual framework. Solid lines represent interactions tested in the present study. Dashed lines indicate other interactions. Growing season defined by water temperature above 9 °C, Qn (e.g. Q10) refers to specific percentiles of stream flow, and Chl:TP is the ratio of mean growing season chlorophyll-a to total phosphorus.

Centre (http://archive.ceda.ac.uk/) (from the Little Rissington station under UK met office MIDAS daily global radiation observations as used by QUESTOR; and from Brize Norton station for wind speed, percent cloud cover, air temperature and relative humidity as required by PROTECH). Metadata for radiation measurements are found at http://artefacts.ceda.ac.uk/badc_datadocs/ukmo-midas/RO_Table.html.

2.2.1. Groundwater and river flow

The Oolitic limestones of the Jurassic provide the main source of flow to the upper reaches of the River Thames and its tributaries and are sustained by rainfall recharge in the Cotswolds Hills. To model this system and its interaction with the river, two models were employed: (i) a gridded recharge model that simulates runoff and recharge across the Limestone catchment, (ii) the Cotswolds groundwater model: a semi-distributed model of the Oolitic limestone aquifer (Mansour et al., 2013).

The recharge model was developed using the distributed recharge model code ZOODRM (Mansour and Hughes, 2004). It simulates rainfall recharge to the water table and determines the amount of surface water runoff to the rivers. The model used the simplified FAO recharge accounting algorithm (Griffiths et al., 2007) and included 9 land use

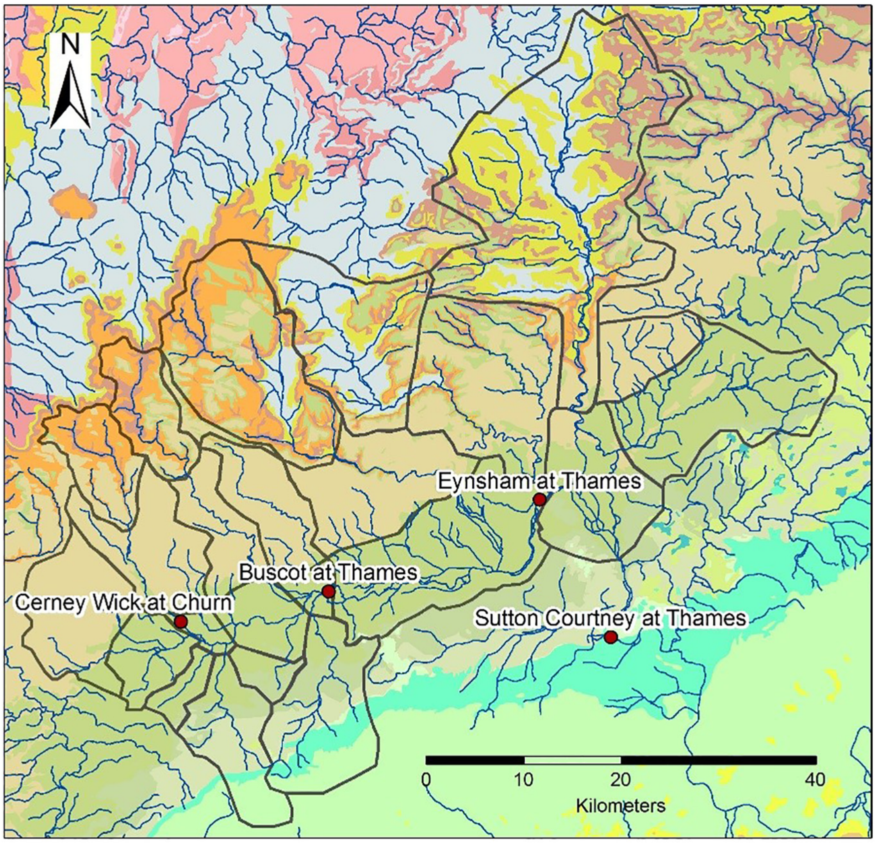


Fig. 3. Map showing geology, cell structure of the groundwater model and locations for evaluation of baseflow simulation. Contains *British Geological Survey Data © NERC All Rights Reserved 2018.*

classes taken from the 1 × 1 km land cover map LCM2000 (Natural Environmental Research Council, 2000): (1) Deciduous trees, (2) Coniferous trees, (3) Arable, (4) Grass, (5) Upland, (6) Urban, (7) Water, (8) Rock and (9) Sea. The recharge model used extensive input data sets, including CEH-GEAR rainfall data (Tanguy et al., 2014) and MORECS evaporation data (Hough and Jones, 1997), to estimate infiltration recharge on a distributed basis, used to drive the groundwater model of the limestone, at a daily time-step. The amount of surface runoff to the river was used for the calculation of total river flows.

The Oolitic Limestone aquifer of the Cotswold was modelled using a semi-distributed model (Scanlon et al., 2003; Mansour et al., 2013) consisting of 30 rectangular-shaped cells in two parallel layers (Fig. 3) with 18 cells in layer 1 and 12 cells in layer 2 (Mansour et al., 2013). The number of cells within the layers decreases due to the geological dip of the bedrock units. Each cell represents a part of the aquifer that is described by one set of averaged hydrogeological properties. Aside from fixed values in cells representing confined areas, transmissivity is calculated at every time step as a function of the saturated thickness (calculated in the previous time step) and the hydraulic conductivity. Connections between cells are specified based on the geological setting. Cells within the same geological unit can exchange water with adjacent cells and across the different layers. Cells belonging to different units can only exchange water vertically, i.e. across different layers. Flows in and out of each cell are calculated from the hydraulic gradients between connected cells, using Darcy's law (Darcy, 1856). In this application, all cells in the top layer, except for one, include a river node, which represents the properties of the river network enclosed within the cell boundaries. River leakage is calculated for each time step as a function of river bed elevation and groundwater level.

The groundwater model was run at a daily time step for the period of 01 January 1971 to 31 December 2013. Time-variant groundwater levels and flows were calculated for every time step from the overall water balance in each cell, including: recharge from rainfall, river leakage, groundwater flows in and out of the cell and abstractions. Model calibration was carried out by optimising the values for hydraulic conductivity, storage coefficients and river bed conductance within a Monte Carlo framework. The objective function is defined by the Nash-Sutcliffe model efficiency coefficient (NSE: Nash and Sutcliffe, 1970), which determines the relative magnitude of the residual variance ("simulated") compared to the measured data variance ("observed"). NSE values range between $-\infty$ and 1.0. Values between 0.0 and 1.0 indicate acceptable levels of model performance. Negative values indicate that the mean observed value is a better predictor than the simulated value, and hence model performance is unacceptable (Moriasi et al., 2007). More specific quantification of acceptability is case-dependent and generalisation cannot be made (Refsgaard et al., 2005). In the Monte Carlo framework, the model is executed multiple times, where each time, the parameter values are randomly picked from a user-defined range. Parameter values that maximise NSE are selected as possible values representing the hydraulic characteristics of the aquifer.

The selected cells outlets and corresponding river gauging stations are listed in Table 1. Calibration was conducted in two steps: (1) in static mode (i.e. river length and bed elevation remains constant throughout) and (2) in dynamic mode (i.e. river length and bed elevation vary with groundwater elevation). The resulting NSE coefficients range between 0.46 and 0.88 (Table 1) and show that the model can adequately predict river flows (runoff plus baseflow) within the selected tributary catchments. Model validation was not performed in this application. Rather, it is believed that using all available observed data for calibration provides the model with a wide range of river flow to reproduce, hence improving its capability of predicting future flows as discussed in Anderson et al. (2015) and Konikow and Bredehoeft (1992).

River base flows and total flows were calculated from the groundwater flow model and the recharge model for the different storylines, and compared against the modelled baseline (base case).

In this paper, we focus on the baseflow response as this is the main source of river flow in the Upper Thames catchment. Four gauging stations are selected to illustrate the observed response. The stations represent different sections of the river, including an upstream tributary

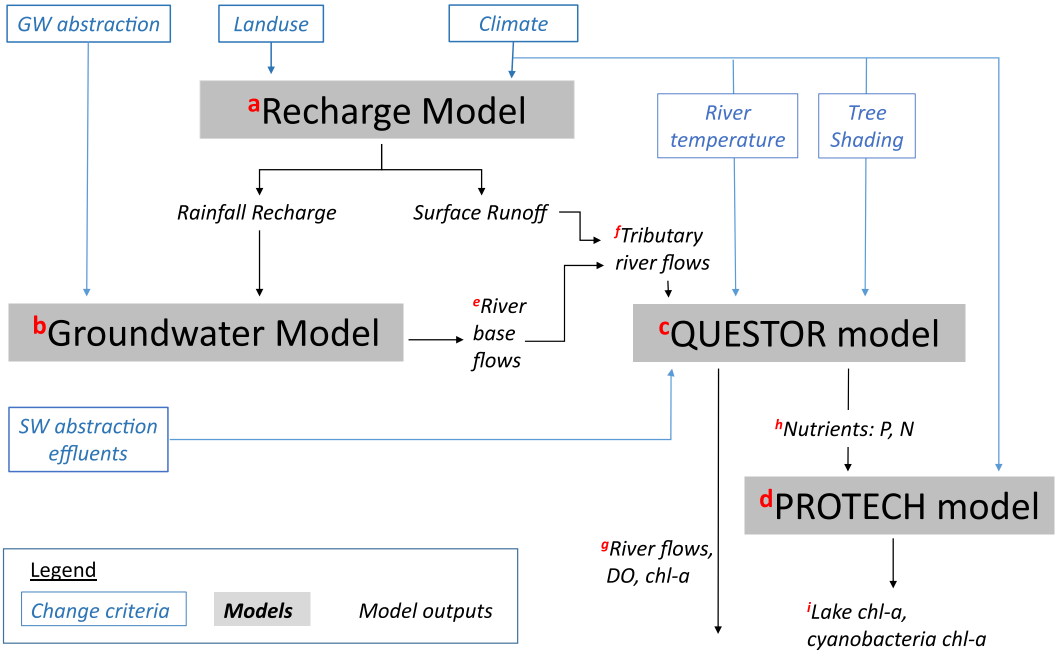


Fig. 4. Flow diagram of the modelling process for the storylines simulations. Models are described in (a) Section 2.2.1 (b) Section 2.2.1 (c) Section 2.2.2 (d) Section 2.2.3. Results are shown in (e) Fig. 6, (f) Table 1, (g) Table 2, Table 4 and Fig. 7, (h) Table 2, Table 4 and Fig. 7, (i) Fig. 5 and Table 5.

Table 1
Cotswold model - calibration points and Nash-Sutcliffe efficiencies (NSE).

Cell number	River gauging station	National grid reference	NSE
Cell1	Thames at Eynsham (site 3)	4445 2087	0.83
Cell 2	Thames at Buscot	4230 1981	0.67
Cell 5	Thames at West Mill Cricklade	4094 1942	0.84
Cell 8	Coln at Fairford	4151 2012	0.46
Cell 13	Coln at Fossebridge	4080 2112	0.87
Cell 14	Churn at Perrot's Brook	4022 2057	0.88
Cell 25	Ray at Islip	4523 2137	0.70
Cell 28	Evenlode at Cassington Mill	4448 2099	0.79
Cell 30	Cherwell at Enslow Mill	4482 2183	0.47

(River Churn) and three reaches along the main River Thames (Burcot, Eynsham and Sutton Courtenay) which represent increasing catchment size and flow (Fig. 3).

2.2.2. River flow routing and water quality

Modelling was undertaken using the 1-D model QUESTOR, a number of versions of which exist. The version used in the present study is described in detail elsewhere (Hutchins et al., 2016). In summary, the model represents flow routing and chemical reactions in the river channel, simulating river flow, pH, temperature, and concentrations of nutrients (N and P species), chlorophyll-a, dissolved oxygen (DO) and biochemical oxygen demand (BOD). The processes represented are aeration, BOD Decay, Deamination, Nitrification, Denitrification, Benthic Oxygen Demand, BOD Sedimentation, Phosphorus Mineralisation, in conjunction with a biological sub-model of Phytoplankton (comprising Growth, Respiration and Death), which includes nutrient uptake and release. In the present application the upper Thames river basin was divided into 41 reaches (33 on the 92 km main Thames between Hannington and Wallingford, and a further 3 and 4 reaches representing 15 km of the River Cherwell and 19 km of the Thame respectively). The Cherwell joins at Thames Reach 19 and the River Thame at Thames Reach 31. Table A1 and Hutchins et al. (2016) provide a more detailed description of the reaches and their influences.

Under present day conditions, nine effluents of total flow 1.335 $m^3\ s^{-1}$ directly influence the river network. Likewise, there are two abstractions removing 2.71 $m^3\ s^{-1}$ (one for water supply 1.62, the Farmoor reservoir, the other 1.09 for industry, the Didcot power station). These data are used as model inputs. As inputs, the model also requires daily data on flow and water quality from 22 tributaries (Table A2). Weekly water quality and river temperature data were available for 10 of the tributaries (column 3 Table A2) and these were summarised on a monthly basis for use in the storylines. Other minor tributaries were monitored much less frequently. For these, mean values for each determinand were estimated from long-term data held by the Environment Agency (see Section 2.2). Output under the three storylines was generated at daily resolution and compared to baseline 2009–12 conditions at Eynsham (Fig. 1 Site 3) and Wallingford (Fig. 1 Site 4).

Model performance under baseline 2009–12 daily conditions is summarised (Table 2) for a selection of determinants of interest at 13 sites along the stretch between Hannington and Wallingford including Newbridge (Site 2) Eynsham (Site 3) and Wallingford (Site 4). As a foundation for the storylines, the 2009–12 period was used to provide a baseline of meteorological fluctuation (e.g. notably water temperature and sunlight) and a reference point for present day land-use and environmental management as reflected in concentrations of pollutants in sewage effluents, magnitudes of those effluents and water abstractions.

A baseline run, representing a combination of the effects of 2009–12 meteorological conditions and current environmental management, was used to underpin the storylines. For this run, observed flow data were taken from 8 of the gauging station sites considered in the groundwater and river flow modelling (column 3 Table A2). To derive baseline conditions for the other tributaries, flows were translated and scaled from one of the same 8 gauging stations (column 4 Table A2). Scaling was based on catchment area as catchment characteristics between tributaries in this region are similar. A different configuration (column 5 Table A2) had been used for the previous model testing exercise described in Table 2. The model testing exercise (Table 2) had taken advantage of the availability of observed data from some of the smaller sub-catchments for which simulations were not feasible using the groundwater and river flow model. In all applications a single time-series of solar radiation was used upon which a single network-wide estimate of the effect of shade from riparian canopies was applied (20% under baseline conditions).

For the storylines themselves, flow datasets for tributaries were derived using change factors based on total monthly flow. In each case, factors were defined as the ratio of storyline flow to baseline flow. These monthly factors (illustrated in Fig. A1) were then applied to the daily observed flows in the 8 tributaries for which groundwater and river flow modelling had been undertaken.

2.2.3. Reservoir water quality

The model PROTECH (Phytoplankton RespOnses To Environmental Change; Reynolds et al., 2001; Elliott et al., 2010) simulates the

Table 2
Paired values under calibration (2009–10) and corroboration (2011−12) conditions (separated by “,”) of Nash Sutcliffe efficiency statistic (Nash and Sutcliffe, 1970) for daily flow, and % error in mean for temperature, DO, nitrate (NO_3), soluble reactive phosphorus (SRP) and chlorophyll-a. Values in bold are based on observed data availability at a resolution of weekly or better. a) Name and reach ID where C = Cherwell, Th = Thame and T = Thames; b) Data for Abingdon only available in 2009. Calibration was undertaken with a single set of parameter values along stretches which were bounded by observed data. This typically means a stretch comprises a number of reaches.

[a]Monitoring site	Flow	Temp	DO	NO_3	SRP	Chl-a
North Oxford (C3)			−2.1			
Dorchester (Th3)			−7.1, −6.0			
Newbridge (T10)		**0.5, 5.9**	3.6, 13.1	**0.82, −5.0**	**−9.3, 6.8**	**−25.5, −9.1**
Farmoor (T11)	**0.93, 0.91**		6.2, 7.1			
Eynsham (T12)	**0.92, 0.91**	**2.2, 8.6**		**−1.3, −5.4**	**2.0, 12.7**	**−27.9, 31.4**
Godstow (T15)			−1.5, 5.6			
Cent. Oxford (T17)			−4.5			
South Oxford (T19)			2.1, 13.6			
Radley Coll. (T22)			−0.4, 10.6			
[b]Abingdon (T23)		**13.4, n/a**	**−3.6, n/a**			**7.3, n/a**
Sutton C. (T27)	**0.95, 0.92**					
Days Lock (T30)	**0.94, 0.89**		−3.3, 2.1			
Wallingford (T33)		**6.1, 7.9**	−1.4, 3.6	**−4.3, −3.0**	**12.3, 24.6**	**−29.4, 1.0**

responses of up to 8 species of phytoplankton to seasonal changes at a daily time step with particular reference to the potentially harmful cyanobacteria types with can so readily cause problems to drinking water supply. PROTECH has been applied in over 30 peer reviewed studies and is one of the most cited lake models in the world (Trolle et al., 2012). Although mainly used for lakes studies, it can also be applied to reservoirs as was the case in this study.

The simulated site, Farmoor reservoir, is an important part of the water supply network in the catchment, supplying water to the major urban areas of Swindon and Oxford in addition to areas of north Oxfordshire. The PROTECH model was initially set-up using observed data collected from the reservoir in 2014, which included inflow and outflow discharges from the reservoir and also weekly observed river nutrient data from the Thames. The weekly nutrient data were derived from colorimetric analysis and ion chromatography for phosphorus species and nitrate respectively (Bowes et al., 2016). The offtake from the Thames is located between Newbridge and Eynsham (Fig. 1: Sites 2 and 3 respectively). Meteorological data for driving the simulations was taken from Brize Norton meteorological station 15 km to the west. Measurements of phytoplankton abundance in the reservoir were available in the form of total chlorophyll *a* concentration as were some qualitative data for the relative abundance of phytoplankton species. The latter were used to select the eight most representative types from PROTECH's phytoplankton library. After some minor adjustments to increase the observed relative humidity values used to drive the simulation, the model captured reasonably well the annual changes in phytoplankton biomass ($R^2 = 0.63$; Fig. 5).

2.3. Storylines of future climate and socio-economic change

To enable possible comparison of the stressors-response relationships across Europe, a set of harmonised storylines of future changes in drivers and stressors developed for MARS project (MARS, 2015) have been identified for use in the present study. The storylines aim to describe plausible but different future worlds and were defined following reference literature including that from the Intergovernmental Panel on Climate Change (IPCC, 2014; IPCC, 2013) and working groups on future pathways (e.g. Van Vuuren et al., 2011; IPCC, 2000). One key consideration was to go beyond climatic scenarios, and also include a range of stressors that could result from contrasting future socio-economic, environmental and political developments in Europe, with a view to focus on the different ways to manage and regulate drivers and stressors that impact on aquatic systems (Sanchez et al., 2015). The future time horizons were chosen to encompass planning (i.e. the planned update of the Water Framework Directive (European Union, 2000), the regulatory framework for water quality and resources within European Union states) and climate change. Three MARS storylines were used. One of these represents an extension of present day rates of economic development ("Consensus World"). The other two encompass more extreme and less sustainable visions of future development ("Techno World" and "Survival of Fittest"). Their development is described in detail in MARS (2015). Here we summarise their main features:

- Techno World or 'Economy Rules' (TW), where government and citizens' objectives are economic growth. Innovative technologies and solutions that would increase capital are stimulated, resulting in energy demand and CO_2 emissions being high. Alternative renewable energies are developed to fulfil the energy gap. There is no regulation on environment, but high citizen awareness stimulates environmental initiatives by individuals and NGOs. Existing environmental policies and guidelines are not renewed, and governmental focus is on trade and economic growth. Water management strategies are based on technical solutions, prioritising industrial and public water supply over environmental demands.
- Consensus World (CW), where economy and population are growing at the same pace as now. Economic growth and sustainable use of resources are stimulated, mixed energy sources (fossil and renewable) are favoured through regulations limiting greenhouse gas emissions. Current environmental regulations are extended and strengthened, and European policies and directives are better integrated, becoming more realistically achievable. Water management strategies rely on cheap mid-term solutions but nature-based solutions are encouraged.
- Fragmented World, or 'Survival of the Fittest' (SoF), where international trade agreements have disappeared and countries focus on their individual economic growth. This results in high economic growth in north-west Europe, contrasting with decline in southern Europe, and an overall lack of resources with currently indebted countries suffering from real scarcity. Fossil fuels are heavily used, and renewable energy only developed when no other alternative exists. Preservation of ecosystems is not part of the agenda, with local-scale solutions in rich countries and no attention to transboundary issues. Current environmental policies are broken around 2020, and only rich countries support local solutions. Water management strategies are absent, with actions aimed only at short-term water and food provision, alongside protection against floods in regions of high economic value.

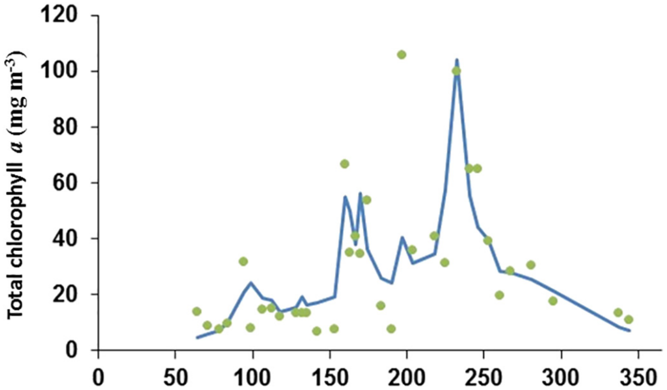


Fig. 5. PROTECH modelling performance: comparison between observed and simulated total chlorophyll *a* in the reservoir for 2014.

Each storyline narrative is associated with semi-quantitative changes in sectors such as environment and biodiversity, land use, agriculture, water management, hydropower energy and water pollution., So that the drivers of change are defined as realistically as possible, they are quantified at the regional (northern, central and southern Europe) and local (catchment) scales in consultation with local authorities and stakeholders.

2.4. Model linkages and quantification and implementation of the storylines

In consultation with the Environment Agency, a major stakeholder in the water management of the Thames, the list of information identified in Section 2.1 defining the main drivers and stressors active in the river basin was used to inform the definition of the storylines (Table 3).

Using the suite of process models illustrated in Fig. 4, a set of 12 model runs was conducted to produce total river flow, river and reservoir water quality indicators for each scenario defined in Table 3. Those simulations were compared with a baseline simulation of

Table 3
Storyline scenarios and criteria applied to the Thames river basin. The scaling values displayed were guided by an international group of specialists defining storylines for the MARS project (Sanchez et al., 2015) for which local values for the Thames were defined in consultation with river basin managers from Environment Agency.

Criteria	Baseline	Techno world	Consensus world	Survival of the fittest
Climate (for 2030 and 2060 time horizons)		RCP8.5 GFDL and IPSL	RCP4.5 GFDL and IPSL	RCP8.5 GFDL and IPSL
Land use change – urban	1	1.5	1.2	1.5
Land use change – arable	1	0.9	1	0.7
Land use change – forest	1	0.9	0.9	1.2
Land use change – grassland and pasture	1	0.85	0.8	1.45
Water levels (i.e. change arising from groundwater abstraction)	1	0.9	0.8	1.25
Total P (i.e. concentration in tributaries and effluents)	1	1.5	0.9	1.5
Urbanisation (i.e. volume of abstractions and effluents)	1	1.35	0.96	1.875
Shade (i.e. riparian tree coverage)	20%	0.75 (to 15%)	2 (to 40%)	0 (to 0%)
Invertebrate (zooplankton) grazers (i.e. response to change in pesticide load in runoff)	1	0.5	0.9	0.5

2009–2012 to quantify the impact of the MARS storylines on the abiotic and biotic systems.

Land use changes were implemented through the recharge model by changing the proportion of land use in the catchment area as defined in Table 3. The primary drivers, as reflected in Fig. 2, were urbanisation and need for arable cropping. Changes in other land uses are compensatory.

Climate change scenarios were implemented through the recharge model, QUESTOR and PROTECH using the change factor method (Hay et al., 2000). Climate change factors were first calculated following the MARS protocol (Panagopoulos et al., 2015) to ensure consistency of methods across catchments; they were derived from bias-corrected climate time series from the ISI-MIP project (Hempel et al., 2013). The bias-correction method uses a 2-step procedure. The first step adjusts the long-term difference between simulated and observed monthly mean, using an additive (temperature) or multiplicative (precipitation) method. The second step aims to correct the daily variability to match that of the observational dataset, based on a linear (temperature) or non-linear (precipitation) regression following a correction of frequency of dry days for precipitation. Other variables follow a method adapted from the precipitation correction. More details can be found in Hempel et al. (2013). For each climate variable of interest v, a 10-year mean monthly average was calculated for each month m from bias-corrected catchment average daily data extracted from climate model projections for the time periods of 2006–2015 (baseline $\overline{v}_{m,baseline}$), 2036–2045 (2030s) and 2056–2065 (2060s) (both $\overline{v}_{m,future}$). These periods were chosen following the availability of bias-corrected climate transient simulations. The monthly change factors ($\Delta v{,}m$) were expressed as absolute change (for temperature) and percentage change (for all other climate variables) between $\overline{v}_{m,future}$ and $\overline{v}_{m,baseline}$ as in Eq. (1).

$$\Delta_{v,m,future} = \begin{cases} \overline{v}_{m,future} - \overline{v}_{m,baseline} \ldots\ldots\ldots\ldots\ldots\ldots \textit{for tas as v} \\ 100x\dfrac{\overline{v}_{m,future} - \overline{v}_{m,baseline}}{\overline{v}_{m,baseline}} \ldots\ldots\ldots \textit{for other variables} \end{cases} \qquad (1)$$

Monthly change factors were calculated for mean air temperature (tas, °C), potential evapotranspiration (PET, %), surface wind speed (wind, %), shortwave radiation (rsds, %), long wave radiation (rlds, %) and precipitation (pr, %), based on the ISI-MIP bias-corrected climate projections (Warszawski et al., 2014). For each time horizon, the climate change factors were applied multiplicatively to observe daily time series for precipitation, potential evapotranspiration and solar radiation, and additively to monthly air temperature to produce time series input to the process based models as shown in Fig. 4.

Following MARS protocol (Panagopoulos et al., 2015), two climate models and two Representative Concentration Pathways (RCPs) were considered to describe the MARS storylines, as shown in Table 3. The recharge model produced the rainfall recharge required to drive the groundwater models as well as the surface runoff component required for the calculation of total river flows.

Flows and water temperature scenarios were calculated by first deriving monthly flow factors from each scenario simulation for all simulated river reaches, and then applying them to the observed daily baseline flows (2009–12), so that any bias in the flow simulation from the recharge and groundwater models does not affect the water quality simulation, which is very sensitive to low flow periods. Temperature change factors were applied additionally to each tributary's monthly mean observed water temperature.

For the daily *non-climatic variables*, Total Phosphorus concentration, abstraction and effluent rates, percentage of shading and percentage of invertebrate grazers, multipliers related to environmental change factors described in Table 3 were applied to the daily baseline values. Farmoor *nutrient concentration* (*NO3*, *P*) scenarios were taken from the QUESTOR simulations (baseline and 12 storyline runs). All other categories of input were held constant at present day levels (e.g. BOD, DO, nitrogen species, suspended sediment, pH). Although some of these have the potential to be influenced by management it was assumed these would not change significantly.

Water level change scenarios were implemented in the groundwater flow models by applying the percentage change to all groundwater abstractions within the model. Simulated river baseflow data from the groundwater model and surface runoff from the recharge model were then used to calculate total river flows at selected river stations in the Upper Thames river basin.

Changes to water management regime: Application of the TW and SoF scenarios resulted in the river drying up. As a consequence, alternative configurations were built in which changes had been implemented to represent

1) new alternative reservoir storage further downstream to meet abstraction demand. To increase abstraction rates beyond capacity of the existing reservoir is unsustainable in the upper part of the river basin. It was assumed that the existing reservoir storage is at 80% of capacity
2) a constant water transfer into the river basin entering in the upper reaches of the network. The water is likely to be sourced from the River Severn, as outline infrastructure is already in place and forms a part of water industry contingencies (UK Water, 2016). The transfer was assumed to be either at a minimum level to ensure sustainability of water resources in the Thames (Techno World: 2 $m^3 s^{-1}$) or to comfortably exceed requirements (Survival of the Fittest: 4 $m^3 s^{-1}$).

3. Results (2030s and 2060s)

3.1. River base flows

An example of a modelled baseflow hydrographs for the Techno World storyline and four climate scenarios for the Thames at Sutton Courtenay is given (Fig. 6a) (additional examples of modelled baseflow hydrographs for the River Churn and the River Thames at Sutton Courtenay are shown in Figs. A2 and A3). For the hydrograph in Fig. 6a and the additional hydrographs, generally, there is little difference in the response during low flows. Differences in hydrograph response between storylines (Figs. A2a and A3a) and climate scenarios (Figs. A2 and A3 (b–d)) are most distinct during winter high flows and during the flood events of 2012/13.

Flow variations predicted by different climate models and time horizons within each storyline (Figs. A2 and A3 (b–d)) are of similar magnitude to or greater than those observed between storylines for the same climate model and time horizon (Figs. A2a and A3a). To be able to better compare and quantify these changes, three descriptors are selected representing low flows (95% exceedance), median flows (50% exceedance) and high flows (10% exceedance). The results are summarised in Fig. 6b–d, illustrating the different baseflow responses observed for the different storyline scenarios.

The Consensus world (CW) scenarios show a general decrease in low flows of 4–28% relative to the base case scenario, except at Burcot where an increase in low flows of up to 4% is predicted. Median flows are predicted to decrease by 1–56%, with some initial increases predicted in the River Churn for the 2030 time horizon. High flows are also predicted to decrease by 1–13%, except in the IPSL model, which predicts a small increase in flows of up to 5% for 2030, but a decrease of up to 30% for 2060. In all cases, the decrease

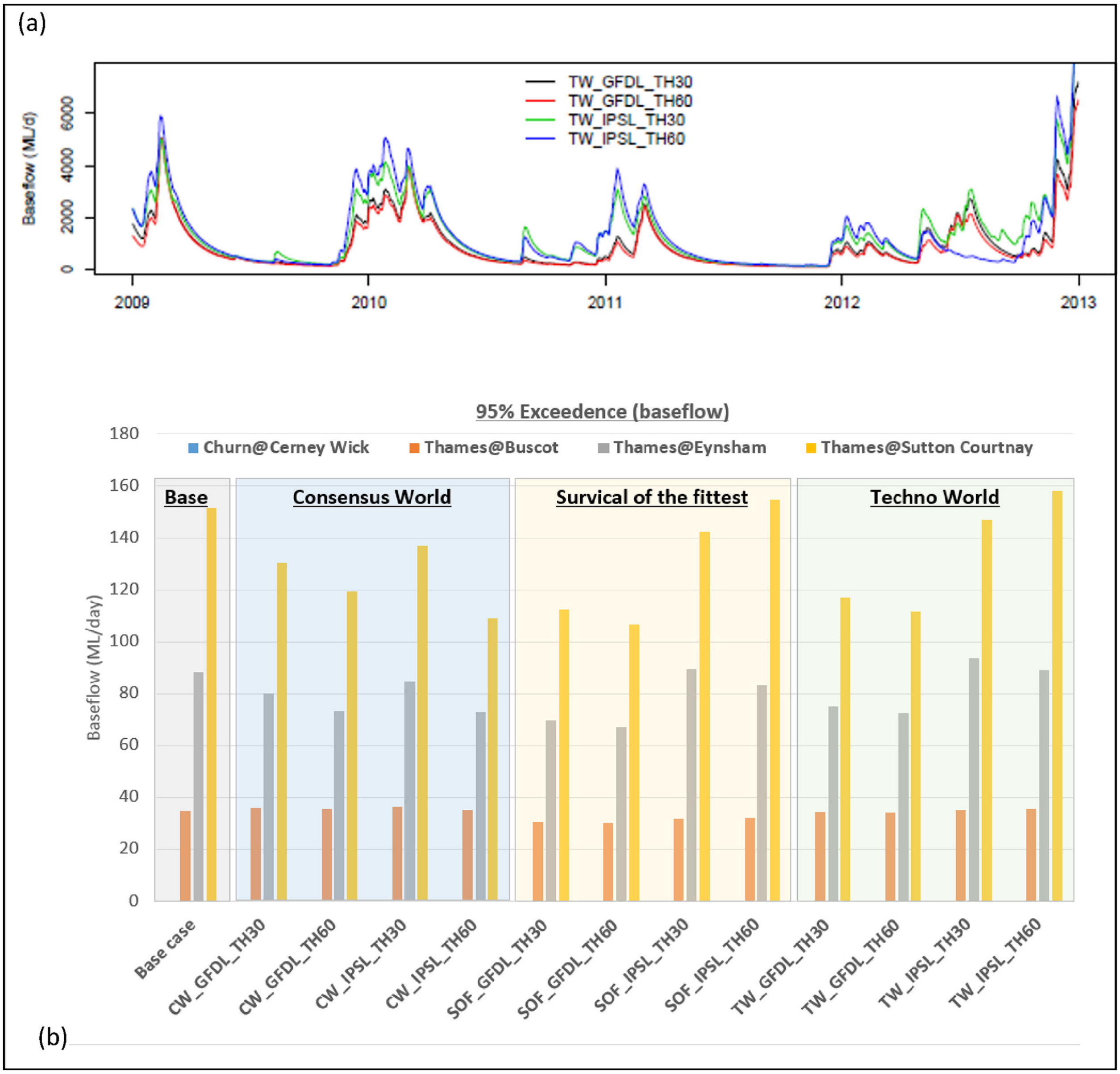


Fig. 6. (a) Example of modelled baseflow for the Techno World storyline and four climate scenarios for the Thames at Sutton Courtenay and complete baseflow descriptors for the four gauging stations and storyline scenarios at (b) low flows (95% exceedance), (c) median river flows (50% exceedance) and (d) high flows (10% exceedance).

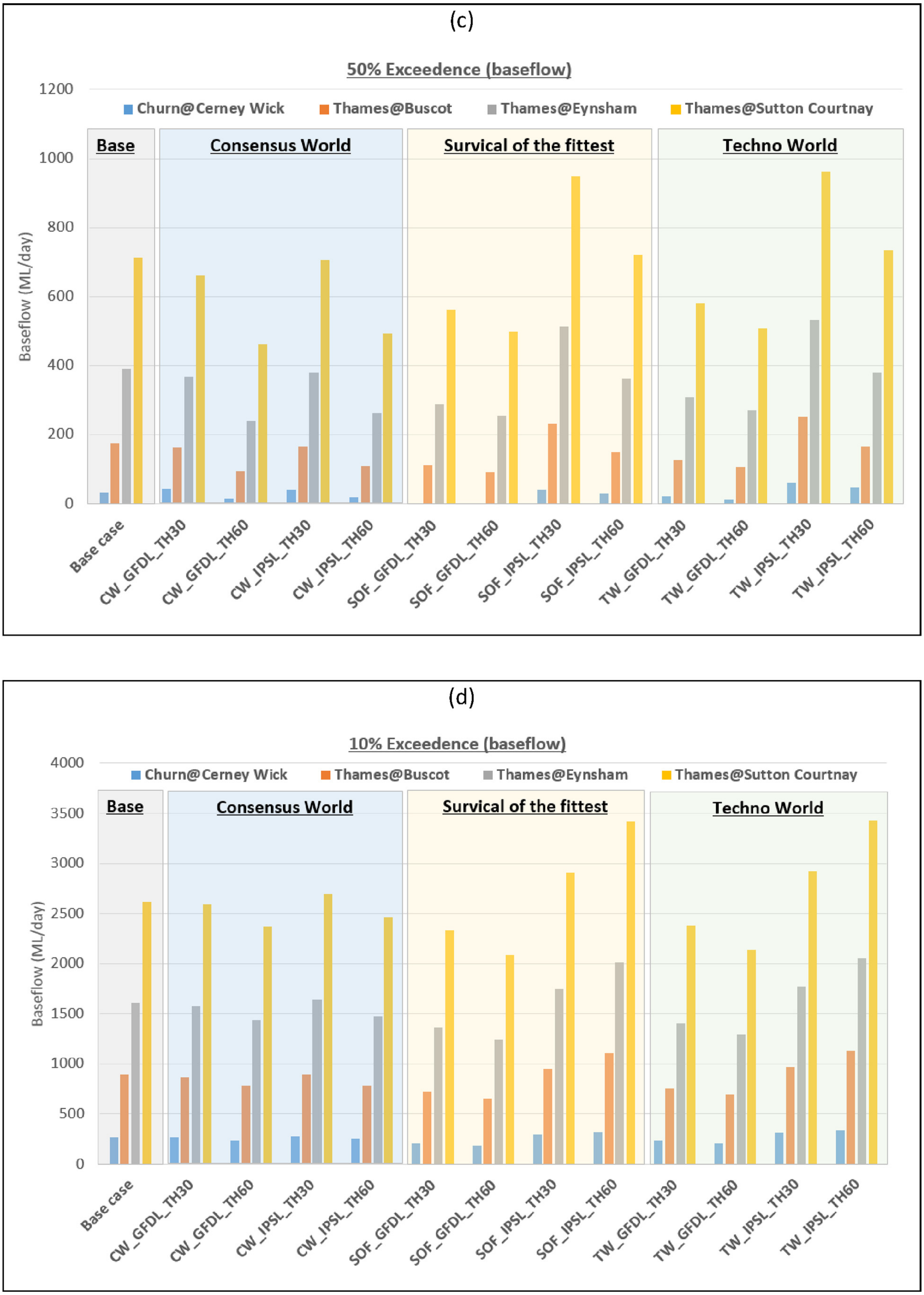


Fig. 6 (*continued*).

Table 4
Modelled baseline conditions (2009–12) for a range of water quality indicators for the Thames river basin.

	Newbridge	Eynsham	Abingdon	Wallingford
Mean total phosphorus (TP) concentration (mg L^{-1})	0.484	0.424	0.536	0.546
Mean growing season (water temperature above 9 °C) chlorophyll-a (chl-a) concentration (mg L^{-1})	0.013	0.018	0.033	0.038
Mean total phosphorus concentration during the growing season (mg L^{-1})	0.528	0.456	0.580	0.583
Mean growing season chlorophyll-a to total phosphorus ratio (chl-a:TP)	0.025	0.045	0.072	0.086
Water temperature: DegreeDays_Above9/yr (°C $year^{-1}$)	1671.5	1692.0	1755.4	1941.3
High flow indicator (flow exceeded 25% of time): Q25 (m^3 s^{-1})	14.49	17.52	31.58	34.80
Low flow indicator (flow exceeded 90% of time): Q90 (m^3 s^{-1})	2.27	1.49	3.94	3.75
Low dissolved oxygen statistic typical of summer conditions: 10th percentile DO (mg L^{-1})	9.68	9.71	9.63	8.94
Mean total nitrogen (TN) concentration (mg L^{-1})	6.80	6.37	6.39	6.35
Water temperature: 90th %ile (°C)	19.5	19.9	20.4	21.8

in baseflow is generally more pronounced for the 2060 time horizon compared to 2030.

The Survival of the Fittest (SOF) scenarios show a different flow response for the different climate models. The GFDL model predicts a decrease in low, median and high flows of up to 30, 100 and 31%, respectively, with slightly lower flows for the 2060 time horizon. The IPSL model predicts a decrease in low flows of up to 10%, but median flows initially increase (19–33%) for the 2030 time horizon, followed by a decrease (7–15%) at all stations except for Sutton Courtenay. IPSL predicts high flow events to rise at all stations, increasing by up to 11% and 31% for the 2030 and 2060 time horizons.

The Techno World (TW) storyline shows similar trends to SOF, with an overall decrease predicted by the GFDL model for low, median and high flows. In contrast, the IPSL model predicts a general increase in baseflows at most stations, with increases of up to 7%, 83% and 31% for low, median and high flows, respectively.

The changes in total flows (Table A3) are largely consistent with the trends described for base flows, although the relative decrease in low flow is generally greater (by about 10%) for total flows than for base flows. For median and high flows, relative changes are largely similar for base flows and total flows.

All future predictions suggest the lowest flows will decrease (Fig. 6a; Table A3) particularly downstream of Oxford. At higher flows (median and Q90) the decrease in flow is not predicted by all combinations of planning/climate scenarios but is expected to be more severe in the upstream reaches.

3.2. Flows and water quality at river sites

The QUESTOR model was applied to the 12 MARS storylines to identify the potential effect of climatic and environmental drivers on abiotic and biotic indicators of stress in the River Thames. Baseline conditions are quantified at 4 sites along the river (Table 4).

Nutrients (TP and TN) are in excess at all sites. Algal blooms (mean growing season chl-a) only develop to a persistent extent downstream of Oxford (at Abingdon and Wallingford Site 4). The Thames becomes increasingly slow flowing downstream and this is reflected in warmer summer water temperatures and higher degree days. Relative change in these indicators under the three storylines is tabulated in terms of percentage change relative to baseline for Eynsham and Wallingford sites (Table A4).

The storylines and climate drivers have little impact on TN (Table A4) as concentrations are high throughout the system and not greatly influenced by change in biotic uptake.

Under CW, the influence of climate is seen more clearly as there are less severe effects of planning and management than under TW and SoF. Despite an increase in tree shading arising from change to riparian management, under drier and warmer conditions appreciable increases in summer water temperature are predicted to occur. Low flows will drop markedly especially by 2060 (Fig. 7b) and high flows are also likely to decrease (Table A4).

Lower P loads from improved waste water treatment and smaller urban drivers of change under CW lead to decreases in river P concentration (Fig. 7c) and slightly lower chlorophyll levels (Fig. 7a). An increase in shading largely accounts for the lower chlorophyll levels. However, the summer oxygen sags at Wallingford will become more severe (Fig. 7e), these are the consequence of limiting conditions for algal growth being reached due to lower P and light levels. At Eynsham, little change in 10th percentile DO is predicted.

Under SoF and TW large increase in P loads result in increases in concentration of P (particularly at Eynsham) and more notably large increases in chlorophyll (Fig. 7a and c). This is due to lower levels of shading promoting more unconstrained algal growth, aided by the more plentiful P availability and the decrease in population control by invertebrate grazing.

The impact of transferring water in from outside the river basin makes a big difference for a number of the indicators. In terms of change in water flow regime, downstream of Oxford under all climate scenarios, whilst baseflow indicators decrease relative to present day under the TW and SoF storylines the river low flow indicator (Q90) increases (Fig. 7b). Incoming transfer of water under SoF and TW raises the flow levels in summer that will become undesirably low under CW. This also affects water temperature (Fig. 7d), particularly at Eynsham, with lower increases being predicted than under CW, though these beneficial effects are not as large as for other indicators. Despite the big increase in chlorophyll, because river flows are faster, unsustainable conditions do not develop and population crashes, which cause DO to be used up, are less likely to occur. Therefore 10th percentile DO remains largely close to present day levels, unlike under the CW storyline (Fig. 7e).

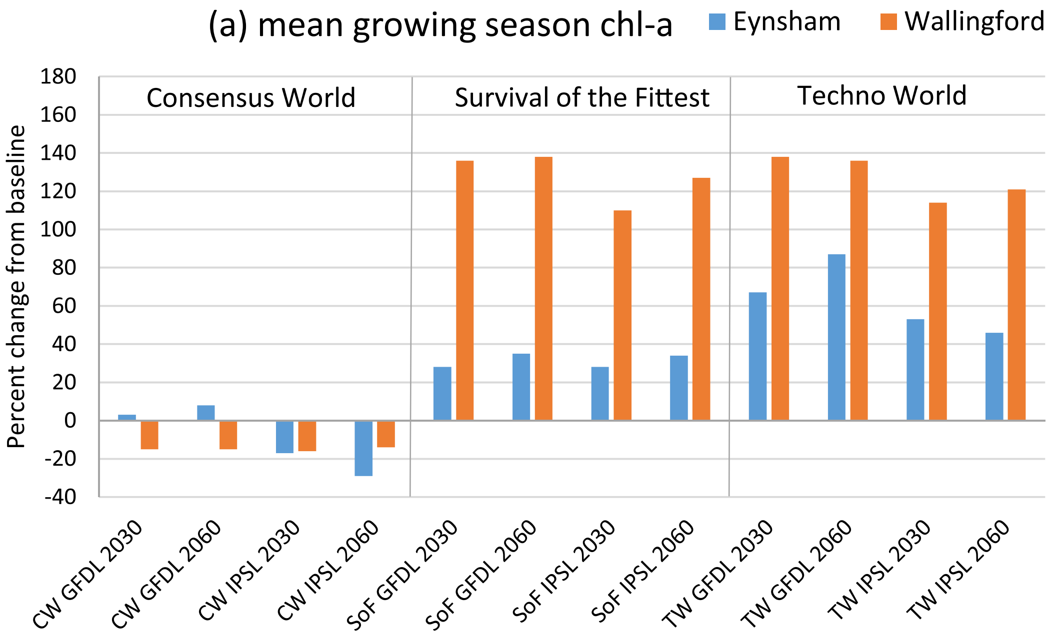
3.3. Reservoir quality

For the reservoir simulations, two key metrics were simulated: total and cyanobacteria (i.e. potentially toxic species) chlorophyll *a* during the growing season. The latter is defined as days where the water temperature was >9 °C. The relative percentage change in mean values of these metrics from their respective baseline values is calculated (Table 5). The baseline values are total chlorophyll $a = 47.2$ mg m^{-3} and cyanobacteria chlorophyll $a = 25.5$ mg m^{-3}.

These results differ greatly between the storylines. Relative to the baseline, CW produces a general decrease in phytoplankton abundance, although this lessens by 2060 and is actually slightly positive for cyanobacteria chlorophyll in one case. Of the two other storylines, there is a general increase in total and cyanobacteria chlorophyll, with the SoF always producing more than TW. The mean cyanobacteria chlorophyll is persistently greater for the 2060 simulations compared to the 2030 ones.

The results are further analysed in order to discover what factors within the storylines could be contributing to the different responses. Thus, for each simulation, the mean surface water temperature in the reservoir and the mean phosphorus concentration in the inflow to the reservoir are calculated for the growing season period. The percentage change in these values from the baseline is calculated and compared to the corresponding changes in total and cyanobacteria chlorophyll *a* (Fig. 8).

This analysis shows that, given the high correlation coefficients, the main driver in the storylines behind the simulated response in chlorophyll is changes in river phosphorus concentrations (Fig. 8a). There is a clear positive relationship where increases and decreases in nutrient concentrations are correspondingly reflected by increases and decreases in chlorophyll. Interestingly, the changes in cyanobacteria chlorophyll are generally larger than those for total chlorophyll when the phosphorus change is also positive. Conversely, when the phosphorus change is negative, the decrease in cyanobacteria chlorophyll is generally much smaller than for total chlorophyll. Increasing reservoir water temperature across the storylines also produce general increases in both total and cyanobacteria chlorophyll with the latter metric being relatively more responsive (Fig. 8b).



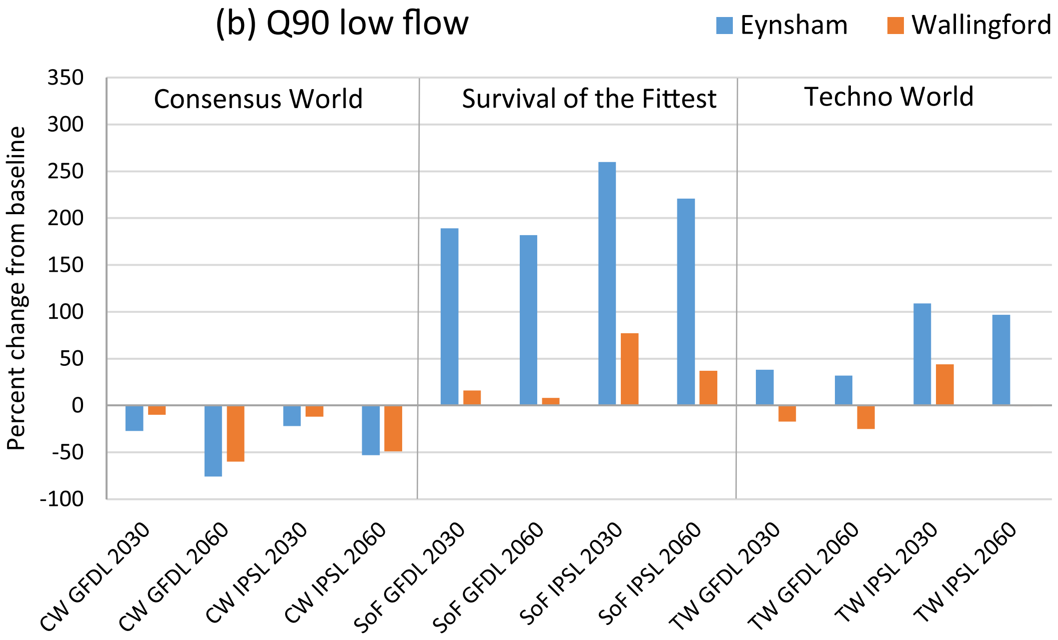
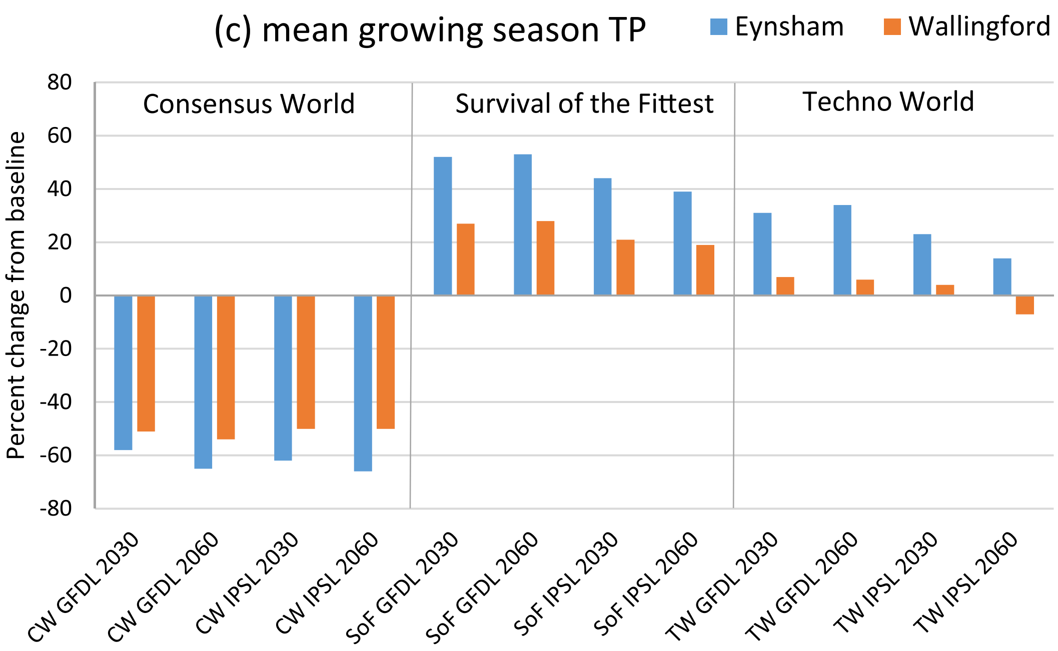


Fig. 7. Percentage changes associated with the MARS storylines for the Thames river basin at Site 3 (Eynsham) and Site 4 (Wallingford), for (a) the growing seasonal chlorophyll-a concentration (days above 9 °C), (b) a low flow indicator, the flow exceeded 90% of the time (Q90), (c) for the Total Phosphorus concentration during the growing seasonal (days above 9 °C), (d) extreme temperature, the water degree days above 9 °C (DegreeDays_Above9) and (e) a low Dissolved Oxygen indicator, the 10th percentile DO (10th percentile DO).



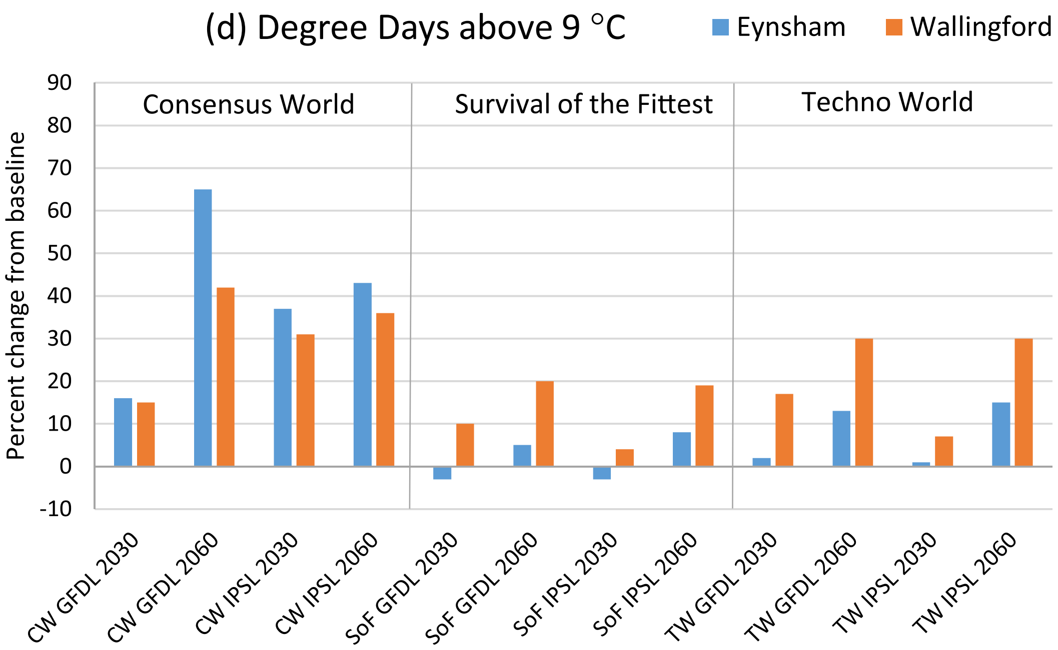


Fig. 7 (*continued*).

4. Discussion

4.1. Differences due to storyline, climate, time-horizon

4.1.1. Storylines

Decreases in flow, whilst universal across the three storylines, are considerably less severe under CW than under SoF and TW. Consequently, only by implementing a radical change in management of catchment water demand can the Techno World and Survival of Fittest World support a sustainable River Thames.

Implementing shading to 40% as defined under CW is very effective at preventing accelerated algal growth particularly in the downstream reaches. However it is markedly less effective at keeping the river cool. This is only achieved (i.e. maintaining temperatures at present day levels) by limiting abstractions and including incoming water transfers (as in TW and SOF). Even then the benefits are only seen in upstream reaches (above Oxford) and start to be overcome by effects of climate change by 2060.

Light is the dominant factor limiting algal bloom development in all storylines. However, CW differs from the other storylines and the present day baseline in that algal blooms are also strongly limited by phosphorus. This limitation, which develops during midsummer, causes algal population crashes which lower DO concentrations. As phosphorus concentrations, by definition due to photosynthetic algal uptake, are also low at this time the large negative percent change relative to the baseline is apparent.

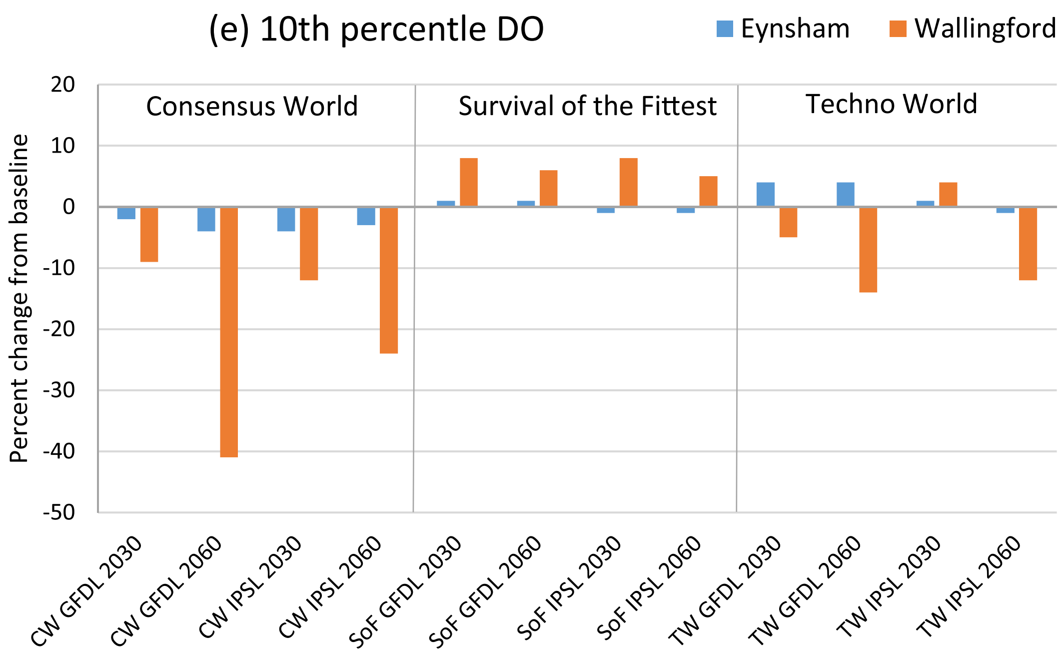


Fig. 7 (*continued*).

In the SoF and TW storylines, phosphorus supply is higher and algal growth continues unconstrained to very high concentrations. A substantial crash was not simulated and DO levels did not dip during the simulation period beyond that expected from high temperatures. If the combination of conditions were to have come together to cause a population crash the consequences would have very likely been considerably more severe than that following the crash under CW. That this did not happen during the somewhat limited 4 year period of simulation available for the model applications is likely due to chance and it should not be concluded that SoF or TW storylines are in relative terms beneficial for DO.

For the Farmoor reservoir, the worst deterioration in water quality was under SoF where there was as much as a 46% increase in cyanobacteria. Under CW, phytoplankton abundance is reduced although this reduction generally lessened with time. The TW presents an intermediate response that, whilst still producing an increase in phytoplankton, was not as severe as that seen under SoF. The differences are largely explained by differences in the input P load, and also by differences in water temperature.

4.1.2. Climate scenarios

Only two climate models were used to explore the uncertainty due to climate change, with a drier signal from GFDL compared with IPSL under the RCP 8.5 (SoF and TW). The differences between GFDL and IPSL are more marked under SoF and TW than under CW. Despite being drier, water temperature is slightly higher by 2060s under IPSL 8 climate at Site 3. At Site 4 differences in water temperature are not apparent. For the CW, the differences between the two climate models appear fairly similar. The largest difference is between DO at Site 4. However, differences in water quality are intractable and cannot be attributed in absence of statistical interpretation and sensitivity analysis.

4.1.3. Time horizons

Future conditions lead to a decrease in low flows and increase in water temperatures and these changes are expected to increase in severity through 2030 to 2060. This hydrological change is apparent for all climate models and is a trend that is pervasive along the river system. However, under highest flows a more complex picture emerges whereby IPSL-based predictions indicate conditions becoming increasingly wet through to 2060.

Changes in low flows in the summer growing season exacerbate any trends in increasing water temperature which may be brought about solely by an increase in air temperature. Higher water temperature leads to a decrease in DO although this is only substantial downstream (at Site 4) by which point there may be impacts from eutrophication.

Table 5
Percentage change associated with the storylines for the reservoir for mean growing season total chl-a and cyanobacteria chlorophyll *a* (Cyanobacteria chl *a*) concentration during the growing season (days above 9 °C). Cells are shaded in red for changes >25%, white for changes between ±25%, and blue for changes < −25%.

		Consensus world		Techno world		Survival of the fittest	
		GFDL 4.6	IPSL 4.6	GFDL 8.5	IPSL 8.5	GFDL 8.5	IPSL 8.5
Mean growing season chl-a	2030	−28.4	−29.0	5.3	14.6	15.0	20.5
	2060	−23.1	−13.8	17.3	11.9	27.2	19.0
Cyanobacteria chl a	2030	−29.1	−26.9	11.4	27.2	18.2	33.1
	2060	−15.6	6.1	32.9	33.2	42.1	38.9

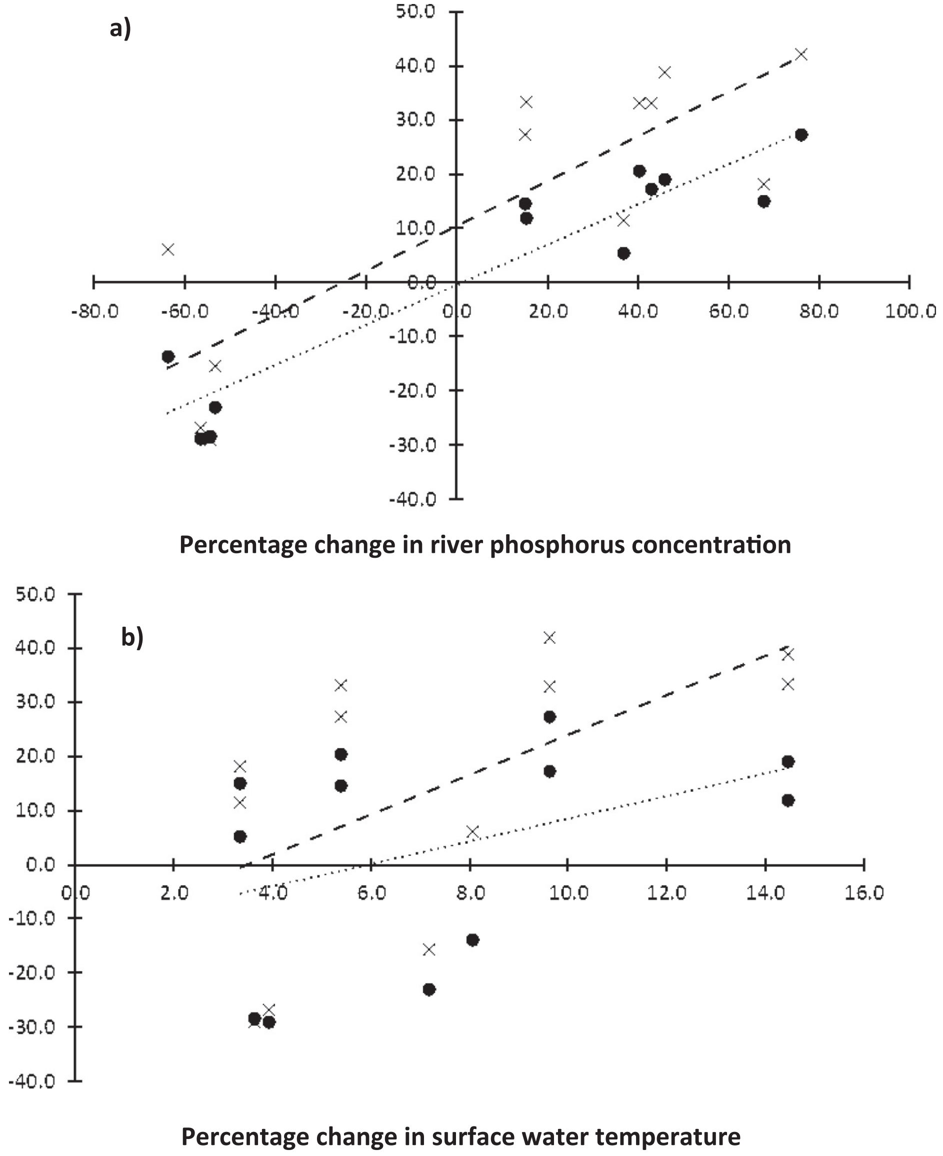


Fig. 8. For the growing season, the percentage change of mean total (solid circles) and cyanobacteria (crosses) chlorophyll *a* in relation to the mean percentage change in: a) river phosphorus concentration and b) reservoir surface water temperature. Linear regressions are dotted lines for total chlorophyll *a* and dashed lines for cyanobacteria chlorophyll *a*.

There is a consistent general pattern of deterioration of the water quality in the Farmoor reservoir across all three storylines between the earlier period (2030s) and the later period (2060s), attributed to an increase in temperature. Regardless of storyline, cyanobacteria biomass changes tended to be relatively greater then total chlorophyll changes, the difference increasing later in the century, also attributed to warmer conditions.

4.2. Uncertainty, suitability and utility of the modelling approach for pinpointing dominant drivers of change

4.2.1. Uncertainties

The process of evaluating study findings so as to identify the relative importance of different drivers of change influencing water resources requires results to be put in the context of various uncertainties. Although quantitative analysis is outside the scope of the paper, it is necessary to appreciate that in a linked model application uncertainties take many forms and these act in concert. Uncertainty in climate projections has been comprehensively evaluated in terms of their impact on basin hydrology. Specific climate-driven uncertainties in river flows (Figs. A1 and 6) and water quality (Fig. 7) are apparent, with water quality model performance subject to much uncertainty (e.g. goodness of fit statistics, Table 2), including structural issues related to the formulations of biological response (Waylett et al., 2013). Nevertheless, Hutchins et al. (2016) suggested that uncertainties arising from climate model projections exceed those from water quality modelling which in turn are greater than those from hydrological modelling. This conclusion was reinforced in the present study, whereby to further contrast the effect of climatic change to that of other factors, two climate change scenarios were considered for each storyline. In addition, different sources of uncertainty may cancel each other out and others cannot be readily quantified. For example the land use projections as specified for the storylines are defined by expert judgement and are not easily incorporated into consideration of uncertainty. We argue the very large dissimilarity between the various storyline simulations provide robust evidence of difference.

4.2.2. Suitability of the approach for identifying dominant drivers of change

Hydrological predictions were impacted by three drivers of change: land use change, groundwater abstraction and climate. Climate appears to be the main driver impacting on the hydrology as illustrated by the fact that changes in river flows between the different climate models and time horizons within each storyline are of similar magnitude to or greater than those observed between the different storylines for the same climate model and time horizon. There is also a noticeable difference in the response of CW, which is based on RCP4.5, compared to TW and SOF. The increase in groundwater abstraction between TW and SoF impacts most on the upper reaches of the catchment, where flows decrease more dramatically for SoF compared to TW and CW. There is no clear indication that landuse change significantly impacts on river flows, but it is likely that the landuse signal is obscured by other changes, specifically by the climate signal.

The QUESTOR model reveals there is an iterative and circular dependency between chlorophyll and phosphorus. Phosphorus is present at levels that do not limit algal growth until the algal populations increase above a threshold. It is unclear what this threshold is but it appears to be over 0.1 mg L^{-1}. Above this level P controls chlorophyll and then chlorophyll starts controlling P. This change in control is complex in particular when decay and recycling of P starts to occur.

It is clear that the multiple applications of process models applied here supports in part existing understanding of the dynamics observed in the Thames. It has confirmed for example that for algal biomass, shading and residence time (flow) are the sensitive response variables. Phosphorus is secondary, but it is largely only when phosphorus becomes important that DO becomes vulnerable. This P response will be fairly transient, more consistently temperature will put some (secondary) stress on DO.

Only under the CW, the quality of the Farmoor reservoir is projected to improve due to less nutrient rich river influent, with severe deterioration found under SoF (and to a lesser extent, under the TW) which would have damaging consequences to drinking water supply in the river basin. The water transfers from outside the river basin implemented under SoF and TW are beneficial in terms of maintaining low flows but cannot improve reservoir water quality unless they are of sufficiently low P concentration to substantially dilute the load into the reservoir.

4.2.3. Utility of the approach for stakeholder uptake

Whilst the assessment of the storylines is very valuable in identifying likely future changes in river basin water resources under a complex suite of interacting drivers and multiple-stressors, the limited number of model applications entailed does not enable identification of the relative impact of each individual driver of change. Instead, systematic sensitivity analyses of multiple drivers of change would be more appropriate to clearly quantify the individual and combined effects of the considered response variables. Under a modelling framework, a comprehensive and robust design would need to use alternative model structures so that uncertainty in process modelling could also be accounted for; for example known limitations of QUESTOR include a tendency to underestimate peak algal levels and simulate blooms that last longer than observed (Hutchins et al., 2016).

River basin managers in the UK and across Europe are actively seeking refinements to the programmes of measures in place to meet requirement of the Water Framework Directive and as such, results from studies like the one conducted here could feed directly in to medium-term policy developments. In the UK, in recognition of a significant and growing risk to water resources from climate change, population growth and environmental drivers of change a recent study has called for both enhancement of supplies, with associated intra-basin transfers to the south and east of England, as well as demand management (UK Water, 2016). Our results, which highlight suitable ameliorative and preventative practices to safeguard water resources, are amongst the sort of information water regulators are keen to access as evidence for future regulatory decisions. There is also incentive to harmonise measures for flood control with those related to water quality targets, and a holistic analysis of the effects of drivers of change on multiple-stressors is compatible with such approach. Uptake of initiatives is already in place, for example, tree planting both for natural flood management and river thermal control (Woodland Trust, 2016) is active in parts of the Thames river basin. The cost-effectiveness of riparian tree planting as an affordable option for eutrophication control has been documented (Hutchins et al., 2010).

5. Conclusion

The application of the MARS storylines to the Thames river basin has highlighted a number of key messages:

- Reduction of low flow and increase in water temperature can increase the risk of algal blooms. It is hence critical to maintain low flows to a minimum level, and to keep the river channel cool, which could be achieved through shading in the Thames upper reaches.
- Because the Thames is not nutrient limited, there is little need to keep P levels low although in upstream reaches this would probably be beneficial.
- There is some evidence that low P levels further down the river system may actually be detrimental to river health.
- Reduction of nutrients in rivers could help reduce the total phytoplankton biomass in reservoirs, but this might be mitigated by an increase in the dominance of that biomass by the toxic cyanobacteria species as the century progresses and becomes warmer.
- Projected climatic changes under the most extreme RCPs might result in drying of the river for part of the year which could only be mitigated with drastic changes in water management through building a new reservoir or water transfer from outside the catchment. They would be associated with severe deterioration of the water quality both in the river and the existing reservoir.
- The CW scenario will lower baseflow, raise water temperature and cause some deterioration of river water quality compared to the present day situation. The consequence of the modifications to water management required under SoF and TW leads to improvement over present day water quality in the river but the changes would not be of a form suitable to prevent a deterioration in reservoir water quality.
- Aquatic ecosystems respond to multiple drivers of change in complex ways that can rarely be captured fully by water quality models. Hipsey et al. (2015) advocate that to better evaluate the effects of multiple drivers of change, linked models of the type considered here should be applied as part of an ensemble which would include deterministic and data-driven approaches within a model learning framework.
- The limited number of storylines with simultaneous changes of multiple drivers does not allow a robust identification of response relationships, notably whether effects in combination act synergistically or antagonistically in aquatic ecosystems (Jackson et al., 2016). A sensitivity analysis where drivers are changed independently of each other, including combinations, would be more appropriate.

Acknowledgements

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Appendix A. Appendices

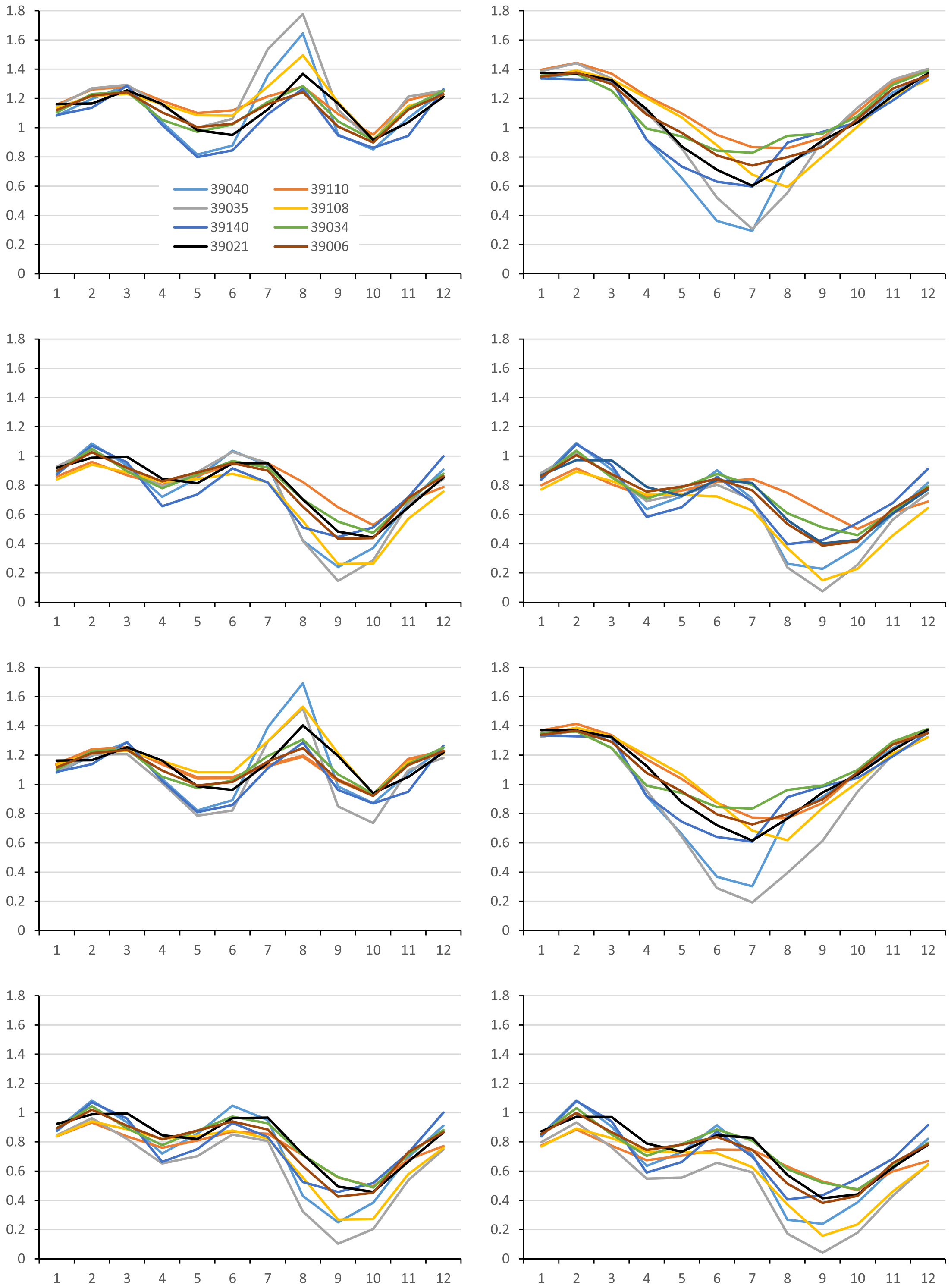


Fig. A1. Monthly ratios (Jan = 1, Dec = 12) of storyline flow to baseline, as applied as multipliers to daily observed flows, for the 8 tributaries in the upper Thames river basin referred to in column 4 of Table A2. (a) TW IPSL 2030s, (b) TW IPSL 2060s, (c) TW GFDL 2030s, (d) TW GFDL 2060s, (e) SOF IPSL 2030s, (f) SOF IPSL 2060s, (g) SOF GFDL 2030s, (h) SOF GFDL 2060s, (i) CW IPSL 2030s, (j) CW IPSL 2060s, (k) CW GFDL 2030s, (l) CW GFDL 2060s; where TW = Techno World, CW = Consensus World, SOF = Survival of the Fittest. The 8 tributaries are: Thames at West Mill Cricklade (39040), Coln at Fairford (39110), Churn at Cerney Wick (39035), Churn at Perrott's Brook (39108), Ray at Islip (39140), Evenlode at Cassington Mill (39034), Cherwell at Enslow Mill (39021), Windrush at Newbridge (39006).

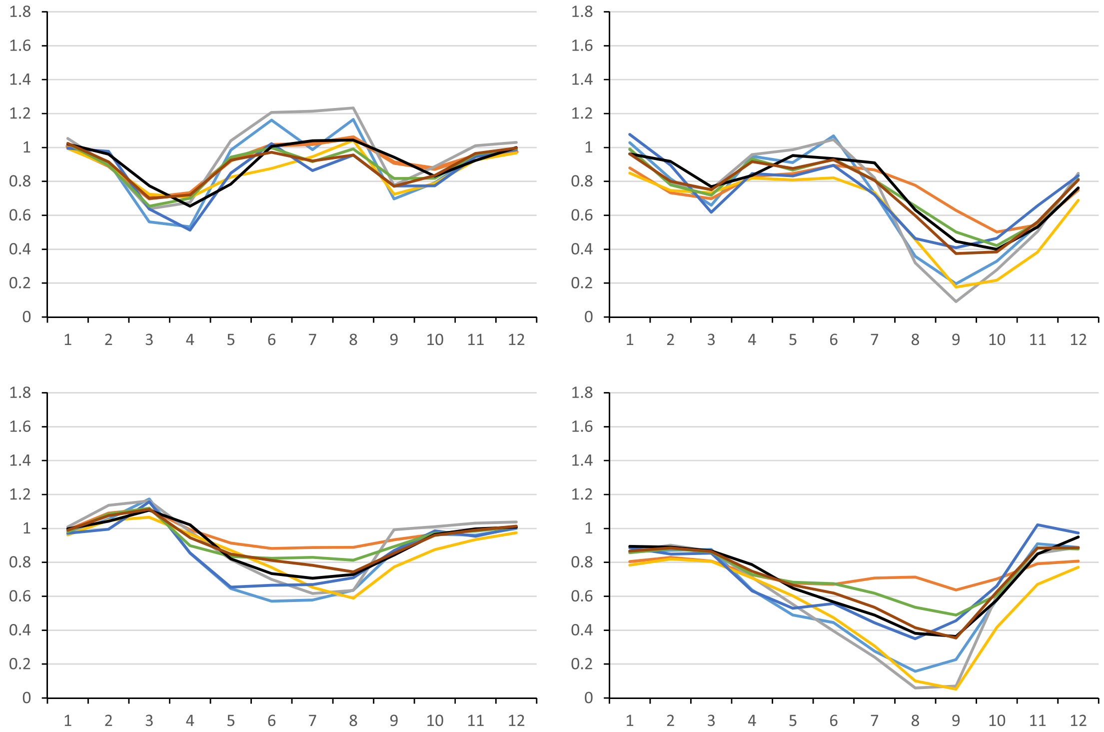
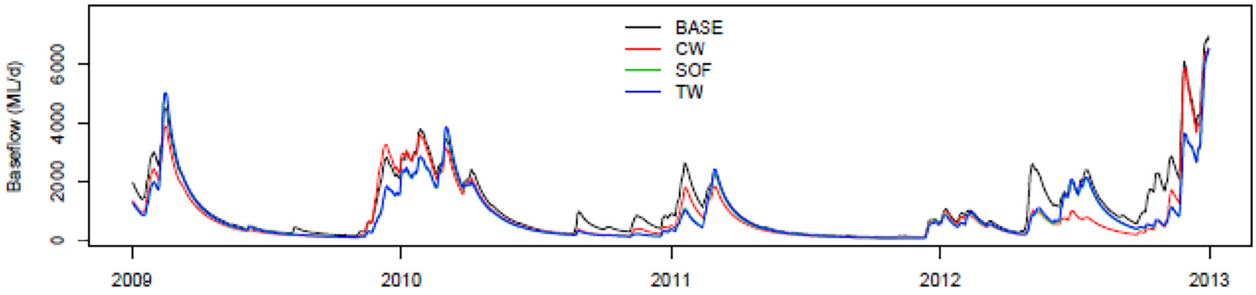


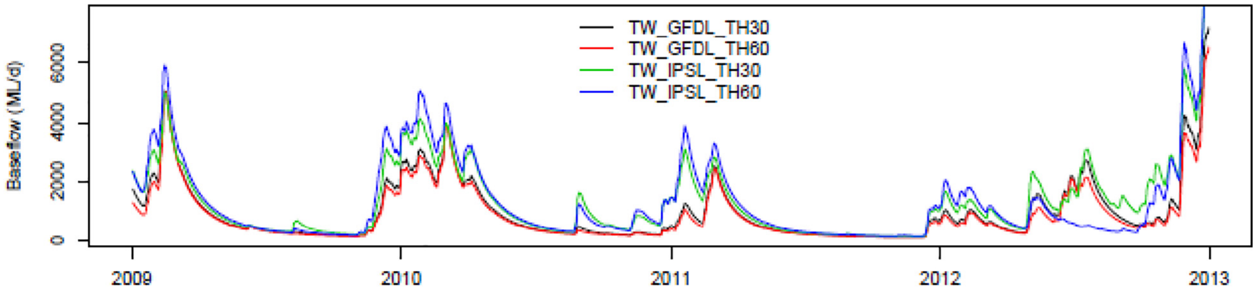
Fig. A1 (*continued*).

3946_Thames_StonCourtney

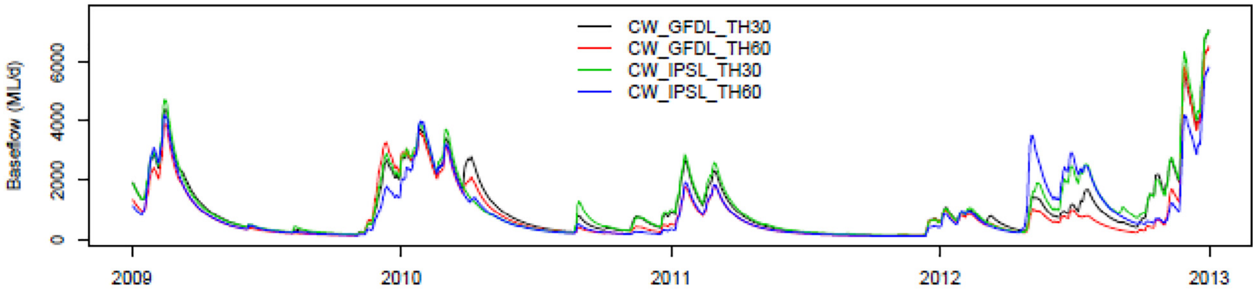
(a) Storylines for same climate scenario (GFDL_TH60)



(b) TW



(c) CW



(d) SOF

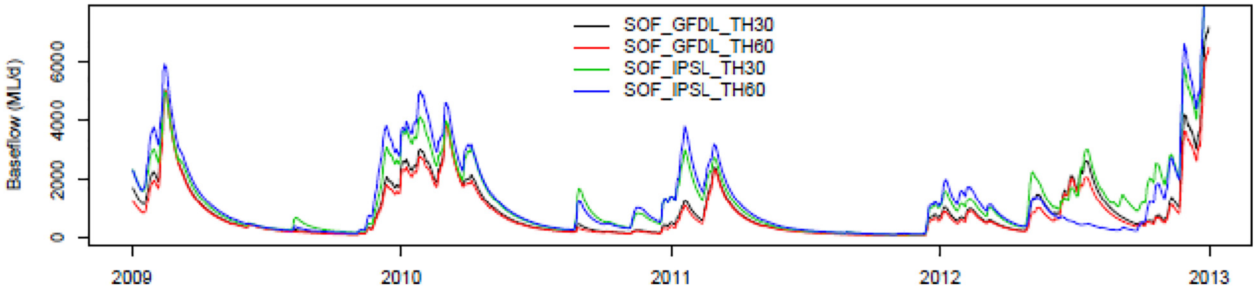


Fig. A2. Modelled baseflow hydrographs for the River Thames at Sutton Courtenay comparing (a) the base case and different storylines for climate scenario GFDL-TH60 and (b–d) different climate models (GFDL and IPSL) and time horizons (2030 = TH30, 2060 = TH60) within each storyline. TW = Techno World, CW = Consensus World, SOF = Survival of the Fittest.

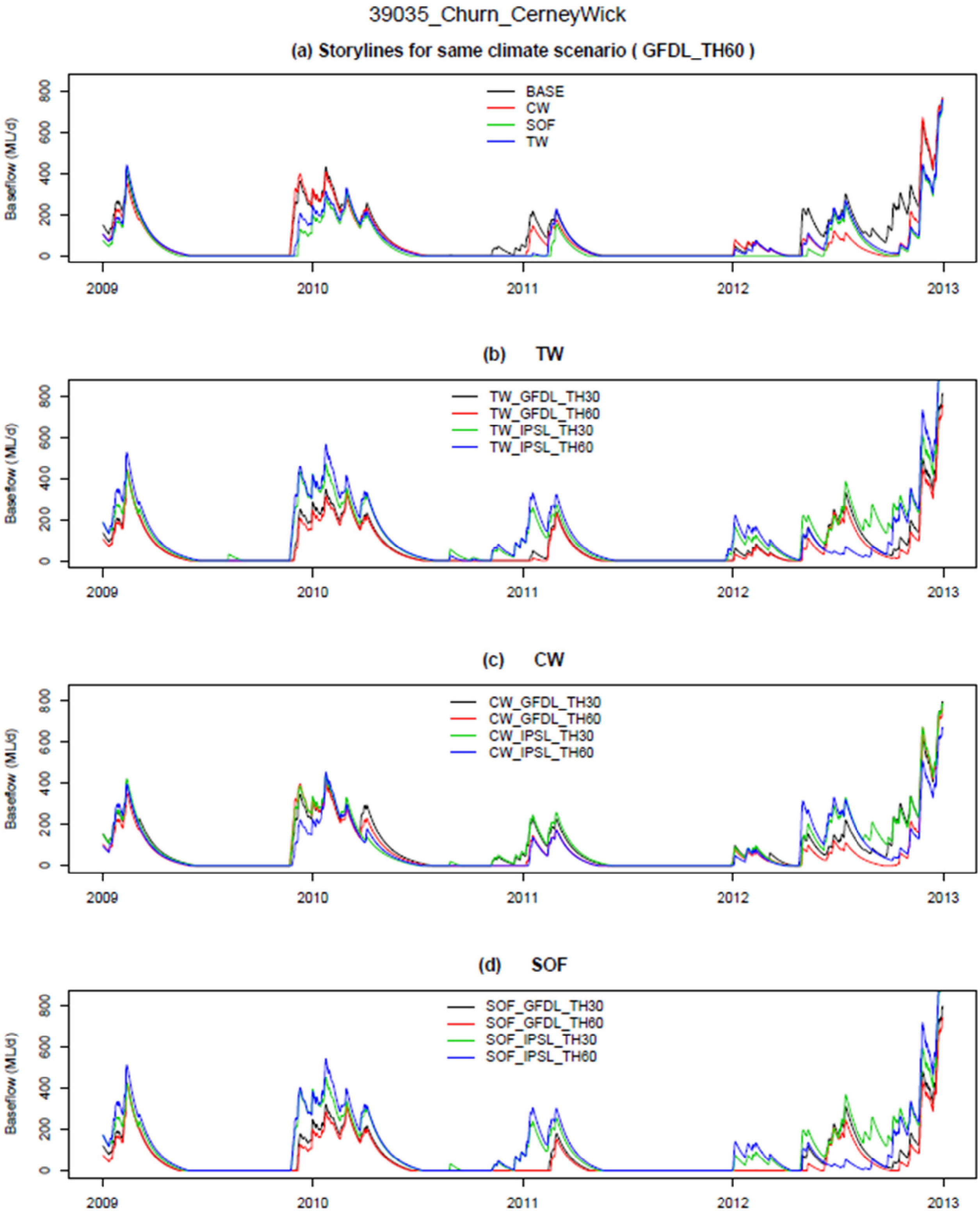


Fig. A3. Modelled baseflow hydrographs for the River Churn at Cerney Wick comparing (a) the base case and different storylines for climate scenario GFDL-TH60 and (b-d) different climate models (GFDL and IPSL) and time horizons (2030 = TH30, 2060 = TH60) within each storyline. TW = Techno World, CW = Consensus World, SOF = Survival of the Fittest.

Table A1
Delineation of reaches and their influences as represented in QUESTOR.

Reach numbers	Influences (network branches, tributaries, point sources)	Flow and quality data from tributaries	Weirs (W) and abstractions (A)	Monitoring sites	Reach length (km)	Cumulative river length (km) (from Hannington)
Cherwell 1	Cherwell	Yes			2.8	n/a
Cherwell 2	Ray	No			5.0	n/a
Cherwell 3	Bayswater Brook			North Oxford	2.6	n/a
Cherwell 4			W		4.6	n/a
Thame 1	Thame Wheatley STW	Yes			7.2	n/a
Thame 2	Haseley Brook	No			2.2	n/a
Thame 3	Lewknor Brook Watlington STW	No	W	Dorchester	9.2	n/a
Thame 4					0.9	n/a
Thames 1	Thames	Yes			2.6	2.6
Thames 2	Bydemill Brook	No			2.8	5.4
Thames 3	Coln	Yes			0.4	5.8
Thames 4	Cotswold Water Park	No	W		1.9	7.7
Thames 5	Leach Cole	Yes Yes	W		6.6	14.4
Thames 6			W		3.5	17.9
Thames 7			W		1.3	19.2
Thames 8	Faringdon Brook	No	W		8.9	28.1
Thames 9			W		1.0	29.1
Thames 10	Great Brook	No		Newbridge (1)	3.5	32.6
Thames 11	Windrush	Yes	W, A	Farmoor	8.8	41.5
Thames 12			W	Eynsham (2)	2.9	44.3
Thames 13			W		2.2	46.5
Thames 14	Evenlode	Yes			0.9	47.4
Thames 15	Cassington STW		W	Godstow	3.1	50.5
Thames 16			W		3.9	54.4
Thames 17			W	Central Oxford	1.9	56.3
Thames 18					0.8	57.1
Thames 19	Cherwell 4			South Oxford	0.9	57.9
Thames 20			W		3.3	61.3
Thames 21			W		0.3	61.5
Thames 22	Northfield Brook Oxford STW	No		Radley College	2.6	64.2
Thames 23				Abingdon (3)	4.7	68.9
Thames 24			W		1.1	70.0
Thames 25	Ock	Yes			1.1	71.1
Thames 26	Abingdon STW				1.9	73.0
Thames 27	Ginge Brook Abingdon STW overflow	No	W, A	Sutton Courtenay	4.2	77.1
Thames 28	Moor Ditch Didcot STW	No	W		2.0	79.1
Thames 29	Culham STW				4.6	83.7
Thames 30			W	Days Lock	1.2	85.0
Thames 31	Thame 4				4.9	89.9
Thames 32	Ewelme Stream	No	W		1.2	91.0
Thames 33	Howbery Ditch	No		Wallingford (4)	0.9	91.9

Table A2
QUESTOR Thames model tributary details and model setups.

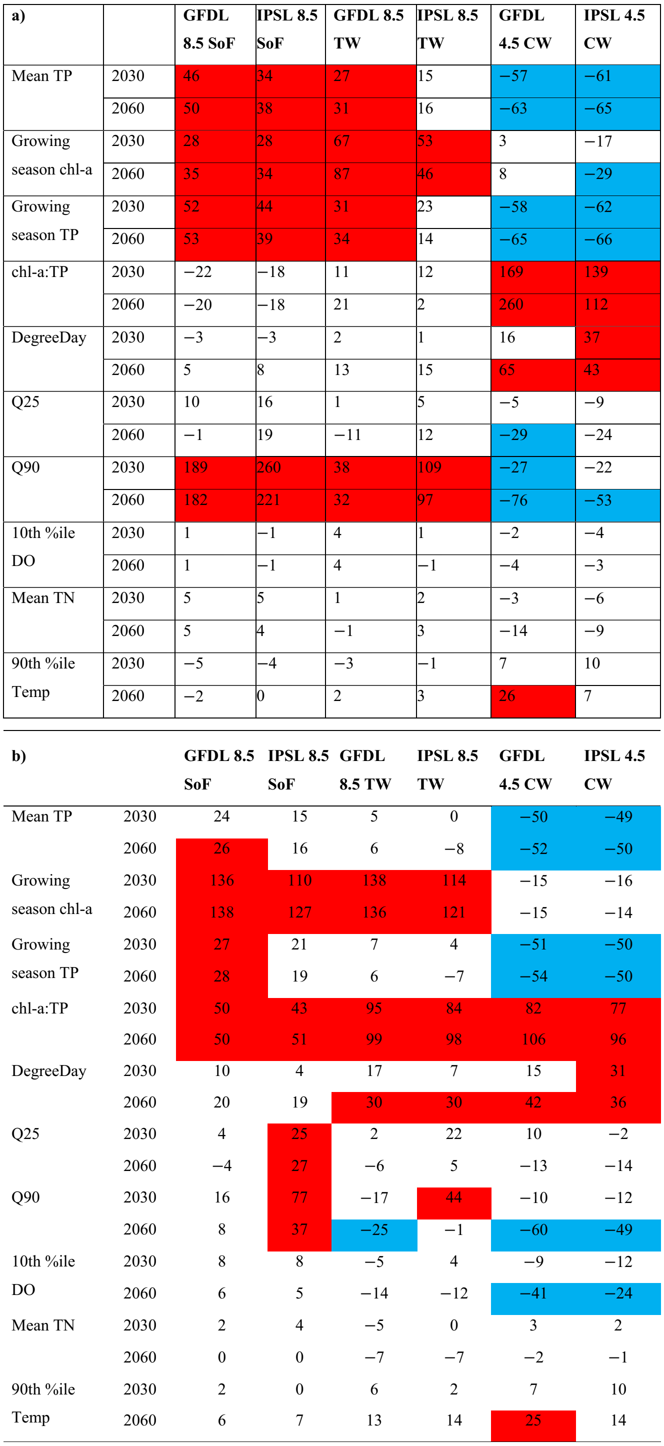
Tributary name	Reach ID (where tributary joins)[a]	Observed flow and chemistry data used in storylines? (catchment area)	Flows donated and scaled: storylines configuration (ID = flow GS number)	Flows donated and scaled: original configuration, as used for 2009–12 model testing (Table 2) (ID = flow GS number)
Cherwell	C1	Y/Y (552 km^2)	Cherwell 39021	Cherwell 39021
Ray	C2	Y/Y (290 km^2)	Ray 39140	Ray 39140
Bayswater Bk	C3	N/N	Ray 39140	Ray 39140
Thame	Th1	N/Y (534 km^2)	Ray 39140	Thame 39105
Haseley Bk	Th2	N/N	Churn 39108	Ewelme Bk 39065
Lewknor Bk	Th3	N/N	Churn 39108	Ewelme Bk 39065
Thames (at Hannington)	T1	Y/Y (468 km^2)	Churn 39035, Thames 39040	Ray 39087, Churn 39035, Thames 39040, Ampney 39074
Bydemill Bk	T2	N/N	Windrush 39006	Cole 39090
Coln	T3	Y/Y (130 km^2)	Cole 39110	Coln 39110
Stream at Cotswold Water Park	T4	N/N	Windrush 39006	Cole 39090
Cole	T5	N/Y (140 km^2)	Windrush 39006	Cole 39090
Leach	T6	N/Y (77 km^2)	Windrush 39006	Leach 39042
Faringdon Bk	T8	N/N	Windrush 39006	Cole 39090
Great Bk	T10	N/N	Windrush 39006	Cole 39090
Windrush	T11	Y/Y (363 km^2)	Windrush 39006	Windrush 39006
Evenlode	T14	Y/Y (430 km^2)	Evenlode 39034	Evenlode 39034
Northfield Bk	T22	N/N	Ray 39140	Ray 39140
Ock	T25	N/Y (234 km^2)	Windrush 39006	Ock 39081
Ginge Bk	T27	N/N	Windrush 39006	Ock 39081
Moor Ditch	T28	N/N	Windrush 39006	Ock 39081
Ewelme Bk	T32	N/N	Churn 39108	Ewelme Bk 39065
Howbery Ditch	T33	N/N	Churn 39108	Ewelme Bk 39065

[a] Reach identifier (C = Cherwell, Th = Thame, T = Thames).

Table A3
Percentage change in river flow descriptors relative to the base case scenario at the selected gauging stations for the different storyline scenarios.

		BASEFLOW				TOTAL FLOW			
		Churn@Cerney Wick	Thames@Buscot	Thames@Eynsham	Thames@Sutton Courtnay	Churn@Cerney Wick	Thames@Buscot	Thames@Eynsham	Thames@Sutton Courtnay
Storyline Scenarios		% change relative to base case				% change relative to base case			
Base case	Q5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CW_GFDL_TH30		0.0	3.3	-9.1	-13.9	-70.0	-9.2	-14.6	-22.6
CW_GFDL_TH60		0.0	1.8	-16.7	-21.3	-70.0	-15.4	-27.0	-35.4
CW_IPSL_TH30		0.0	3.9	-3.8	-9.6	-60.0	-5.9	-9.2	-13.9
CW_IPSL_TH60		0.0	0.5	-17.2	-28.1	-80.0	-14.3	-27.0	-43.1
SOF_GFDL_TH30		0.0	-12.4	-21.0	-25.8	-80.0	-23.5	-30.3	-40.0
SOF_GFDL_TH60		0.0	-13.2	-23.9	-29.6	-80.0	-25.5	-33.0	-43.8
SOF_IPSL_TH30		0.0	-9.2	1.6	-5.9	-50.0	-9.1	-8.7	-10.8
SOF_IPSL_TH60		0.0	-7.9	-5.5	2.2	-60.0	-17.5	-11.9	-3.7
TW_GFDL_TH30		0.0	-1.6	-14.7	-22.7	-80.0	-15.3	-25.8	-38.6
TW_GFDL_TH60		0.0	-2.3	-17.7	-26.2	-80.0	-17.0	-28.5	-42.3
TW_IPSL_TH30		0.0	1.4	6.5	-3.0	-60.0	-1.8	-4.8	-10.1
TW_IPSL_TH60		0.0	2.6	0.9	4.5	-60.0	-9.6	-6.5	-2.7
Base case	Q50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CW_GFDL_TH30		26.2	-6.9	-6.1	-7.3	22.1	-8.7	-7.2	-5.8
CW_GFDL_TH60		-56.4	-46.6	-39.1	-35.2	-55.4	-41.2	-38.0	-37.3
CW_IPSL_TH30		16.7	-6.5	-2.8	-1.3	13.7	-0.4	-0.6	-3.6
CW_IPSL_TH60		-38.7	-38.1	-32.8	-31.1	-38.5	-39.9	-34.4	-34.1
SOF_GFDL_TH30		-100.0	-36.5	-26.4	-21.3	-80.4	-35.7	-29.0	-26.2
SOF_GFDL_TH60		-100.0	-47.7	-35.2	-30.3	-85.9	-45.7	-36.8	-34.4
SOF_IPSL_TH30		18.8	32.5	31.0	32.7	18.5	32.1	26.9	23.5
SOF_IPSL_TH60		-13.8	-15.0	-7.4	0.9	-12.8	-16.5	-11.3	-5.8
TW_GFDL_TH30		-36.0	-28.1	-21.5	-18.7	-34.5	-30.2	-26.3	-25.2
TW_GFDL_TH60		-64.3	-40.2	-31.1	-29.0	-59.2	-41.1	-34.3	-33.5
TW_IPSL_TH30		82.5	43.9	35.5	34.8	70.3	37.1	31.4	24.3
TW_IPSL_TH60		40.7	-6.5	-2.8	2.7	34.3	-10.0	-7.3	-4.8
Base case	Q90	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CW_GFDL_TH30		-0.7	-2.7	-1.8	-1.0	-1.9	-5.4	-2.5	-5.2
CW_GFDL_TH60		-13.2	-11.9	-10.2	-9.4	-15.4	-13.8	-10.9	-12.0
CW_IPSL_TH30		4.9	0.3	2.2	2.8	4.3	0.6	1.9	0.6
CW_IPSL_TH60		-4.2	-12.3	-8.5	-5.9	-4.6	-10.0	-6.7	-4.8
SOF_GFDL_TH30		-21.1	-18.6	-15.3	-10.7	-21.4	-19.0	-14.2	-13.1
SOF_GFDL_TH60		-30.6	-26.9	-22.5	-20.3	-30.9	-25.6	-20.8	-20.7
SOF_IPSL_TH30		9.1	7.1	8.6	11.0	7.7	6.3	8.2	8.4
SOF_IPSL_TH60		19.4	24.3	25.4	30.5	16.2	22.4	24.9	26.1
TW_GFDL_TH30		-12.9	-15.0	-12.7	-9.3	-12.3	-16.0	-12.1	-12.0
TW_GFDL_TH60		-21.2	-21.9	-19.4	-18.5	-21.7	-22.8	-19.2	-19.7
TW_IPSL_TH30		16.0	9.2	10.5	11.8	13.5	7.9	9.2	9.5
TW_IPSL_TH60		25.4	27.2	27.8	31.0	23.4	25.7	26.7	27.4

Table A4
Percentage change associated with the MARS storylines for the Thames river basin at: (a) Site 3 and (b) Site 4. Cells are shaded in red for changes >25%, white for changes between ±25%, and blue for changes lower than −25%.



a)		GFDL 8.5 SoF	IPSL 8.5 SoF	GFDL 8.5 TW	IPSL 8.5 TW	GFDL 4.5 CW	IPSL 4.5 CW
Mean TP	2030	46	34	27	15	−57	−61
	2060	50	38	31	16	−63	−65
Growing season chl-a	2030	28	28	67	53	3	−17
	2060	35	34	87	46	8	−29
Growing season TP	2030	52	44	31	23	−58	−62
	2060	53	39	34	14	−65	−66
chl-a:TP	2030	−22	−18	11	12	169	139
	2060	−20	−18	21	2	260	112
DegreeDay	2030	−3	−3	2	1	16	37
	2060	5	8	13	15	65	43
Q25	2030	10	16	1	5	−5	−9
	2060	−1	19	−11	12	−29	−24
Q90	2030	189	260	38	109	−27	−22
	2060	182	221	32	97	−76	−53
10th %ile DO	2030	1	−1	4	1	−2	−4
	2060	1	−1	4	−1	−4	−3
Mean TN	2030	5	5	1	2	−3	−6
	2060	5	4	−1	3	−14	−9
90th %ile Temp	2030	−5	−4	−3	−1	7	10
	2060	−2	0	2	3	26	7

b)		GFDL 8.5 SoF	IPSL 8.5 SoF	GFDL 8.5 TW	IPSL 8.5 TW	GFDL 4.5 CW	IPSL 4.5 CW
Mean TP	2030	24	15	5	0	−50	−49
	2060	26	16	6	−8	−52	−50
Growing season chl-a	2030	136	110	138	114	−15	−16
	2060	138	127	136	121	−15	−14
Growing season TP	2030	27	21	7	4	−51	−50
	2060	28	19	6	−7	−54	−50
chl-a:TP	2030	50	43	95	84	82	77
	2060	50	51	99	98	106	96
DegreeDay	2030	10	4	17	7	15	31
	2060	20	19	30	30	42	36
Q25	2030	4	25	2	22	10	−2
	2060	−4	27	−6	5	−13	−14
Q90	2030	16	77	−17	44	−10	−12
	2060	8	37	−25	−1	−60	−49
10th %ile DO	2030	8	8	−5	4	−9	−12
	2060	6	5	−14	−12	−41	−24
Mean TN	2030	2	4	−5	0	3	2
	2060	0	0	−7	−7	−2	−1
90th %ile Temp	2030	2	0	6	2	7	10
	2060	6	7	13	14	25	14

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