Impacts of climate change scenarios on dissolved oxygen in the River Thames, UK
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ABSTRACT
A water quality model is used to assess the impact of possible climate change on dissolved oxygen (DO) in the Thames. The Thames catchment is densely populated and, typically, many pressures are anthropogenic. However, that same population also relies on the river for potable water supply and as a disposal route for treated wastewater. Thus, future water quality will be highly dependent on future activity. Dynamic and stochastic modelling has been used to assess the likely impacts on DO dynamics along the river system and the probability distributions associated with future variability. The modelling predictions indicate that warmer river temperatures and drought act to reduce dissolved oxygen concentrations in lowland river systems.

Key words | climate change, dissolved oxygen, model, River Thames, water quality

INTRODUCTION
Much discussion has taken place in the literature concerning predictions of future climate (IPCC 2000, 2007) but the impacts of climate change also need to be investigated, in order to form mitigation or adaptation strategies (Whitehead et al. 2006). Potential changes in water quality are important because rivers are key habitats and have an amenity value for recreational purposes. There is also an economic value; industry is concerned about the quality of water available for abstraction and the dilution of effluent. The European Water Framework Directive (WFD) requires that all water should have a “good status” by 2015, and in order to achieve this it is necessary to consider all of the driving forces affecting water quality.

Estimating how water quality conditions and fluxes may change in the future requires a method of extrapolation from current to possible future conditions. Process-based models can provide a means of making this extrapolation. However, this requires that the model is capable of simulating a wide range of conditions and that adequate calibration and validation procedures are adopted. In Cox (2002, 2003), it has been shown that the Q² model is capable of simulating flow and water quality in one of Europe’s most important rivers, the River Thames, under a wide range of flow and climate conditions. Thus Q² can be used as a tool for scenario analyses such as estimating the impact of climate change on river water quality.

THE RIVER THAMES SYSTEM AND WATER QUALITY
The River Thames is a major river, draining 9,948 km² of central southern England, as shown in Figure 1, with mixed sedimentary geology of mainly Jurassic age. The hydrology and water quality, particularly in the upper catchment, is dominated by the chalk aquifers that underlie the Thames, creating “hard water” with high pH and high base cations. Water quality is generally good (Neal & Whitehead 2002), although low dissolved oxygen levels do occur at certain times (Williams et al. 2000) as do algal blooms (Whitehead & Hornberger 1984). Average rainfall for the catchment down to Teddington is relatively low for the UK at 706 mm/yr on average (1961–1990 average at Kingston) and the River Thames is subject to drought in certain dry
years. Indeed a recent report by the WWF (2008) has suggested that the Thames is highly vulnerable to future changes in land use, population and climate.

Whitehead et al. (2006) have investigated the impacts of possible climate change on nitrogen in the River Thames and concluded that there could be significant problems in the future as dryer conditions generate increased mineralisation of nitrogen which would be flushed into the Thames in storm events. Also, climate change will affect diffuse sources of phosphorus and sediments (Whitehead et al. 2008) with decreased summer flows increasing phosphorus concentrations due to reduced dilution and increased sediments at higher winter flows generated by more erosion. In this paper, the likely impacts on the dissolved oxygen regime under likely future climates is considered. The $Q^2$ model (Cox 2003) has been utilised as the principal tool for this analysis.

THE $Q^2$ MODEL

The following section provides only an outline description of the $Q^2$ model. A fuller description can be found in Cox (2002) and Cox & Whitehead (2005). The $Q^2$ model is based on the Quality Simulation along Rivers Model (QUASAR), as developed by Whitehead et al. (1997), a model of intermediate complexity, which is well suited to simulating water quality in large river systems (Whitehead & Young 1979; Whitehead et al. 1981, 1984, 1995; Lewis et al. 1997; Eatherall et al. 1998; Cox 2003). However, since the development of the QUASAR model, improved process equations have been developed and Cox (2003) has undertaken a major review of these processes and created the new model $Q^2$.

The $Q^2$ model is well suited to this application as it benefits from a structure that is relatively straightforward to calibrate and which can be used in a stochastic (or probabilistic) framework as well as for dynamic simulations (Cox 2003). This means that the $Q^2$ model is quicker and easier to set up than hydraulic models based on solutions of the advection–dispersion equations and yet, unlike many steady state models, is still able to deal with the interactions between different water quality determinands and also to simulate river temperatures in a meaningful way.

The structure of $Q^2$ is of continually stirred tank reactors (CSTR) in series, which can be used to represent the dynamic transport and transformation of solutes in branched river systems using zero-dimensional ordinary,
lumped parameter, differential equations of mass conservation. The linked ordinary differential equations are simultaneously solved using a fourth-order Runge–Kutta numerical integration algorithm with a variable-step routine, and this ensures that the equations are solved accurately. The technique has proved to be fairly stable with few numerical problems. The equations used in $Q^2$ are described in detail in Cox (2003), but the major processes are shown in Figure 2. Several improvements to the original QUASAR model have been made, as follows:

1. The stream depth in each reach is estimated at every time step in $Q^2$.
2. The temperature model in QUASAR is conservative, but this approach has been found to be poor at simulating summer river temperatures. Thus, a simple heat balance is used in $Q^2$ with a surface solar heat flux term included to represent solar heating (Chapra 1997).
3. The nitrate denitrification rate parameter in $Q^2$ explicitly relates the rate to the bed area available for removal, since these processes typically occur in the sediments (Toms et al. 1975).
4. The BOD decay (oxidation) rate parameter in $Q^2$ uses empirically derived Equations (Hydroscience 1971), which describe the relationship between the decay rate and the stream depth for shallow rivers ($<2.4$ m deep).
5. The net BOD sedimentation rate parameter in $Q^2$ is expressed as a net settling velocity (settling minus re-suspension), which therefore accounts for the stream depth in BOD removal.
6. The Sediment Oxygen Demand (SOD) rate parameter in $Q^2$ is related to the bed area available for this oxidation and the first-order relationship with the DO concentration is replaced by a “Michaelis–Menten” half-saturation term using the method of Lam et al. (1984).

The $Q^2$ model also retains the ability of QUASAR to run in either a dynamic or stochastic mode. The utility of stochastic modelling is well documented (Whitehead & Young 1979) and relates directly to statistical quality standards in UK legislation. The two most important benefits of stochastic modelling are: (a) for investigations of the errors associated with laboratory analysis and sampling, and the uncertainty associated with imprecise knowledge of model parameters and process mechanisms and (b) for the provision of model results in a form suitable for comparison with the guidelines and standards in the EC Directives and legislation for the UK.

Figure 2 | A graphical representation of the processes currently included in the $Q^2$ model.
UK CLIMATE CHANGE AND FUTURE CLIMATE SCENARIOS

The UK climate has changed over the last century and the central England temperature record shows a rise of almost 1°C, with the 1990s being the warmest decade since the 1660s. Very hot summers have become more common, and there are now fewer frosts and winter cold spells than in the past. Together with this temperature rise, UK winters seem to have been getting wetter (Osborn et al. 2000) with an increasing proportion of the precipitation falling on heavy rainfall days. All of the United Kingdom Climate Impacts Programme (UKCIP) climate scenarios predict further changes, because the climate of the next 30–40 years will already have been affected by past and present emissions of greenhouse gases and by the “inertia” of the climate system. However, the volume of greenhouse gases emitted over the next few decades will increasingly influence the climate of the second half of the twenty-first century and, as illustrated by Whitehead et al. (2008), will generate greater variability in flows and water quality in UK rivers.

The latest UK Climate Impacts Programme report (UKCIP02, Hulme et al. 2002) describes predictions based on four alternative scenarios for three future 30-year periods referred to as the 2020s (2011–2040), 2050s (2041–2070) and 2080s (2071–2100). These scenarios relate to future global emissions of greenhouse gases referred to as Low Emissions, Medium–Low Emissions, Medium–High Emissions and High Emissions and encompass nearly the full range of projections developed by the IPCC Special Report on Emissions Scenarios (IPCC 2000). The “high” projected emissions for the 2080s represent more than twice the current atmospheric carbon dioxide concentration (Table 1), but the four scenarios are treated as being equally likely, because it is not possible to predict future socio-economic conditions (IPCC 2000; Hulme et al. 2002).

To generate the UKCIP02 scenarios the Hadley Centre global climate model, HadCM3, has been used to simulate changes in UK climate due to each of these emission scenarios and the key findings (Hulme et al. 2002) are that the UK climate is likely to be warmer in the future, with very hot summers becoming more common and very cold winters becoming increasingly rare. Moreover, there is likely to be increased seasonal variability in precipitation, with drier summers and wetter winters and that heavy winter precipitation events are likely to become more frequent. The UKCIP results therefore indicate that extreme weather events (both high and low rainfall events) will become more frequent. However, it is possible that this degree of change might be an under-prediction. Indeed, it had already been suggested that the UK is undergoing a period of climate instability (e.g. Marsh & Sanderson 1997). However, predictions of such extreme events are beyond the scope of this study and so this type of enhanced climatic volatility is not explicitly considered here.

Temperature

Estimates of future temperatures range between a 2°C increase for the low emissions scenario and 3.9°C for the high emissions scenario in the 2080s (Table 1). Furthermore, they predict greater warming in the south and east of the UK than in the north and west. Also predicted is greater warming in the summer and autumn than in the winter and spring, and greater warming during the nights in winter than during the days in summer. Furthermore, it is predicted that there will be an increased frequency of extreme high temperature periods (Table 2), with more frequent high
summer temperatures and very cold winters becoming increasingly rare.

Precipitation

Winter precipitation over the whole of the UK is predicted to increase for all of the future periods considered in every scenario. By the 2080s, this increase ranges from 10–20% for the low emissions scenario to 15–35% for the high emissions scenario, with the largest changes predicted in the south and east of England and the smallest in north-west Scotland. In the summer, the pattern is reversed and almost the whole of the UK may become drier, with precipitation decreases of up to 35% for the low emissions scenario and 50% or more for the high emissions scenario (Hulme et al. 2002). Furthermore, the frequency of storms is also predicted to increase, with two-year (return period) winter precipitation event intensities across England and Wales estimated to become between 5% (low emissions) and 20% (high emissions) heavier by the 2080s (Table 3).

**CLIMATE CHANGE IMPACTS ON STREAM FLOW**

Applications of hydrological models to assess climate change reveal two broad patterns of flow changes in the southern UK (Arnell 1998):

- a decline in mid- to late summer flows, which is less pronounced in groundwater-dominated catchments,
- an increase in winter and a larger increase in spring flow, although this is subject to significant uncertainty.

Changes in the seasonal patterns of flow under a range of scenarios are shown in Figure 3 and illustrate the broad changes with predicted dryer summers and wetter winters. Greater precipitation intensities may lead to a higher incidence of high flows and floods, with the response also affected by catchment characteristics and changes in antecedent conditions. Reduced low flows due to lower summer precipitation and increased evapotranspiration will have implications for the maintenance of water supply and quality.

Therefore, inter-annual variability is a consideration and, for example, the four-year period 1996–1999 contained periods of both drought and spate in the River Thames (Cox 2002). Figure 4 shows this variability by comparing mean daily flows in the River Thames at Teddington (the tidal limit) based on the whole period with the “dry” year, 1997, and the “wet” year, 1999. Thus, any predictions of the impact of climate change on river flows must recognise that, at least over the short and medium terms (less than 20 years), the year-on-year variability is significant and is likely to be greater than any climate change signal.

**CLIMATE CHANGE AND DISSOLVED OXYGEN**

It is well known that water quality can be affected by changes in flow and temperature. Higher water temperatures increase the rate of biological activity and chemical reactions in rivers, and also mean that the saturated DO concentration of a river is lower. Changes in runoff imply a change in the flow volume, which defines the residence time and dilution, and reactions often take place faster in shallower streams where there is also an increased atmospheric aeration rate. For example, it has been shown for the River Nitra in Slovakia that higher temperatures and lower summer flows could combine to produce substantial reductions in DO concentrations (Carmichael et al. 1996). The $Q^2$ model requires time series of flow and water quality in order to simulate the day-to-day impacts on water quality. For mean temperature, UKCIP monthly time series are available with 5 km resolution and Figure 3 provides
predicted monthly flow changes for the four UKCIP02 scenarios. Thus, it was possible to take the temperature and flow changes (relative to long-term means) predicted for the region of the River Thames catchment (Figure 3 and Table 1) and apply them to the available input data for the period 1996–1999. While being a pragmatic approach, this has the effect of over-estimating the temperature for a future scenario, since the late 1990s were particularly warm in the UK, but it probably represents the situation of a similarly warm year in the future. For the flows, it was possible to compare statistics from the available flow data with summaries provided in the hydrometric register for each gauge (CEH 2001). This was carried out for seven gauges on the River Thames and 23 of its tributaries, and revealed that the combination of drought and spate conditions over the four year period 1996–1999 was sufficient to reproduce very similar flow statistics to the long-term flow record.

The Q^2 model was set up to simulate the non-tidal River Thames between Cricklade (the location of the most upstream gauge) and Teddington (the tidal limit) for a single year using mean daily time series for the water quality determinands and flow, and a parameter set previously shown to be suitable for the period 1996–1999 in Cox (2002). The first run used mean daily flow and temperature time series derived from all of the available data and this formed the “baseline” simulation for the mean flow condition. Every flow and temperature input time series was then perturbed according to the predicted changes for each emission scenario for each of the three periods (2020s, 2050s and 2080s) and the model re-run. This whole process was then repeated using a “dry” year flow baseline (based on flows in 1997) and a “wet” year flow baseline (based on flows in 1999).

A set of results of the Q^2 simulations for the different future climate scenarios are presented in Figures 5–7 for the most downstream reach in the system (Molesey to Teddington). The three figures show the “mean”, “dry” and
“wet” baselines, and in these plots each line represents a baseline or emissions scenario as used in the UKCIP02 report (Hulme et al. 2002).

The overall impression from Figures 5–7 is that the potential effect of climate change on water quality is relatively minor, although there are significant temperature increases in the 2080s scenarios. This is consistent with other analogous studies: for example, the Land Ocean Interaction Study (LOIS) found that even relatively large simulated flow changes did not change a river ecosystem class (Boorman & Shackle 2002). In the \( Q^2 \) simulations, the flows show very little change between the different emission scenarios, but all show increased winter flow and decreased summer flow, with exaggerated changes in the higher emission scenarios. However, larger differences are observed when the different flow baselines are compared, showing that natural variability may have a far greater impact on the hydrology of the River Thames than the climate change suggested by these scenarios.

Although the water quality impacts are not dramatic, there are clear trends and patterns in the simulations, which suggest that climate change might have an important effect on water quality and on dissolved oxygen in particular. Warmer temperatures also tend to favour problem algae that can cause aesthetic nuisances, anoxia when the algae die off and produce toxins (especially cyanobacteria). The simulated water temperatures are elevated throughout the year—particularly in the summer—and this rise is generally larger with higher emission scenarios and in the later periods. In a “dry” year, this can be very significant, with the \( Q^2 \) model predicting summer temperatures of up to 35°C in some reaches as compared to maxima of 24–28°C in the baseline simulations. The temperature rises are also exaggerated by lower flows in the “dry” year simulations and this can be significant if the flows are particularly low (e.g. Figures 5 and 6).

The \( Q^2 \) simulations of future climate scenarios all predict lower dissolved oxygen concentrations in the River Thames, and this is more significant with increasing emissions and in the later periods. This is primarily the result of higher temperatures that reduce the saturation concentration of DO, but is also influenced by increased nitrification and BOD oxidation rates. The middle reaches experience the lowest DO concentrations in the river and
there are some significant reductions when particularly low flows occur in the “dry” baseline simulations. In the mean and “wet” baseline simulations DO concentrations are always greater than 7 mg O₂ l⁻¹, but the “dry” baseline simulations predict concentrations as low as 6.6 mg O₂ l⁻¹. The additional impact of climate change can then reduce this further to just 5.0 mg O₂ l⁻¹, approaching levels at which fish could be harmed (USEPA 1985; UKTAG 2007). Furthermore, diurnal variations might produce short-term concentrations (e.g. just before dawn) that are much lower than the daily mean (Williams et al. 2000). This could be of particular importance if accelerated plant growth is a result of future climate conditions, as suggested by some studies (e.g. Wade et al. 2002). Diurnal variations can be amplified at lower depths, but on the Thames depths are very closely managed and would not be expected to change dramatically (although velocities, of course, then reduce with decreasing flow).

Figure 8 compares simulated DO statistics for the 2080s at Teddington for each emission scenario and all three flow baselines. The DO concentration statistics, plotted in Figure 8(a), show that the future emissions will have a greater impact than “natural” flow variability, because there is a maximum difference of 0.2 mg O₂ l⁻¹ between the different flow baselines, while differences of up to 0.9 mg O₂ l⁻¹ occur between the different emission scenarios. Thus, the DO concentrations in the River Thames are more sensitive to temperature changes than flow changes. However, the dynamic predictions (Figures 5–7) showed that particularly low flows could impact on and reduce DO concentrations, and this is important because central tendency statistics, such as the mean or median, suggest that lower flows improve DO concentrations, while periods of very low flow can be detrimental to DO concentrations (Figure 8(a)). Conversely, the DO saturation levels would appear to be higher under drier conditions and more dependent on flow variability than on increasing emissions (Figure 8(b)). However, some caution must be attached to this statement: shallow waters have elevated reaeration rates, which act to bring the DO concentration to saturated levels, but (even near saturation) concentrations of oxygen in the river may still be below acceptable limits in this situation.
Dynamic–stochastic simulations

The $Q^2$ model may be operated in a dynamic–stochastic manner using Monte Carlo techniques where the flow and water-quality inputs are defined as distributions rather than as time series. To facilitate this, summary statistics describing the input data for each influence (e.g. flow and substance concentrations of tributaries, effluent discharges and abstractions) were calculated to describe the mean, variance and distribution type (normal, log-normal, or uniform/rectangular) for every input time series based on all of the available data (1996–1999). The input distributions for the 2080s medium–high emission scenario were then generated by applying the relevant changes to the baseline time series and then fitting distributions to the resulting data. As with the dynamic simulations, no changes were made to the flow rates at effluent discharge or abstraction sites. For each “shot”, the model selects input values at random from the specified distributions for each influence, ensuring that temperature and tributary flow data are correlated so that there are consistent conditions throughout the system for any given shot. Seasonality is included in the simulations by having the model select dates at random from a user-specified range, and diurnal effects are simulated by using a sub-daily internal time step for each shot.

In order to see the effect of rare or extreme events on the system, the $Q^2$ model was run for the equivalent of 80 years (29,200 shots) to allow the model time to sample from the extremes of the distributions as well as to take values close to the mean condition. Thus, the results of the dynamic–stochastic simulations provide an insight into the effects of climate change on extreme behaviour. This could be of particular importance if, as some researchers suggest, the frequency of extreme events may be increasing (Marsh & Sanderson 1997).

The flow simulations show that both the present and future (2080s medium–high emissions) climate scenario conditions are sufficient to produce a very wide range of flows at the bottom of the River Thames (Figure 9). Indeed, under both regimes it is possible that the River Thames could cease to flow at certain times if, as is simulated, the rate of abstraction in the lower reaches were not mitigated.

**Figure 7** $Q^2$ simulations of flow, temperature DO and nitrate in the River Thames at Teddington for different future climate scenarios, based on a "wet" flow baseline.
in response to such low flows. The $Q^2$ simulations suggest that these extreme low flows might be more prevalent in the Thames under the future climate scenario and that the predictions also suggest much higher flows in the future at the other extreme. The effect of the future climate scenarios on extreme temperatures is less dramatic. The results agree with the dynamic simulations, predicting a simulated temperature rise of 3–5°C above present conditions for this scenario, and there is, therefore, the possibility of some very high (up to 35°C) summer temperatures in the future.

The result of the predicted higher temperatures is one of decreased DO concentrations, and the stochastic results show that the difference is greatest at the extremes (Figure 9) where the difference between “current” and “future” simulations can be up to 1.6 mg O$_2$ l$^{-1}$. At least 1% of the future minimum DO concentrations are below the 5 mg O$_2$ l$^{-1}$ limit for cyprinid fish, whereas this never occurs under the current conditions, and the 7 mg O$_2$ l$^{-1}$ salmonid fishery limit is exceeded more often under the climate change scenario conditions than under the present conditions. The modelled DO saturation levels indicate that these lower DO concentrations will actually be closer to the saturation concentration than the higher concentrations under the present conditions and that...
the highest extremes can produce much higher levels of super-saturation under the future climate scenario conditions than the present conditions.

To examine the effect of climate change on flow and DO along the length of the River Thames, Figure 10 provides downstream profiles between Cricklade and Teddington for the current condition and a future climate scenario. Different percentile levels from the stochastic simulations (e.g., the 90th percentile flow or 10th percentile DO concentration) are shown and the results of both dynamic and dynamic–stochastic simulations are included for comparison. The downstream profiles show that the stochastic simulations tend to smooth the profile due to the much larger number of data points behind the statistics. Above the median (50th percentile) level, flow increases all the way down the system, but below this level the flow can drop off in the lower reaches, because the model does not mitigate abstraction rates. Indeed, because of this the $Q^2$ model predicts that the River Thames could cease to flow and, in Figure 10, it was necessary to omit a few points from the lowest percentiles of the future scenario because the simulated chemistry in a near-dry river represented an unrealistic situation. Careful management could probably alleviate a water resources crisis since the simulations also show increased capacity in winter. However, this would not be simple and the likelihood of an increasingly large range of flows at the bottom of the Thames in the future may cause a number of water resource problems.

The plots of DO concentration in Figure 10 show that the River Thames has relatively consistent (near-saturation) DO concentrations along its length despite the uneven distribution of effluent discharge and abstraction sites. Furthermore, the stochastic simulations of DO (unlike flow) predict a narrower range than does the dynamic simulation. This is true for both the current and future climate scenario conditions but, as already discussed, the concentrations are lower under the future climate scenario. This is particularly evident in the dynamic simulation, which shows depressed DO concentrations in the middle of the system after a series of effluent discharges enter the River Thames below Oxford. The impact of these discharges is greater under the future climate scenario than the present conditions and is sufficient to bring the 5% level below the limit for Salmonid fisheries in the EC Directive.
Uncertainties

There are three main levels of uncertainty in predictions of climate change impacts on water quality. First, future emissions scenarios are uncertain (Stott et al. 2000), because it is impossible to predict future socio-economic development. Second, there are uncertainties in the representation of atmospheric and ocean processes by climate models and, third, there is further uncertainty in the models used to predict the impacts of the future climate on water quality (Cox & Whitehead 2005). A range of different scenarios were used in this study because of the difficulty in predicting future emission levels and because the UKCIP02 report (Hulme et al. 2002) suggests that uncertainty margins on the climate model predictions could be up to ±2.0°C for temperature and 40% for precipitation (Table 4). The uncertainty in predictions of precipitation is large and may result in very large uncertainties in stream flow predictions, which impact on the water quality and dissolved oxygen concentrations.

IMPLICATIONS OF RESULTS

The implications of the simulations carried out in this study are that the overall effect on water quality is unlikely to be dramatic or catastrophic, but may well be important. Furthermore, it is clear that a model such as $Q^2$ is unable to predict all of the effects that such changes might have on...
the ecosystem of the river. The scenario simulations suggest higher winter flows and lower summer flows with increased likelihoods of both drought and spate. Temperatures will be warmer all year around and this will act to reduce DO concentrations. Summer low flows will also generally reduce nitrate concentrations. However, water resources managers should be concerned by predictions of increasingly low summer flows that would require a reduction in abstraction rates and, if nitrate levels exceed 11.3 mg NO₃-N l⁻¹, this too will reduce the number of days on which abstractions can take place. Together, there is the potential for increased potable supply failures due to reduced flow and water quality outages in the River Thames. There is also the possibility that the lower flows will generate increased algal blooms, as evidenced in the drought year of 1976 (Whitehead & Hornberger 1984). This could create problems by causing increased diurnal variations in DO levels.

Many decisions made by the Environment Agency regarding the management of water quality in rivers are based on the General Quality Assessment system, with four grades ranging from A (very good) to C (fairly good) on an A (very good) to F (bad) scale. The results of the dynamic simulations were used to classify four reaches distributed along the length of the freshwater River Thames according to the GQA, the Surface Waters Abstraction Directive and the Freshwater Fisheries Directive. This was done for the three different flow baselines and for each of the emission scenarios in the 2080s. The results of comparing simulations of DO saturation level, and BOD and ammonium concentrations with the Environment Agency standards in the four reaches suggest that the predicted changes are insufficient to impact greatly on the river’s classification. Indeed, the simulations using possible future climate scenarios appear to suggest there could be an improvement in the status of the River Thames. However, this is related in part to the use of DO saturation levels rather than DO concentrations. Furthermore, the classification is based on 10th and 90th percentile values and so the extremes where many of the largest impacts of climate change were seen are not included. The “dry” flow baseline again improves the quality because the higher temperatures increase the rates of reactions that remove BOD and ammonium, while BOD settles out of the water column more quickly when the river is shallower.

CONCLUSIONS

Water quality in the River Thames, like many other rivers, is heavily dependent on direct and indirect human activities. Land use and agricultural practices can have a very significant effect on water quality, as do management actions to control pollution and treat wastewater discharges into the environment. In heavily used rivers like the Thames, future water quality will be very much dependent on future human activities, including water management policies, and the direct effect of climate change may be small in relative terms (Hanratty & Stefan 1998). Furthermore, water quality impacts will probably be less important than changes in flow at the large catchment scale. However, the problem is a dynamic one and, while higher flows might give greater dilution, lower summer flows and raised temperatures in a nutrient-rich river like the Thames could increase aquatic plant growth, thus changing the ecosystem and causing greater DO variability in a way that the Q² model is unable to predict. Therefore, the “unspecified” secondary effects of climate change may well be more important than the direct effects.

The implications of the simulations carried out in this study are that the overall effect on water quality is unlikely to be dramatic, but may well be important. Furthermore, it is clear that a model such as Q² is unable to predict all of the effects that such changes might have on the ecosystem of the river. The scenario simulations suggest higher winter flows and lower summer flows, with increased likelihoods of both drought and spate. Temperatures will be warmer all year around and this will act to reduce DO concentrations.

Non-climate-related factors, such as increasing water quality standards, may lead to increased costs of water pollution control for wastewater treatment plants, and so the translation from effect to impact is not necessarily linear or simple. Assessing the implications of a possible future climate on current water management practice, as has been done here, is a pragmatic approach, but consideration must also be given to future needs and demands dependent on changes in population, future demand for water, changes in the legislative framework and changes in public and professional attitudes. Such changes may mitigate the consequences of climate change or exacerbate them (Arnell...
1998). Therefore, the impact of future climate change will depend not only on climate change itself, but also on changes in water management practices over time and the actions that are taken by water managers. The cost of climate change will, therefore, be a combination of the cost of adaptation plus the cost of impacts that cannot be mitigated and, as with the impacts, these costs will be very difficult to assess. However, it is important that work continues towards obtaining better climate scenarios and linked climate/economic and policy/land-use scenarios.

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REFERENCES


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