Climate change and eutrophication risk in English rivers

Chief Scientist's Group report

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Professor Doug Wilson
Chief Scientist

Executive summary

Eutrophication occurs when there is too much nutrient in rivers and lakes, causing excessive growth of algae and plants. This affects the quality of the water and how it can be used, as well as damaging local ecosystems. Potential reductions in river flow as a result of climate change could directly affect the concentration of nutrients and the risk of eutrophication.

This report presents the results of a study that is a first step towards a better understanding of eutrophication risk from climate change in rivers across England. It examines how future changes in river flow may alter the dilution of phosphorus (as phosphate), because phosphorus is considered a primary driver of eutrophication.

Few existing studies investigate the magnitude, timescale or spatial extent of such impacts and no studies provide a national overview for England. This study developed an approach using available models and time series of future river flows to project change in phosphorus concentrations for 115 sites across England. The study did not consider the effects of projected increased temperature, which is also likely to alter eutrophication risk, and so the results may underestimate future change.

The results indicate that climate change will increase phosphorus concentrations by reducing river flows in the future. However changes in ecological status classifications, in particular with regard the phosphorus status boundaries, made for the EU Water Framework Directive (WFD) could potentially be mitigated with more management intervention.

The approach taken in this study was to describe the relationship between current (2005 to 2014) phosphorus concentrations and current river flows at 115 sites, based on observed data and the use of a load apportionment model (LAM). The model describes the relationship between phosphorus and river flows at each site by defining the proportion of phosphorus that comes from point sources (sewage) and diffuse sources (rain-related catchment run-off). The chosen study sites were co-located with pre-existing data about how climate change will alter future river flows – the so-called Future Flows Hydrology sites.

The Future Flows dataset describes how river flows might change under a wide range of possible climates, derived from hydrological modelling of the climate projections underpinning the latest climate change projections (UKCP09). The dataset consists of 11 equally likely scenarios of river flow from 1951 through to 2098. The relationship between phosphorus and river flows, as defined by the LAM, was projected into the future based on these future river flows.

It was then possible to compare estimates of baseline (1961 to 1990) and future (for example, 2040 to 2069) phosphorus concentrations and the corresponding WFD phosphorus status boundaries for 3 treatment scenarios:

- current management – 'as now'

- a future management scenario – a targeted reduction to 0.5mg/l phosphorus at each point source and no reduction in diffuse pollution after 2010

- a 'good' WFD phosphorus status scenario – calculation of what reduction is necessary to reduce all future phosphorus concentrations to good status

Climate change is projected to cause small increases in annual average phosphorus concentrations in rivers, although there is considerable variability across the country and between climate change scenarios. Associated phosphorus status is unlikely to change significantly as a result of the future projected flow changes alone. Changes in summer and low flow period phosphorus concentrations are of more direct relevance to eutrophication risk than annual averages and show greater rates of increase as low flows are projected to decrease in volume.

The indicative wastewater treatment improvements have the potential to reduce future phosphorus concentrations and improve WFD status for phosphorus. However, these improvements are not sufficient to produce good phosphorus status at all investigated sites, suggesting that further intervention is necessary to ensure targets are achieved. Further intervention may have to include strategies to address diffuse pollution in addition to further improvements in wastewater treatment. Diffuse pollution changes were not addressed in this study.

The outputs of this project provide useful tools – spreadsheets and maps – with which to visualise and interpret phosphorus changes across a range of future scenarios at a national scale. Taking account of their indicative nature and the sources of uncertainty outlined, they may also allow better understanding, targeting and design of phosphorus management solutions at a regional or local scale.

To improve understanding of future risks, more work is needed to capture further eutrophication risk factors that may alter biological responses, particularly details of the duration and frequency of low flow periods and future increases in summer temperatures. This will also benefit from a better understanding of the potential effects of climate change on storminess (influencing nutrient run off from agricultural land and rainfall-driven point sources) and, conversely, periods of calm, stable weather (influencing the development of blue green algae).

Further work is also needed to understand the contribution of future land use and management changes to agricultural practices to grow more food and to manage nutrient losses better. More information on nutrient discharges from wastewater treatment works would help to refine the potential for point source nutrient management to reduce phosphorus concentrations in the future.

Contents

1　　Introduction

Climate change is expected to increase the risk of eutrophication in rivers, yet there are few studies that investigate the timescale or spatial extent of such impacts. This report describes the development of an approach which using available models and time series of future river flows to project change in phosphorus concentrations – considered a primary driver of eutrophication in rivers across England. It also assesses the efficacy of some wastewater treatment scenarios. This work represents a first step to understand and map how climate change might increase the risk of eutrophication in English rivers.

This section provides background information about the project and the risks of eutrophication. The methodology is described in Section 2 and the results are presented in Section 3. Following a discussion in Section 4, conclusions are presented in Section 5.

1.1　Eutrophication – cause and effects

There are numerous definitions of eutrophication. For this project it is defined for simplicity as too much nutrient in water, causing algae and plants to grow excessively.

Phosphorus (P) is often assumed to be the most important limiting nutrient in freshwater ecosystems (Mainstone and Parr 2002). Plant growth is therefore restricted by low phosphorus concentrations. Reducing phosphorus concentration is also routinely used as a mechanism to assist ecology improvements and to meet the objectives of the Water Framework Directive (WFD).

A mechanistic description of how phosphorus concentration affects the processes associated with eutrophication is summarised here. Increasing phosphorus concentration can increase the growth rate and biomass of both benthic (on the bed of the river) and pelagic (in the main part of the river body) algae. This directly increases the turbidity of the water column and increases algal colonisation or growth rate on macrophyte leaves, thereby reducing light availability to higher plants and potentially altering the river from a macrophyte dominated system to an algal dominated system (Hilton et al. 2006). A loss of higher (vascular) plants and increased periphyton (material attached to submerged surfaces) growth reduces invertebrate habitat quality and can lead to a reduction in invertebrate abundance and diversity. Excessive algal primary production and bacterial consumption of decaying organic matter can lead to large diurnal fluctuations in dissolved oxygen concentrations, with low overnight concentrations; these fluctuations can lead to ecological stress and ultimately fish kills. Excessive algal growth has important economic implications for water and power companies (due to filter blockages at abstraction points and water treatment requirements due to algal blooms producing taints and toxins), and the poor aesthetics of an 'eutrophication-impacted' river also has financial impacts on tourism, leisure and house prices in its vicinity (Pretty et al. 2003).

The WFD has a requirement to ensure the health of freshwater ecosystems and to avoid eutrophication (Hutchins 2012). Hence there is a link between nutrient

enrichment and a whole range of ecological symptoms as discussed above. Although there are other environmental stressors (temperature, light, flow, grazing and food web interactions and so on) that can all exert significant controls on primary productivity and ecosystem community structure, this project focused solely on the potential impacts on future phosphorus concentrations of projected changes in river flow under climate change. Neither the direct role of changes in temperature nor the nature of the ecological interaction are examined. However, consideration is given to the likely effects of increased phosphorus removal at wastewater treatment works in the future.

1.2   Project approach

Future changes in river flows driven by climate change are likely to result in changes to phosphorus inputs to watercourses from diffuse sources and changes in the dilution of point source phosphorus inputs. The resulting changes to in-stream phosphorus concentrations could present an increased risk of eutrophication.

This report provides projections of future phosphorus concentrations in rivers in England. These projections incorporate the flow effects of climate change and the potential implementation of improved treatment of sewage effluent discharges. The approach is based on the 'Future Flows Hydrology' (FFH) dataset of river flow projections in England (Prudhomme et al. 2012), including the potential effects of climate change, and an empirical Load Apportionment Model of recently monitored phosphorus–flow relationships parameterised to distinguish phosphorus loads from point and diffuse sources.

The load apportionment model (LAM) developed by the Centre for Hydrology (CEH) was deployed at 115 river monitoring sites to estimate the relative proportions of phosphorus inputs from point and diffuse sources under present day conditions (that is, baseline phosphorus). The baseline models were then used, along with projected future river flows that incorporate the impact of climate change, to estimate phosphorus concentrations under future flow conditions. These estimates assume present-day point source (sewage) inputs are maintained across the entire projected time series. Scenario projections incorporating theoretically achievable future improvements in wastewater treatment were also modelled. The projections of future water quality were compared with thresholds for WFD phosphorus boundary values to produce estimates of the future WFD phosphorus status of the monitoring sites.

As detailed in Appendix A, the main outputs from this project are:

- spreadsheets providing projections of future phosphorus concentrations and load apportionment at 115 river locations in England (a) under baseline conditions that incorporate the impacts of climate change and (b) which incorporate improvements in wastewater treatment

- maps showing estimated changes in phosphorus concentrations at these locations due to (a) climate change and (b) potential point source improvements in wastewater treatment

- maps showing the corresponding estimated WFD status under each scenario (all maps are in a separate, standalone GIS package)

- a slide pack (reproduced in Appendix C) and associated narrative (Sections 2 and 3, and Appendix A) which presents the project's main findings

The remainder of this report describes in more detail the most important datasets, and the model and methods used in the work. It presents a summary and discussion of the main results, the strengths and limitations of the approach, and how these may be addressed through further work.

2   Methodology

2.1   Overall approach

The overall approach allowed the development of relationships between current (usually 2009 to 2014) phosphorus and flow data using the LAM. Ensembles of future river flow time series were then applied to estimate phosphorus concentrations at 115 FFH sites across England for the full FFH time series period (1951 to 2098).

Future phosphorus concentrations, WFD status and changes were then mapped for each of the 11 FFH climate scenarios to allow an illustration of the range of climate change projections and to compare future projections with baseline estimates. Future time series periods are defined as '2050s' (2040 to 2069) and '2070s' (2060 to 2089). The baseline time series period is defined as 1961 to 1990. Three indicative phosphorus treatment scenarios were assessed under these climate change scenarios:

- current management – 'as now'

- a future management scenario – a targeted reduction to 0.5mg/l phosphorus at all point sources and no diffuse reduction after 2010

- a 'good' WFD phosphorus status scenario – calculation of what reduction is necessary to reduce all 2050s phosphorus concentrations to good WFD phosphorus status

The outputs from these stages are listed in Appendix A along with details of the analysis spreadsheets that provide the underlying data for the maps.

There are other approaches that could be used for this analysis, but they are generally data intensive and challenging to apply at a national scale. Furthermore, unlike other approaches, the LAM allows application to the full FFH time series, facilitating detailed understanding of flow and phosphorus interactions as a result of climate change. The LAM also offers the potential to define signatures of point versus diffuse catchments and understand their changes into the future.

2.2   Estimating present phosphorus–flow relationships

2.2.1   Paired phosphorus and river flow data

For each FFH site, available time series of mean daily river flow (Q) records were acquired from the Environment Agency's WISKI database. Phosphorus (as orthophosphate; Environment Agency analytical method 0180) records were acquired from the Environment Agency's Water Management Information System (WIMS). These datasets were processed to pair flow and phosphorus values for the available length of each record.

Environment Agency 'orthophosphate' is largely equivalent to soluble reactive (bioavailable) phosphorus, which is the most relevant phosphorus species when assessing eutrophication risk. It is derived by using the colorimetric method developed by Murphy and Riley (1962) on an unfiltered sample and is more accurately described as total reactive phosphorus (TRP). This term is used throughout the rest of the report.

Flow records, phosphorus records and FFH sites are not always co-located, largely due to monitoring sites no longer being in operation. In these cases, the flow and phosphorus sites located nearest to the FFH sites were used provided they were on the same river stretch. This meant that not all the original FFH sites could be used in this project.

2.2.2 Initial time series analysis

Each TRP concentration dataset was first plotted as a time series to identify any sudden and obvious changes in phosphorus concentration over time, as these would affect the concentration–flow relationship. For example, step changes in phosphorus can occur when new water treatment systems are installed for example.

These time series plots were used to determine the length of dataset that could be used for the LAM modelling. Some sites such as the River Fal (Figure 2.1a) had no obvious changes in TRP concentration. In all such cases, the last 5 years of data (approximately 2009 to 2014, depending on data availability) were used to fit the model. Other sites showed clear step changes in TRP concentration (for example, River Taw, Figure 2.1b), but these changes usually occurred prior to 2007 and so again the last 5 years of data were used for model fit purposes. If any sites showed step changes in TRP concentration within the last 5 years, the model was fitted to a shorter period of recent stable concentrations.

The time series plots illustrated that other sites had TRP concentrations that were often below the limit of detection (for example, River Glen, Figure 2.1c). This makes them unsuitable for estimating changes in minimum TRP concentrations, but maximum concentration predictions may still be valid using LAM. Some sites (such as the River Ehen, Figure 2.1d) periodically use a 0.02mg/l limit of detection. All 0.02mg/l data points were removed for such sites and the remaining data used to fit the LAM, if the data below 0.02mg/l looked reliable.

(a)

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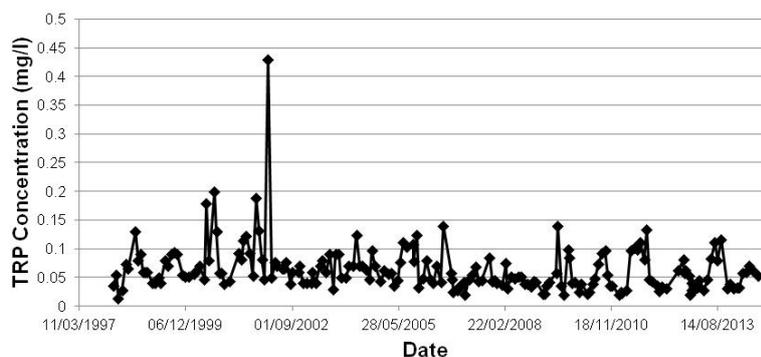
(b)
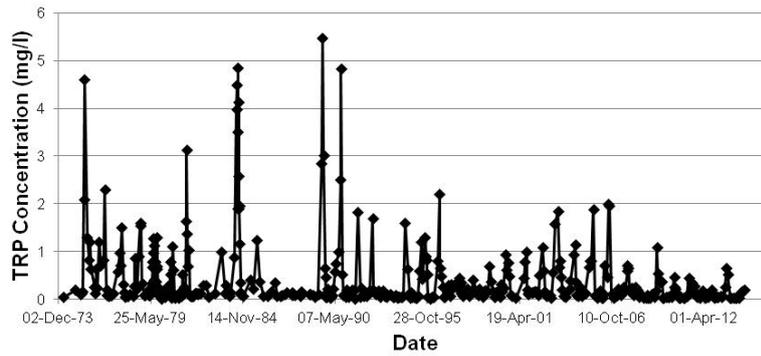
(c)
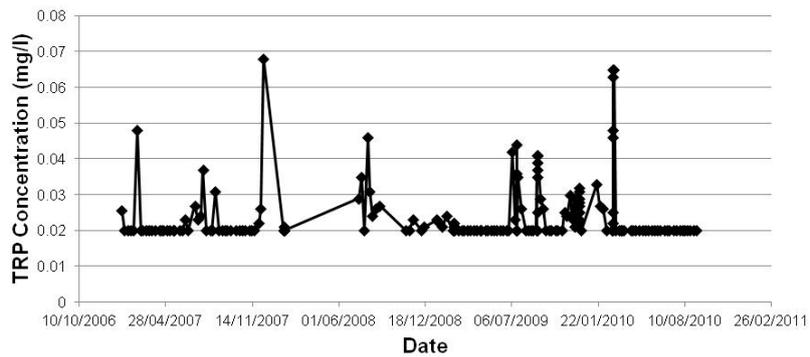
(d)
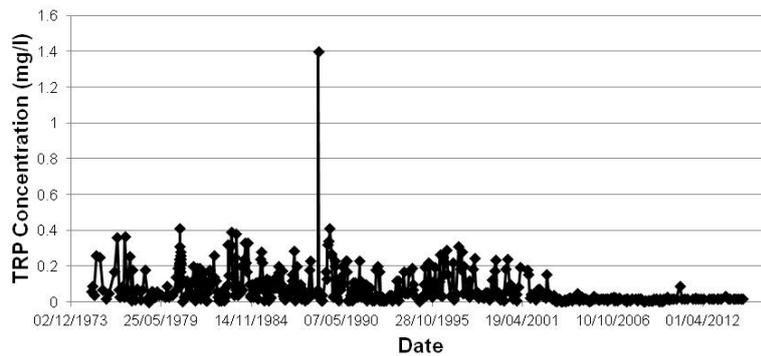
When using the model in support of decision making it is important to consider, on a site-by-site basis, how representative the river flow conditions were at the time of the sampling period(s) chosen to establish the TRP concentration–flow relationship. This is achieved by consideration of relative flow duration curves (see Appendix B).

The LAM offers a simple yet robust method for quickly estimating the relative loads of point and diffuse inputs to a river, based entirely on routinely gathered concentration and flow data.

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The model is based on the observation that rivers that are known to receive the majority of their phosphorus inputs from sewage treatment works (STW) always have their highest phosphorus concentrations at lowest flows and this rapidly decreases with increasing flow. This is because STW inputs are relatively constant from day to day, and therefore the dilution of this constant input within the river is at its lowest when flow is at its minimum. As the river flow increases due to rainfall, these dominant STW inputs will be diluted and hence the phosphorus concentration–flow relationship produces a dilution curve (see Figure 2.2a, River Thame). Conversely, rivers that receive no STW point inputs will not exhibit this dilution relationship. Rivers dominated by diffuse, rain-related inputs will exhibit increasing phosphorus concentrations or loads with increasing river flow (Figure 2.2b, River Lambourn).
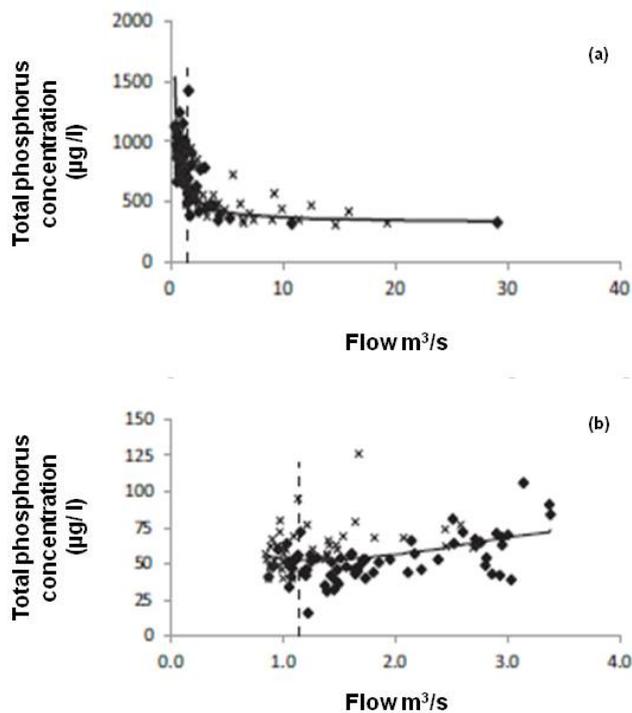
Figure 2.2   Total phosphorus concentration (µg/l)/flow (cumecs) relationships for (a) the sewage-dominated River Thame at Wheatley and (b) the diffuse-dominated River Lambourn at Boxford

Notes: Crosses represent samples taken outside the growing season (October 1st to February 28th); diamonds represent samples taken during the main algae growing season (March 1st to September 30th). Dashed line represents the river flow at which the estimated point and diffuse inputs are equal.

The model produces a line of best fit to the empirical data (Figure 2.2) by applying:

- a rain-related diffuse component – consisting of 2 parameters, describing the quantity of diffuse phosphorus inputs and how this input responds to increasing river flow (a gradient component)

A full description of how the model operates is given elsewhere (Bowes et al. 2008, Bowes et al. 2009). In brief, the phosphorus concentration, C_p (mg/m^3), at the monitoring point can be expressed as:

$$C_p = A.Q^{B-1} + C.Q^{D-1} \quad (2.1)$$

where Q (m^3/s) is the volumetric flow rate of the river, and A, B, C and D are load coefficients to be determined empirically.

The $A.Q^{B-1}$ term in Equation 2.1 is the nutrient concentration originating from 'constant' (that is, non flow-related) sources which, in most catchments in Britain, will equate to point sources, particularly sewage effluent from an STW.

The $C.Q^{D-1}$ term in Equation 2.1 is the nutrient concentration originating from rainfall and flow-related sources, and will largely equate with diffuse source inputs derived from agriculture, groundwater, road run-off and septic tank soakaways.

The B load coefficient, which takes into account within-river phosphorus retention and release rates, was set to zero for this project. It is not usually required for relatively short UK rivers and removing the B coefficient allows sewage reduction scenarios to be investigated.

The effects of varying the A, C and D load coefficients on the nutrient concentration / flow relationships are shown in Figure 2.3, along with an example (for the River Cole near Swindon) of how the model fits the empirical concentration and flow data (Figure 2.3d). The model solution is the sum of the constant source contribution (derived from the A load coefficient) added to the rain-related source contribution (derived from the C and D terms).

Once the LAM has been successfully calibrated to the empirical data for a river site, this nutrient concentration–flow relationship is applied to the daily mean river flow dataset for the monitoring period to calculate the total annual phosphorus load, T_p (mg/year):

$$T_p = 86400.\sum_{i=1}^{i=365} A.Q_i^B + C.Q_i^D \quad (2.2)$$

where Q_i is the mean daily volumetric flow rate (m^3/s), A, C and D are the empirically-determined load coefficients from Equation 2.1), and 86,400 is the number of seconds in one day.

The total annual phosphorus load represents only the form of phosphorus used in the modelled dataset. Within this project, the LAM therefore produces estimates of total annual TRP loads.

Equation 2.2 consists of a constant source ($A.Q_i^B$) and a flow-related source ($C.Q_i^D$) term. Therefore, the results of the model fitting can be used to determine the proportion of the total annual phosphorus load that is contributed by constant and flow-dependent phosphorus sources.
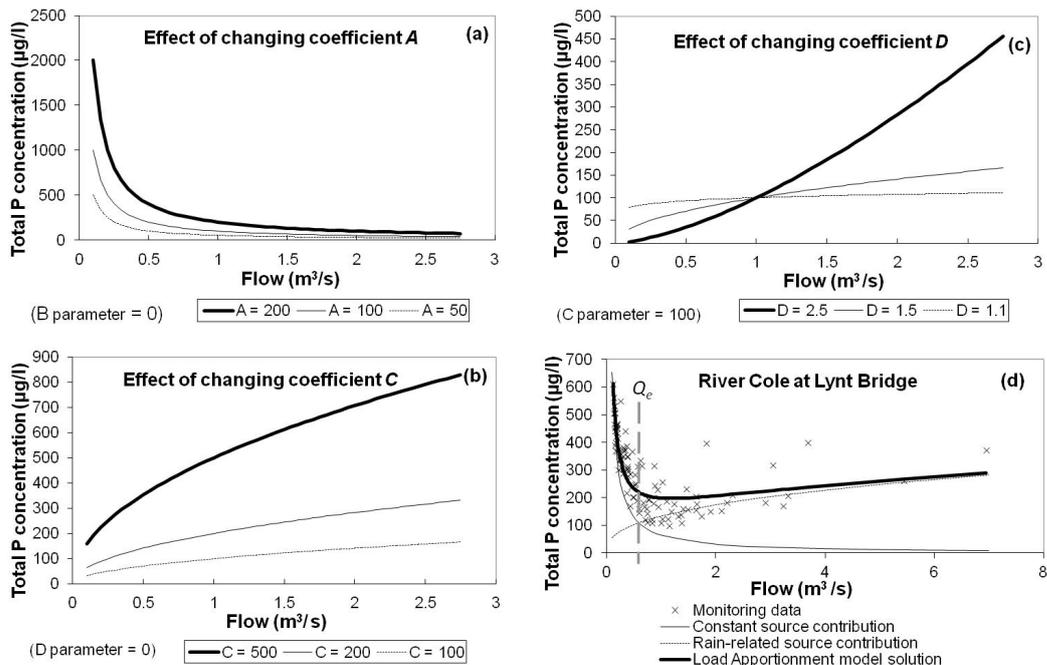
Figure 2.3   Effect of changing model load coefficient values on the total phosphorus concentration–river flow relationship: (a) effect of changing load coefficient _A_ (equivalent to constant source loading in mg/s); (b) effect of changing load coefficient _C_ (equivalent to quantity of rain related inputs); (c) effect of changing load parameter _D_ (describing how rain related inputs vary in response to changing river flow; and (d) example of model fit for the River Cole

Notes: Q_e is the point at which constant and rain-related inputs are equal.

2.2.4   LAM model fitting

The LAM was able to produce realistic looking model fits to most of the recently monitored datasets. From initial map investigations, the model correctly identified sites both with a sewage treatment input (River Exe, Figure 2.4b; River Fal, Figure 2.4e) and without a sewage treatment input (River Dudden, Figure 2.4f). Two sites had problems with limits of detection (River Glen, Figure 2.4a and the River Dudden Figure 2.4f); model fits for these sites were problematic, although the data do not show a dilution curve and therefore significant STW inputs are unlikely. Figure 2.4d represents a typical mixed-source catchment, with characteristic sewage dilution curves at low flow and a rain-related source becoming dominant at high flows. Figure 2.4c (River Axe) is an example of a study site where there is a wide range of TRP concentrations at low flows. This suggests that there is a STW dilution signal, but also a significant biological uptake, reducing the TRP concentrations to below 0.06 mg l-1.
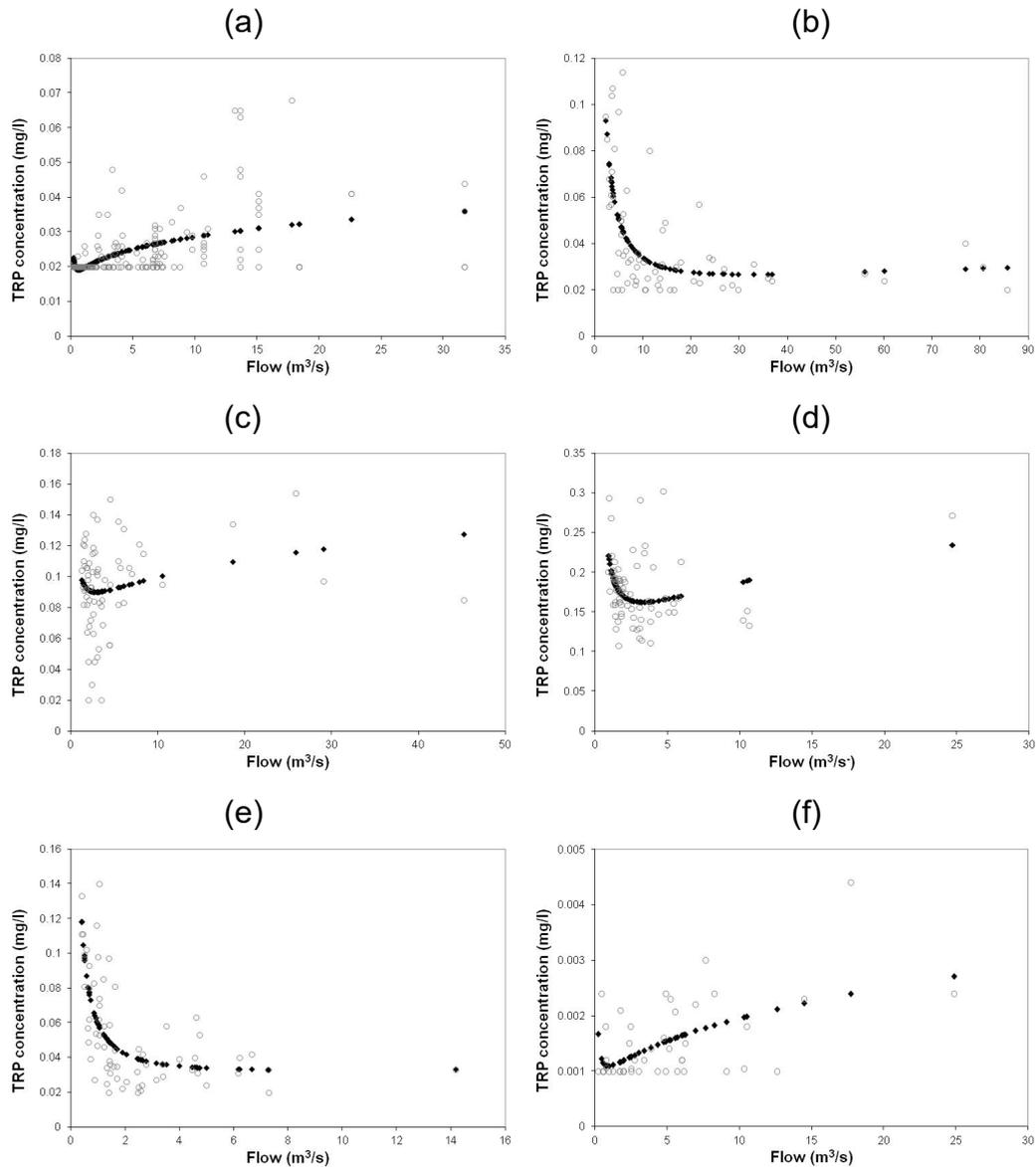
Figure 2.4   Examples of TRP concentration–flow relationships and LAM fits: (a) River Glen (21032); (b) River Exe (45001); (c) River Axe (45004); (d) River Otter (45005); (e) River Fal (48003); and (f) River Dudden (74001)

Notes: Open circles are observed data; solid diamonds indicate the LAM solution.

2.3 Estimating future phosphorus concentrations

2.3.1 Future Flows Hydrology datasets

The approach to estimating future phosphorus concentrations in rivers requires estimates of river flows including the effects of climate change. The FFH dataset (Prudhomme et al. 2012; Haxton et al. 2012) was used to provide these estimates.

The dataset describes simulated daily river flows for 282 river catchments in Great Britain for the period from1951 to 2098. Eleven equally likely scenarios of river flow are provided, each of which corresponds to one of the 11 equally likely members of the Future Flows Climate ensemble. This in turn is based on the Hadley Centre's regional climate model ensemble, which is the same model output underlying the UKCP09 climate projections. Each member of the climate ensemble consists of a 1km gridded time series of projected rainfall and temperature. These have been bias corrected and downscaled, and used to derive time series of rainfall and potential evapotranspiration covering the whole of England, Wales and Scotland. All ensemble members are based on the IPCC Special Report on Emissions Scenarios (Nakicenovic et al. 2000) SRES A1B medium emissions scenario.

CEH used the 11 climate time series projections as input to a hydrological model to produce 11 time series of natural river flows – ignoring the influence of abstractions and discharges.

All Future Flows simulations have already been statistically evaluated using a number of metrics including mean annual bias, errors on high and low flow percentiles, and Nash-Sutcliffe tests (delivered as factsheets as part of the metadata associated with the Future Flow Hydrology product) to identify which model produces the best set of scenarios.

The general conclusion from this evaluation is that the Continuous Estimation of River Flows (CERF) model is good for low flow estimations and flow simulations from this model are used in this work. The development of CERF in the context of the Future Flows and Groundwater Levels project is outlined in the project report (Haxton and Young 2012). For each site, the entire time series or maps that represent river flow for various time slices – annually and seasonally – can be downloaded; see the project website for more information.[1]

2.3.2 Application of the modelled recent relationships to Future Flows scenarios

The modelled relationship between TRP concentration and flow for each site, based (usually) on the observed data over the last 5 years, was then applied to the FFH datasets for that site to produce projections of TRP concentrations for all 11 Future Flow scenarios. The future daily river flows provide the Q term in Equation 2.1.

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[1] www.ceh.ac.uk/our-science/projects/future-flows-and-groundwater-levels

The complete output from the LAM modelling is a set of 11 time series of phosphorus concentration projections. These correspond to the 11 ensemble members of the FFH dataset based on diffuse catchment and point source inputs as they are 'now'. This means that the entire phosphorus concentration time series from 1951 to 2098 is based on the modelled relationships developed, as discussed in Section 2.1 (that is, for the period of approximately the last 5 years). The observed record of phosphorus concentrations prior to this period is often higher than after it as a consequence of management interventions to reduce phosphorus concentrations. This means that estimated phosphorus concentrations for this earlier period, and therefore the climate baseline of 1961 to 1990, are likely to be lower than observed, potentially reducing the change from baseline to future.

Annual average and summer average phosphorus concentrations for the baseline (1970s: 1961 to 1990) and future (2050s: 2040 to 2069; 2070s: 2060 to 2089) climate periods were calculated to produce maps of future concentrations and change for different treatment scenarios. Details of the mapping outputs are given in Appendix A.

2.3.3 WFD phosphorus standards

This study compared measured and projected phosphorus concentrations with standards for phosphorus levels already used in the regulation of water quality. Revised phosphorus standards for rivers introduced for the second cycle of WFD river basin management planning were employed for this task. These revised standards are available on the UKTAG website[2] (see also Defra 2014) and will be incorporated in relevant directions to the Environment Agency.

The revised standards are designed to be site specific so as to take account of the natural variation of nutrient concentrations along and between rivers. They also take account of parallel changes to other WFD standards, most pertinently those for water plants in rivers. Alkalinity and altitude data are used to produce a site-specific, annual mean reactive phosphorus standard; however, aquifer-specific adjustments have not been made.

The Environment Agency has used the revised methodology to calculate site-specific phosphorus standards at WFD water quality monitoring locations. These data were used to provide proxy WFD phosphorus standards for the Future Flow and phosphorus sites within this study. Where more than one water quality monitoring location is located in the same WFD water body as the Future Flows site, the nearest monitoring location was used. The Future Flows locations included in this study are spread across a range of WFD typologies, that is, across a large range of alkalinities and altitude.

Processing of the underlying phosphorus data for each climate and treatment scenario makes it easier to map both WFD phosphorus status and the change in status between different climate and/or treatment scenarios.

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[2] www.wfduk.org/resources/new-and-revised-phosphorus-and-biological-standards

2.4 Indicative phosphorus treatment scenarios

2.4.1 Treatment scenarios

Although the LAM, in conjunction with the FFH dataset, can estimate likely changes in diffuse phosphorus loads entering rivers, advances in wastewater treatment and the wider implementation of tertiary treatment at STW are likely to reduce point source inputs in the future. The potential impact of these reductions, combined with changes in diffuse inputs resulting from changes in river flows, was assessed through the implementation of 'future treatment' model scenarios.

Three indicative phosphorus treatment scenarios were assessed under the different climate change scenarios:

- current management – 'as now'

- a future management scenario – a targeted reduction to 0.5mg/l phosphorus at each point site and no reduction in diffuse pollution after 2010

- a 'good' WFD phosphorus status scenario – calculation of what reduction is necessary to reduce all 2050s phosphorus concentrations to good WFD status

In more detail these alternative TRP projections are:

- **TRP 'as now' projections** (Section 2.2). These assume that the flow–phosphorus relationships established through calibration against recent monitored data remain unchanged, that is, the TRP inputs from diffuse catchment and point STW sources stay as they are now. Changes in TRP are predicted by the CEH LAM model according to projected Future Flows associated with the 11 equally likely climate models.

- **Future 'Scenario TRP' projections** (Section 2.3.2). These are based on the assumption that all STWs could be equipped to reduce TRP concentrations to a maximum of 0.5mg/l. For monitored catchments where the average point inputs from STWs are currently higher than this 'theoretically achievable P stripping concentration', the Scenario TRP projections demonstrate the potential reductions associated which such a treatment intervention. A revised flow– phosphorus equation reflecting the lower STW inputs is used in association with the same 11 climate and flow scenarios.

- **Good Status projections.** Using the WFD phosphorus boundaries, the change in phosphorus concentration required to achieve, where necessary, good WFD phosphorus status was estimated for the 'as now' and 'Scenario TRP' projections.

Using these indicative scenarios, it is possible to assess both the efficacy of potential management interventions under climate change and where further intervention may become necessary. These scenarios do not imply a preferred

management strategy but only what could be achieved based on the current modelling incorporating climate change uncertainty.

2.4.2   Scenario TRP

The future treatment scenario for each river water body represents the point source phosphorus loading that would result if every STW in the water body were to discharge effluent with a concentration of no more than 0.5mg-P/l. This figure was chosen because current technology can in theory deliver this level of treatment at larger works.

As explained in Section 2.2.3, the LAM is based around Equation 2.1 (reproduced here for convenience):

$$C_p = A.Q^{B-1} + C.Q^{D-1}$$

For this work, coefficient *B*, representing the variation in point source load with river flow, has been set to zero. The phosphorus concentration in the river arising from point source inputs thus becomes:

$$C = AQ^{-1} \ (2.3)$$

Coefficient *A* therefore represents the phosphorus load originating from point sources (mg/s). The future treatment scenario is based around a re-calculation of the value of the *A* parameter for each water body to represent the loading from all STW discharges discharging at the current volumetric rate but with a phosphorus concentration reduced to 0.5mg-P/l where appropriate.

The calculation was performed as follows.

1. The total population equivalent of all STWs in the river water body was calculated.

2. The total dry weather flow associated with this population equivalent was calculated on the basis of a discharge of 180 litres/person/day.

3. This calculated discharge rate was compared with independent calculations of anthropogenic discharge based on the upstream routing network of waterbodies, using Water Resources GIS (WRGIS) as described below, to ensure broad consistency.

4. The point source load was calculated by multiplying this discharge volume by the assumed concentration (0.5mg-P/l) if this was lower than the implied concentration from the treatment works now.

Figure 2.5 shows the results of the regression of the total upstream rate of anthropogenic discharge estimated from STW population equivalent against that taken from the Environment Agency's WRGIS September 2014 dataset. The WRGIS is not a hydrological or hydrogeological model, but is based on national datasets of natural river flows and artificial influences. The latter include surface water abstractions, groundwater abstractions, discharges and other more complex impacts such as reservoirs and water transfers. The datasets are updated and improved through an iterative process based on Environment Agency local staff knowledge and surface water and groundwater models.

The relationship in Figure 2.5 demonstrates good correlation between the estimates of discharge, though the estimate based on population equivalent is systematically lower than the WRGIS estimate (not shown). This is to be expected as the latter estimate includes all anthropogenic inputs, not just sewage discharges.
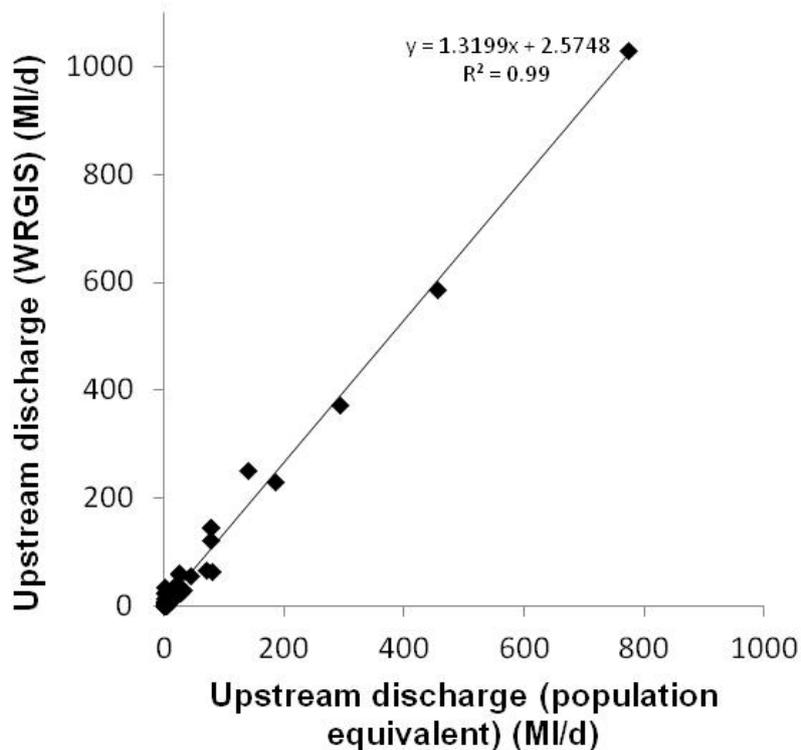
Figure 2.5   Regression of total real actual upstream anthropogenic discharge from routed water body network (from WRGIS) against discharge based on population equivalent upstream of STW

Notes: Assuming a discharge of 180 litres/person/ day
Ml/d, million litres per day;

The potential treatment analysis results in a new value for the LAM *A* parameter, which was compared with the value originally derived for the baseline model. The expectation is that the value of *A* should decrease in the future treatment scenario. In practise, this was not always the case. There are several possible explanations for this.

- The population equivalent is not the human population served by a treatment works, but a metric calculated on the basis of all consented discharges served by the works including trade discharges. The phosphorus content of these discharges is not always known and may not be the same as the equivalent volume of sewage discharge.

- The calculated discharge volume of 180 litre/person/day is also an estimate and, in practice, will vary between catchments.

- The model *A* parameter represents all flow rate independent inputs of phosphorus to rivers. In most cases, these will be dominated by

15

sewage discharges, but could also include other discharges or inputs in groundwater.

- The baseline value of *A* will depend on the level of sewage treatment already present in the catchment. If the majority of large STW in a river water body have already implemented tertiary treatment, then the additional reduction in point source load achievable through better treatment will be small.

In cases where the re-calculated *A* parameter was larger than the baseline value, the original baseline was retained, that is, the future treatment scenario was assumed to be identical to the present day in terms of point source discharges.

This approach is clearly an approximation and would benefit from further development based on improved understanding of sewage treatment as it is now. This is discussed in Section 4. Further details of the spreadsheet processing are given in Appendix A.

3   Results

3.1   'As now' projections

The maps (Figure 3.1 and Figure 3.2) show, for each of the 115 FFH sites, the suite of 11 climate projections grouped together as a series of concentric circles (in consistent order) coloured according to fixed scales. This allows visualisation of the degree of variation or uniformity between the equally likely futures at each site. Circles with little variation in colour indicate little variation between the 11 projections, while circles with more variation in colour indicate greater differences between the 11 projections. This indicates some of the uncertainty related to climate change.

The TRP 'as now' annual average projections of phosphorus concentrations for the 2050s are very variable between sites, but relatively uniform between climate scenarios as shown in Figure 3.1a and **Slide 10**.[3] In other words, for a given site there is little variation in colour across the 11 concentric circles, but there is more variation in colour between different sites. The variability is also characteristic of the climate baseline period (1970s, **Slide 9**). Compared with the baseline period (**Slide 9**), the projections of annual average phosphorus concentrations typically show small increases by the 2050s (**Slide 10**) and further increases with slightly more variability into the 2070s (**Slide 11**).

Summer month averages in the 2050s are typically higher (Figure 3.1b and **Slide 18**) than annual average TRP concentrations (Figure 3.1a and **Slide 17**). Absolute changes in flow-related projections from the baseline to 2050s period are more marked in the summer months (**Slide 19**) than for the annual averages (**Slide 20**).

Climate and flow-related changes in projected TRP 'as now' mostly show increases from the baseline to 2050s period – both as absolute mg/l values (**Slide 15**) and also as percentages (Figure 3.2a and **Slide 16**) – with a few site exceptions where TRP concentrations are reduced in some projections. There is limited consistency in the spatial distribution of percentage change in phosphorus between baseline and 2050s periods. There is some indication that there are more reductions projected in East Anglia and the north-west compared with other areas, but most sites show an increase. These results are consistent with an earlier study for the Environment Agency's Anglian Region (Atkins 2014) which suggested that, for the majority of rivers, phosphorus concentration is estimated to increase.

WFD phosphorus status classification projections based on site-specific thresholds change little with time (**Slides 12, 13** and **14** for the baseline, 2050s and 2070s periods respectively), although there are reductions in status in some East Anglian sites between baseline and 2050s, for example. There are further, but fewer, reductions into the 2070s. Importantly, the maps show that current flow and phosphorus relationships result in frequent failure of the WFD status throughout England and that climate change exacerbates this pattern

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[3] The figures presented in Section 3 are used to convey the overall narrative, with reference made to the slide pack in Appendix C for further detail. Slide numbers are highlighted in bold.

(Figure 3.2b and **Slide 13**). It is also notable that, in the north-west, climate change does not appear to reduce WFD status for phosphorus. In general, however, these projections suggest that further management intervention is necessary to improve WFD status for phosphorus.
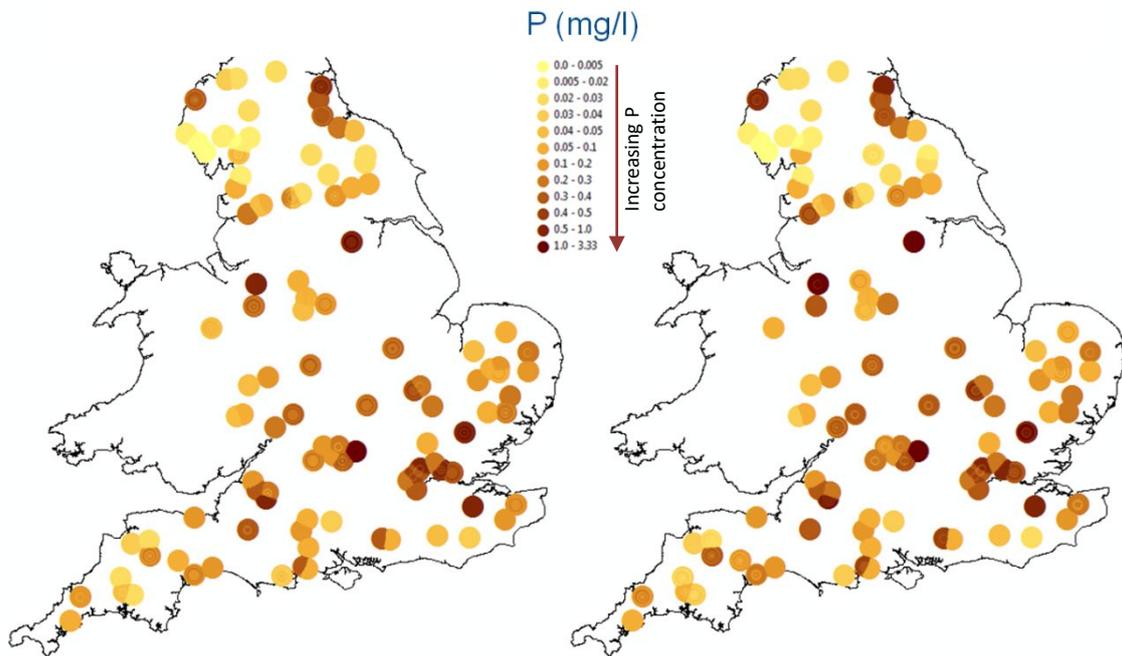
Figure 3.1 **Estimated 2050s phosphorus concentrations for each site and each ensemble member for (a) average annual and (b) average summer projections**

Notes: Each site consists of 11 nested concentric circles representing phosphorus concentrations for each climate scenario. The less variation in the colour of the 11 circles at each site, the more consistent across climate scenarios is the phosphorus concentration.
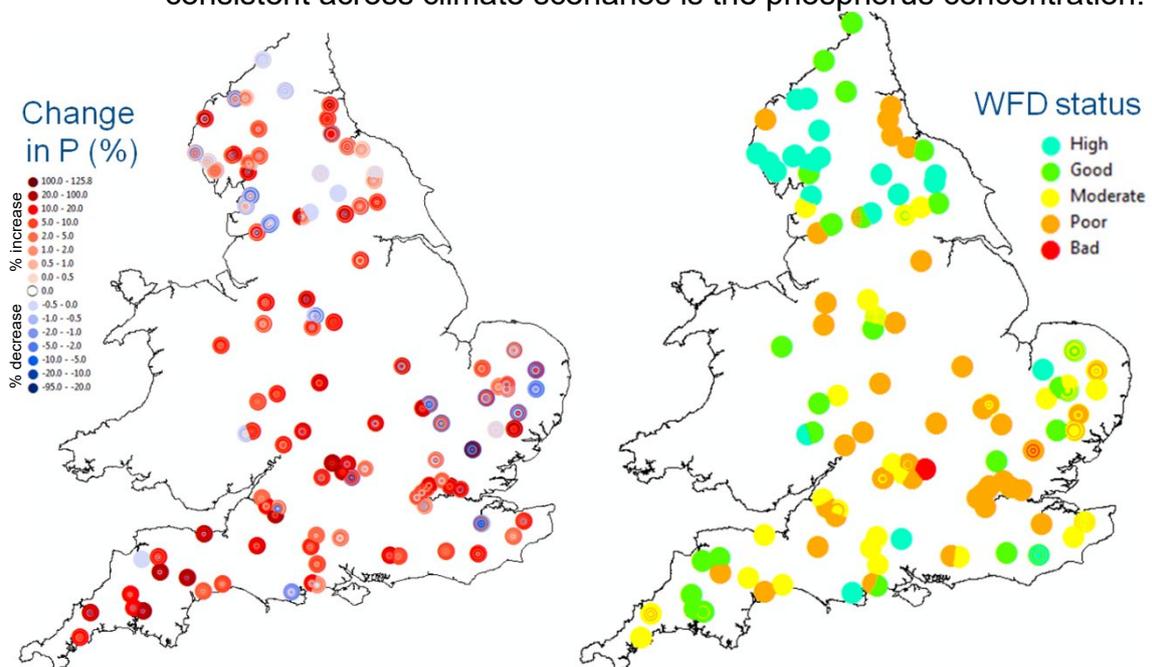
Figure 3.2 **(a) Percentage change in average annual phosphorus concentrations between Baseline (1970s) and Future (2050s) for each site**

and each ensemble member and (b) projected WFD phosphorus status in the 2050s

Notes: Each site consists of 11 concentric circles representing change in phosphorus concentrations or WFD phosphorus status for each climate scenario. The less variation in the colour of the 11 circles at each site, the more consistent across climate scenarios is the change in phosphorus concentration or the WFD phosphorus status. At the majority of sites there are large increases in phosphorus concentrations, although there is considerable variable between climate scenarios. The majority of sites show consistent WFD phosphorus status across scenarios (partly as a consequence of the broad banding of the standards) and that most sites are moderate to poor in terms of their status.

3.2   Scenario TRP projections

Scenario TRP projections for the 2050s are much lower at many sites (**Slide 22**), with the absolute differences (reductions) associated with the assumed additional phosphorus stripping at STWs mapped in **Slide 23**. Associated WFD status projections suggest considerable improvements would be realised by such intervention (Figure 3.3a, Figure 3.3b, **Slides 24, 25 and 26**) at many sites; Figure 3.3 shows that ~40 sites improve. However, further work would still be needed to achieve good status everywhere (Figure 3.3a and **Slide 25**), probably associated with action to reduce diffuse catchment sources of nutrient inputs.

The poor status boundaries for WFD phosphorus standards are much wider than the envelope for good status boundaries, so no change in status boundaries does not necessarily mean that there is no significant effect on ecosystems. There is a gap in the understanding between phosphorus concentrations and eutrophication, which means that changes in the concentrations themselves are likely to be more useful in understanding ecosystem response.
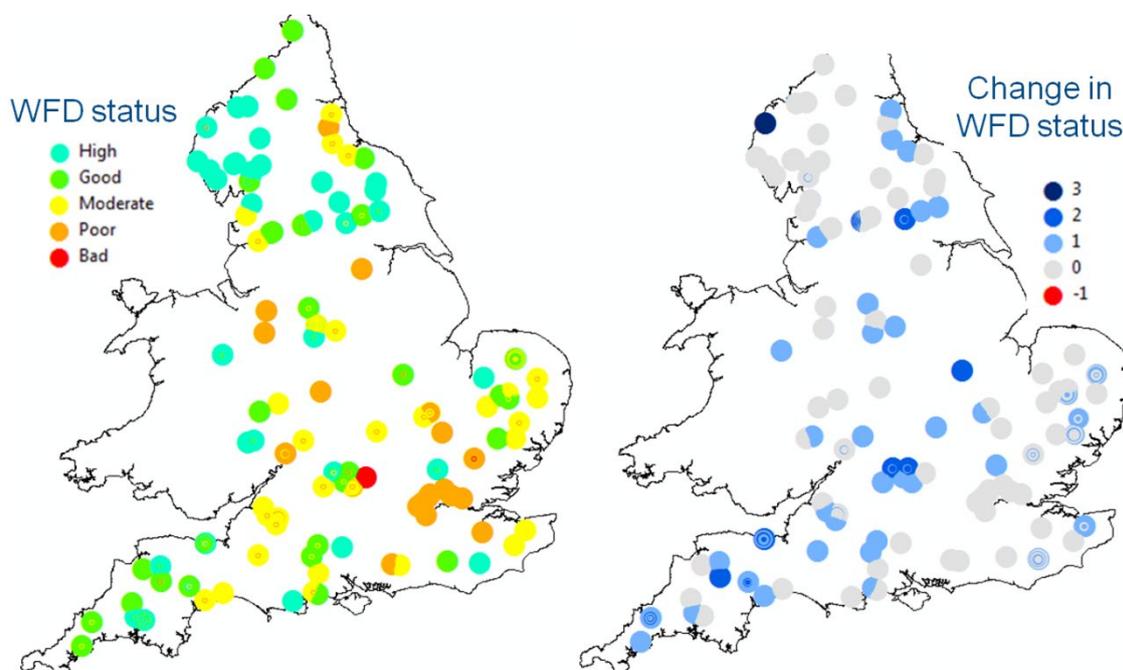
Figure 3.3   (a) 2050s WFD status under Scenario TRP and (b) change in WFD status (as number of class boundaries changed) between 'as now' and 'Scenario TRP' in the 2050s

Notes: Each site consists of 11 concentric circles representing WFD phosphorus status and change in WFD status for each climate scenario. The less variation in the colour of the 11 circles at each site, the more consistent across climate scenarios is the WFD phosphorus status or its change.
The majority of sites show consistent WFD phosphorus status and change across scenarios. Most fail to achieve good status and the sewerage treatment scenario improves status at a number of sites (~40).

3.3   Further reductions needed

The reductions in TRP required to reach good status thresholds in 2050s assuming that catchments and STWs remain 'as now' are relatively small (Figure 3.4 and **Slide 27**), affecting over half of the studied sites. However, some substantial additional reductions are necessary, particularly around London and parts of the Midlands. Lesser residuals would remain if the stripped Scenario TRP were to be realised (**Slide 28**).
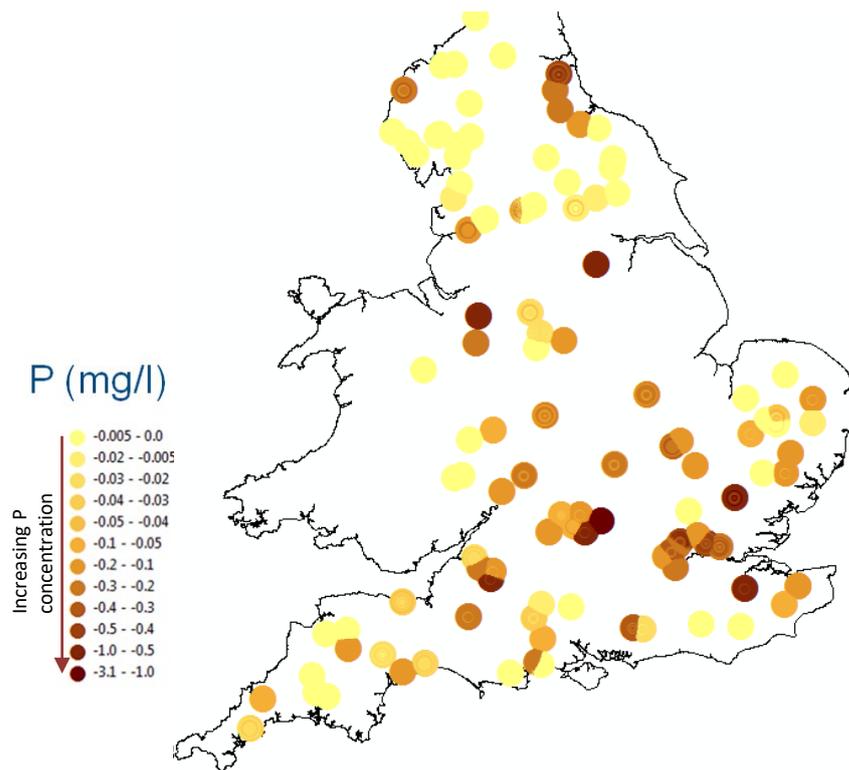
Figure 3.4   Further phosphorus reductions needed to achieve good status for WFD phosphorus standards compared with 'as now' under climate change in the 2050s

Notes: Each site consists of 11 concentric circles representing phosphorus concentrations for each climate scenario. The less variation in the colour of the 11 circles at each site, the more consistent across climate scenarios is the phosphorus concentration.
About 50 sites consistently require additional reductions of over 0.2mg/l across the different climate scenarios.

4   Discussion

The results presented in Section 3 indicate that climate change produces small but variable increases in phosphorus concentrations by the 2050s for the 115 sites studied due to changes in projected river flows – both spatially and across climate change ensemble members. This produces a slight worsening of WFD status for phosphorus across England compared with the climate baseline.

The analysis also shows that current management interventions are inadequate to achieve good status by the 2050s. A feasible change in phosphorus treatment at STWs improves the status at many sites, but fails to achieve good status in most sites across the climate change scenarios. Climate change exacerbates this problem. Further reductions are necessary at some sites to achieve good status in the face of climate change and to address diffuse sources of phosphorus.

This work is focused on phosphorus concentrations and WFD status. The poor status boundaries for WFD phosphorus are wider than the envelope for good status boundaries. However, not changing boundaries does not necessarily mean that there is no significant effect on ecosystems. There is a need to better understand the link between phosphorus standards and eutrophication to identify when eutrophication impacts occur. This may include understanding the seasonal circumstances that lead to eutrophication (that is, temporal dynamics of phosphorus, flow, sediment phosphorus retention, and temperature) which may be hidden by generalised flow–phosphorus models.

Focusing on actual changes in phosphorus concentration make this easier. This project has identified some adjacent sites with very different changes in phosphorus concentrations but has not investigated why this pattern exists. It may be due to the relative dominance of STWs upstream of some sites. This requires a greater understanding of the other factors driving phosphorus dynamics.

The maps are a useful tool with which to visualise and interpret TRP changes across a range of scenarios at a national scale. They may also enable the understanding, targeting and design of phosphorus management solutions at a regional or local scale. However, the maps should be viewed as indicative and interpretations should be made with an element of caution given that there are a number of sources of uncertainty in the projected estimates of phosphorus concentrations. These include:

- the original climate projections

- the hydrological simulations to produce the future flows data

- the paired phosphorus and river flows data, including co-location as well as record length issues

- the error associated with fitting regression relationships to empirical data, especially where there is limited observational data of high flows where much of the load may be shifted

- assumptions about the model parameters remaining valid in the future (for example, changes in retention of phosphorus in river-bound sediment)

- assumptions made in the future treatment scenario

Some of these issues are discussed below in more detail with a view to developing the work and, in particular, a more sophisticated risk map of eutrophication under climate change that includes risk factors other than just phosphorus inputs.

4.1   Future treatment scenario

The potential future treatment scenario (Sections 2.3 and 3.3) is an approximation based on several assumptions. These include the assumption that population and effluent discharge per person per day will remain unchanged in the future. Both assumptions are questionable: population growth is likely to increase the population connected to the sewerage system in most catchments and increasing water efficiency is likely to reduce water use per head of population. The net effect of these factors is uncertain, but both could be included in the assessment of future treatment scenarios.

The actual quality of final effluent discharged from larger treatment works is frequently monitored. Using monitoring data would enable more accurate estimates to be made of current point source phosphorus loads, taking into account levels of treatment as they are now. This would be a significant undertaking, but would greatly improve the accuracy of the baseline model results and hence the prediction of improvements that could be realised through enhanced treatment.

4.2   Land use and population change

So far the analysis has not considered the potential effects of land use change, which may affect river flow and sediment-related nutrient inputs in a number of ways. Examples include:

- changing the permeability of catchments (for example, through urbanisation) and hence the rate of run-off to watercourses

- changing evapotranspiration (for example through the introduction of more drought tolerant crops)

- increasing sediment-bound nutrient inputs through poor land use management practices, or reducing them, for example, through catchment sensitive farming

The analysis has also not considered population change. Increased population could affect sewage loads, while a drive for greater food production and intensification of farming could increase nutrient loads from agricultural land to river water.

A previous study for the Environment Agency's Anglian Region (Atkins, 2014) looked at the impacts of climate change and population change separately

using SAGIS (Source Apportionment GIS). The study showed that both climate change and population change contributed to a deterioration of phosphate concentrations and ecological status, but did not assess their relative contributions. Further work could usefully consider the implications of land use and population change on catchment hydrology and water quality.

4.3   Estimating eutrophication risk

This project has focused solely on projections of in-stream concentrations of phosphorus. But while phosphorus is frequently the limiting nutrient in causing eutrophication in inland waters, other risk factors need to be considered. In particular, algal growth depends on temperature and light levels during the spring and early summer growing season. In reality, 'typical summer' concentrations may be a more important indicator of ecological condition than annual average concentrations, and specific 'low flow and warm periods of longer duration' phosphorus concentrations may be an even more significant indicator of eutrophication risks. Further analysis of this nature could be carried out within the analysis spreadsheets provided if the future temperatures associated with the climate projections were added into the data.

A greater understanding of flow, phosphorus and sediment dynamics would enable refinement of the current maps through the development of a more comprehensive map of eutrophication risk. For example, while low flows will decrease phosphorus dilution, higher flows may increase release of phosphorus bound to sediment.

A more complete analysis would also consider the role of other nutrients, in particular nitrogen. The LAM can also be applied to nitrogen loads.

Future eutrophication risk also needs to consider ecological response (algal growth is indicated by chlorophyll-a concentrations) and other detrimental impacts, such as decreased dissolved oxygen which may lead to fish kills. Climate change may have both direct and indirect impacts on these responses and a full assessment of future eutrophication risk at the national scale requires the understanding of thresholds for the onset of algal blooms and the development of relationships to characterise these climate-related impacts. This should be set within the context of the other pressures such as future land use and population change.

5 Conclusions

This project has used projections of future river flow in combination with a load apportionment model to estimate future changes in phosphorus concentrations and associated Water Framework Directive phosphorus standards as a first step in understanding future eutrophication risk at a national scale.

Climate change could alter river flows and the dilution of phosphorus in rivers, and lead to an increased risk of eutrophication, that is, the excessive growth of plants and algae stimulated by increased supply of nutrients such as phosphorus.

The project's main conclusions are summarised below.

- Future river flows, driven by climate change, are projected to result in small, but variable increases in annual average phosphorus concentrations in rivers.

- The projected magnitude of change in summer phosphorus concentrations is generally greater than the change in the annual average.

- At most sites, the projected flow-related changes in annual average phosphorus concentrations would not, by themselves, be expected to result in deterioration in WFD phosphorus status classification. In combination with other pressures (both climate and non-climate), however, this pattern may change.

- The broad status boundaries used in classification may mask change in ecological response to changing phosphorus concentration. A more thorough assessment of future eutrophication risk needs to consider changes in phosphorus concentrations and ecological response in more detail.

- Despite uncertainty, the analysis suggests that improvement in WFD status could be achieved with additional treatment at wastewater treatment works.

- The analysis also suggests that improved treatment, combined with the effects of climate change, is not sufficient to meet WFD objectives at all sites. Other diffuse catchment phosphorus inputs would remain and would need to be managed.

- The map outputs of this project provide a useful tool to visualise and interpret total reactive phosphorus changes across a range of future scenarios at a national scale. Taking account of their indicative nature and the sources of uncertainty outlined, they may also make it easier to understand, target and design phosphorus management solutions at a regional or local scale.

- This analysis is based on the CEH's load apportionment model and the Future Flows Hydrology dataset. It is a first step in understanding the implications of climate change for achieving WFD good status for

phosphorus in the future, and in understanding the future risk of eutrophication of surface waters.

An important limitation of this work is that no account was taken of other climate changes that might occur such as:

- increasing temperature

- changes in the radiation balance and light intensity (through the water column)

- seasonal changes in flow – averaged in the long-term averaging of annual phosphorus concentrations

- potential effects of climate change on storminess (influencing nutrient run off from agricultural land and rainfall-driven point sources) and, conversely, periods of calm, stable weather (influencing the development of blue green algae)

These may have a greater impact on driving the ecological response directly and through impacts on nutrient concentrations. A greater understanding of these changes and the interaction with future phosphorus concentrations is required to understand potential ecological response to future phosphorus concentrations and the risks of eutrophication.

The range of additional climate impacts in addition to other factors relating to phosphorus concentration and dynamics and ecological response means that the risk of eutrophication in the future may be greater than is suggested by indicative changes in phosphorus concentrations alone.

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List of abbreviations

%ile	percentile
CEH	Centre for Hydrology
FDC	flow duration curve
FFH	Future Flows Hydrology
GIS	geographical information system
LAM	Load Apportionment Model
MAPE	mean absolute percent error
Ml/d	million litres per day
P	phosphorus
PE	population equivalent
NBB	new building blocks [Water Framework Directive]
NRFA	National River Flow Archive
STW	sewage treatment works
TRP	total reactive phosphorus
WB	water body
WFD	Water Framework Directive
WRGIS	Water Resources GIS

Appendix A: Outputs and processing

The main outputs from this project are:

- spreadsheets providing projections of future phosphorus concentrations and load apportionment under baseline conditions at 115 river locations in England, including the impacts of climate change, and also incorporating improvements in wastewater treatment

- maps showing estimated changes in phosphorus concentrations at these locations due to (a) climate change and (b) potential point source improvements in wastewater treatment

- maps showing the corresponding estimated WFD status under each scenario (maps supplied as a standalone GIS package)

- a slide pack and associated narrative which presents the main findings of the project as an 'executive summary for stakeholders'.

The following sections of this appendix detail the outputs and processing involved in producing and analysing the underlying data and maps. The analysis spreadsheets and map outputs from the project are summarised in a Microsoft® PowerPoint slide pack, provided as a printed copy in Appendix C. This section provides a narrative summary of this slide pack which serves as an overview of the processing and presentation work carried out post LAM modelling. The slide reference numbers are given in **bold** for clarity.

A.1   Outputs from load apportionment modelling

For each of the 115 monitoring sites, CEH provided the Environment Agency and its contractors, Amec Foster Wheeler, with an Excel workbook (TRP Model spreadsheet) containing all of the LAM modelling output. This includes:

- a time series of all matched TRP and flow data supplied by the Environment Agency (Raw Data tab)

- a graph of the model fit to the observed data (TRP Model_Sheet 1) (labelled A in Figure A.1)

- the load coefficients *A*, *B*, *C* and *D* for the model solution (TRP Model_Sheet 1) (labelled B in Figure A.1)

- the percentage of observations that were dominated by constant (point source) inputs (that is, the time that sewage treatment inputs dominate the total TRP input (TRP Model_Sheet 1) (labelled C in Figure A.1)

- the flow at which constant and flow-related inputs are equal (Q_e value) (TRP Model Sheet 1) (labelled D in Figure A.1)

- the percentage load estimates derived from constant (point source) and rain-related (diffuse) inputs, based on 'present day' observations (that is, typically within the last 5 years) (TRP Model_Sheet 2)

- projections of TRP concentrations for all 11 Future Flows ensemble members (scenarios) at a daily time step from 1951 to 2098, based on present day data

This worksheet also has the capacity to input percentage reductions in point source inputs and will calculate the estimated phosphorus concentrations at daily time step for all 11 ensemble members. These phosphorus concentration estimates formed the basis of the scenario testing and GIS mapping (Future Flow Data tab).
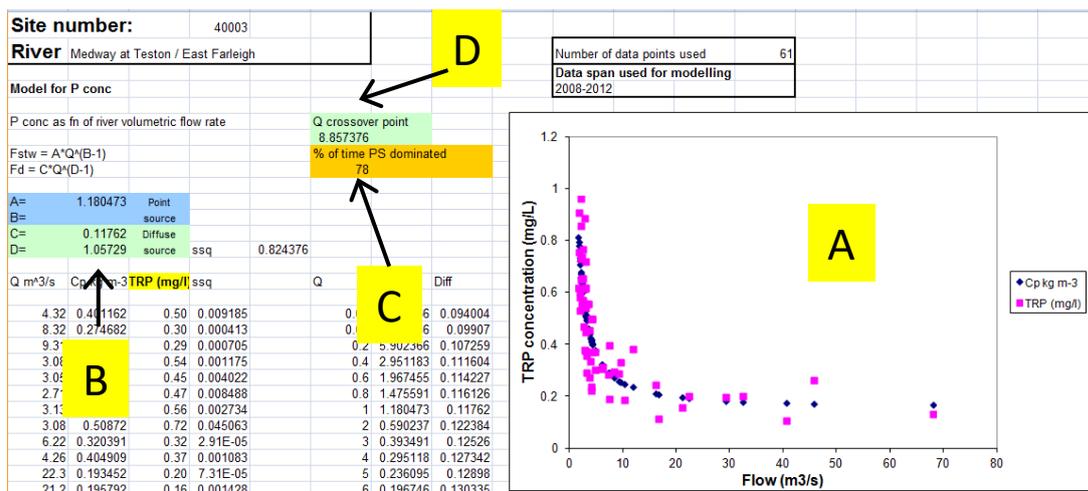

Figure A.1   Screenshot of TRP Model Sheet 1 tab

A.2   LAM outputs – processing and visualisation

To analyse and visualise changes to TRP concentrations projected by application of the LAM to the Future Flows hydrology, Amec Foster Wheeler developed analysis spreadsheets and carried out subsequent GIS visualisation of the results.

Each spreadsheet includes 2 tabs.

A 'Data' tab contains the 10-day averaged time series of flows and phosphorus concentrations as estimated by the LAM, including the effects of climate change and separately the effects of future wastewater treatment (see also below). To make processing easier and to improve the speed and functionality of the analysis spreadsheets, 10-day average time series were calculated from each daily time series. This is appropriate given the typical frequency of the monitored TRP data (monthly) and the eutrophication focus of the analysis; risks are highest during low flow periods so the loss of short duration flood peaks is not critical.

An estimate of the total STW discharge rate in the catchment upstream of the WFD water body within which the monitoring site is located is also included for contextualisation. This is further discussed in Section A.3.

A 'Plots' tab allows the user to carry out statistical analysis and simple 'what if' modelling. The results of the modelling can also be compared with site-specific WFD status threshold values to determine estimates of future WFD status (good, moderate and so on). Results can be averaged or analysed for selected percentiles over a number of years, as chosen by the user, to visualise longer term trends for various high or low flow conditions, as well as annual and seasonal summer averages.

A.3 Spreadsheet analysis

The site analysis spreadsheets are best reviewed digitally and have detailed user guidance built into them, where it is most useful. Screenshot summaries of what the spreadsheet does are shown as illustrations in **Slides 1, 2** and **3** in Appendix C.

The user can carry out exceedance statistical analysis and simple 'what if' Scenario TRP modelling using the spreadsheet. The time series which can be analysed are projections of:

- natural flow in cumecs ('Future Flows')

- TRP 'as now' in mg/l

- Scenario TRP in mg/l

A dummy projection of temperature is also provided to enable improvements in the analysis of eutrophication risks, but the underlying data are simply a repeated seasonal signal with a long-term rising trend which is **not** derived from any of the climate modelling.

The user can enter the maximum mg/l STW concentration used for the calculation of the Scenario TRP projections (**Slide 1**). As delivered, this is set to 0.5mg/l in all spreadsheets. For the exceedance analysis shown in **Slide 1**, the user first selects a Primary Parameter (for example, 'Nat flow, cumecs'), an exceedance percentile to calculate (for example, 95%ile) and a long-term rolling period in years which should be used (for example, 30 years). The upper graph will then plot that statistic for each of the 11 projections over the full Future Flow period (1951 to 2098 inclusive). The top right 'traffic light plot' shows the number of projections which show the indicated increases or decreases in the calculated statistic relative to its value in the year 2000. Changes are plotted every 10 years to indicate trends for all the projections across the 21st century.

A Secondary Parameter is then selected (**Slide 1** – this example shows 'TRP as now, mg/l'), which is calculated by averaging all values for periods when the Primary Parameter is close to the selected percentile. Hence, the example shown indicates that the natural low flow statistic QN95 (over 30 years) is projected to decline throughout the century in most models; 10 out of the 11 Future Flow models have low flows in the 2090s which are more than 15% less than in 2000. During such flow conditions which are likely to be associated with higher eutrophication risks (depending on other factors), the secondary parameter 'TRP as now, mg/l' increases; as low flows fall, TRP concentrations rise. The projected TRP concentration increases relative to 2000 are more varied according to the climate projection ranging from 'little change' (within 1% for one of the projections) to more than 15% by the 2090s in 2 of the projections.

This type of analysis is intended to provide a foundation for further improvements in the characterisation of eutrophication risks which might incorporate climate projection-based temperature data and information on existing STW discharge rates and treatment standards. Approaches might, for example, enable time series calculation of the number of consecutive days when flows, TRP concentrations, temperature and light levels combine to

suggest higher eutrophication risks – and to project trends in such 'annual average' eutrophication risk days into the future.

For the current phase of work, however, the analysis and subsequent mapping focused more simply on TRP projections related to flow changes due to the climate, with the emphasis on annual average TRP concentrations which are linked to WFD status classification, with additional calculation of averages for summer months. Hence the spreadsheet includes a plot of the annual average concentration for either TRP 'as now' or Scenario TRP for a preceding rolling period which the user can choose (**Slide 2**). The site-specific WFD status classification boundaries are included on this plot and tabulated next to it.

While small increases in annual average TRP are just visible over the century in the example shown, the site remains within 'good status' throughout. It is generally the case that annual average TRP is not as sensitive to the climate changes in flow as, for example, low flow TRP because the catchment response – which may include flashier higher flows as well as lower, more prolonged lower flows – is integrated together over the longer period. Hence the TRP projections for a particular scenario typically stay within the (relatively broad) WFD status bands unless they are close to a threshold concentration.

The mapping of TRP projections to meet the Environment Agency specification focuses on annual and summer month averages calculated in the spreadsheet for a variety of standard time periods (**Slide 3**).

A.4   Treatment scenarios and processing

CEH collated time series pairs of TRP and associated gauged river flow data for each of the 115 FFH monitoring sites into a spreadsheet version of its LAM model (**Slide 3**). The spreadsheet establishes correlations between these data over the recent period of record – typically after the installation of phosphorus stripping associated with the implementation of the Urban Waste Water Treatment Directive.

The TRP monitored data frequency is usually monthly, but the spreadsheet uses the relationships to model daily TRP concentrations according to the Future Flow projections for the flow gauging station.

Flow duration curves are also provided within the output analysis spreadsheets which compare the range of gauged flows used for model calibration with the long-term historical record for the station and also with the range of Future Flow projections. These quality assurance checks allow the reviewer to consider the extent to which the calibration flow range is representative of the fuller gauged flow record, as well as highlighting differences between the 'historical' patterns of flow, which incorporate abstraction and discharge influences, and the climate change projections of 'natural' flows to which the modelled TRP relationships are subsequently applied. The flow duration curves are thus an important contextualisation tool.

CEH passed the flow–TRP relationships and future daily projections to Amec Foster Wheeler for onward processing in spreadsheets and maps. Amec Foster Wheeler added WFD thresholds specific for each monitoring site to the analysis

spreadsheet to allow projections of annual average TRP to be summarised into status classification categories (high, good, moderate, poor, bad).

An estimate of the total STW discharge rate in the catchment upstream of the WFD water body within which the monitoring site is located is also included. This is based on population equivalent flow estimates (assuming 180 litres/person/day) and is compared with the 'typical dry summer' discharge dataset available in the September 2014 WRGIS. The total STW discharge estimate is used to indicate the average mg/l concentration of treated effluent from the parameterisation of the CEH correlation model on the assumption that these point inputs dominate the low flow loading in the catchment. This may not be the case if there is a significant input of phosphorus in groundwater baseflow derived, for example, from the Upper Greensand aquifer. The catchment STW estimate is also used to parameterise the Scenario TRP model relationship assuming a maximum stripped concentration of 0.5mg/l TRP. Improvements in the data incorporated to constrain actual STW discharge rates and TRP concentrations should be considered in subsequent phases of work.

The projections calculated by each of the 115 site analysis spreadsheets are collated together into a single summary table which underpins the ArcGIS .mxd file of output map layers. In drawing together the projections, the summary spreadsheet calculates the minimum and maximum TRP concentrations for all sites, scenarios, future climates and time periods. These are built into the .mxd file so that common fixed colour scales can be applied to all layers making comparison between them easier.

A.5   Map layers

Tabulated data for each site are collated from these analyses into a summary spreadsheet from which the mxd map layers (including the examples listed in **Slide 4)** are drawn. Each suite of results includes 11 Future Flow based projections. The full listing of the 330 map layers in the ArcGIS mxd is summarised in Table A.1.

<p style="text-align:center">Table A.1   Summary of map layers</p>

Scenario	Layer groups
TRP 'as now' projections	Annual average mg/l and associated WFD status for: • 'Baseline' = 1961 to 1990 period • '2050s' = 2040 to 2069 period • '2070s' = 2060 to 2089 period • changes, 2050s minus Baseline, as absolute values and percentages Summer months (June, July, August) average mg/l for: • 'Baseline' = 1961 to 1990 period • '2050s' = 2040 to 2069 period

	• '2070s' = 2060 to 2089 period
	• changes, 2050s minus Baseline, as absolute values and percentages
Scenario TRP projections assuming STW concentrations <0.5mg/l	Annual average mg/l and associated WFD status for:
	• 'Baseline' = 1961 to 1990 period
	• '2050s' = 2040 to 2069 period
	• '2070s' = 2060 to 2089 period
	• differences, 2050s Scenario TRP minus 2050s TRP 'as now', as absolute values and percentages
	Summer months (June, July, August) average mg/l for:
	• Baseline' = 1961 to 1990 period
	• '2050s' = 2040 to 2069 period
	• '2070s' = 2060 to 2089 period
	• differences, 2050s Scenario TRP minus 2050s TRP 'as now', as absolute values and percentages
2050s TRP mg/l reductions required to reach good status site thresholds	• TRP 'as now'
	• Scenario TRP

The site data tables underpinning these layers also lists the parameterisation of the CEH LAM model projections. The .mxd file incudes reference river lines, STW population equivalent points, and WRGIS routed catchment abstraction management strategy (CAMS) assessment point (AP) and WFD water body sub-catchment polygons.

The layer logic and structure of the ArcGIS mxd project, as set out above, is shown (with annotations) in **Slides 5, 6, 7** and **8**.

A.6 Other map layers and STW data

The .mxd file includes the location of STWs with calculated population equivalent discharge rates (assuming 180 litres/person/day) based on data provided by CEH (**Slide 29**). The routed sub-catchment accumulation functionality available for the integrated water body network of new building blocks (NBB) in the September 2014 WRGIS dataset was used to estimate total upstream catchment discharge rates from these point STW data (**Slide 30**). The yellow routing arrow buttons in the .mxd can be used to show the upstream or downstream catchment relationships (**Slide 31**).

The catchment STW discharge rates estimated in this way are representative of the outflow points of the integrated water body network, but have been spatially associated with any TRP monitoring site located within their sub-catchment. So while there is a reasonably close correlation between the population equivalent discharges and the WRGIS Recent Actual Discharges upstream (DischRAups) at the water body scale (**Figure 2.5**), this does not necessarily guarantee that they are appropriate for the TRP monitoring site which may be located at some distance upstream of the water body outflow point.

Given the uncertainty regarding upstream STW rates and their current TRP concentrations, and the possibility that there may be other steady baseflow inputs of phosphorus associated with some aquifers, it is not surprising that the parameterisation of the CEH LAM models implies a large range of current STW concentrations. **Slide 32** shows this range and indicates the number of sites in each mg/l category. So, for example, there are 14 sites where the implied TRP concentration is already less than the 0.5mg/l assumed for the stripping scenario. These sites will therefore show no difference between TRP 'as now' and Scenario TRP. There is also one site where the TRP concentration lies between 20 and 22mg/l, which is not credible. This illustrates the uncertainty in the STW related information which should be improved in any future phase of work.

Appendix B: Flow duration curve analysis

B.1   Flow duration curves – introduction

When using the LAM in support of decision making it is important to consider on a site-by-site basis how representative the river flow conditions were at the time of the sampling period(s) chosen to establish the TRP concentration–flow relationship. This is possible by an analysis of flow duration curves (FDCs). These calculate the flow rate in the time series which was exceeded for 1%, 2%, 3% successively up to 99% of the time (that is, the percentile levels). For example, the 95th percentile (Q95) is a common statistic used in hydrometry as representative of low flow conditions; this is the flow that would be expected to be exceeded 95% of the time.

At each site the following flow duration curves were derived:

- **FDC_A**: recent instantaneous gauged river flows from the National River Flow Archive (NRFA)[4] at the times of the TRP sampling that were used to define the site-specific LAM parameters – denoted 'model period' on graphs

- **FDC_B**: NRFA gauged daily flows for the entire time envelope within which data were used to define the LAM parameters – denoted 'NRFA model period' on graphs

- **FDC_C**: NRFA gauged daily flows for the entire gauged flow record at the site – denoted 'NRFA full record' on graphs

- **FDC_D**: Future Flows Hydrology daily flows for the period 1961 to 1990.

FDC-D was calculated for each simulated flow time series for the 11 different members of the ensemble. For each percentile level, the maximum and minimum flow rate of the set of 11 was calculated – denoted 'max FFHx11' and 'min FFHx11' respectively on graphs – for comparison with the other FDCs.

B.2   Flow duration curves – review method

The flow duration curves and goodness-of-fit for flow duration curve metrics are given in the 'flow duration curves' tab on the spreadsheet for each monitoring site. The representativeness of the flow duration curve (FDC_A) was assessed in 2 ways:

- by visually inspecting the graphs

- by considering a mean absolute percent error (MAPE) statistic

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[4] www.ceh.ac.uk/data/nrfa/

The MAPE was calculated by comparing the deciles (10th, 20th, 30th and so on percentile flows, that is, Q10, Q20, Q30 and so on) of 2 FDCs. Statistics are given as shown in Table B.1.

Table B.1   Flow duration curve statistics provided

Cell in Excel tab	Error statistic	Comparison made
K2	MAPE_AC	FDC_A with FDC_C
K17	MAPE_AB	FDC_A with FDC_B
K3 to K13	MAPE_CD	11 simulations of FFH (FDC_D) with the full NRFA record (FDC_C)

It must be stressed that any differences between FDC_A and the other curves in themselves in no way implies that a site LAM model lacks validity. They purely form contextual information. It is perfectly possible to have a reliable site-specific LAM model based on flow data biased towards high (or low) flow samples that has a much better calibration fit than a LAM model from a site based on sampling which is very closely representative of the flow regime. The intention is that if aspects of decision making in respect of eutrophication are made at a site-specific level, then the implications for LAM of the flow duration curve assessments should be considered carefully.

To be confident of a LAM model built on data representative of present day conditions, FDC_A should be very similar to FDC_B.

For the purposes of making future estimates of phosphorus concentration, ideally FDC_A would fall within the maximum–minimum envelope defined by FDC_D. In reality, mismatches will arise due to one, some or all of the following:

(1)   Flows at time of sampling not being representative of flows in the period chosen for derivation of the LAM (that is, the comparison of FDC_A and FDC_B cited above)

(2)   Flows at time of sampling not being representative of long-term flow (comparison of FDC_A and FDC_C)

(3)   Climate baseline (1961 to 1990) flows simulated under Future Flows Hydrology not being representative of the long-term flow record (comparison of FDC_D and FDC_C)

Three case examples are presented below.

B.2.1   Site 21032

At Site 21032 (Figure B.1), FDC_A ('model period') lies above the other FDCs suggesting the data used in the LAM are probably biased towards high flows. Around a third of the phosphorus samples were taken when flow exceeded the long-term Q10 value. The LAM model at this site would be improved given additional data around 1.5–2.0m^3/s (around the median flow of 1.66m^3/s). However, the representation of low flows is good. This is reflected in the values for MAPE_AB (46.4%) and MAPE_AC (73.7%). FDC_D (minimum and maximum 'FFHx11') fits closely to FDC_B ('NRFA model period') and FDC_C

('NRFA full record'), suggesting a sound basis for future predictions from a hydrological perspective, which is reflected in the values for MAPE_CD which are fairly low (9.7–22.9%).
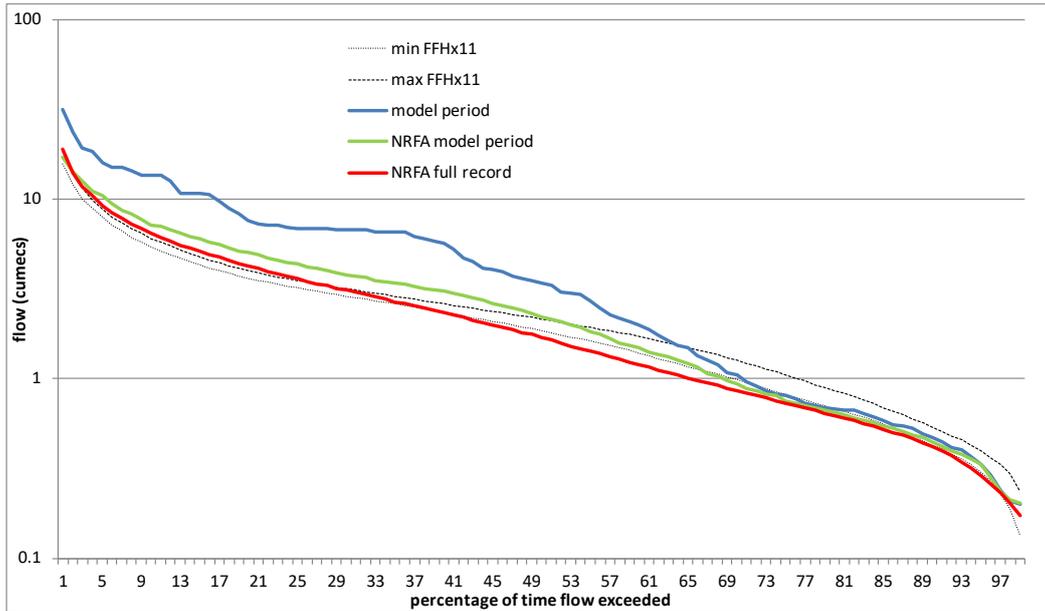

Figure B.1   Site 21032 flow duration curves

B.2.2   Site 33012

In contrast to Site 21032 and despite having only a small number of samples on which to base a LAM model, the flow regime at Site 33012 (Figure B.2) appears to fit the observed NRFA data well (MAPE_AB and MAPE_AC being 14.4% and 12.9% respectively). However, the difficulty here is the simulation underpinning the future flow projections (MAPE_CD range 53.9–110.3%). It seems that, although high flows look realistic, moderate and low flows are overestimated by the hydrological model.
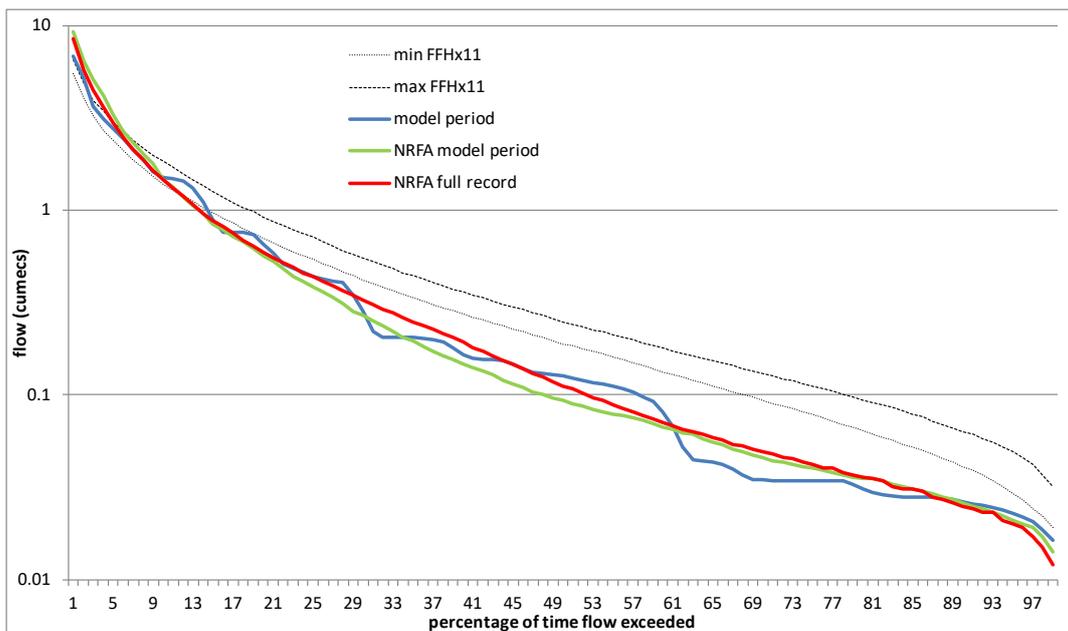

Figure B.2   Site 33012 flow duration curves

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B.2.3   Site 39105

At Site 39105 (Figure B.3), the fits of the FDCs look reasonably good in all respects. Perhaps the days of sampling were over-representative of the extremes. This is reflected in the moderately low MAPE values: MAPE_AB = 16.0%, MAPE_AC = 32.3% and MAPE_CD range is 19.2–32.6%.
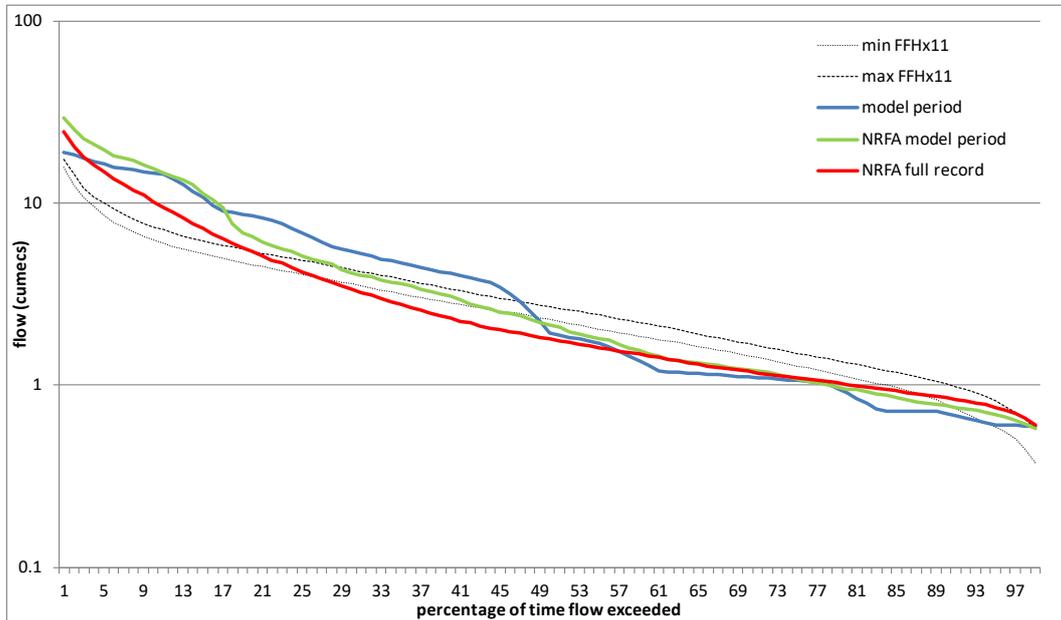

Figure B.3   Site 39105 flow duration curves

B.2.4   Site 39006

At Site 39006 (Figure B.4), the FDC_A ('model period') very closely resembles FDC_B ('NRFA model period') and FDC_C ('NRFA full record') and hence the very low MAPE_AB and MAPE_AC values (4.5% and 8.4% respectively). However, the simulated hydrology fits less well (MAPE_CD values are 43.8–52.6%), as illustrated by the deviation of the FFH FDCs from the NRFA data.
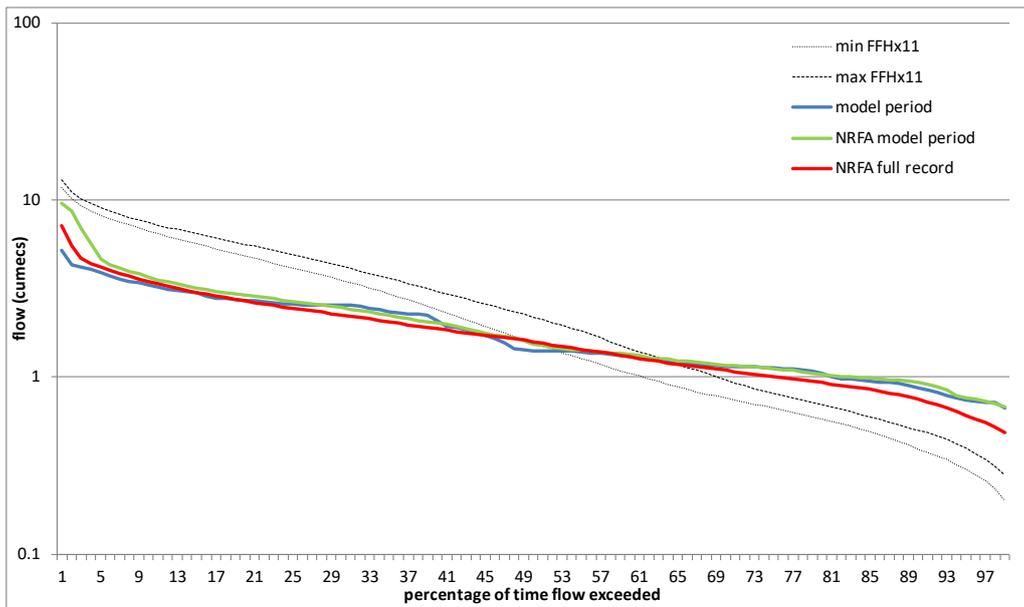
Figure B.4   Site 39006 flow duration curves

B.3 Phosphorus duration curves

A final consideration when evaluating the flow duration curves is to look at the impact of mismatch between FDC_C and FDC_D (that is, as summarised by the MAPE_CD statistic) on LAM simulated phosphorus time series concentrations. To illustrate, this was done for 2005 to 2013 at Site 39105 (Figure B.5) and Site 39006 (Figure B.6).

At Site 39105, the MAPE_CD values were relatively low whereas at site 39006 they were markedly higher. In Figures B.5 and B.6, the 'true' simulated phosphorus duration curve is denoted 'NRFA' and the concentrations derived by Future Flows Hydrology are represented by the other 11 curves (for example, 'FF-Had RM3-Q0_afgcx'). In the case of Site 39105, the FFH curves resemble the 'true' curve fairly well but at site 39006 there is overestimation of the higher phosphorus concentrations. Mean concentrations are the issue from a legislative perspective. These are summarised in Table B.2, indicating that the range of mean FFH-derived TRP concentrations successfully spans the mean derived from NRFA flows at Site 39105 but do not at Site 39006.
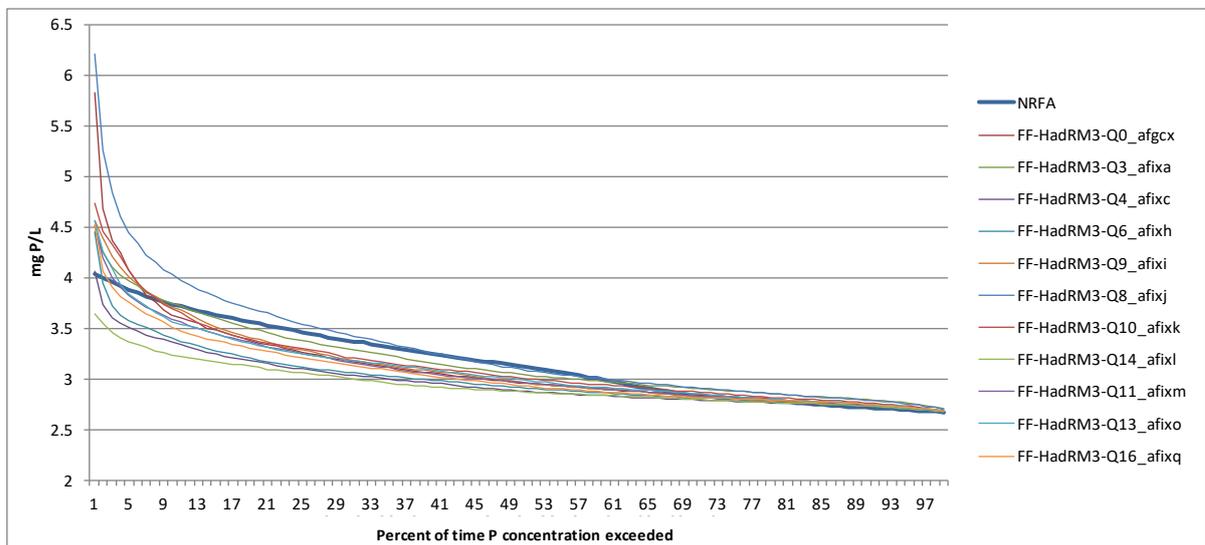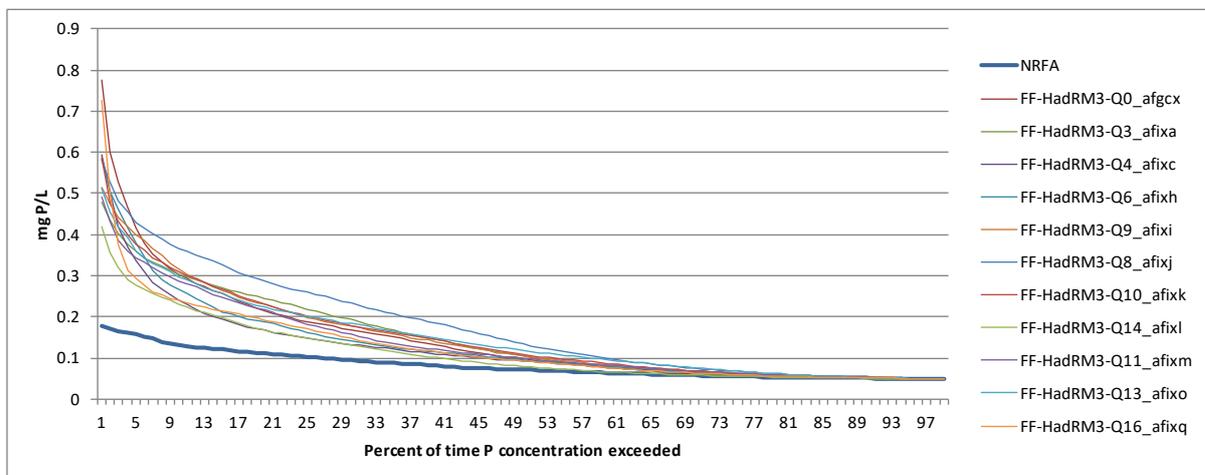

Figure B.5   Site 39105 phosphorus duration curves

Figure B.6   Site 39006 phosphorus duration curves

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Table B.2   LAM mean TRP concentrations derived from different flow records for the period 2005 to 2013

Site	Mean mg TRP/l (derived from NRFA observed flows)	Range of mean mg TRP/l (derived from 11 FFH applications)
39105	3.19	2.95–3.31
39006	0.083	0.116–0.179

Appendix C: Slide pack

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