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A Cost Effectiveness Analysis of Water security and Water Quality: Impacts of Climate and Land Use Change on the River Thames System

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Abstract
The catchment of the River Thames, the principal river system in Southern England, provides the main water supply for London but is highly vulnerable to changes in climate, land use and population. The river is eutrophic with significant algal blooms with phosphorus assumed to be the primary chemical indicator of ecosystem health. In the Thames Basin phosphorus is available from point sources such as wastewater treatment plants (WWTPs) and from diffuse sources such as agriculture. In order to predict vulnerability to future change, the Integrated Catchments Model for Phosphorus (INCA-P) has been applied to the river basin and used to assess the cost effectiveness of a range of mitigation and adaptation strategies. It is shown that scenarios of future climate and land use change will exacerbate the water quality problems but a range of mitigation measures can improve the situation. A cost effectiveness study has been undertaken to compare the economic benefits of each mitigation measure and to assess the phosphorus reductions achieved. The most effective strategy is to reduce fertiliser use by 20% together with the treatment of effluent to a high standard. Such measures will reduce the instream phosphorus concentrations to close to the EU Water Framework Directive target for the Thames.

Keywords: Modelling, Climate Change, Water Quality, Phosphorus, Cost Effectiveness, Mitigation, Adaptation, INCA, Thames

INTRODUCTION

Water security is an issue facing every country as populations increase and changing climate and land use alter water availability and water demand (Grey et al, 2013). The need for the optimal use of water resources is vital but the problems of data uncertainty and system complexity make traditional optimization approaches impractical (Hall, 2013). Thus a satisficing approach is often used in the UK and the EU whereby a decision-making strategy is adopted that attempts to meet an acceptability threshold. One example of this is the EU Water Framework Directive (WFD, European Union, 2000) where instream standards or thresholds are set to achieve a desirable ecological goal. The WFD implementation is reaching a critical point throughout Europe whereby catchment management plans have to be put in place (the first target being 2015, with 6 year cycles thereafter) in order to meet specific water quality and ecological thresholds for rivers, lakes, wetlands and groundwaters.

In the UK, a wide range of measures have been proposed and evaluated to achieve the required status (Newell Price et al. 2011). Many of these measures, such as source control of pollutants, enhanced effluent treatment or changed agricultural practices, are expensive and require cooperation from a wide range of stakeholders. Phosphorus is considered to be the key parameter controlling ecology and hence eutrophic status in the UK and worldwide (UK Tag, 2007, Vollenveider, 1968), although Barker et al. (2008) have raised the issue of nitrogen being of concern, especially in terms of biodiversity. Bowes et al. (2012) has identified water residence time as a factor controlling algal growth, but there are many other factors such as flow, light intensity, suspended solids, nutrient concentrations that affect algal growth as well as shading by riparian vegetation (Hutchins et al., 2010)

Phosphorus (P) control has therefore been determined to be the main management strategy to be used to prevent the growth of nuisance algae in UK river systems. There are many diffuse sources of P in catchments including run off from land used for agriculture and other purposes. Then there are point sources from Wastewater Treatment Plants (WWTPs) and septic tanks which receive phosphorus inputs from principally domestic sources. These include detergents and phosphorus present in both natural foods and food supplemented by additives. In addition, P is dosed into drinking water to suppress lead concentrations in drinking water (Comber et al., 2009). Thus catchment management of P often involves agreement between riparian land owners, farmers, water companies, the chemical industry, the Environment Agency and DEFRA (Department of Environment, Food and Rural Affairs). Needless to say, with so many stakeholders, a complicated set of negotiations are required. The Environment Agency has a primary role as a water quality regulator, with pollution control functions and the licensing of consents for water abstraction and for effluent discharges from industry and Water Companies. DEFRA also has a major role in planning national controls on farming and the control of nutrients from farming activities and industry, as they affect international protocols and agreements. The banning of phosphorus (P) in domestic laundry cleaning products is a good example of this (DEFRA, 2008) to reduce P in WWTPs at source.

Integrated modelling tools can assist in the planning and catchment management process by providing an assessment of source apportionment, processes and dynamics so that strategic plans can be agreed between parties. Such integrated models need to represent the whole catchment mass balance and incorporate source and sinks and the physical, chemical and ecological processes so that a fair distribution of causal effects can be ascertained. Also, because of the varying costs of P mitigation measures and demand management options, assessment of the cost-effectiveness of different measures or combination of measures is required to reach economic decisions (Balana et al., 2011).

In addition to any mitigation measures, the longer term changes imposed on the catchment by external factors, such as climate change and land use change must be considered. In the case of land use change, it is predicted that world food prices will increase rapidly in future years as a response to both global food scarcity and dwindling natural resources of phosphate fertiliser. Farmers are likely to respond to these changing prices by altering the mix of crops grown and by also increasing crop area. On the climate change issue, there is now a consensus amongst scientists and policy makers that human induced climate change is occurring (IPCC, 2007) and that regardless of future greenhouse gas emission reductions, substantial climate change is unavoidable. One of the most significant effects of climate change will be on the UK hydrological cycle (Wilby et al., 1994). Extremes in the hydrological system during the past decades have reflected the vulnerability of our water resource systems to climatic fluctuations (Marsh, 2007; Marsh and Sanderson, 1997). UK Climate Projections 2009 (UKCP09, Murphy et al., 2009) is the latest climate model output and is the fifth generation of climate information for the UK. It provides climate change projections with greater spatial and temporal detail and is the first dataset which gives probabilistic projections of future climate change (Murphy et al., 2009). UKCP09 reports that by 2080s under the medium emission scenario, all areas of the UK will become warmer relative to 1961-1990 baseline conditions. Summer mean temperature in parts of Southern England could increase and precipitation patterns are projected to change significantly into the future. Also potential evaporation will change so that summer evaporation rates will increase, imposing a further stress on summer river flows and hence water supply.

In this paper we address all of the above issues with respect to water quality, catchment processes and cost effectiveness to identify the best strategy for catchment management. The analysis also takes into account changes in climate, land use, and water resources under a range of mitigation or adaptation strategies. The River Thames is utilized as a case study as this is a critical river flowing through Southern England, and supplying about two thirds of London’s water from the main abstraction points in the lower Thames. The demands for water in London are likely to increase with a projected population rise of 14% in the region by 2020 according to the UK Office of National Statistics. Moreover, the Thames has been identified as a vulnerable river system by the World Wildlife Fund (WWF, 2008) and thus it is a very suitable catchment for study from the perspectives of water scarcity, water quality and cost effectiveness.

The Integrated Catchment Model INCA has been applied to the whole Thames System to assess a range of scenarios and mitigation measures (Crossman et al., 2013) and the likely future impacts on water quality in the river system. Based on the outcomes of this scenario and mitigation analysis, a cost effectiveness analysis has been undertaken to assess the relative performance of different mitigation/adaptation options and determine the best strategy for water quality management.

THE RIVER THAMES SYSTEM

The Thames River is a key river in southeast England and has a catchment area of 10,000 km^2 (Figure 1) and a length of 218 km from the source in the Cotswold Hills of Gloucestershire to the Teddington in West London. The bedrock in the region is mainly of permeable chalk which gives a base flow index of approximately 0.65, although there are sub-catchments of low permeability clays. The water quality is characterized by high base cation concentrations due to the chalk aquifers and groundwater flows. The mean annual flow (1999-2008) ranges from 1.5 m^3/s at Cricklade, to 33.5 m^3/s at Days Weir in the centre of the catchment, and to 65.5 m^3/s at downstream Teddington (Figure 1). Seasonally, the high flows normally occur in the winter and early spring (January to April) and low flows occur in the summer and late autumn (July-November). Average rainfall for the catchment is low at 711 mm/year and the catchment is predominantly rural in the upper reaches and becomes more urban further downstream. The low average annual rainfall explains the vulnerability of the Thames to drought and hence climate change. The Thames is a crucial water source for London with the population of Greater London of approximately 14 million. In addition there have been large changes in land use in the Thames catchment since the 1930s (Whitehead et al., 2002) and this has also affected flows, water quality and ecology (Whitehead et al., 2009).

The potential future impacts of climate change are being taken very seriously by the water company responsible for London's water supply, namely Thames Water Utilities Limited, as they are predicting a shortfall in water resources by the 2030s (Thames Water, 2011). This follows from serious droughts in recent decades (Marsh, 2007) and a major water resource problem in 1976 when London Reservoirs dried up and London was within days of running out of water (Whitehead, 1990). Thames Water has been trying to convince the UK Government, the Environment Agency and the general public that a new reservoir is required to meet the predicted future shortfall. The cost of this will be high at approximately £1000 million for the full size reservoir proposed, and these costs would eventually fall on the water users. Thus water scarcity is a major issue for the South East of England and for London and this issue will be exacerbated in the future as climate change reduces summer flows (Jin et al., 2012).

The water quality of the Thames has always suffered from high phosphorus loading derived from both point sources, from WWTPs along the river, and diffuse sources from agriculture. Exceedence of the P concentration standard is the largest single reason for UK water bodies not reaching good ecological status (GES) under the WFD. Achieving GES requires water bodies to exhibit characteristics close to reference, pristine conditions or to move towards that condition. Diatom numbers and types have been used to generate a P standard by which river quality may be judged to be in high, good, moderate or poor condition (UKTAG, 2008). The WFD is being applied to the Thames and, as shown in Table 1, for a high alkalinity river such as the Thames, of any altitude, a soluble reactive phosphorus (SRP) standard for good status is estimated to be 0.12 mg/l. Current SRP in the river is in the order of 0.18 mg/l, some 50% above the required standard. Thus the challenge for any mitigation measure or set of measures is to get below this standard.

Table 1 WDF Phosphorus standards for the UK Rivers

Water type	**SRP (mg/l) mean standards for High to Poor WFD Chemical Status**			
	High	Good	Moderate	Poor
Under 80m altitude and less than 50 mg/l alkalinity	0.03	0.05	0.15	0.5
Over 80m altitude and less than 50 mg/l alkalinity	0.02	0.04	0.15	0.5
Any altitude and more than 50 mg/l alkalinity	0.05	**0.12**	0.25	1

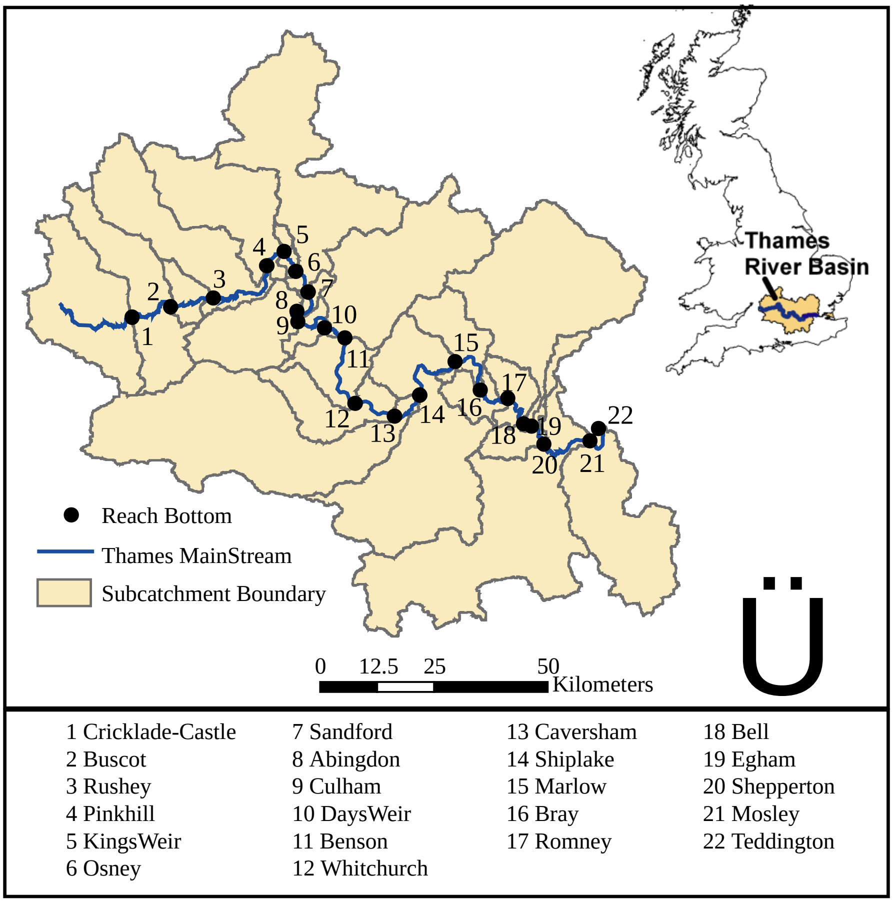

Figure 1 Map of the River Thames showing Reach Boundary Locations (after Jin et al. , 2012)

INCA-P MODELLING OF THE THAMES

A comprehensive process based dynamic model INCA (Whitehead et al., 1998, Wade et al., 2002 a and b) has been set up for the whole of the Thames Catchment so that we can investigate changes in land use and climate on flow, water quality and ecology. Jin et al. (2012) applied the nitrogen version of INCA to the whole Thames system and evaluated the effects of climate change on flow and water quality. The impacts of climate change on flow and water quality have also been assessed for the River Kennet, a tributary of the Thames, by Wilby et al. (2006) and Whitehead et al. (2006). In all these studies, the general conclusion is that late summer flows will be reduced significantly, due to reduced rainfall and increased temperatures driving up evaporation. Studies on these and other UK rivers by Whitehead et al. (2009) have shown that the changes in flow regime and temperature have significant effects on nitrogen, phosphorus and ecology, with changes in dilution and reaction kinetics affecting water quality on a seasonal basis, with consequent effects on stream ecology.

The INCA-P version of the model has been applied recently to the Thames by Crossman et al. (2013). and a wide range of scenarios and mitigation strategies have been evaluated. INCA-P is a physical, process-based model, as shown in Figure 2, which simulates flow, sediment, phosphorus (TP, PP and SRP) in soils, groundwaters and streams (Wade et al., 2002, Wade et al., 2009, Whitehead et al., 2011). It has both a land component and a river component, allowing it to track P inputs which flow into the river from the land surface throughout the catchment. INCA-P is a distributed model and takes account of spatial variations in land use, vegetation and hydrology by dividing the catchment into sub-catchments (Wade et al., 2002, 2009) or into a multibranch network of tributaries and streams that flow into a main river system (Whitehead et al., 2011). Hydrology in each reach is characterized by specifying the *a* and *b* parameters of the velocity–flow relationship,

$V = aQ^b$, which is used to calculate residence times within each reach. The model then sequentially integrates P inputs to each reach and can also consider point effluents such as sewage discharges. The model is dynamic and calculates variations in flow, P fluxes and P concentrations on a daily basis. The model includes all key biochemical processes taking place in the soil zone (Wade et al., 2002, 2009). Process rate estimates and other parameters may be measured, derived from the literature, or fitted during model calibration. Fluxes and concentrations of P are simulated by solving mass balance equations for terrestrial processes whilst simultaneously solving flow equations which determine the amount of runoff and leaching into the channel and the dilution potential of the river (Wade et al., 2002). INCA requires daily time series of soil mosture deficit (SMD), hydrologically effective rainfall (HER), air temperature and precipitation as well as spatial data describing the major land use types, estimates of growing season for different crops and vegetations types, fertiliser application quantities (DEFRA, 2012) and timings and locations of point sources and effluent concentrations as inputs. INCA then provides daily time series of flow, TP and SRP at each reach boundary, as well as profiles along with descriptive statistics of these variables at selected sites.

In order to model the Thames, Jin et al. (2012) and Crossman et al. (2013) divided the river system into 22 reaches and sub-catchments from the source at Cricklade to the lowest weir on the freshwater downstream boundary at Teddington (Figure 1). Reach boundaries were selected at confluences, gauging stations and water quality monitoring stations. The sub-catchment boundaries were derived using a Digital Terrain Model (DTM). The daily time series of hydrological effective rainfall (HER), soil moisture deficit (SMD) have been derived using a combination of Meteorological Office Rainfall and Temperature data and the HBV model (Crossman et al., 2013, Saelthun 1996). The effects of land surface and topography on flow are simulated through a semi-distributed approach incorporating the dynamics and characteristics of each sub-catchment. The residence times and flow rates in the soil and groundwater zones in the model are also essential to the simulation of flows through these zones.

Crossman used the extensive data set for hydrology, water quality, land use and P inputs to model the system selecting the 2001-2004 dataset for calibration and the 2005 – 2008 dataset for validation. INCA modelling applications to the catchment were highly successful, with excellent correspondence achieved with observed data for flow and SRP simulations, giving average R^2 values of 0.9 and 0.6 respectively. Validation coefficients were marginally lower than for calibration, with R^2 values of 0.8 and 0.5 respectively. The model has been the subject of extensive sensitivity and uncertainty analysis (Wade et al, 2002) and in general, there are a series of key parameters which control the behaviour of models. In the Thames three most sensitive parameters are hydrological, with groundwater residence time being the most important, followed by base flow index, and river water velocity. The Thames has a high groundwater flow component and as such residence times, flow pathways and velocities affect dilution and reaction kinetics of both diffuse and direct inputs. The detailed application of INCA-P of the Thames is described by Crossman et al. (2013) and in this paper we utilize the simulation results to assess cost effectiveness of a range of P control or mitigation measures.

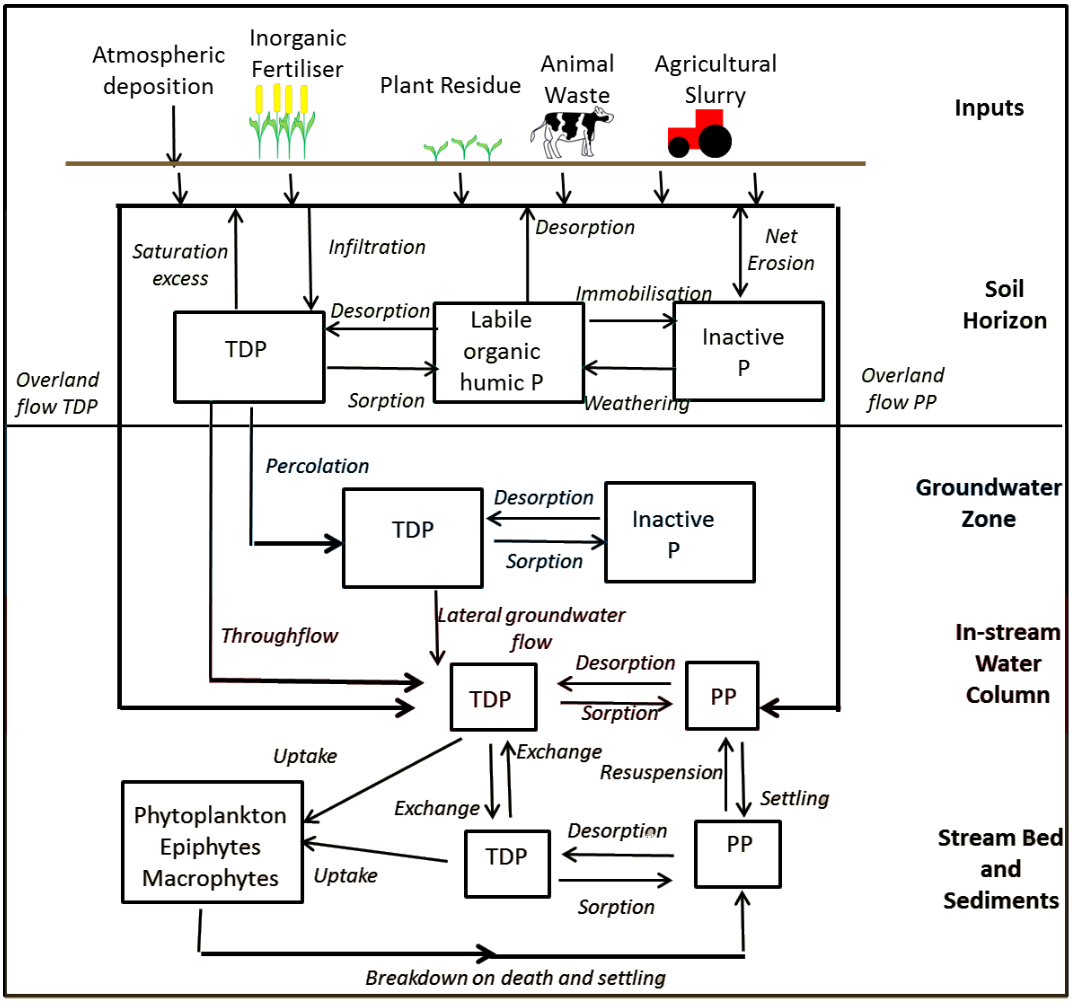

Figure 3 The INCA-P Model nutrient flows and process controls (after Crossman et al, 2013)

THAMES CATCHMENT SCENARIOS AND MITIGATION RESULTS

As part of the EU REFRESH project (see www.refresh.ucl.ac.uk), a set of scenarios have been evaluated for the Thames to assess climate change, land use change and water resource issues. In addition, a set of mitigation or adaptation measures have been evaluated, with the results being described in detail by Crossman et al. (2013). Here we are concerned with the cost effectiveness of the measures and their ability to reduce SRP in the river to meet the WFD standard.

A partial factorial computer experiment (Sacks et al. 1989) was performed to analyse the potential response of in-stream SRP concentrations to a series of climate, land use and water management scenarios.

The 7 scenarios considered in the cost effectiveness analysis are:-

1. Baseline (i.e. current) conditions
2. Future climate for the period 2030-2060
3. Future climate plus a future land use (LU1) under a Global Food Security scenario such that arable land is increased from the current 35.5% to 50%. The land use change scenarios are based on the LandSFACTS model (Castellazi et al., 2010, Crossman et al., 2013)

4. Future climate and a more extreme projection of future land use (LU2) which assumes a Global Food Security scenario such that arable land is increased from the current 35.5% to 60% (Crossman et al., 2013)

5. Thames Water Resource Strategy with the construction of a new reservoir at Abingdon under Future Climate for the period 2030-2060

6. Thames Water Resource Strategy with the construction of a new reservoir under future climate plus the future land use (LU1)

7. Thames Water Resource Strategy with the construction of a new reservoir under future climate plus the future land use (LU2)

For climate change the KNMI atmospheric regional climate model (RACMO) has been used with the model being driven by the general circulation model (GCM) to project future climate variables (Hewitt and Griggs 2004). The land use change scenarios are based on the LandSFACTS model (Castellazi et al., 2010) and The water resources model assumes that Thames Water construct a new reservoir at Abingdon (Reach 8 on Figure 1) with winter water abstractions from the river into the new reservoir and subsequent water releases during summer months to enhance the water supply to London.

Options available to regulators and operators for phosphorus measures are essentially three fold:

1) Reduce loss from agricultural land runoff via a number of measures including:
    a. reduced application rate
    b. use of buffer zones or riparian wetlands
    c. better manure management
    d. control of loss of soil and runoff from land through stock management and farm infrastructure
2) Tertiary treatment at WWTP typically via:
    a. the currently considered 'Best Available Technique' of iron dosing to reduce effluent P levels to a minimum level of 1 mg/l as total phosphorus; this is required already under a number of EU Directives including the Urban Wastewater Treatment Directive, WFD and Birds and Habitats Directive
    b. apply enhanced technology to reduce phosphorus levels to less than 1 mg/l. This is possible via a combination of optimized dosing and ultra-filtration and is practiced in the USA, but owing to cost is not currently used in the UK (EA, 2012), although it is being evaluated by Wessex Water.
3) Source control of P entering WWTP via sources other than natural diet:
    a. domestic laundry cleaning products – already to be banned by 2015
    b. automatic dishwashing detergents
    c. tap water dosing for controlling lead concentrations in drinking water
    d. use of phosphorus in food additives

It should be emphasized that the UK Water Companies have a 5 year cycle of planning which is agreed with the UK Water regulator OFWAT. As part of this planning cycle, which results in 5 year water company Asset Management Plans (AMP), water resources strategies such as the Thames Reservoir are discussed, as well as phosphorus reduction strategies at WWTPs. In this paper we consider 2 levels of treatment, namely PR-1 with effluent discharge concentrations down to 1mg/l and PR-2 with effluent concentrations at 0.3 mg/l. Thus, taking account of these phosphorus inputs to the aquatic environment, the 5 mitigation measures considered for the Thames Catchment are:-

1) Reducing P fertiliser application by 20%;

2) P removal at WWTPs to meet a discharge concentration of P of 1mg/l total P, referred to here as the PR-1 strategy;

3) P removal at WWTPs to meet a discharge concentration of P of 0.3mg/l total P, referred to here as the PR-2 strategy;

4) A combined mitigation strategy of reducing fertilisers by 20% plus the PR-2 removal strategy;

5) Introducing riparian wetlands along the river system.

Table 2 shows the mean instream SRP concentrations simulated in the lower Thames under these scenarios and mitigation measures. The model results show that the future scenarios indicate a marginal effect of climate change on annual average SRP concentrations. However, future land use change under a global food security scenario has a large impact as the enhanced area of intensive agriculture increases the use of P fertilisers, a proportion of which will be lost to the river system. Even under the water resource strategy the SRP stays high, despite the release of water to augment flows in the summer months. The riparian wetlands seem to have minimal effect on the phosphorus concentrations. Thus the target of meeting the WFD phosphorus concentration of 0.12mg/l is going to be very difficult, if not impossible, without some significant mitigation measures. As illustrated in Figure 3, the fertiliser reduction and the PR-1 and PR-2 mitigation measures are most effective at reducing the SRP concentrations. The most effective combined strategy is to reduce fertilisers together with the PR-2 strategy. This generates a 50% reduction in SRP (Figure 3) and provides the best means of getting to the 0.12 mg/l SRP in-stream standard. The riparian wetlands do not seem to give a large decrease in SRP. This is unlike nitrogen where such a strategy would enhance the natural denitrification processes (Whitehead et al., 2006). With phosphorus there does not seem to be such a beneficial effect and Prior and Johnes (2002) have demonstrated this experimentally for wetlands on the River Lambourn, a tributary of the Thames, showing the flushing of P from the wetland during storm events. However, Hutchins et al. (2011) report that riparian vegetation overhanging water bodies can produce significant ecological advantages.

Table 2 Effects of the 7 Scenarios and 5 mitigation measures on mean SRP (mg/l) in the Lower Thames (Summary results from Crossman et al., 2013)

SCENARIOS	Baseline	20% Fertiliser Reduction	PR-1	PR-2	PR-2 + 20% Fertiliser Reduction	Riparian Wetlands
Present	0.187	0.149	0.154	0.145	0.097	0.186
Future CC	0.186	0.148	0.151	0.142	0.094	0.185
Landuse 1	0.232	0.178	0.198	0.189	0.122	0.231
Landuse 2	0.263	0.198	0.229	0.220	0.141	0.263
Water Resource future CC	0.185	0.146	0.156	0.147	0.099	0.185
Water Resource Landuse 1	0.229	0.171	0.203	0.195	0.123	0.229
Water Resource Landuse 2	0.261	0.187	0.235	0.227	0.139	0.261

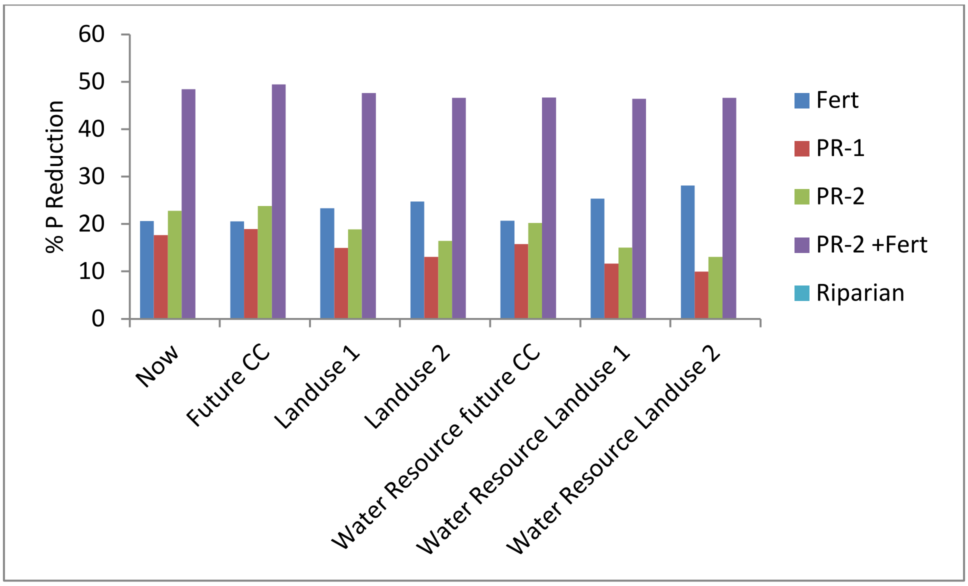

Figure 3 Percentage Reduction in baseline SRP in the Lower Thames under a range of Scenarios and Mitigation Measures (Summary results from Crossman et al., 2013)

COST EFFECTIVENESS ASSESSMENT

The WFD requires Member States to set water quality standards and identify cost-effective mitigation measures to achieve good ecological status (GES). Annex III of the WFD (EU, 2000) stipulates that a cost-effectiveness analysis (CEA) of water pollution mitigation measures be conducted as a pre-requisite in formulating programme of measures in order achieve the objectives set out in the WFD at the least economic cost. The cost effectiveness of measures can be determined for a catchment by estimating the costs and effects of a range of measures to reduce phosphorus concentrations. Cost-effectiveness of a measure can then be obtained by computing the cost per unit reduction in the load discharged, concentration within a water body or cost per the percentage reduction in concentration. Cuttle et al. (2007) and Fezzi et al. (2008, 2010) report costs of agricultural measures based on a detailed economic analysis of farm statistics. However, the effectiveness of such measures is assessed in terms of P load reductions to the land surface from the farm. This is not really that useful from a river perspective as what is required is the impact on river water quality with respect to the standards expected to be achieved. Hutchins et al. (2009) address this issue by using a catchment-scale model to assess the impacts of N controls on instream nitrogen. Likewise, in this analysis we make use of the INCA-P model to assess the impacts on instream P.

Depending on the nature of the environmental problem, the specific mitigation/adaptation measures identified, and the scale of analysis, various estimation techniques or data sources can be utilized to obtain cost information. Direct private costs accruing from policy implementation have a local character and refer to specific economic sectors. This category comprises financial costs associated primarily with changes in farm economic returns. These costs are relatively easy to identify and quantify. Hence, they usually represent the main focus in cost-effectiveness analysis. However, besides private costs, the compliance process entails a wide range of costs such as administrative costs incurred by the regulating authorities (e.g., costs of monitoring and enforcing compliance) and other social costs. These indirect wider economic impacts are generally less tangible than the direct effects making their estimation a more difficult task. Here, we argue that cost estimates need to be based on the principle of 'opportunity cost' which actually incorporates both the direct private costs and indirect social costs of the activity. However, the decision on which costs to include in a CEA depends on the availability of data for different cost components. Other important issues to address, when measuring or estimating costs, are how to normalize for different time periods and quantifying uncertainties.

For the purpose of this paper our cost estimates were mainly based on those that occur at the sectors or agents directly affected by the mitigation or adaptation measures and public investment costs on environmental and water infrastructure. Accordingly, costs for agricultural measures represent the whole farm costs for fertiliser reduction. These estimates were collated from existing literature sources (DEFRA, 2003; Fezzi et al., 2008, 2010; Cuttle et al., 2007) and scaled up to the whole Thames catchment. Cuttle et al. (2007) report that a 20% reduction in phosphorus fertiliser has a whole farm cost (i.e. including loss of yield) of £2.3 per hectare per year. Thus the costs of the fertiliser reduction for the whole Thames can be calculated based on the area of intensive agricultural land in the Thames river basin under the different scenarios. This area under baseline conditions is available from DEFRA farm statistics, and has been estimated for the future land use change scenarios LU1 and LU2 (Castellazi et al., 2010, Crossman et al., 2013). The costs for the whole Thames river basin calculated for the baseline land use would be £16.38 million per year and, for the LU1 and LU2 scenarios, £23.0 and £37.49 million per year respectively. Note the costs increase in future years as the land use changes and the area of intensive farming increases. The costs of the riparian areas are quoted by Cuttle et al. (2007) as £15.8 per hectare per year. The area of riparian zones are calculated as 15m strips either side of the main river giving a total area of 653 hectares and a total cost of £0.01 million per year. The costs of the WWTPs P removal have been calculated from Water Industry cost estimates of £19 per person per year to meet the 1mg/l standard and £32 per person per year to meet 0.3 mg/l standard (EA, 2012). Given a population of 717,000 people being served by the main WWTPs on the river, then this generates an annual cost of £13.6 million per year for the 1mg/l standard and £22.9 million per year for the higher standard. The reservoir costs are estimated as £750 million based on the Thames Water Resources Plans, assuming a smaller reservoir is built to gain government, Ofwat and public approval. Assuming an interest rate of 3% and a 20 year loan repayment time, the annual cost of the reservoir will be £50.4 million per year.

The costs of all the mitigation measures under the full range of scenarios are shown in Table 3. Note the costs increase into the future as land use changes generating larger areas of intensive agriculture and the reservoir is constructed. Also, the costs increase to cover the combined strategy of PR-2 plus the 20% fertiliser reductions.

Cost effectiveness has then been calculated by dividing the costs in Table 3 by the percentage reductions in SRP from the baseline, calculated using the data in Table 2. In general, the lower the cost effectiveness, the better the value of that particular mitigation measure, as shown in Table 4. The results shown in Table 4 indicate that riparian buffer zones are the most cost effective strategy but this alone does not generate the kind necessary P reductions in the Thames, as indicated in Table 2. The combined strategy of fertiliser reduction and PR-2 is the next most cost effective strategy and should meet the WFD P target of 0.12mg/l. Table 4 shows the increasing trends in cost through the scenarios and into the future due to the deleterious effects of firstly climate change, then land use change and the projected cost of the reservoir. Reservoir development increases costs significantly, but this high cost is justified by Thames Water Utilities Limited from a water scarcity point of view, rather than any water quality advantage. Note the reservoir effect masks the riparian effect in terms of concentration reduction (Table 2), so the cost effectiveness calculation generates unrealistic high numbers and is therefore not shown on Table 4. The next most cost effective measures are the PR-1 and PR-2 phosphorus removal strategies at the WWTPs. However, as mentioned above, the combined strategy of both reducing fertilisers and implementing PR-2 has by far the biggest impact on SRP concentrations. Only this combined mitigation strategy could actually meet the WFD compliance target of 0.12mg/l. They are also the most reasonable in terms of cost effectiveness and thus would be the best combined strategy for the Thames Catchment. However, the costs are significant, as a 50% reduction in SRP from the current concentration of 0.18 mg/l (Table 2) is required to meet the WFD standard of 0.12mg/l so the annual costs under each scenario are shown in Table 5 and indicates a significant annual cost to meet the WFD directive. Note this analysis excludes any source reduction measures, such P sources from dishwashers but this is not a realistic P control at the moment as no acceptable alternative is available. Also P reduction in drinking water due to a switch away from lead piping is certainly possible but this would require a considerable investment.

Table 3 Cost of Mitigation Measures in £millions/year for the Thames for all Scenarios

	Cost of Mitigation Strategies £millions/year				
SCENARIOS	20% Fertiliser Reduction	PR-1	PR-2	PR-2 + 20% Fertiliser Reduction	Riparian
Present	16.4	13.6	22.9	39.3	0.01
Future CC	16.4	13.6	22.9	39.3	0.01
Landuse 1	23.0	13.6	22.9	45.9	0.01
Landuse 2	37.5	13.6	22.9	60.4	0.01
Reservoir plus Future CC	66.8	64.0	73.3	89.7	50.4
Reservoir plus Future CC plus Landuse 1	73.4	64.0	97.0	96.3	50.4
Reservoir plus Future CC plus Landuse 2	87.9	64.0	97.0	111	50.4

Table 4 Cost Effectiveness for the Mitigation Strategies for Whole Thames Catchment in millions £ per year per percentage SRP reduction

	Cost Effectiveness-£millions per year per % SRP reduction				
SCENARIOS	20% Fertiliser Reduction	PR-1	PR-2	PR-2 + 20% Fertiliser Reduction	Riparian
Present	0.79	0.77	1.01	0.81	0.06
Future CC	0.80	0.72	0.96	0.79	0.09
Landuse 1	0.99	0.91	1.21	0.96	0.11
Landuse 2	1.52	1.04	1.39	1.30	0.13
Reservoir plus Future CC	3.23	4.06	3.63	1.92	n/a

Reservoir plus Future CC plus Landuse 1	2.90	5.50	6.45	2.07	n/a
Reservoir plus Future CC plus Landuse 2	3.12	6.42	7.42	2.38	n/a

Table 5 The Total Costs of Meeting the WFD P target for the Thames River System

Scenario	Total Annual Cost £million/year
Now	40.6
Future CC	39.7
Landuse 1	48.2
Landuse 2	64.8
Water Resource future CC	96.1
Water Resource Landuse 1	103.7
Water Resource Landuse 2	118.9

DISCUSSION

In this study on the Thames, a wide range of scenarios and mitigation measures have been evaluated and the results assessed in terms of cost effectiveness. Crossman et al. (2013) have addressed the environmental impacts in detail and emphasized the deteriorating situation into the future with both climate change and land use change affecting water quality. The reaction of farmers to rising cereal prices driven by Global Food Security issues will almost certainly shift land use to more intensive agriculture, with increased fertiliser use. Thus the mitigation measures are important to counter these trends. The cost effectiveness analysis shows that fertiliser reductions are the most effective method to control instream SRP concentrations but significant WWTP P reductions are required to supplement this to meet WFD compliance target for P of 0.12mg/l.

One interesting potential new development in the Thames Catchment is the construction of a new reservoir at Abingdon. This will provide extra capacity to sustain flow in low flow summers. It is important to consider the operation of the reservoir to minimize the impact of climate change induced low flows and provide the sufficient water supply downstream to London. The plans for the reservoir operation are to fill it in winter months (e.g. December to April) and then release water at approximately a rate of 10 m^3/s during the summer low flow period (e.g. June to September). This water would then be abstracted from the lower Thames for filling the London reservoirs. Such a scheme will have several consequences, although the extra flows will be of considerable benefit to London's water supply and decrease the vulnerability of London to drought, there could be unintended impacts. For example, in summer months the nutrient rich reservoir will be ideal for phytoplankton growth (Elliott et al., 2006) and these could seed the river system as the warmer reservoir water is released back into the river. Toxic algae such as cyanobacteria are already becoming a potential problem in the Thames with cyanobacteria blooms in summer months, as shown in Figure 4. These new cyanobacteria data were collected using a Beckman-Coulter Gallios Flow Cytometer (Bowes et al., 2012). Whilst the current levels of cyanobacteria in the Thames are not high at present, there is a major peak in the summer, and with reduced summer flows in the future, with longer residence times and increased temperatures there could well be future problems in the Thames, thereby imposing a further water security issue. Future research is needed to obtain an accurate assessment of the impacts of the reservoir, changing flows and temperatures on downstream ecology.

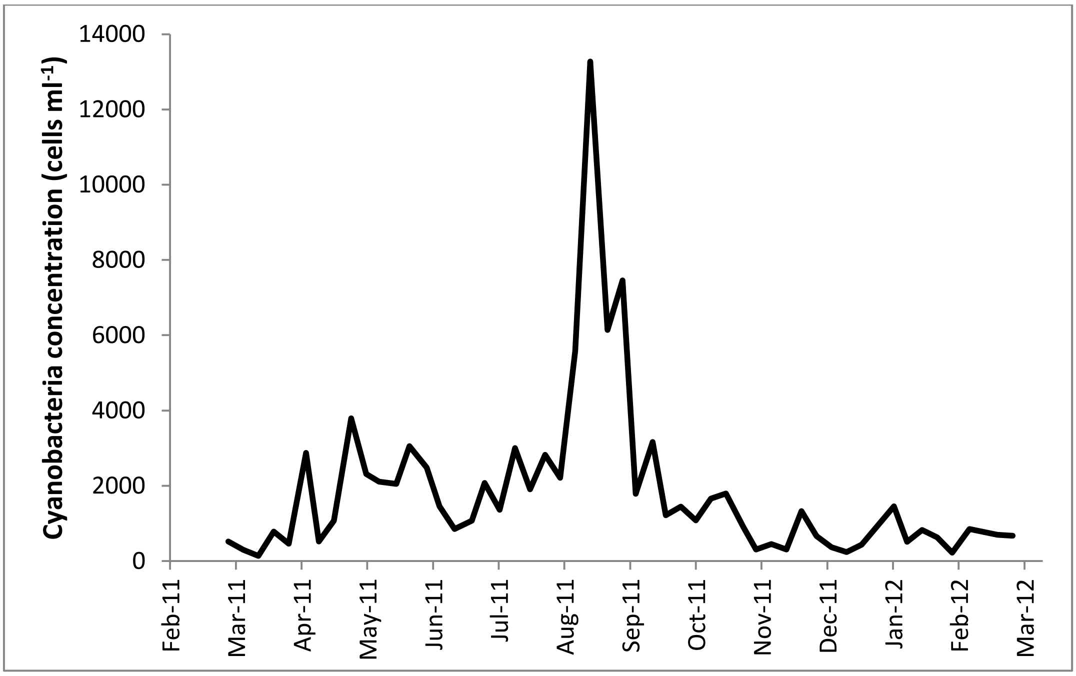

Figure 4 Cyanobacteria Concentrations in 2011/12 in the Lower Thames at Egham (Reach 19)

CONCLUSIONS

The methodology adopted in this paper draws on the complex set of interactions linking social systems of water supply and management and the ecological system of the Thames, and addresses the specific issue of the EU WFD. The implementation of this directive has been accepted by the UK government but has strong social impacts, as it will inevitably raise water costs to the general public and raises the question of how best to spend limited resources. The approach also addresses conservation needs so as to improve river ecology with consequent wildlife and societal benefits. At the heart of this paper is the question of water security, as climate change and land use change together with increasing water demand will put great strain on water resources in the Thames Region. The constraints of water quality are an added dimension to this, with the WFD drive to secure water quality improvements over time, which would hopefully lead to ecological benefits. Thus water quality is an essential aspect of water security. Sustainable management of water quality requires a long term perspective, with careful management of trade-offs between cost, water quality and other objectives for water security in river basins.

The application of INCA to the whole River Thames to address a range of scenarios and mitigation measures is a sophisticated but highly practical methodology for addressing future management options. It has been shown that the combined strategy of treatment for P removal at WWTPs combined with the fertiliser reductions is the best and least cost approach to manage P in the River Thames. It is highly likely that this strategy will apply to other similar UK lowland catchments. Moreover, it is almost certainly applicable to other catchments across the EU and potentially to other catchments worldwide.

It is striking that global food security could have a large effect on land use and hence fertiliser use, which would be highly detrimental to water quality and hence water security. Most catchments in developing countries face the same tipping point that the Thames reached several years ago, when P concentrations ceased to become limiting to the growth of nuisance algae. As nearly all these catchments are being been subjected to industrial and domestic effluent discharges as well as runoff from agricultural development, it is almost inevitable that a similar strategy will be required. Planning for these controls up front would make a lot of sense to avoid the threat to water supply from unregulated pollution.

The modelling in the paper has demonstrated a powerful linkage between societal decisions and ecology, allowing satisfying solutions to problems to be evaluated in a quantitative manner. Such quantitative assessments are required by governments, water companies and environment agencies to justify expenditure on costly water demand and mitigation strategies. This will especially important in the uncertain world of future climate change and global food and water security. Integrated modelling is even more valuable when there are questions of water governance (Gober, 2013) and where multiple stakeholders need to negotiate an agreed water security solution. These can be national issues that need resolving at the national level or at the multinational level where transboundary issues arise (Garrick et al, 2013). The modelling approach allows an independent and unbiased view of system behaviour and the scenario and mitigation analysis can help build trust between negotiating parties so that water security strategies can be evaluated, discussed and agreed.

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