Evidence

Climate change and eutrophication risk thresholds in English rivers

Report – SC140013/R2

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Professor Doug Wilson
Director, Research, Analysis and Evaluation

Executive summary

Climate change is expected to alter water quality in rivers, but where and when this may happen is uncertain. This report describes a study of projected response in the amount of algal plant growth (phytoplankton biomass). Increasing algal growth is one of the ecological manifestations of eutrophication in slow flowing rivers, where the water starts to resemble a green soup. Eutrophication is a process in which too much nutrient in water causes algae and higher plants to grow excessively.

Eutrophication alters the quality of the water and how it can be used. Phytoplankton (suspended algae) is considered to be a useful indicator of eutrophication in standing freshwaters and can also be useful as one measure of impacts in rivers, particularly slow flowing rivers. Excess algal growth can result in blooms that eventually die off. The disruption of dissolved oxygen dynamics in the water column may, in turn, have adverse impacts on fish and macroinvertebrates. The onset and decline of algal blooms is measured by the concentration of chlorophyll (a green pigment in algae) in the water. In this context, algal bloom risk – and the risk of negative eutrophication impacts in the lower reaches of rivers – is identified through observations of threshold chlorophyll concentrations. Exceedence of a chlorophyll concentration threshold is not by itself used in the diagnosis of river eutrophication but can be used as a proxy for algal blooms for understanding and modelling risk.

The future risk of eutrophication impact, including algal blooms, is affected by changes in the concentration of nutrients from altered river flow and changes in phosphorus inputs from a range of sources. An earlier study (Phase 1 of this project) demonstrated that climate change impacts on river flow would increase phosphorus concentrations by 2050 and beyond. However, climate-driven changes in river temperature regime and light, and plant responses to these, are also important in altering the future risk of excess algal growth. This report considers these aspects.

The first step was to identify the variables that control eutrophication and the thresholds in these variables which determine the potential for algal blooms. Algal blooms tend to occur only in rivers with a residence time (the time water takes to travel from an upstream distance to a site) of over 4 days. Below 4 days, blooms are rare. Such long residence times in the UK tend to occur in canals, and slow flowing and shallow gradient rivers (often in their lower reaches). Using this residence time threshold of 4 days, a total of 26 sites in England on 24 different rivers with available data for analysis of trends were identified out of the 115 sites from Phase 1.

Water quality data were used to identify the ranges of river flow and water temperature within which algal blooms were measured (as determined by chlorophyll concentration) for each site. Site-specific thresholds were identified from plots of variables of water quality against chlorophyll concentration.

In this study, a chlorophyll threshold of 30μgl^{-1} indicated the onset of an algal bloom for most rivers. Thresholds ranged between 15μgl^{-1} and 100μgl^{-1}. For larger rivers, with higher chlorophyll levels (such as the Thames), the thresholds for algal blooms are higher. A phosphorus threshold of 30μgl^{-1} was selected for all sites, based on understanding developed through nutrient limitation experiments across a range of UK rivers in other studies. A sunlight duration threshold of 65W/m^2/day was chosen for all the sites based on a minimum of at least 3 hours of full sunshine per day over ~3 consecutive days (derived from earlier work). A bloom is likely to occur if all thresholds are met at the same time. These are called bloom risk days and they represent overall risk based on all measured variables.

A spreadsheet model was developed and applied to the 26 sites. The model used daily estimates of controlling variables (phosphorus concentrations, river flow, water

temperature and sunlight duration) from 1951 to 2098 to estimate when the derived thresholds for each variable were met and likely to cause an algal bloom. Phosphorus concentration estimates from earlier work were used under current wastewater treatment conditions and under an improved wastewater treatment scenario.

Bloom risk days (when the river flow, water temperature, sunshine duration and phosphorus concentration thresholds for algal growth were all met) increased between the baseline period (1961 to 1990) and the 2050s future period (2040 to 2069). The median increase is about 8 days across all sites from about 50 in the baseline period, although the maximum increase is up to 15 days. The change in risk is variable by the 2080s (2070 to 2098), with about 50% of sites showing reduced risk relative to the baseline period, resulting in a median increase of about 4 days and a maximum of up to 16 days.

Analysis of the number of threshold days for each individual driver indicates that phosphorus thresholds are met most days of the year and that phosphorus concentrations do not prevent bloom development except at one site. Phosphorus management strategies may therefore not be effective in reducing the risk of algal blooms occurring in slow flowing rivers, an observation confirmed by the fact only 3 sites showed a reduction in risk using an improved phosphorus treatment scenario.

There is more variability in the number of days the other thresholds are met, resulting in a varying pattern of risk between sites and time periods. After phosphorus concentration thresholds, river flow thresholds are most frequently met. Sunlight duration and water temperature thresholds are least often met. The interaction between flow variability, water temperature and sunlight duration would appear to determine the variability that emerges by the 2080s.

The role of water temperature and sunlight duration seems to be significant in both limiting the number of days all thresholds are met and in controlling the timing of attainment of all thresholds, with both thresholds tending to be exceeded later in the year than those for river flow and phosphorus concentration. With the lowest number of threshold days at the greatest number of sites, exposure to sunlight may be the most important factor in preventing algal blooms.

There is considerable uncertainty in the estimation of future water temperature, which was derived from air temperature using simple regression methods. This may result in a variable estimate of bloom risk days that requires further exploration with more reliable projections of future water temperature. A better way of estimating water temperature would really help to model future water quality.

These results suggest that management strategies focusing on reducing sunlight and thermal interactions (both through river shading by trees) may be particularly effective in reducing the risk of blooms on some rivers in the future. This could be explored using the spreadsheet model developed for this project. Whilst phytoplankton blooms tend to be observed in lowland reaches of English rivers, the approach applied here is independent of this, is equally applicable anywhere, and has potential for use in an approach for assessing eutrophication in slow flowing rivers. It would also be useful to identify more sites across England at which residence time thresholds are met in order to assess potential vulnerability to eutrophication.

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1 Introduction

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

It is anticipated that climate change will exacerbate existing problems and potentially lead to new issues, increasing challenges in meeting water quality objectives. It is helpful to know more about this so action can be targeted to:

- prevent future deterioration of water quality
- understand which interventions work best in different situations

This report presents the findings of the second phase of a study to identify rivers across England that are likely to suffer from increasing risk of eutrophication through the 21st century under a range of future climate change scenarios. An earlier report described the estimated changes in phosphorus concentrations at river sites across England resulting from changing flow regimes caused by climate change (Environment Agency 2016; see also Charlton et al. 2018). This earlier work is referred to hereafter as Phase 1. The Phase 1 report also projected the impact of improved sewage treatment on future phosphorus concentration.

This report sets out how these changing phosphorus concentrations, along with other likely controlling variables such as water temperature, sunlight and flow (not just through impact on phosphorus concentrations) are likely to have an impact on eutrophication risk as expressed by the occurrence of algal blooms.

Phytoplankton (suspended algae) is considered to be a useful indicator of eutrophication in standing freshwaters and can also be useful as one measure of impacts in rivers, particularly slow flowing rivers. Excess algal growth can result in blooms that eventually die off. The disruption of dissolved oxygen dynamics in the water column may, in turn, have adverse impacts on fish and macroinvertebrates. Although there is currently no UKTAG method for diagnosing eutrophication in rivers under the Water Framework Directive, due to variability of response and difficulties in defining ecological boundaries, algal bloom evidence is used as part of a weight-of-evidence approach across nutrient and impact factors to assess whether there is a eutrophication issue.

Alongside cell counts and taxa composition, chlorophyll levels are one aspect of phytoplankton but are not, on their own, diagnostic of eutrophication problems. Water column chlorophyll concentration has been identified as a primary indicator of the onset and decline of algal blooms in slow flowing rivers; being a measure of algal biomass (see Bowes et al., 2016). The onset and decline of algal blooms is measured by the concentration of chlorophyll (a green pigment in algae) in the water. This provides useful data from which to explore relationships between chlorophyll concentrations and other variables. Although measurement of chlorophyll concentrations is not part of most routine monitoring, it is particularly relevant in slower flowing rivers – though it is not currently used as an indicator of ecological status.

1.1 Algal blooms – cause and effects

Eutrophication is a complex process resulting from nutrient enrichment and includes a range of ecological responses.

Phosphorus is a major contributor to eutrophication in fresh waters; according to POST (2014), reactive phosphorus was the reason for the failure of 45% of river water bodies in England to achieve the Water Framework Directive phosphorus standard for good ecological status. A mechanistic description of how phosphorus concentration affects the processes associated with eutrophication is summarised in the Phase 1 report (Environment Agency 2016). Of particular importance in some rivers are the conditions that produce excessive algal growth, which can lead to large diurnal fluctuations in dissolved oxygen (DO) concentrations, with low overnight DO concentrations, resulting in ecological stress and ultimately fish kills.

The timing, magnitude, duration and frequency of algal blooms and subsequent oxygen sags are expected to change with changes in climate impacts (such as on river flow and water temperature). In this report, references to algae refer to phytoplankton, rather than filamentous algae or benthic diatoms, as the focus is on chlorophyll measured in the water column. In this context, algal bloom risk – and the risk of negative eutrophication impacts in lowland rivers – is identified through observations of threshold chlorophyll concentrations (chlorophyll peaks).

The climatic controls exert both direct and indirect influences on ecological response and some aspects of this complexity need to be considered in the refinement of the eutrophication risk. In addition, climatic changes should be considered in the context of other future pressures – in particular population changes (affecting water abstraction demands and wastewater inputs) and land use changes (affecting nutrient and sunlight inputs to the river and hydrology) – although these are not considered here.

The seasonal changes in phytoplankton are relatively well understood in lakes, and well-established conceptual models exist. These describe the annual pattern in algal biomass and community succession, principally controlled by the impacts of light, grazing by zooplankton and nutrient availability (Sommer et al. 1986, 2012). In contrast, there has been much less research on river phytoplankton dynamics and the level of understanding is relatively limited (Reynolds 2000).

Algal blooms in rivers have generally been attributed to high nutrient concentrations, particularly phosphorus (Vollenweider 1968, Herath 1997, Chételat et al. 2006). However, there are a growing number of riverine studies that suggest that physical factors play an important role in controlling phytoplankton dynamics. The importance of river flow rate, residence time and the presence of aggregated dead zones within the river channel have been shown to have a major impact on phytoplankton biomass (Reynolds 2000, Bowes et al. 2012).

Other studies have highlighted the impact of multiple stressors on algal dynamics. Flow and light intensity were identified as the key controls on bloom dynamics for agricultural streams in Illinois in the USA (Figueroa-Nieves et al. 2006) and the River Elbe in Germany (Hardenbicker et al., 2014). Other abiotic combinations that have been proposed include:

- flow and water temperature (Desortová and Punčochář 2011)
- flow, temperature and nutrient concentration (van Vliet and Zwolsman 2008, Larroudé et al. 2013)
- flow, temperature and light (Reynolds and Descy 1996, Balbi 2000, Waylett et al. 2013)

The impacts of invertebrate grazing (Lazar et al. 2012, Waylett et al. 2013) and self-shading (Whitehead and Hornberger 1984) have also been postulated as a mechanism for limiting phytoplankton biomass and causing bloom cessation ('die-off') in modelling studies of the River Thames catchment in the UK.

The wide variety of potential stressor combinations suggested by these studies makes it challenging to produce a conceptual model of the processes that control phytoplankton biomass in rivers. However, there is a need for a simple and rationalised approach to feed into national scale strategic decision-making.

1.2 Building on Phase 1 and aims of Phase 2

Phase 1 mapped change in phosphorus concentrations driven by projected changes in river flows under climate change. This provided a first step in understanding the implications of climate change for achieving Water Framework Directive 'good' status for phosphorus in the future, and in understanding the future risk of eutrophication of surface waters. A model based on the relationship between river flow and phosphorus concentration – the Centre for Ecology and Hydrology (CEH) Load Apportionment Model and Future Flows Hydrology (FFH) – was used (Haxton et al. 2012, Prudhomme et al. 2012).

The work in Phase 1 found:

- small increases in annual average phosphorus concentrations in rivers
- a greater increase in summer concentrations of phosphorus compared with the annual average
- at most sites, flow-related change in annual average phosphorus concentrations would not result in deterioration in phosphorus status classification under the Water Framework Directive
- despite uncertainty, the analysis suggested that improvement in Water Framework Directive phosphorus status could be achieved with additional treatment at sewage treatment works

Phase 1 took no account of other expected changes such as increasing temperature and the role of sunlight and flow on algal blooms. The overall aim of Phase 2 was to map changes in future eutrophication risk in English rivers using a simple and rationalised approach based on:

- identifying the controlling variables
- identifying thresholds in these variables
- determining how these variables could change over time and how this affects the potential for algal blooms

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.

2 Methodology

Following an initial exploratory investigation, the approach adopted involved the steps listed below and explained in more detail in the following sections.

1. Explore the links between observed algal blooms measured by chlorophyll concentrations and values of river flow, phosphorus concentrations, water temperature and sunlight duration. This was done at sites where a high-resolution time series of monitoring data was available that included periods where had blooms developed. The aim was to test whether it was possible to develop a predictive algal bloom model based on flow, phosphorus concentration, water temperature and sunlight duration (Section 2.1).
2. Select sites where the residence time was sufficient to generate algal blooms (Section 2.2).
3. Identify thresholds in flow, phosphorus concentration, water temperature and sunlight that describe the onset and decline of algal blooms using existing datasets (Section 2.3).
4. Use statistical modelling to assess whether the variables provided predictive capability for estimating chlorophyll concentrations for these sites using observed data (Section 2.4).
5. Develop time series of flow, phosphorus concentration, water temperature and sunlight into the future for 11 future climate scenarios (Section 2.5).
6. Apply site-specific thresholds to the time series to calculate days when all bloom thresholds are met using a spreadsheet model (Section 2.6).
7. Map minimum, median and maximum values (absolute and change) in ArcGIS to represent uncertainty across an ensemble of 11 FFH scenarios for baseline and future periods (Section 2.7).

2.1 Variables controlling chlorophyll concentration

A vital first step was to develop an understanding of how the multiple physical and chemical (nutrient) conditions control the timing, magnitude and cessation of algal blooms/chlorophyll peaks. Although this level of data was not available in the published literature, CEH had developed a strong understanding of the multiple-control conditions/thresholds required to promote rapid algal growth in the middle stretches of the River Thames (see, for example, Bowes et al. 2016). This work identifies the following controls on chlorophyll concentrations:

- residence time
- river flow
- water temperature
- nutrient concentration (phosphorus)
- sunlight duration

Thresholds in all of these controlling variables need to be met before chlorophyll concentrations begin to increase and an algal bloom occurs. The following sections describe the methods for deriving these controlling variables as well as determining relevant thresholds.

2.2 Estimating residence times

When residence time is insufficient for photosynthesis to progress sufficiently for a substantial biomass of phytoplankton to develop, blooms cannot occur regardless of the temperature, sunlight and nutrient status. If cell division (driven by photosynthesis), progresses more slowly than the time to travel the length of river in question, large planktonic biomass will not occur.

Residence times in excess of 4 days are known to be sufficient to potentially foster significant algal blooms in the downstream reaches of river networks (Kinniburgh et al. 1997). Consequently, residence time was decided to be the primary variable. This was used to identify sites likely to be at risk of eutrophication now and in the future using by following procedure.

1. The residence time for all the study sites from Phase 1 was calculated using the Low Flows 2000 software used for modelling flow and water quality. Phase 1 sites were selected because future projections of flow and phosphorus had already been made.
2. The longest stretch of river upstream of each study site was defined using a truncated national river network dataset based on CEH’s 1:50,000 digital terrain model (DTM). The network was truncated at locations where the most upstream Environment Agency Water Information Management System (WIMS) monitoring point was located –typically just downstream of a wastewater input.
3. Travel times along the river stretches were calculated under 2 conditions chosen to encompass a range experienced in summer: mean flow and the 90th percentile flow (Q90).
4. The times were derived via the calculation of flow velocity using a method developed specifically for use across the UK (Round et al. 1998). Statistical analysis performed during the derivation of this method pinpointed a method of flow velocity calculation that was robust without including climatic and catchment characteristics as explanatory variables (Round et al. 1998). A subset of rivers where the Q90 residence time exceeded 4 days was retained for subsequent analysis.

2.3 Flow, phosphorus, water temperature and sunlight thresholds

Previous studies had been unable to explain and predict the timing, magnitude and duration of algal blooms in rivers (Waylett et al. 2013). However, a recent study of the River Thames based on 5 years of Environment Agency and CEH higher frequency water quality monitoring data had allowed specific thresholds in temperature, flow and light to be identified for the Thames (Bowes et al. 2016). These data covered:

- weekly phosphorus, nitrate and dissolved silicon concentrations
- daily sunshine hours and river flow
- hourly chlorophyll concentrations and water temperature

No simple linear relationships between these physicochemical parameters (water temperature, flow, sunshine duration and nutrient concentration) and chlorophyll were found. However, there were distinct ranges when high chlorophyll concentrations/growth rates occasionally occurred. Figure 2.1 shows that, in the middle stretches of the River Thames (Wallingford to Reading), high chlorophyll concentrations occurred only at water temperatures between 9 and 19°C, flows <$30m^3s^{-1}$, and when sunshine duration was long and sustained over the previous days. The breakthrough observation is that all of these thresholds need to be met before chlorophyll concentrations begin to increase.

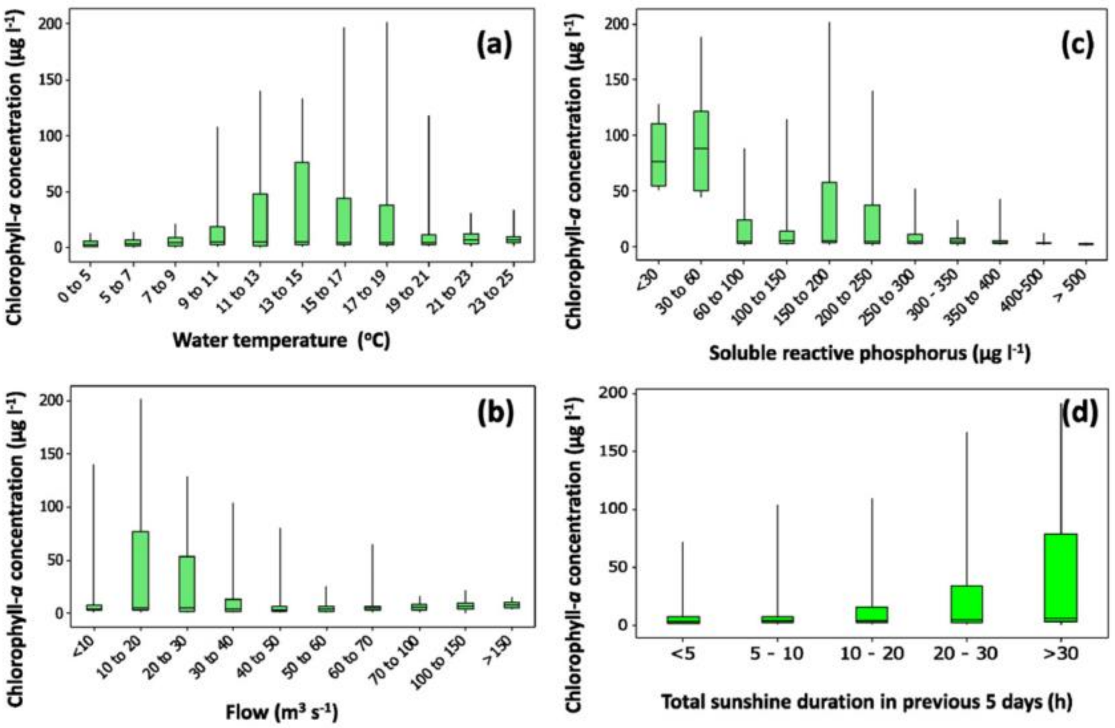

Figure 2.1 Monitoring data from the River Thames between Wallingford and Reading

High chlorophyll concentrations occurred only when soluble reactive phosphorus (SRP) concentrations were low (Figure 2.1c). This demonstrates that algal blooms were not being triggered by peaks in SRP concentration, and actually it was the algal blooms that were controlling the SRP concentration (due to algal uptake causing nutrient depletion during blooms). However, this study suggested that low silicon and SRP concentrations potentially contributed to the collapse of some blooms due to nutrient limitation.

The thresholds derived in this Thames study (from 2009 to 2013) were able to explain and accurately predict the timing, size and duration of the blooms in the following 2 years – a year of very low algal biomass in 2014 and the longest sustained algal bloom for over 20 years in 2015. This simple method, which was derived from a data-rich catchment, therefore offers a potential means to predict blooms and identify thresholds in other catchments with a long period of standard monthly water quality data.

2.3.1 Deriving water temperature and flow thresholds from study site data

Standard monthly Environment Agency data from gauging stations at sites where time series of future river flow had already been developed were used to identify site-specific thresholds for flow and water temperature. This was done by plotting the river flows and water temperature against observed chlorophyll concentrations. Periods of increased chlorophyll concentrations (>$30\mu gl^{-1}$) were used to identify the flow and temperature ranges where enhanced phytoplankton growth was possible at the study sites (Figure 2.2).

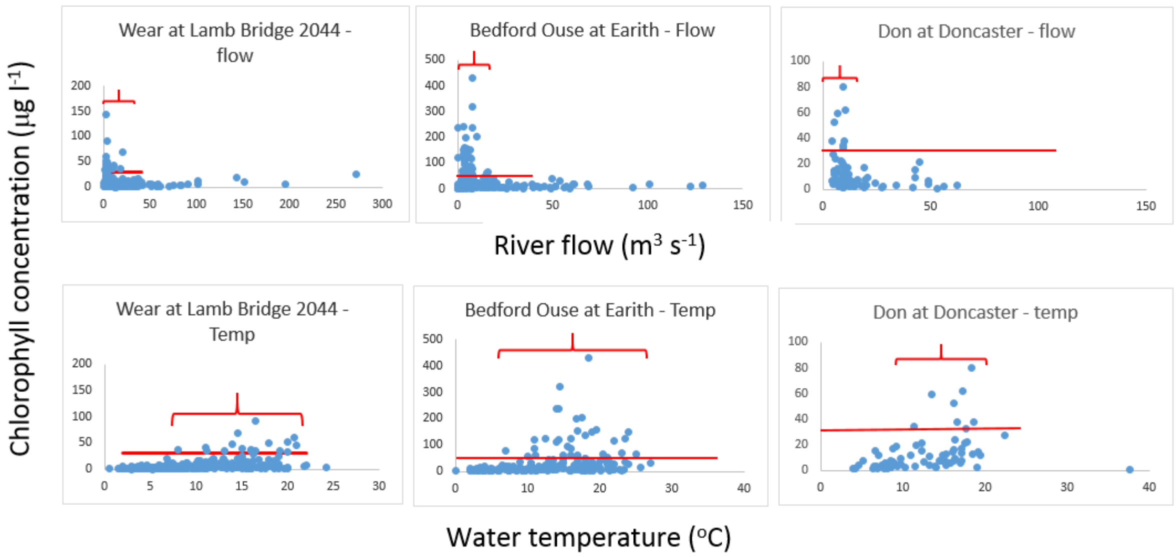

Figure 2.2 Example chlorophyll/river flow and chlorophyll/water temperature relationships

Notes: Red lines show chlorophyll concentration at 30µgl^{-1}.
: Red brackets indicate the range in river flow or water temperature when chlorophyll was >30µgl^{-1}.

Most sites showed a clear range of temperatures and flows where high chlorophyll concentrations where able to be produced.

For one site (the River Evenlode in Oxfordshire; data not shown), there was a very scattered relationship, with chlorophyll concentrations >30µgl^{-1} being observed at water temperatures as low as 3°C. This scatter may be due to disturbances during storm events of benthic algae, which dominate phytoplankton production within the water column. To provide more robust thresholds, it was decided to use available CEH dissolved silicon concentration data for this site – instead of chlorophyll concentrations – as an indicator of algal biomass and growth rate. The period of silicon depletion (indicating diatom growth and silicon uptake from the water column) was used to determine the water temperature range when growth was possible.

Previous studies of the Thames (Bowes et al. 2012, 2016) and other UK rivers (Bowes et al. 2011) have shown that diatom growth dominates the algal blooms in the spring and early summer. Having derived the thresholds, regression analysis was conducted on each of the thresholds and catchment characteristics (catchment area, base flow index, rainfall and urban extent) to see if there was any correlation that could be used to scale these thresholds up to a national scale.

2.3.2 Deriving sunlight duration thresholds

For each of the 30 sites identified, sunlight duration was estimated by calculating global solar radiation reaching the water surface in the stretches of river upstream of each monitoring site. The average upstream length evaluated was approximately 10km. Estimates were made using hourly global radiation observations and a canopy cover surface to account for blocking by riparian vegetation. A detailed description is provided in Section A.1 in the appendix; the steps are summarised below.

1. Rivers were defined as polygons from the Ordnance Survey (OS) MasterMap Topography Layer® and a 50m buffer created around each of these polygons.
2. A dataset of individual trees (National Tree Map, NTM) comprising location, height and tree crown extent was queried for each 50m buffer zone. A

continuous canopy surface model was created by interpolating the NTM to a 1m grid.

3. The canopy surface model was added to a DTM (NEXTMap®) to create a canopy height model of the riparian vegetation surface.
4. Daily riparian shade maps were created for each of the 30 river stretches using the canopy height model as input to the ArcGIS solar radiation tool. This produces a grid of daily duration in hours of direct incoming radiation, which can be interpreted as a map of shading (a map defining the fraction of the daylight length receiving direct radiation).
5. The shading maps were calculated at 10 day intervals covering the growing season between 2 March and 30 September to cover seasonal shift in the relative position and orientation of the Earth and the Sun.
6. A single estimate of total daily shading for each river was estimated by averaging the number of hours of direct incoming radiation for all grid cells. Linear interpolation was carried out to derive values on a daily resolution from the values calculated every 10 days.
7. Hourly global radiation observations from 2010 to 2014 from Met Office stations (selected based on their proximity to each of the 30 river stretches) were aggregated to daily values. To calculate radiation reaching the water surface, the daily radiation values were multiplied by the fraction of the daylight length receiving direct radiation.
8. It was assumed that all sites required at least 3 hours of full sunshine per day over ~3 consecutive days (derived from the Thames study; Bowes et al. 2016). Such periods were identified from the recent British Atmospheric Data Centre data for each site. The minimum W/m^2 that equated to this period was then determined – a value of 65W/m^2/day.

2.4 Testing the assumptions made

To ensure that all the important variables controlling current chlorophyll risk were being considered, whether they provided reliable predictions of chlorophyll concentrations for observed data was tested.

An important feature of this regression approach was that it included a deterministic means of assessing the factors controlling phytoplankton growth based on established mechanistic theory (Chapra 1997) adopted in process-based river quality models in contrast to the empirical approach adopted in the development of the time series predictive model. A multiple linear regression approach was adopted to estimate the growing season mean chlorophyll concentration in the 30 sites used following residence time calculations. This formed a national level regression model.

In the approach, the mean chlorophyll concentration (y) is related to up to 2 independent variables (x). These variables are:

- Growth rate – defined based on a combination of limitation factors (phosphorus, light, temperature). These are formulated for a mixed population of either algae (x_1), or for centric diatoms (x_3) which have optimum light intensities that are ~30% lower.
- Residence time (see Section 2.2) – either at mean flow (x_2) or low flow (Q90) (x_4)

Methods for calculating the maximum growth rate (a function of temperature) and the light and phosphorus limitation factors are described more fully by Hutchins (2012) and Waylett et al. (2013). The analysis is described fully in Section A.2 of the appendix.

Eight different models were tested. A combination of low flow residence time and growth rate provides an acceptable predictive model for mean chlorophyll concentration in the rivers tested here. Although the low flow indicator and mixed algae growth model is best, it only explains 54% of the variance in inter-site mean chlorophyll, indicating that other hydraulic and biological factors are operating.

2.5 Deriving time series projections

A range of data sources was used to produce daily time series of the controlling variables for each FFH site from 1951 to 2098.These were input to a spreadsheet model for calculating risk (see Section 2.6).

The original FFH time series was used to provide daily flow values for each site. The FFH datasets consist of an ensemble of time series of daily average river flow for 11 potential flow futures from 1951 to 2098 for 150 sites in England. These flows were used to estimate future phosphorus concentrations in Phase1 of this project for 115 sites; these series were used directly in Phase 2 for those sites that satisfied the residence time criteria. Of the 115 Phase 1 sites, 30 had a residence time of more than 4 days. The calculated phosphorus concentrations based on the analysis in Phase 1 (see Section 1.2) were used to provide daily phosphorus concentrations for each site.

No projections of water temperature currently exist. A number of different approaches can be used to estimate future water temperature as discussed in Section A.3 in the appendix. Only 4 of the 30 sites identified had observed water temperature records that could be related to air temperature records – from UK Climate Projections 2009 (UKCP09) observed gridded data.

After comparing different approaches (outlined in Section A.3 in the appendix), the following approach was used.

1. Acquire the water temperature and air temperature records for the 4 sites.
2. Take a rolling average of the preceding 5 days of air temperature and match these with the observed water temperature for each site.
3. Determine a linear regression equation for each season at each site.
4. Average these 4 sets of seasonal parameters and assess estimation error.
5. Apply the seasonal regression equations to daily time series of air temperature that were used in the generation of Future Flows Climatology within the spreadsheet model for all sites.

Air temperature projections are not readily available as a Future Flows Climatology product (which provides time series of precipitation and potential evapotranspiration) and were extracted for the 30 sites meeting the residence time criteria by CEH.

For sunlight duration, time series of radiation data (W/m^2) were extracted from the FFH climate scenarios by CEH. The shading factor developed in Section 2.3.2 was applied to these.

This approach resulted in 11 daily time series for each variable from 1951 to 2098.

2.6 Spreadsheet model for eutrophication risk

Having identified critical thresholds for the various potential controls of eutrophication risk, a spreadsheet where these could be entered (and altered easily) was constructed. The spreadsheet contains times series of:

- river flow
- phosphorus concentration (under current management and a future sewage treatment scenario)
- air temperature – converted by an inbuilt model to water temperature using a seasonal regression (parameters are input on the threshold input page for each site)
- sunlight duration – converted by the model into a 3-day average value

For each day, the spreadsheet takes the threshold inputs for each site and compares them with the time series to determine if each threshold is met. For each day, for 11 climate scenarios, the spreadsheet then determines when all 4 thresholds are met. Within the spreadsheet, the total number of days each threshold and all 4 thresholds are met is calculated for the baseline period (1961 to 1990) and the 2 future periods defined as ‘2050s’ (2040 to 2069) and ‘2080s’ (2070 to 2098). These totals are divided by the number of years in the period to give an annual average of threshold days when excessive algal growth is possible. When all 4 thresholds are met, this is termed a bloom risk day (BRD).

For the future periods, percentage changes are calculated from the baseline period for each ensemble member. To represent the uncertainty across the range of the 11 ensemble members, the compute maximum, minimum and median BRD values (absolute and percentage change) are computed. The model also determines the first day of the year on which all thresholds (individual and BRD) are met for each decade from 1951 onwards.

All values were calculated for current sewage treatment works (STW) conditions and a future scenario likely to be implemented by water companies.

2.7 Mapping eutrophication risk

Future values of controlling variables and their combined occurrence were then mapped (using ArcMap 9.3) 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.

3 Results

3.1 Residence time

Of the 115 stations used to estimate future phosphorus concentrations in Phase 1, only 30 met the criteria of having a residence time of 4 days or more. Figure 3.1 shows:

- the location of the 30 sites on 28 rivers
- the average residence time in days
- the low flow residence time
- the length of river stretch over which these were determined (route length)

There are strong relationships between residence time and both catchment area (not shown) and route length. Geographically there is no obvious pattern, either in the distribution of sites exceeding or not reaching the threshold residence time. However, residence times appear higher in sites in the relatively dry and flat south-eastern parts of the country. In regions apart from the south-east, it is rare for residence times to be sufficient at sites where the catchment area is <500km^2 and the upstream river length <50km.

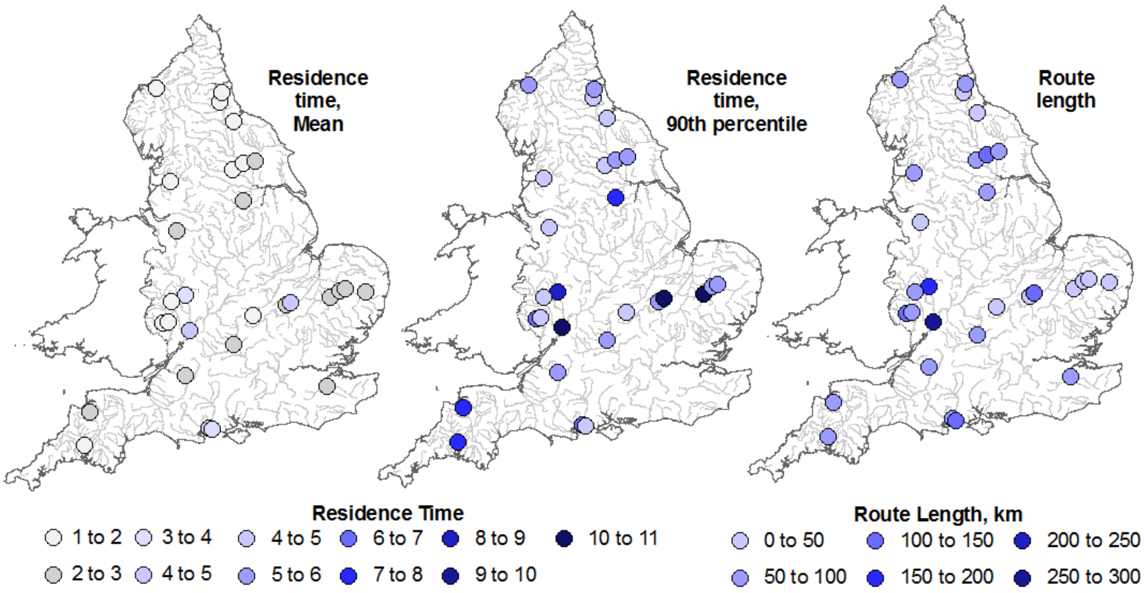

Figure 3.1 **Residence time in days (mean and 90th percentile) of sites meeting the ≥4 days' criterion and route length (km)**

3.2 Thresholds

Following an approach outlined in Bowes et al. (2016), the ranges of flow and water temperature were determined where high chlorophyll concentrations were measured (Table 3.1). This was achieved by looking at an observed time series of chlorophyll and noting the temperature and flow conditions when high chlorophyll values were observed.

There were no data for the Kim at Meagre Farm (33012) and so the threshold analysis was conducted on a total of 29 sites. The Thet at Milford Bridge (33019) and the Thet at Bridgham (33044) both had no chlorophyll data, making it impossible to determine the flow and temperature thresholds. This reduced the number of sites for the risk analysis to 27.

Table 3.1 Threshold values for the controls of chlorophyll concentrations for each location with residence times >4 days

Site name (number)[1]	Chlorophyll threshold (μgl^{-1})	River flow threshold		Water temperature threshold		Sunlight duration threshold (W/m^2/day)	TRP threshold (μg/l)
		Lower (m^{3}s^{-1})[2]	Upper (m^{3}s^{-1})	Lower (°C)	Upper (°C)		
Browney at Burn Hall (24005)	30	0	2.09	12	21	65	30
Wear at Chester le Street (24009)	30	0	20	8.4	21	65	30
Leven at Leven Bridge (25005)[2]	24	0	4.2	6	15.6	65	30
Wharfe at Flint Mill Weir (27002)	30	0	60	10.7	18.8	65	30
Ouse at Skelton (27009)	23	0	15	13	21	65	30
Don at Doncaster (27021)	30	0	11	11	19	65	30
Derwent at Buttercrambe (27041)	17.5	0	18.2	7	16	65	30
Kym at Meagre Farm (33012)[3,4]							
Lark at Temple (33014)	30	0	1.85	10	19	65	30
Tove at Cappenham Bridge (33018)	30	0	0.65	13	18	65	30
Thet at Melford Bridge (33019)[3,4]	30					65	30
Bedford Ouse at Offord (33026)	40	0	18.8	7	25	65	30
Thet at Bridgham (33044)[3,4]	30					65	30
Waveney at Needham Mill (34006)	26	0	1.1	10	18.3	65	30
Thames at Kingston (39001)	100	0	75.5	10	22.5	65	30
Evenlode at Cassington Mill (39034)	30	0	7.5	6	14.3	65	30
Medway at Teston (40003)[4]	40	2	10	10.5	20	65	30
Stour at Throop (43007)	30	5.1	13.1	7.7	16	65	30
Avon at Knapp Mill (43021)	30	15	24	9.9	13.2	65	30
Tamar at Gunnislake (47001)	20	0	50	5	14	65	30
Torridge at Torrington (50002)	28	0	92	9	20	65	30
Avon at Bathford (53018)	30	0	7.8	9	22	65	30
Severn at Bewdley (54001)[4]	30	0	32	12	17	65	30
Teme at Tenbury (54008)	15	0	17	12	17	65	30
Severn at Haw Bridge (54057)	50	20	56	12	17	65	30
Wye at Belmont (55002)	20	0	84	10	21	65	30

Site name (number)[1]	Chlorophyll threshold ($\mu g l^{-1}$)	River flow threshold		Water temperature threshold		Sunlight duration threshold ($W/m^2/day$)	TRP threshold (µg/l)
		Lower ($m^3 s^{-1}$)[2]	Upper ($m^3 s^{-1}$)	Lower (°C)	Upper (°C)		
Lugg at Lugwardine (55003)	19	0	6.1	11	16	65	30
Weaver at Ashbrook (68001)[4]	50	0	32	13.9	23.5	65	30
Ribble at Samlesbury (71001)	30	0	97	8.9	22.5	65	30
Eden at Sheepmount (76007)	30	0	21	12.6	22.2	65	30

Notes:

[1] For details of the individual gauging stations, see the National River Flow Archive (NRFA) (http://nrfa.ceh.ac.uk).

[2] A zero flow indicates that high chlorophyll concentrations could occur at any flow below the upper threshold.

[3] Not used in the spreadsheet analysis (see Section 2.6).

[4] Not used in the statistical modelling (see Section A.2 in the appendix).

TRP = total reactive phosphorus

A summary of the results is given below.

- For the 29 sites with chlorophyll thresholds indicating the onset of algal blooms from eutrophication, almost half of the sites (14) have a threshold of $30 \mu g l^{-1}$, with 5 above this and the remainder below. The range is between $15 \mu g l^{-1}$ for the Teme at Tenbury (54008) in Worcestershire and $100 \mu g l^{-1}$ for the Thames at Kingston (39001). This is because the chlorophyll thresholds were identified subjectively appropriate to each site. On larger rivers with higher chlorophyll concentrations (for example, the Thames), the thresholds were higher to ensure that changes in chlorophyll were identified. There is no association with catchment characteristics and no clear spatial distribution in these values.

- All 29 sites have a TRP concentration threshold of $30 \mu g l^{-1}$.

- Of the 27 sites with flow thresholds, 23 had a lower flow threshold of $0 m^3 s^{-1}$, indicating that high chlorophyll concentrations could occur at any flow below the upper threshold. At 4 of the sites, high chlorophyll concentrations did not occur at the very lowest flows and there was clearly also a lower threshold of up to $20 m^3 s^{-1}$. This is probably due to the phytoplankton settling out of the water column because of the extremely low flow velocities. The upper flow thresholds range is between $0.65 m^3 s^{-1}$ and $97 m^3 s^{-1}$, and there is a weak association with standard-period average annual rainfall (SAAR 61-90) ($R^2 = 0.5$).

- Water temperature thresholds are very site-specific ranging from 5°C to 14°C for the lower threshold and from 13°C to 25°C for the upper threshold. The distribution is uneven with the range of temperatures conducive to algal blooms ranging from 3°C at the Avon at Knapp Mill (43021) to 18°C at the Bedford Ouse at Offord (33026).

- All 29 sites have a sunlight duration threshold value of $65 W/m^2/day$ over 3 days.

3.3 Change in the number of BRDs

Spreadsheet modelling (see Section 2.6) was conducted for 26 sites. Three were excluded because thresholds could not be derived (see Section 3.2) and a fourth (Leven, 25005) had no sunlight time series. One site (Eden, 76007) had no BRDs in either baseline or future periods, despite satisfying the residence time criteria. This site is also excluded from the BRD results (but not later analysis of individual variables).

Estimated BRDs for the baseline period range between 1 day and 165 days across all sites and all 11 flow projections in the ensemble, with the median ranging from 2 days to 147 days (Figure 3.2, Table 3.2). Differences are greater between sites than within sites across different projections, with the greatest range across the ensemble being 37 days (Lark at Temple, 33014). There is no clear geographical spread in BRDs. Estimates have not been validated against observed chlorophyll concentrations.

Eutrophication risk increases into the 2050s relative to the baseline (Figure 3.3, Table 3.2) except at 2 sites (Stour at Throop, 43007; Avon at Knapp Mill, 43021) for the median projection. These changes are variable between sites with percentage change ranging from –43% to +92% across all sites and ensemble members (the range is -12% to +44% for the median across all sites). There is an increase in the maximum, median and minimum across the sites with an eutrophication risk of 96%, 92% and 54%, respectively, reflecting decreases in the minimum at almost half the sites, but overall agreement in the direction of change for median and maximum days.

Eutrophication risk shows a much more variable change into the 2080s relative to the baseline (Figure 3.4, Table 3.2). There is a reduction in the number of sites with very low risk day estimates. Changes are variable between sites, with the percentage change ranging from -65% to +688% across all sites and ensemble members (the range is -43% to +392% for the median across all sites). The very large percentage increase occurs at the Browney at Burn Hall (24005), while the increase is below 100% at all other sites. This is because of a large change (from about 2 to 12 BRDs) for 2 members of the ensemble. There is an increase in the maximum, median and minimum across the sites with an eutrophication risk of 92%, 52% and 28% respectively, reflecting a much more variable pattern of risk. There is less agreement in the direction of change for the 2080s than there for the 2050s.

Table 3.2 Absolute annual BRDs for all time periods and percentage change relative to baseline across ensemble and for median BRDs

	Baseline BRDs		2050s BRDs		2080s BRDs	
	Absolute (days)	**Relative change (%)**	**Absolute (days)**	**Relative change (%)**	**Absolute (days)**	**Relative change (%)**
Ensemble range	1 to 165	–	2 to 173	-43 to +92	4 to 172	-65 to +688
Ensemble median range	2 to 147	–	2 to 160	-12 to +44	6 to 160	-43 to +392
Ensemble agreement	–	–	–	Max: 96 Med: 92 Min: 56	–	Max: 92 Med: 52 Min: 28

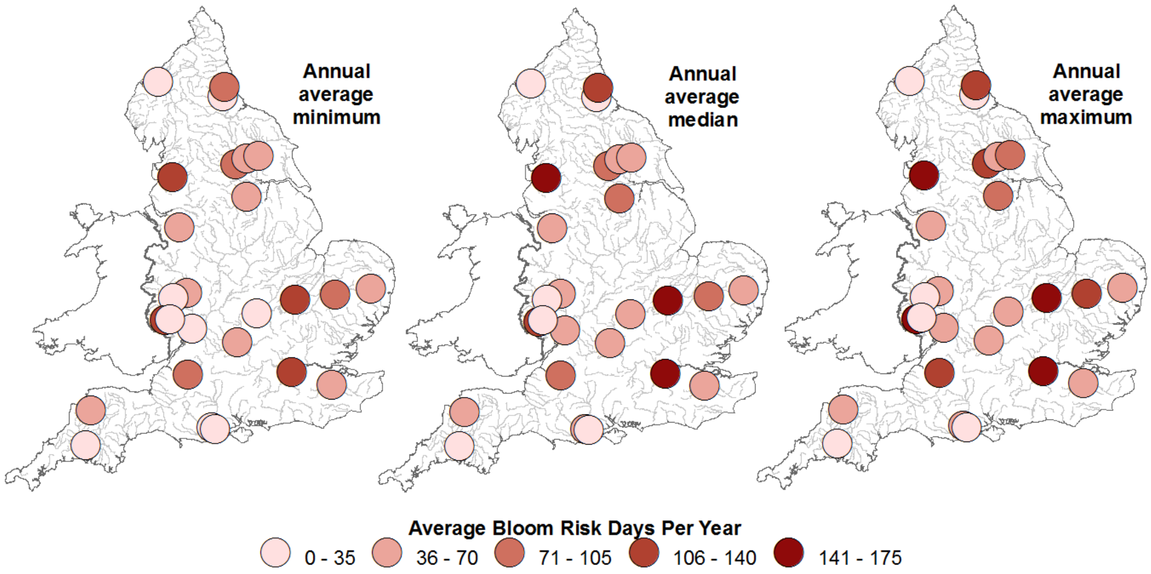

Figure 3.2 Average number of BRDs per year for baseline period (1961 to 1990)

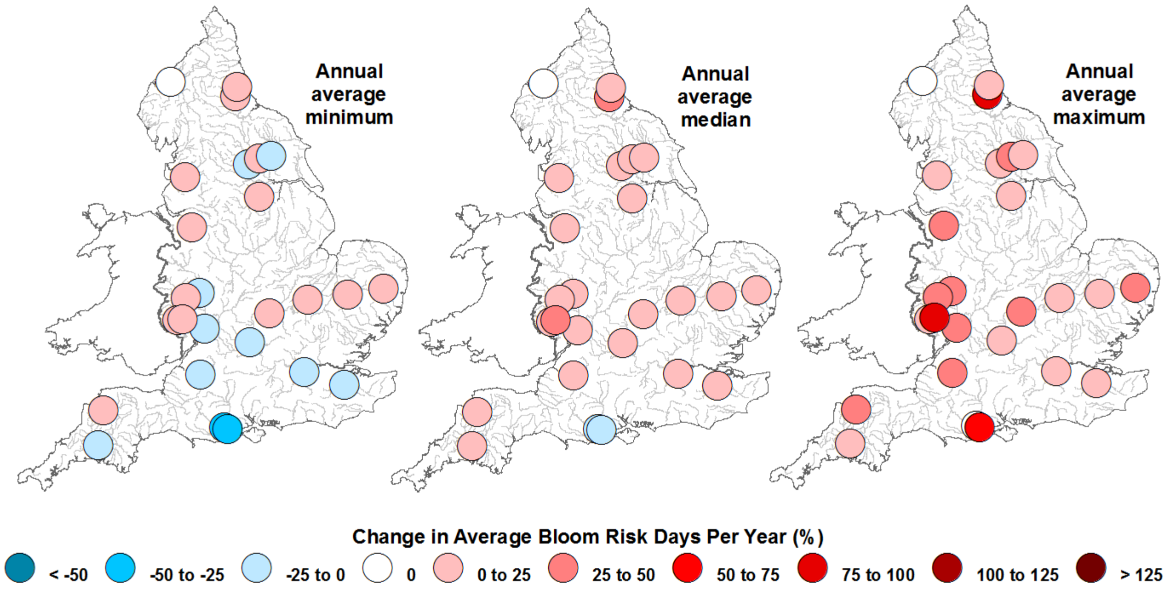

Figure 3.3 Percentage change in BRDs from baseline to 2050s

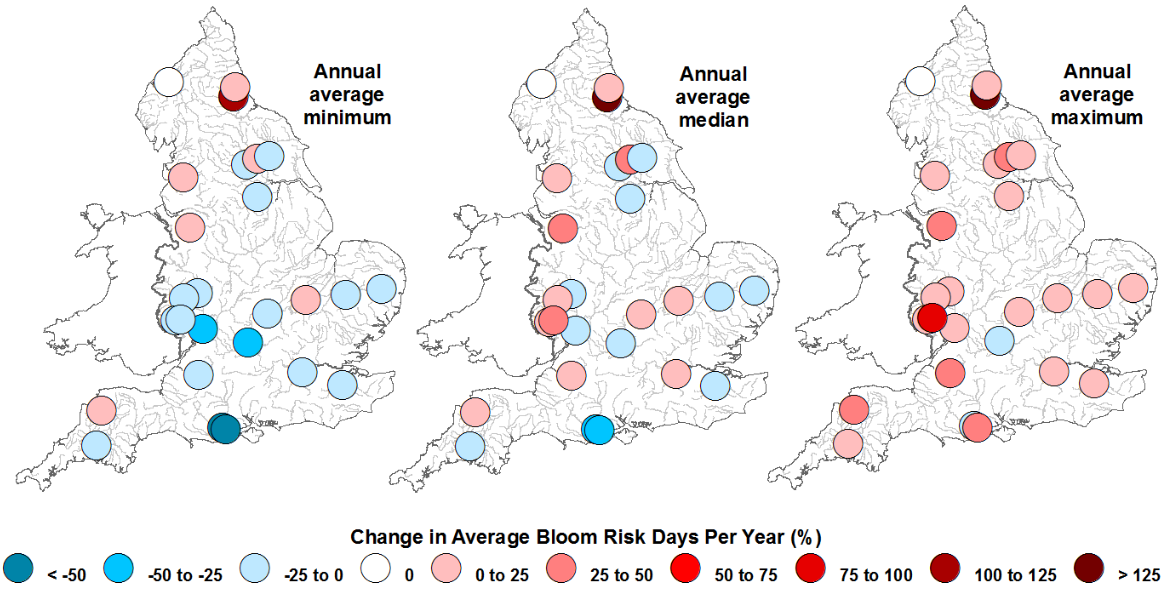

Figure 3.4 Percentage change in BRDs from baseline to 2080s

The analysis of BRDs shows that risk increases from baseline to the 2050s for all but 3 sites, of which 2 show a reduced risk and the other has no risk at all. The change in risk is mixed between the baseline and 2080s, with 50% of sites increasing and 50% decreasing. This reflects a reduction in risk at many sites between the 2050s and 2080s as illustrated in Figure 3.5. There is more variation between sites than across time periods. While only 2 sites have reduced median BRDs between the baseline and the 2050s, this number increases to 13 sites between the baseline and 2080s. However, 80% of median BRDs reduce between the 2050s and 2080s.

The improved treatment scenario from Phase 1 resulted in limited improvement in phosphorus concentrations (between 0 and 20%; Charlton et al. 2018) at about half of the 115 sites modelled (greater improvements were realised at the other sites). Removing phosphorus from effluent is currently the main treatment strategy for reducing eutrophication risk. The threshold analysis was repeated using the time series for phosphorus reductions from Phase 1. Of the 26 sites assessed, only 3 (Wharfe, 27002; Tamar, 47001; Lugg, 55003) demonstrate any changes in the number of days that all 4 thresholds are met. This is because in, all other cases, the phosphorus concentrations exceed the phosphorus threshold of 30µgl^{-1} despite the removal of more phosphorus from sewage effluent.

Based on the thresholds used in this study and the assumed level of phosphorus reduction applied in Phase 1, control of phosphorus from effluent alone would not be sufficient to prevent the risk of algal blooms occurring in the majority of these rivers. Other means of reducing eutrophication may therefore be necessary or much more substantial reductions in phosphorus are required to eliminate eutrophication risk. It should also be remembered that algal blooms are only one aspect of eutrophication.

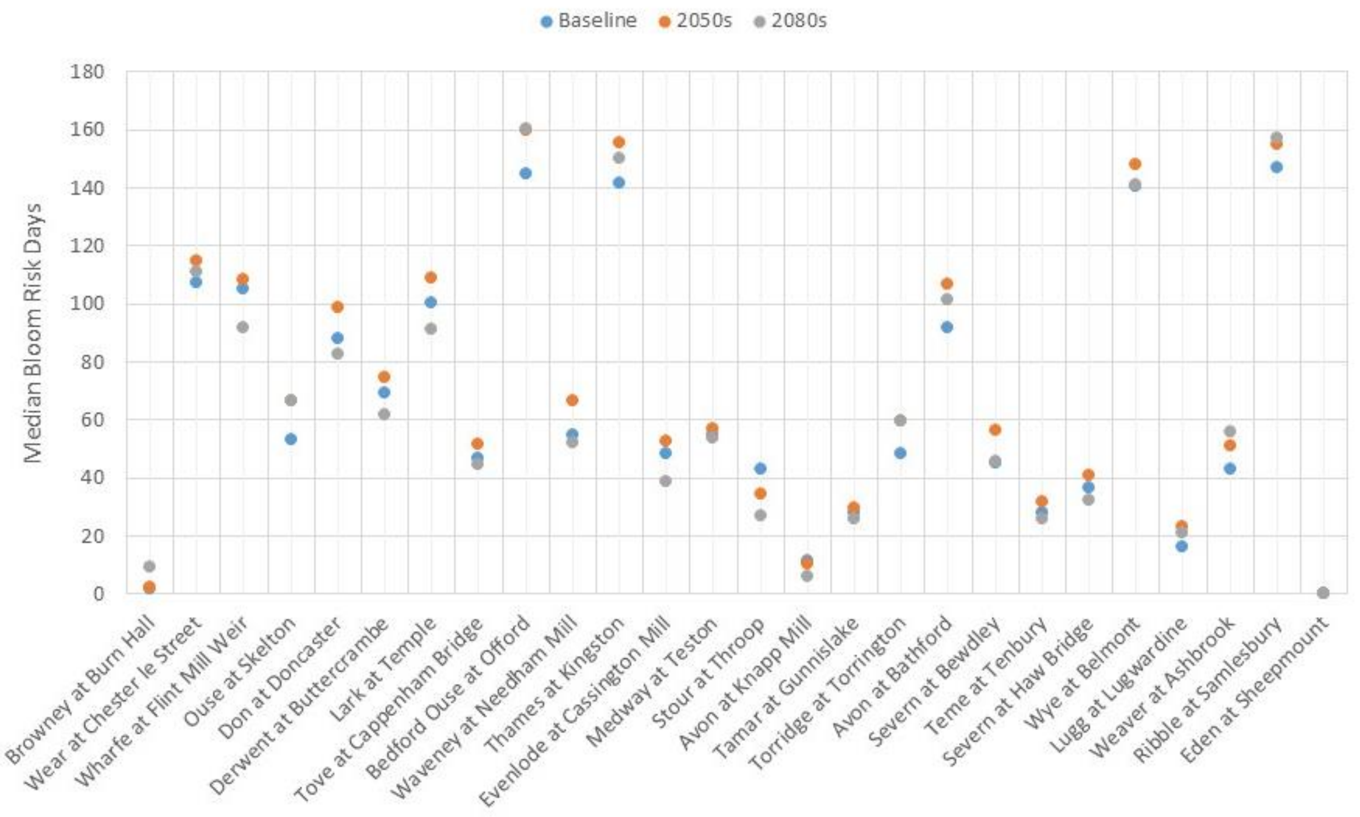

Figure 3.5 **Median BRD for each site for each time period**

3.4 Understanding risk

The results described above give a clear indication of a variable pattern of generally increasing future eutrophication risk, particularly into the 2050s. However, it is not clear what is driving the changes in risk. In particular, what is driving the increase to the 2050s and the subsequent decrease in risk to the 2080s?

The average number of days that thresholds for each driver (phosphorus concentration, river flow, water temperature and sunlight duration) were met for each time period (baseline, 2050s and 2080s) were extracted for the median value across the ensemble of 11 projections. The range of days thresholds are met for are as follows:

- Phosphorus concentration – between 295 and 366 days
- River flow – between 65 and 361 days
- Water temperature – between 66 and 297 days
- Sunlight duration – between 28 and 202 days

The driver with the smallest number of days when thresholds are met will determine the number of days on which all thresholds are met. The number of BRDs will also depend on when the individual thresholds are met. Thus, the driver with the lowest frequency of exceedance will limit the occurrence of BRDs. The analysis of individual drivers in the spreadsheets (Figures 3.6 to 3.9) suggests that, in general at a given site, there is consistency between the years and also the order in which the greater number of days the thresholds are met.

- For 25 sites, phosphorus concentration thresholds are met most frequently, normally on 365 days of the year (the average is over 365 due to the inclusion of leap years). For the Wharfe (27002) in Yorkshire, the phosphorus threshold is met on 300 days in baseline with a slight reduction to about 295 days for the future periods. For the Eden (76007) in Cumbria, the phosphorus threshold is met most frequently of all the drivers but only for about 195 days.
- There is more variability in the other drivers, with river flow thresholds tending to be the second most frequently exceeded. Thresholds for water temperature and sunlight duration are met on far fewer days.
- The number of days for the least frequent driver often closely matches the number of days when all thresholds are met and can be seen as limiting bloom risk at a particular site.
- Sunlight duration appears to be the dominant limiting factor, having the lowest number of threshold days at 14–16 of the 26 sites, depending on the time period.
- Apart from at 5 locations, the pattern of drivers is consistent throughout the time periods (Table 3.3), suggesting that changes in magnitude and timing are important.
- There is no clear geographical distribution in the patterns of the limiting factors.

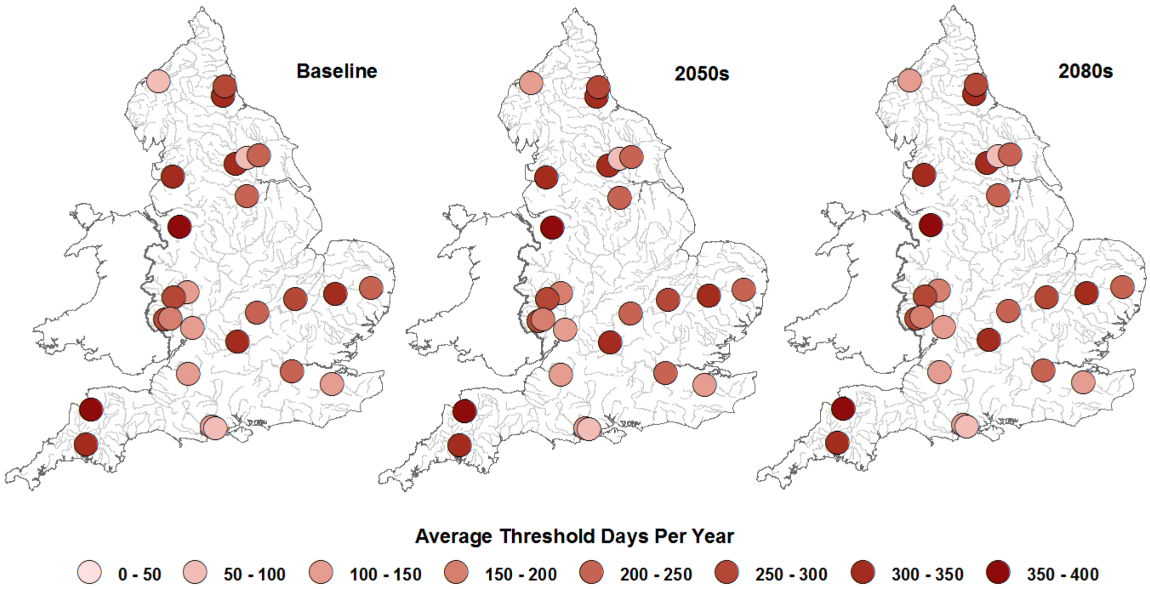

Figure 3.6 Average number of days per year in each time period where river flow thresholds are met

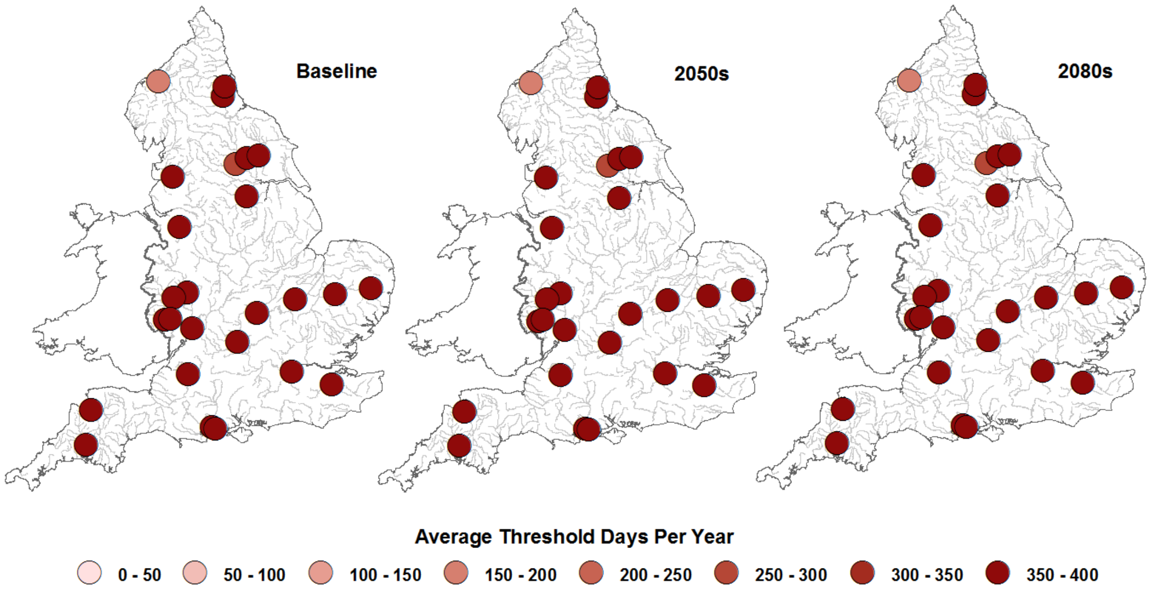

Figure 3.7 Average number of days per year in each time period where phosphorus concentration thresholds are met

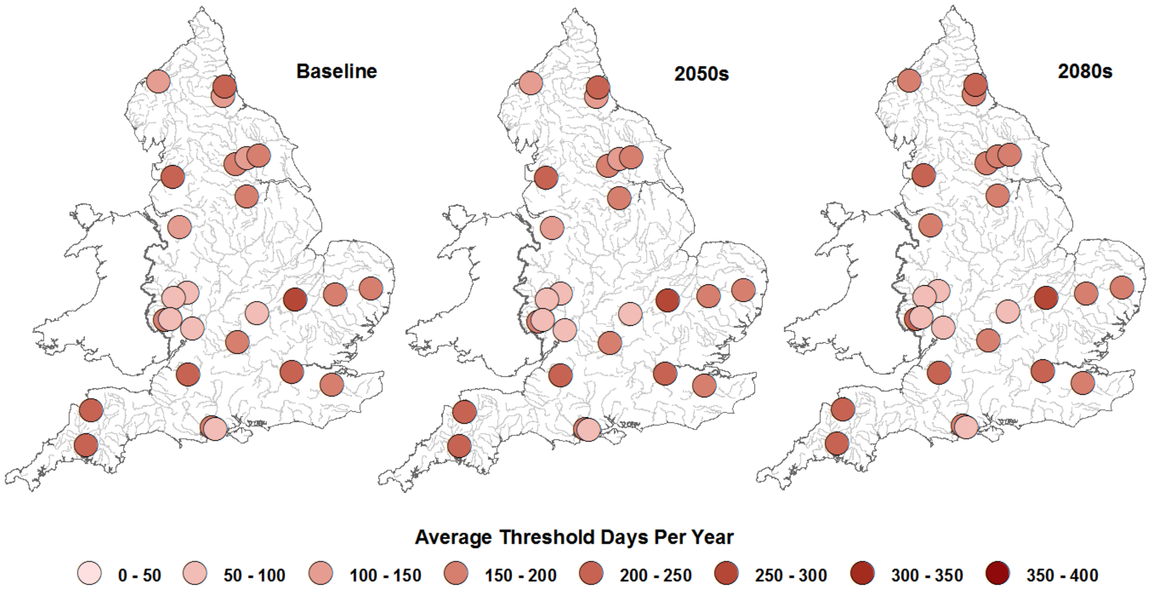

Figure 3.8 Average number of days per year in each time period where water temperature thresholds are met

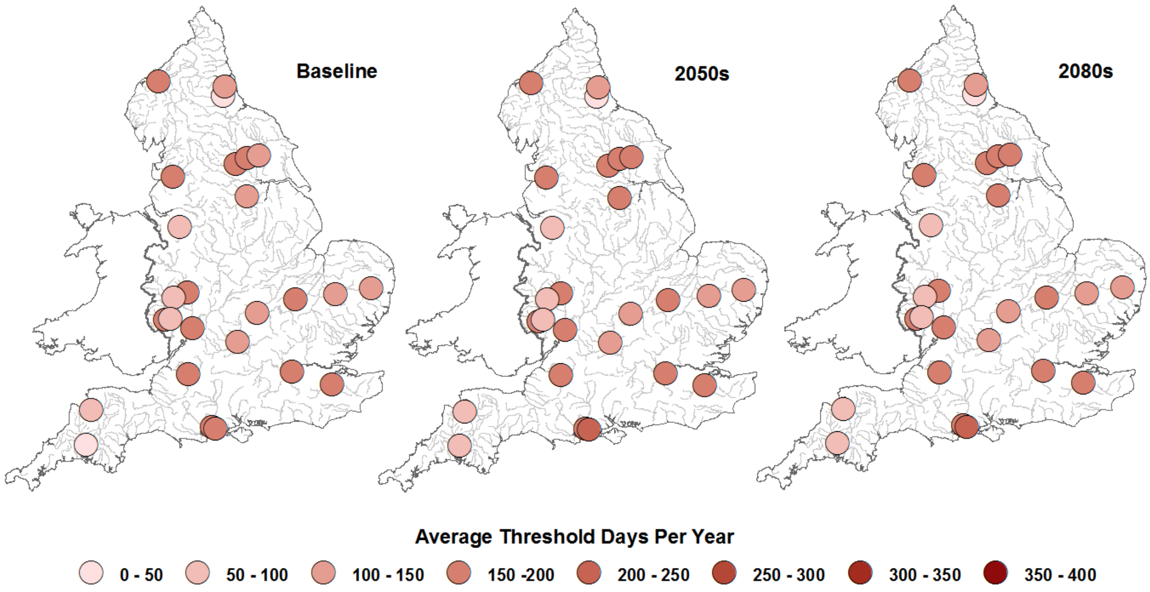

Figure 3.9 Average number of days per year in each time period where sunlight duration thresholds are met

Table 3.3 Patterns of lowest to highest number of thresholds exceeded for the 26 sites across all time periods

Pattern (lowest to highest number of days)	Number of sites	Sites
Sunlight duration – Water temperature – River flow – Phosphorus concentration	13	Browney (24005) All others not listed below
River flow – Water temperature – Sunlight duration – Phosphorus concentration	4	Eden (76007) Ouse (27009) Medway (40003) Stour (43007)
Water temperature – River flow – Sunlight duration – Phosphorus concentration	2	Severn at Bewdley (54001) Severn at Haw Bridge (54057)
Water temperature – Sunlight duration – River flow – Phosphorus concentration	1	Tove (33018)
River flow – Sunlight duration – Water temperature – Phosphorus concentration	1	Avon at Bathford (53018)
Not consistent across future time periods	5	Wharfe (27002) Don (27021) Bedford Ouse (33026) Avon at Knapp Mill (43021) Lugg (55003)

To determine which controlling variable is influencing the change in risk from the 2050s to the 2080s, the sites were split into 2 groups:

- Group 1 – sites with fewer risk days in the 2080s compared with the baseline (13 sites)
- Group 2 – sites with more risk days in the 2080s compared with the baseline (13 sites but includes the site with no overall change in risk, that is, Eden).

This gave the following for the number of days thresholds are met for.

- Phosphorus concentration – does not change for both groups
- River flow – sometimes increases and sometimes decreases in both groups (5 sites increase and 8 decrease)
- Water temperature – always increases for Group 2 and increases for only 6 sites in Group 1
- Sunlight duration – mainly increases in Group 1 (10 increase, 3 decrease) but mainly decreases in Group 2 (3 increase, 10 decrease)

Increases in the number of days where temperature thresholds are met appear to be driving the increase of risk into the 2080s, with changes in sunlight moderating this at some sites.

- Where water temperature tends to increase, sunlight duration tends to decrease or change very little in the number of threshold days.
- At sites with more risk days in the 2080s (that is, Group 2), increases in the number of water temperature threshold days tend to be quite large, increasing by more than 10%.
- The analysis is sensitive to sunlight duration because of the limited number of days that sunlight duration thresholds are met.

3.5 The timing of risk

The spreadsheet determines the earliest BRD of each decade and shows no clear trend for maximum, median or minimum first days taken as a median across all sites (Figure 3.10).

The timing of individual thresholds was analysed to determine any trends that may influence the occurrence of future eutrophication risk. The analysis suggested the following.

- In all cases, the median first day for meeting the phosphorus concentration threshold is unchanging through time (no trend) and occurs on the first day of the year (concentration threshold is always met except for the Eden site).
- For river flow, the median first day always occurs in the first 45 days.
- Water temperature thresholds are met later in the year than phosphorus concentration and river flow thresholds. The median first day for meeting the water temperature threshold across all sites and decades is between 63 to 93 days.

- For sunlight duration, the median threshold is met later still at between 121 and 137 days.
- As with the first day for BRDs, the analysis of the first day that each driver threshold is met shows no clear trend over time.
- However, there is a weak tendency towards first day thresholds for river flow being met slightly later over the course of the time series and for water temperature thresholds to be met slightly earlier. For sunlight duration, the response is more variable, with about 50% of sites showing a weak tendency towards later threshold attainment as time progresses.
- Where the pattern is the dominant Sunlight duration – Water temperature – River flow – Phosphorus concentration, the timing of the overall threshold first day is dependent on the timing of the sunlight duration threshold.

It is not currently clear to what extent the timing of thresholds being met influences the risk of algal blooms. However, it is likely to modify the impact of the limiting controlling factors.

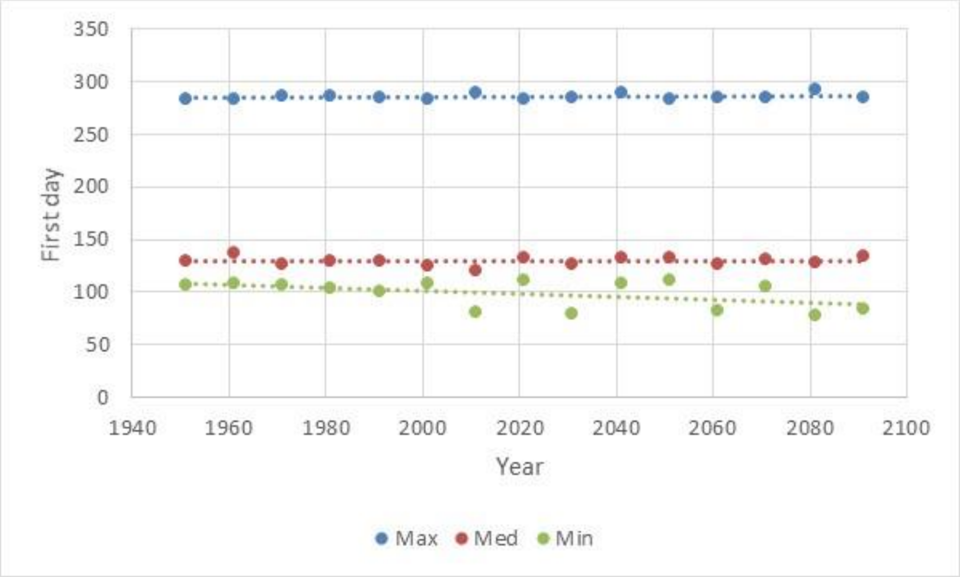

Figure 3.10 Timing of first BRD in each decade across all sites: maximum (latest), median and minimum (earliest) day in year

4 Discussion and recommendations

The analysis of thresholds applied to generated time series of controlling variables made it possible to assess change in eutrophication risk (as expressed by algal blooms) due to climate change based on changes to the number of days in which all thresholds are exceeded. This approach identified 5 controls on future algal bloom risk:

- Residence time is critical. Only 30 of the original 115 sites exceeded the residence time threshold of 4 days.
- Three controls are directly climate related being dependent on changes in climate variables: river flow, water temperature and sunlight duration.
- Climate factors indirectly influence phosphorus concentration through changes in flow.

Testing was conducted to determine whether these variables provided reliable predictions of chlorophyll concentrations for observed data.

A combination of low flow residence time and algal growth rate was found to provide an acceptable predictive model for mean chlorophyll concentration in 24 of the 30 rivers that could be tested (the best model only explains 54% of the variance in inter-site mean chlorophyll). The residence time (or transit time) is not the same thing as the flow threshold, but they are linked. The residence time is simply used to select the rivers that are long enough to produce reasonable chlorophyll concentrations (at low flow). At these 30 selected sites, the flows will be too high for most of the year and the residence times will be too short to enable high chlorophyll levels to develop. The flow threshold identifies when the flow gets low enough to allow algal biomass to accumulate (due to the longer residence time) and is site-specific.

Such an analysis could be used to produce a map of residence time for every river in England to show the current risk of algal bloom development. However, these residence times are based on current and not on future conditions, and therefore future risk may be slightly different. An assessment of future residence time in all rivers would be a useful indicator of future eutrophication risk and indicate where measures to reduce solar radiation penetration through shading might be most effective.

The threshold analysis shows that, across the sites, phosphorus concentration and sunlight duration thresholds are consistent but that there is considerable variability in the upper and lower water temperature and river flow thresholds, and therefore the potential range over which algal bloom risk (indicating eutrophication) could occur under changing conditions of these drivers.

High-resolution monitoring data were critical to the identification of thresholds. Without it the detailed understanding of algal dynamics in response to climate change would not have been possible. Such monitoring is necessary, at the very least, at important or vulnerable sites to:

- increase understanding
- direct and assess management options using the model developed here

Analysis of BRDs indicates that:

- baseline risk is between 1 and 165 bloom days depending on site and scenario

- risk increases from the baseline to 2050s time period for all but 2 sites
- risk increases from the baseline to 2080s time period for 52% of sites (48% of sites decrease in risk from the baseline to the 2080s)
- risk consequently decreases from the 2050s to the 2080s time period for most sites 80%)
- there is no trend in the timing of the risk, with the first day of the year that all thresholds are met remaining relatively constant through time, though it is variable between sites

The changes in the attainment of individual thresholds were also examined to assess which controlling variables had the greatest influence on the overall risk outlined above and, in particular, why the risk decreases into the 2080s.

Although variable between sites, the phosphorus concentration threshold is exceeded most frequently, usually followed by the river flow threshold and then either the water temperature or sunlight duration threshold.

Phosphorus concentration is only limiting to the risk of algal blooms in the future at one site – the River Eden (76007) in Cumbria. The phosphorus concentration at all other sites is almost always sufficient for eutrophication onset to occur, based on the thresholds selected for this study, even under the improved treatment scenario.

This means that water temperature and sunlight duration are more often limiting for eutrophication risk. Of these, sunlight duration appears to be the most important factor at over half the sites, tending to reach threshold conditions less often and later than the other drivers in these cases. At sites that increase in risk from baseline to 2080s, there is an increase in the frequency of water temperature thresholds being exceeded. At the 5 sites where risk increases between the 2050s and 2080s, changes in water temperature appear to drive an increase in the number of days the water temperature threshold is met of more than 10% relative to small changes in other variables. The water temperature range is important to the frequency of days within the threshold, but it is currently not clear that the increase in range is greatest at those sites with increased risk into the 2080s. It is also not clear whether the reduction into the 2080s at the other sites is caused by a reduction in this range or by the change in sunlight duration that seems to occur at these sites but not the others.

Furthermore, the water temperature results are very dependent on the water temperature time series generated from regression analysis with air temperature. There is a fundamental lack of future projections of stream temperatures and the approach adopted here provides only an approximation of future potential changes, with standard error of the estimate up to 1.48 for 4 test sites. Although errors have been minimised in the approach adopted here, these may have a strong influence on the results for eutrophication risk. Preliminary investigations suggest that the model is very sensitive to this variable. Understanding future impacts of climate change on water quality are hampered by the limited availability of suitable models – this is a key risk noted in the UK Climate Change Risk Assessment 2017 Evidence Report (Committee on Climate Change 2017). Water temperature is a fundamental driver for many ecological riverine processes and future projections of water temperature are critical to understand how these other impacts in addition to changing eutrophication risk may be affected by climate change.

One site (Eden, 76007) is not at risk of eutrophication in baseline and future periods. This is primarily because the phosphorus concentrations are very low at this site. The site was identified previously as having high Water Framework Directive status in all time periods and under all scenarios (Environment Agency 2016). The phosphorus concentration threshold was reduced at this site until BRDs occurred. With all other thresholds constant, the phosphorus threshold needed only to decrease to 26μgl^{-1} (from 30μgl^{-1}) to result in eutrophication risk. This shows that only a small increase in phosphorus concentration will result in eutrophication. Furthermore, in the original analysis, phosphorus concentrations are often sufficient to exceed the threshold but do not coincide with exceedance of the other thresholds (they still occur earlier in the year than the others).This result also shows that it is not always the case that, if residence time threshold is met, there will be eutrophication risk.

The fact that the phosphorus concentration does not seem to limit algal bloom risk under current or improved treatment scenarios suggests that phosphorus reduction strategies will only be effective if phosphorus concentrations can be lowered sufficiently to be below trigger thresholds. It should be noted that algal blooms are only one biological response to nutrient enrichment and reduction of phosphorus may have other benefits not considered here. Whilst phytoplankton blooms tend to be observed in lowland reaches of English rivers, the approach applied here is independent of this and is equally applicable anywhere. It offers the potential for use in an approach for assessing eutrophication in slow flowing rivers.

Sunlight duration and water temperature have the fewest number of days when the thresholds are exceeded, resulting in lower overall risk (fewer days on which all thresholds are met). This suggests that there may be more value in targeting sunlight duration and water temperature regimes (for example, through managing riparian shade) at some locations to reduce the adverse impacts of blooms.

Management options should be evaluated on a case-by-case basis, taking into account the change in the controlling variable that results in the fewest number of days of risk. This can be achieved using the approach and the spreadsheet developed here. The spreadsheet could be updated with improved relationships (for example, between air and stream water temperature) and can be used to explore future management options (for example by changing shading factors) for the 26 sites used in this study.

4.1 Recommendations

4.1.1 Map current and future residence times

It is clear that residence time is the most important variable in eutrophication risk. A wide assessment of all rivers under current and future flow conditions would therefore be helpful. In particular, this may indicate where water quality might deteriorate and identify sites beyond those investigated here where increased riparian shading may be effective at reducing risk. This can be achieved using the approach used here and existing FFH data.

4.1.2 Develop water temperature projections

Robust evaluation of future water quality is severely constrained by a lack of water temperature projections. An assessment of modelling options is needed to develop future water temperature projections to support future planning. The analysis is currently limited by the approach used in this study to derive water temperature estimates. Ideally, dedicated water temperature projections generated in a way consistent with the other climatic and impact factors would be used. Such projections would be consistent with other climate and impact factors, and would make it easier to assess the impacts on other aspects of the riverine environment, such as salmonid spawning.

4.1.3 Explore other drivers of risk

Climate change is one of many drivers and its impact relative to others such as changes in population growth and land use should be explored to understand the context of climate change and assess more fully how different management options will reduce future risk.

5 Conclusions

- Eutrophication risk was, in general, found to increase in the future at the 26 FFH sites in England assessed in this study. The number of days where blooms are likely to occur increased into the 2050s for 24 of the 26 sites. After the 2050s, the pattern of increasing risk of eutrophication is inconsistent, with about 50% of sites showing a reduction in risk by the 2080s relative to the baseline period.
- Residence time is the primary control on algal bloom occurrence. There needs to be sufficient river length and time for algal biomass to develop to cause algal blooms.
- Phosphorus concentrations are only low enough at one of the studied sites to prevent a risk of algal blooms. At all the others, the phosphorus concentration is high enough for all time periods.
- Flows are regularly low enough to contribute to bloom risk.
- The risk of eutrophication is dependent on conditions that are warm and sunny enough, although the interaction of these and their impact on the risk assessed here needs to be explored fully.
- The results suggest that phosphorus reduction strategies will only be effective in reducing the incidence of algal blooms if phosphorus concentrations can be lowered sufficiently to be below trigger thresholds, and that there may be better value in targeting sunlight and temperature regimes (for example, through managing riparian shade).
- The methods developed here could help to evaluate the most effective options for reducing bloom risk and preventing deterioration in water quality.
- Better estimates of future water quality depend on better information about how water temperature will change.
- A map of future residence times would be a useful tool for planning sustainable catchments in future.

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List of abbreviations

AIC	Akaike Information Criterion
BRD	bloom risk day
CEH	Centre for Ecology and Hydrology
CHM	canopy height model
CSM	canopy surface model
DO	dissolved oxygen
DTM	digital terrain model
FFH	Future Flows Hydrology
GIS	geographical information system
NRFA	National River Flow Archive
NTM	National Tree Map
OS	Ordnance Survey
Q90	90th percentile flow
SAAR	standard-period average annual rainfall (1961 to 1990)
SEE	standard error of the estimate
SRP	soluble reactive phosphorus
STW	sewage treatment works
TIN	triangulated irregular network
TRP	total reactive phosphorus
WIMS	Water Information Management System [Environment Agency]

Appendix: Technical information

A.1 Sunlight duration

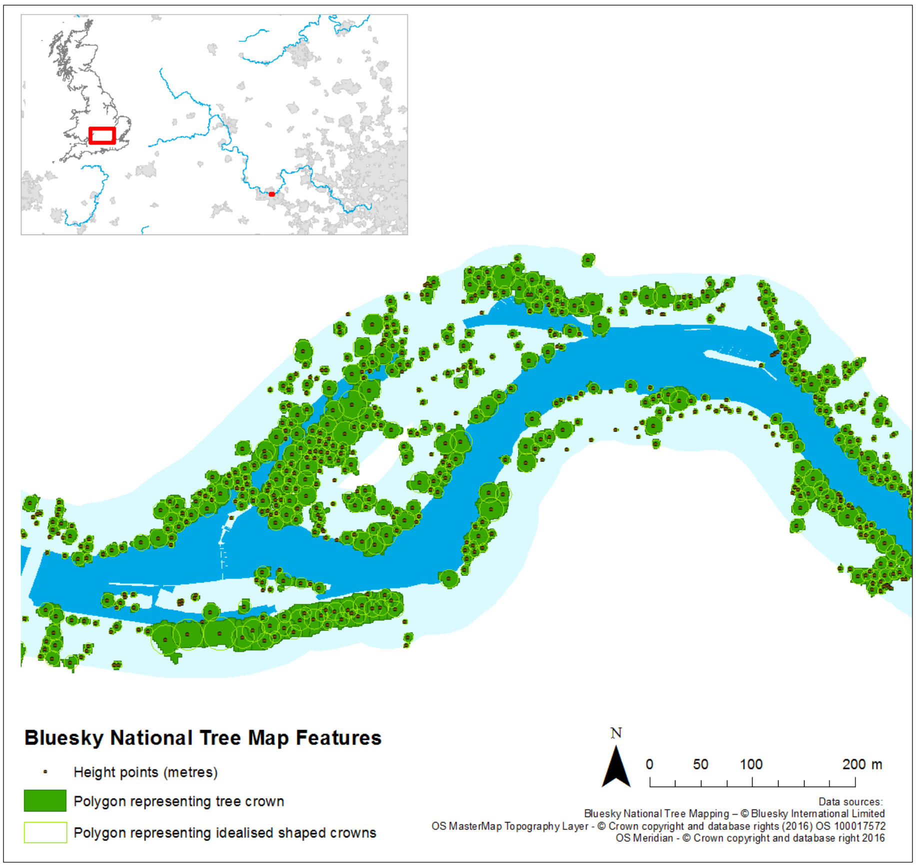
A.1.1 Input datasets description

River polygons extracted from the OS MasterMap Topography Layer®[1] were used to define the river channel.

Bare ground elevation models for the river riparian zones were extracted from 5m resolution NEXTMap® DTM data (Intermap Technologies 2007).

Canopy cover surfaces were produced using NTM data (Bluesky International 2013). A NTM for the riparian areas (the extent of which are defined and described in the methodology below) of the 28 rivers studied was purchased from Bluesky International Ltd. This dataset includes the location and maximum height of every single tree of height ≥2m in the riparian zones both as points and as polygons of the tree crown extent (Figure A.1).

Hourly global radiation observations were downloaded from Met Office’s MIDAS database (Met Office 2006).



Data sources:
Bluesky National Tree Mapping – © Bluesky International Limited
OS MasterMap Topography Layer - © Crown copyright and database rights (2016) OS 100017572
OS Meridian - © Crown copyright and database right 2016

Figure A.1 **Detailed view of NTM dataset: an example from the River Thames**

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[1] GML geospatial data. Coverage: England and Wales, updated December 2015. Downloaded December 2015 from the Ordnance Survey Order Service.

Details of the gauging stations selected for the study are given in Table A.1. The locations of the rivers and the gauging stations are shown in Figure A.2.

Table A.1 Details of the gauging stations at the downstream end of selected river stretches and the nearby meteorlogical station from which they were assigned radiation data

River	NRFA station ID	NRFA station name	Meteorological station ID	Meteorological station name
Browney	24005	Browney at Burn Hall	315	Boulmer
Wear	24009	Wear at Chester le Street	315	Boulmer
Leven	25005	Leven at Leven Bridge	17314	Leeming
Wharfe	27002	Wharfe at Flint Mill Weir	533	Church Fenton
Ouse	27009	Ouse at Skelton	533	Church Fenton
Don	27021	Don at Doncaster	556	Nottingham: Watnall
Derwent	27841	Derwent at Buttercrambe	370	Leconfield
Kym	33012	Kym at Meagre Farm	461	Bedford
Lark	33014	Lark at Temple	440	Wattisham
Tove	33018	Tove at Cappenham Bridge	595	Church Lawford
Thet	33019	Thet at Melford Bridge	440	Wattisham
Bedford	33026	Bedford Ouse at Offord	461	Bedford
Thet	33044	Thet at Bridgham	440	Wattisham
Waveney	34006	Waveney at Needham Mill	440	Wattisham
Thames	39001	Thames at Kingston	862	Odiham
Evenlode	39034	Evenlode at Cassington Mill	692	Little Rissington
Medway	40003	Medway at Teston	30620	Charlwood
Stour	43007	Stour at Throop	842	Hurn
Avon	43021	Avon at Knapp Mill	842	Hurn
Tamar	47001	Tamar at Gunnislake	1415	Cardinham: Bodmin
Torridge	50002	Torridge at Torrington	1415	Cardinham: Bodmin
Avon	53018	Avon at Bathford	676	Filton
Severn	54001	Severn at Bewdley	643	Shawbury
Teme	54008	Teme at Tenbury	669	Shobdon Airfield
Severn	54057	Severn at Haw Bridge	643	Shawbury
Wye	55002	Wye at Belmont	669	Shobdon Airfield
Lugg	55003	Lugg at Lugwardine	669	Shobdon Airfield
Weaver	68011	Weaver at Ashbrook	1144	Hawarden Airport
Ribble	71001	Ribble at Samlesbury	1144	Hawarden Airport
Eden	76007	Eden at Sheepmount	1083	Shap

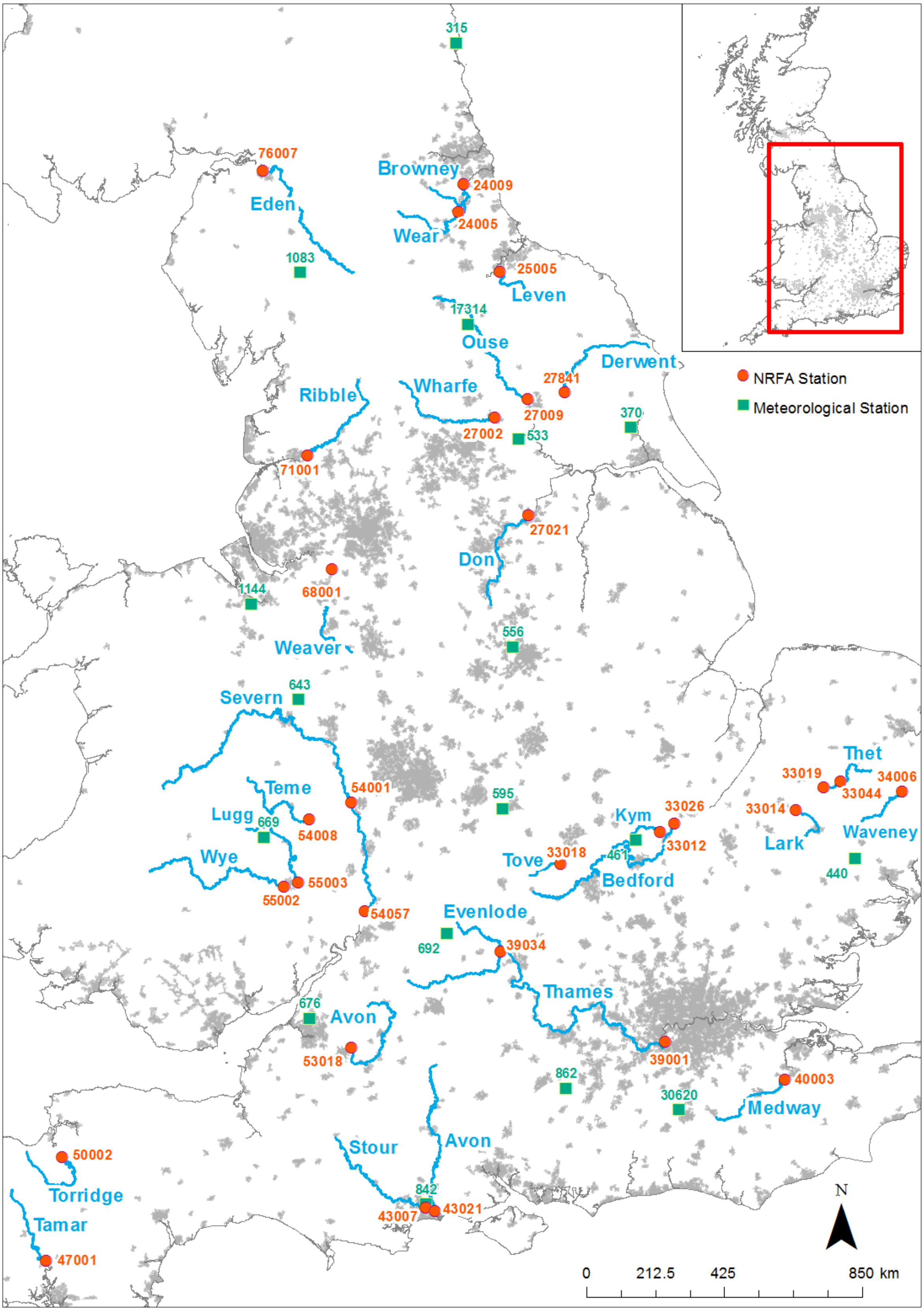

Figure A.2 Map of rivers selected for this study showing location of the gauging stations

A.1.2 Riparian shading analysis

The processing steps to create canopy height models of the riparian zone of the 28 rivers selected and the calculation of their shade maps were created using ArcGIS tools.

Step 1: Definition of riparian zone

The polygons representing the width of the selected rivers were extracted from the OS MasterMap Topographic Layer. The polygons were manually edited to remove man-made features from the river channel or riparian zone. A 50m buffer around each river was then calculated. This buffer zone defines the extent of the riparian area to each side of each river, and it was used as mask to define the extent of the rest of spatial datasets used to calculate riparian shade maps (OS MasterMap Topography Layer river polygons, NEXTMap and NTM).

Step 2: Creation of surface model generation

Canopy height models (CHMs) of the riparian zones were created for the 28 rivers selected, using Bluesky NTMs and NEXTMap as source datasets. To generate CHMs for the selected rivers, it first necessary to calculate canopy surface models (CSMs). A CSM maps tree heights as a continuous surface thus, capturing canopy structure and spacing.

Initially, Environment Agency LIDAR (light ranging and detection) and vegetation object map[2] (Orr and Lenane 2012) were the datasets of choice to create the CSM for this analysis. However, close assessment of the 2 datasets highlighted their unsuitability to represent riparian vegetation due to a number of limitations (described in Orr and Lenane 2012).

The NTM was therefore used instead. The NTM represents the most detailed record of tree location, height and canopy extent in England and Wales. It is commercialised as 3 shapefiles:

- a point shapefile of tree location (at its apex)
- 2 polygon shape files representing the tree crown both as capture and as an idealised circular shape

The tree location points and crown polygons were processed into a canopy cover surface.

Canopy surfaces for the riparian zone of each studied river were derived from the NTM tree points and crown polygons as follows:

- Step 2.1: Triangulated irregular network (TIN) surfaces were created from NTM points using the NTM crown polygons as breaklines[3] to enforce the mean tree height value at the canopy edge.
- Step 2.2: Each TIN was converted into a 1m grid.

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[2] The Environment Agency vegetation object dataset maps the location of vegetation over 2.5m and its height in a 2m resolution grid. The dataset was derived from Environment Agency LIDAR data captured over a number of years.

[3] See Fundamentals of creating TIN surfaces (http://desktop.arcgis.com/en/arcmap/10.3/manage-data/tin/fundamentals-of-creating-tins.htm) (retrieved 25 June 2016).

- Step 2.3. Using the NTM crown polygons as masks, each 1m grid was redefined to cover only the canopy extent (that is, a CSM).

To create the CHMs, the 1m resolution CSMs were normalised using a bare ground elevation model or DTM (that is, CSMs were added to bare ground elevation models of the riparian areas). Due to the limited coverage of the Environment Agency LIDAR-captured 1m elevation data, the bare ground elevation surface (or DTM) of the 28 river riparian zones were created by resampling NEXTMap 5m DTM to a 1m grid. The resultant surfaces were 1m resolution CHMs or riparian vegetation surfaces.

The 1m CHMs were resampled to 2m grids to reduce the processing time required to create the riparian shade maps.

Step 3: Creation of riparian shade maps

Riparian shade maps were created for the catchments of interest using the ArcGIS Area Solar Radiation tool.[4] This tool calculates the incoming global solar insolation for a particular location or area, based on methods from the hemispherical viewshed algorithm developed by Rich et al. (1994) and further developed by Fu and Rich (2000, 2002). In addition, it produces a series of optional raster outputs, among them a grid representing the daily duration of the direct incoming radiation in hours. This can, in effect, be used as a shading map (that is, the hours of shade at each grid cell would result from subtracting to the maximum number of hours of direct exposure the cell value). Figure A.3 shows an example.

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[4] Area Solar Radiation (http://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/area-solar-radiation.htm), retrieved 26 June 2016.

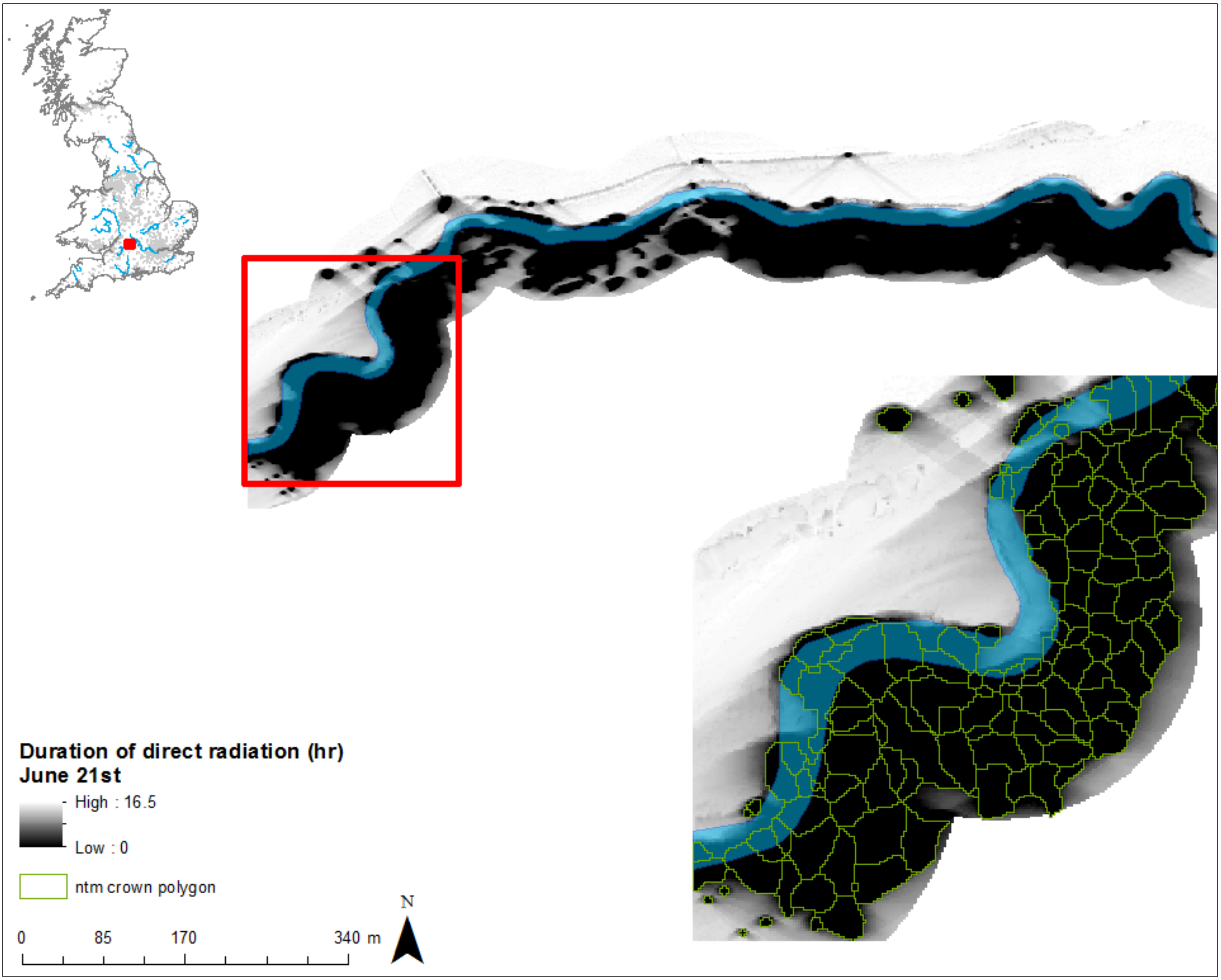

Figure A.3 **Duration of direct radiation grid for 21 June in a short stretch of the River Thames**

Using the 2m CHM surfaces as input to the ArcGIS Area Solar Radiation tool, daily riparian shade maps were created for each selected watercourse. To capture the changes in shade due to the variation in the relative position of the Sun along the year, maps were created at 10-day intervals for the period between 2 March and 20 June. This resulted in 12 shading maps for each selected watercourse. During the period 20 June to 30 September, the day-to-day relative position and orientation of the Sun and Earth follow the same pattern but in reverse. Hence the same surfaces can be used for the 2 subperiods.

Step 4: Estimation of total daily shading for each river

To compute a single daily total value of shade for each of the 28 rivers studied, the number of hours of direct radiation for the grid cells in river surface (that is, under the river polygon) were averaged into a unique value. This was done using the ArcGIS Zonal Statistics as Table tool.[5] The daily maximum number of hours of direct radiation for each river was also extracted.

To complete a daily record of total shade for each river, the gaps were filled in by incremental linear interpolation between the existing values 10 days apart.

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[5] Zonal Statistics as Table (http://pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/zonal-statistics-as-table.htm), retrieved 27 June 2016.

Step 5: Estimation of total daily radiation reaching the river surface

Hourly global radiation observations from the Met Office synoptic network (Met Office 2006) spanning 2010 to 2014 were downloaded from a number of meteorological stations selected based on their proximity to the watercourses of interest (Table A.1 and Figure A.2). It is assumed that the radiation measured at the selected meteorological stations is a close estimate of the amount of sunlight at the exposed patches in the riparian areas analysed.

The hourly observations were aggregated to daily values (by adding the hourly values). Before aggregating the hourly values, gaps in the hourly record were filled in by interpolation of available values either side of the temporal record. Days when the numbers of hourly observations were 60% of the expected number of daylight hours (10 for March, 12 for April, 15 for May, 17 for June, 16 for July, 14 for August, 11 for September and 9 for October) where flagged to be replace with observations from other weather stations.

To calculate the daily total radiation reaching the river surface taking into account the shading effect of the riparian vegetation, the daily radiation was multiply by the daily number of hours of direct radiation reaching the water surface (averaged along the river stretch) and divided by the daily maximum number of hours recorded at that site (that is, the daylight length).

A.2 Modelling to test assumptions

A.2.1 Statistical models for estimating chlorophyll levels in rivers in England and Wales

To ensure that all the important variables controlling current chlorophyll risk were being considered, testing was conducted to determine whether they provided reliable predictions of chlorophyll concentrations for observed data.

An important feature of this regression approach is that it included a deterministic means of assessing the factors controlling phytoplankton growth based on established mechanistic theory (Chapra 1997) adopted in process-based river quality models in contrast to the empirical approach adopted in the development of the time series predictive model. A multiple linear regression approach was adopted to estimate the growing season mean chlorophyll concentration in the 30 sites used following residence time calculations. This forms a national level regression model.

Calculation of dependent and independent variables for use in regression modelling

In the approach, the mean chlorophyll concentration (y) is related to up to 2 independent variables (x_1, x_2, x_3, x_4):

- Growth rate – defined based on a combination of limitation factors (phosphorus concentration, light, temperature). These are formulated under 2 alternative assumptions: (i) for a mixed population of algae (x_1) or (ii) for diatoms (x_3). The consideration of the 2 contrasting alternative assumptions (that is, whether or not a known specific and abundant type of phytoplankton dominates the community) reflects current uncertainties as to how phytoplankton respond to environmental factors and how this is manifested in terms of chlorophyll concentrations.

- Residence time – either at mean flow (x_2) or low flow (Q90) (x_4)

Light limitation was calculated based on the incident light reaching the water surface (that is, after riparian tree shading has been considered). A limitation factor was calculated for every day in the period from 3 March to 9 October for which radiation data were available since 2010. The value used in the final calculation of growth rate is the average of all the daily values. Calculation of the limitation factor is described by Hutchins (2012). Optimum light intensities used were 60 and 40 for mixed algae and centric diatoms respectively. Suspended sediment and chlorophyll-a concentrations were assumed to be 20mgl^{-1} and 0.05mgl^{-1} respectively. A typical depth of the water column for the March to October period was estimated on a site-by-site basis from the Environment Agency water level record.[6]

The effects of phosphorus concentration and temperature were calculated using TRP records from the Environment Agency WIMS and Harmonised Monitoring Scheme (HMS) databases respectively. Only data in the March to October period were considered. An additional filtering of phosphorus data was made whereby only a period indicative of present day sewage treatment (that is, after any step change improvements resulting in a reduction in concentration) was retained. The method for calculating the maximum growth rate (a function of temperature) and the phosphorus limitation factor is described more fully by Hutchins (2012) and Waylett et al (2013). This includes a description of the formulations for relating maximum growth rate to water temperature for the 2 assumptions of phytoplankton composition (mixed or centric diatom). The half constant for phosphorus limitation and the maximum growth rate at 20°C were held at 0.01mgl^{-1} and 1.35 per day respectively. These are values used in water quality process modelling applications of the River Thames by Waylett et al. (2013) and Hutchins et al. (2016).

All the individual daily values of the phosphorus limitation factor and maximum growth rate were used to derive a mean value of each.

From these calculations, a mean maximum growth rate, a mean light limitation factor (taking values from 0 to 1) and a mean phosphorus limitation factor (taking values from 0 to 1) were determined for each site. These 3 values were multiplied together to estimate growth rate (Equation A.1):

$$Growth\,rate\ (x_1, x_3) = maximum\,growth\ \times\ f(light)\ \times\ f(phosphorus) \quad \text{(Equation A.1)}$$

The dependent variable (that is, mean growing season chlorophyll concentration) was taken from Environment Agency WIMS databases for the same period identified for calculating the phosphorus limitation factor.

At this stage, 4 rivers – Kym (33012), Thet at Melford Bridge (33019), Thet at Bridgham (33044) and Severn at Bewdley (54001) – were rejected from the analysis as no suitable chlorophyll data were available.

Residence time was calculated from daily flow data using the method of Round et al. (1998) to relate flow to travel time.

Two outliers, the Medway (40003) and Weaver (68001) were removed from the analysis based on local knowledge of canals and reservoirs; these have a strong influence, increasing the residence time above values calculated by the river hydraulics model (see Round et al. 1998 and Section 2.2). Therefore, this analysis is based on 24 sites. There was no evidence in these 24 sites of the artificial influences such as those at Medway and Weaver enhancing residence time.

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[6] Shoothill GaugeMap (www.gaugemap.co.uk)

Model formulation

Scatter plots of the untransformed y variable and the candidate x variables x_1 and x_2 reveal 2 points to be outliers (Figure A.4) – the Medway (68001) and Weaver (40003) (top left hand corner of right hand scatter plot). These were omitted for the reason outlined above.

The histograms show that mean chlorophyll is not normally distributed and therefore requires transformation prior to modelling. A Box–Cox transformation (Box and Cox 1964) was therefore performed on this variable (Equation A.2):

$$yT = (y^{\lambda} - 1)/\lambda \qquad \text{(Equation A.2)}$$

where $\lambda = 0.309$, optimised such that yT is distributed normally under a Shapiro–Wilk test.

Eight alternative linear models were formulated to explain the mean growing season chlorophyll content (y) dependence on different combinations of independent variables (x). Table A.2 shows the formulation of these linear models and their diagnostics under test.

The models with 2 x variables included main effects, plus interactions, account for any synergistic or antagonistic effects on the dependent variable when 2 variables act together. The tests reveal the best model to be Model 3 – the lowest value of the Akaike Information Criterion (AIC) (Table A.3). In terms of AIC, the model is only a marginal improvement on the best univariate model (Model 8).

Of the 2 options relating to growth rate, formulation models making assumptions about the composition of the phytoplankton (that is, centric diatom dominance x_3) perform slightly less well. Low flow (x_4) appears to be a better predictor than mean flow (x_2). Analysis of the distributions of the residuals is acceptable. The comparison of observed and theoretical residuals is acceptable for Model 3 (that is, x_1x_4 in Figure A.5, right hand side of top row). There is little apparent relationship between values of x variables and residuals (Figure A.6). Transformation of the y variable (to yT) appears to be beneficial, although there is still some suggestion of a positive relationship with the residuals (Figure A.6). Because data are not always comprehensive, there is uncertainty about what the mean chlorophyll level is and this will weaken the statistical relationships.

Conclusions

- A combination of low flow residence time and growth rate provides an acceptable predictive model for mean chlorophyll concentration in the 24 rivers tested here.
- Mean growth rate based on assumptions of a mixed algal population (x_1) is the basis for a slightly better model than rates based on assumption of a dominant species (centric cool water diatoms, x_3).
- Upstream residence time is very important in controlling chlorophyll levels in rivers. Artificial influences such as canals and reservoirs can clearly be important, effectively lengthening residence times above those calculated. This is why 2 rivers were removed from the analysis (Medway and Weaver).
- The best model only explains 54% of the variance in inter-site mean chlorophyll. A detailed understanding of river morphology (for example, identifying the presence of low velocity zones and areas of differing

hydraulic relationships) and other biological factors would potentially provide for a more powerful model.

Table A.2 Formulation of linear models and their diagnostics

Model	Model formulation[1]	Adjusted R^2	AIC	Shapiro–Wilk p value (normality of residuals)
1	$yT = x_1 \times x_2$	0.35 [2]	63.38	0.00599 [3]
2	$yT = x_3 \times x_4$	0.51 [2]	56.61	0.2575
3	$yT = x_1 * x_4$	0.54[2]	55.14	0.1817
4	$yT = x_3 \times x_2$	0.34	63.80	0.01035 [3]
5	$yT = x_1$	0.18	67.39	0.7479
6	$yT = x_2$	0.37 [2]	61.02	0.01316 [3]
7	$yT = x_3$	0.00	72.08	0.5882
8	$yT = x_4$	0.49 [2]	55.99	0.1682

Notes:

[1] y = mean chlorophyll concentration, x_1 = mixed population of algae, x_2 = mean flow, x_3 = diatoms, x_4 = low flow (Q90)

[2] $p < 0.01$

[3] Reject at $p = 0.05$ level (hypothesis that residuals are normally distributed fails)

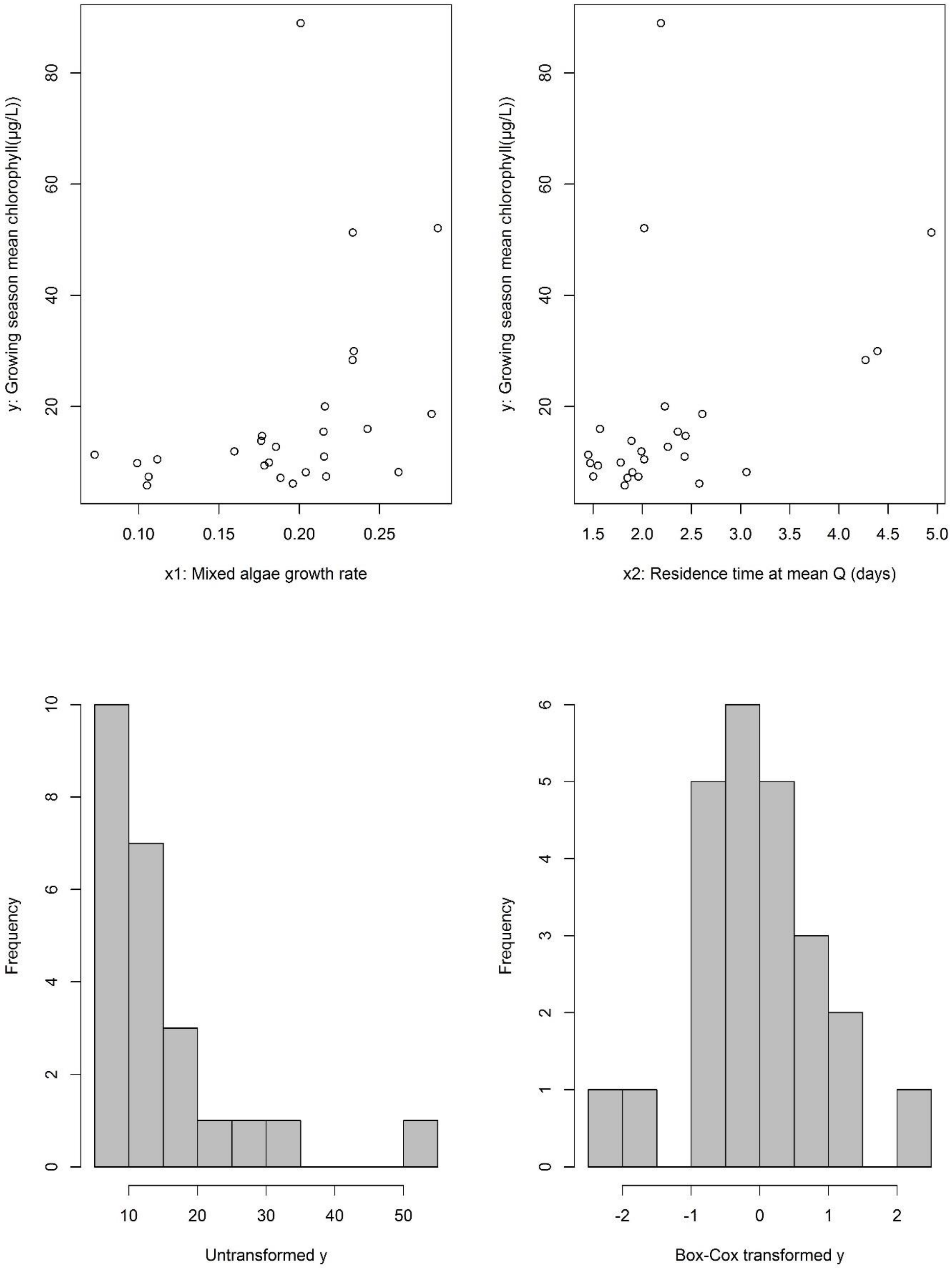

Figure A.4 Scatter plots of untransformed variable y variable and variables x_1 and x_2 (top row) and histograms of untransformed y and Box–Cox transformed y variable (bottom row) s

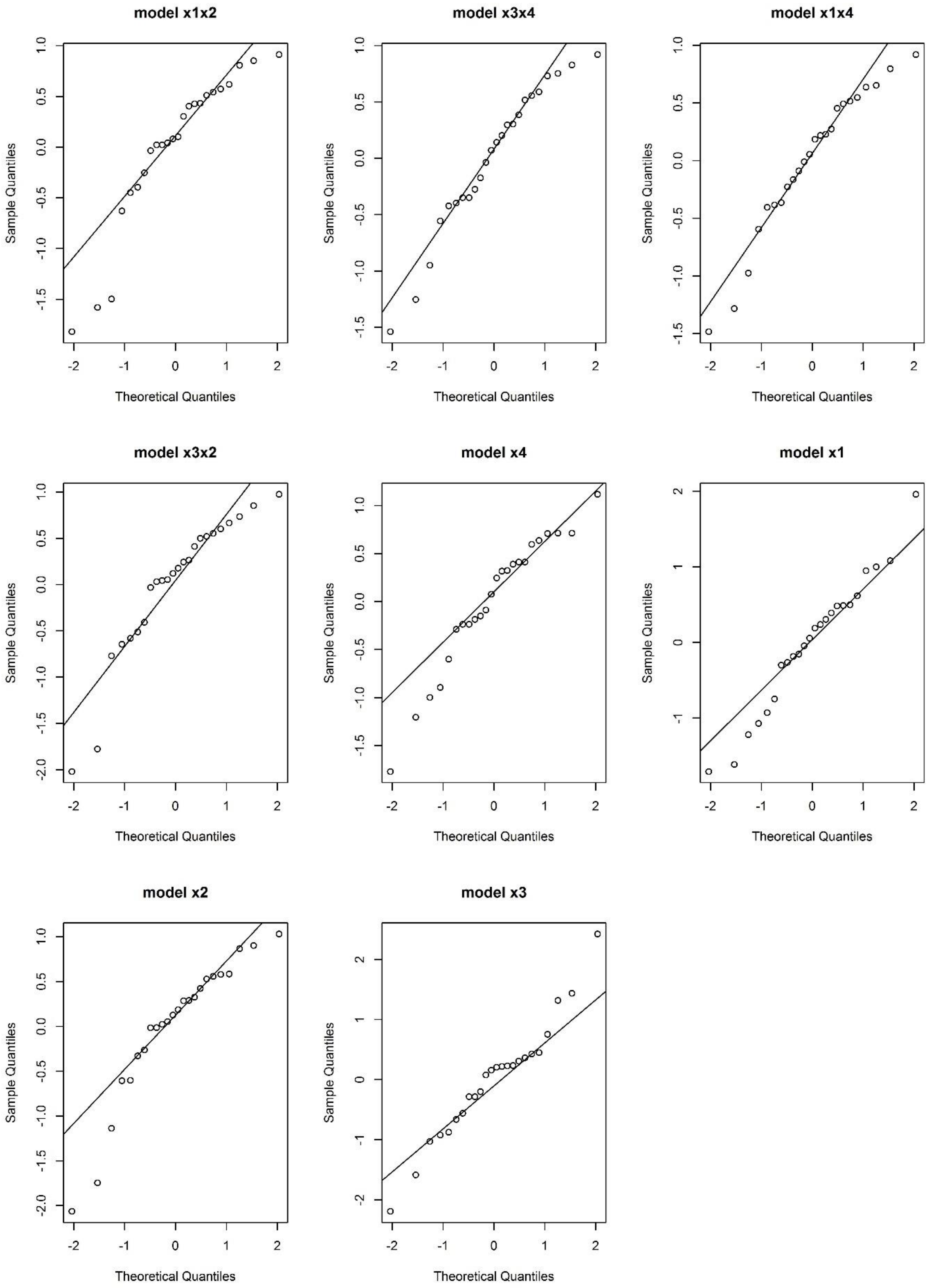

Figure A.5 Theoretical and sample residuals

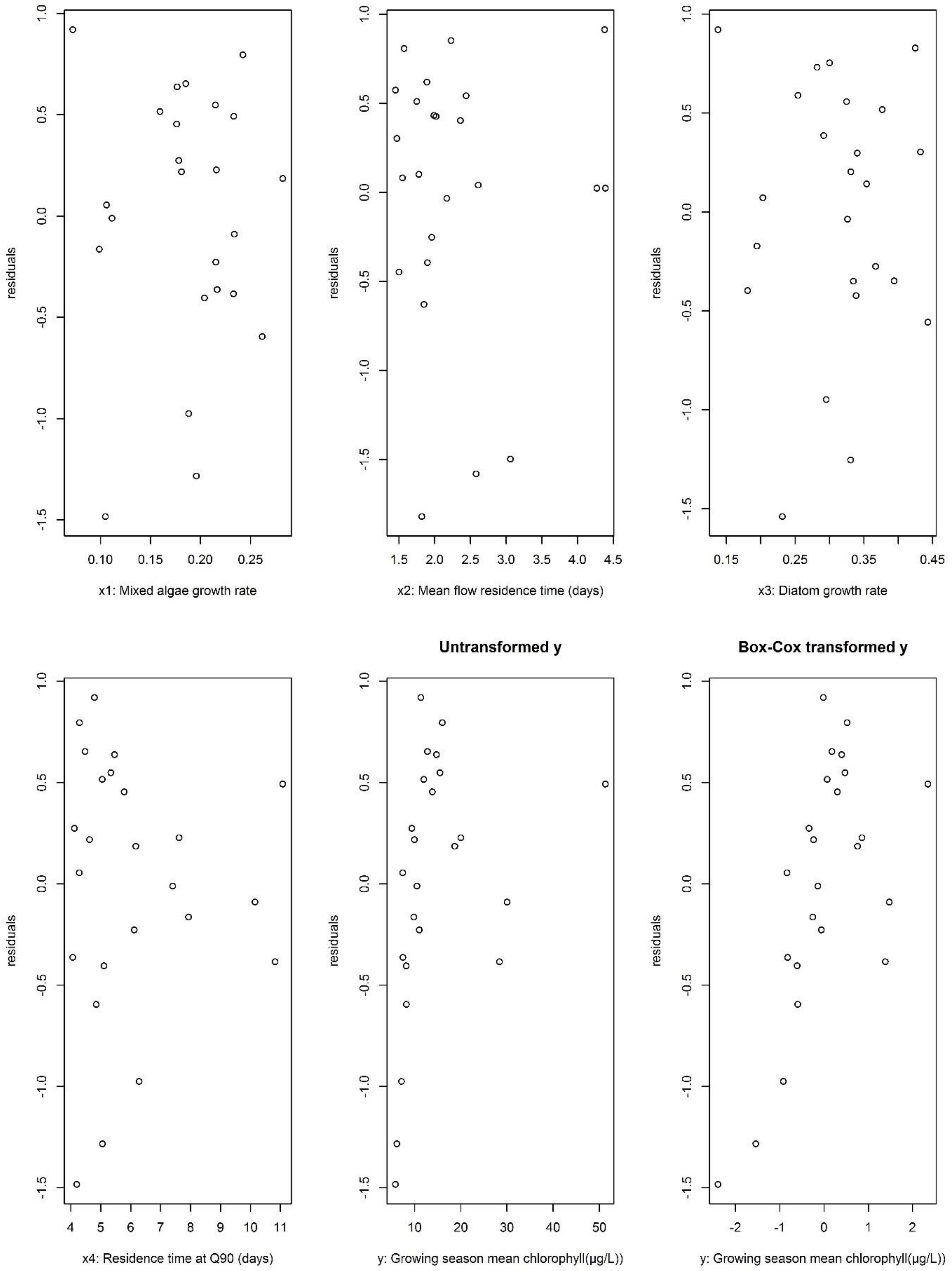

Figure A.6 Plots of predictor variables against model residuals

Notes: The model for which the residuals were taken was the best AIC in each case (that is, Model 1 for x_2, Model 2 for x_3 and Model 3 in all other cases).

A.3 Estimating water temperatures

There are currently no future projections of water temperature. Future projections of air temperature are available and a number of studies have looked at estimating water temperature from air temperature.

There are 3 main approaches to developing future projections of water temperature:

- Perturbing observed records of current water temperature using a change factor approach akin to a standard climate change impacts assessment – no change factors currently exist and existing observed records of water temperature are rarely of adequate length to perturb
- Using a range of current regression relationships between water temperature air temperature – these could be generic, site-specific and also temporally specific
- Physically based modelling of energy dynamics in the river system – this approach is time-consuming and data-intensive as well as very site-specific and inappropriate for a national scale assessment

The first 2 approaches were explored using 3 methods:

1. Applying a change factor of 0.9 to air temperature projections (Approach 1)
2. Using regression relationships between air and water temperature from the literature to estimate water temperature from air temperature projections – Approach 2 (Stefan and Preud'homme 1993) and Approach 3 (Webb et al. 2003)
3. Deriving regression relationships between current observed air and water temperatures at the sites that met the residence time thresholds and applying these to the air temperature projections. There are 4 approaches under this method:
    - Approach 4: average annual regression equations
    - Approach 5: average seasonal regression equations
    - Approach 6: site-specific annual regression equations
    - Approach 7: site-specific seasonal regression equations

Approaches 4 and 5 are derived by averaging the site-specific annual and seasonal parameters across all sites.

Air temperature projections were extracted from the Future Flows Climatology by CEH. Observed air temperature was extracted from the UKCP09 gridded observation datasets.[7] Observed water temperature data were extracted from WISKI 7. Only 4 of the sites provided paired air and water temperature data, all of which were in southern England. The air temperature was recalculated using a 5-day rolling average before site-specific and average relationships were explored for seasonal and annual time scales. The regression parameters and R^2 are shown in Table A.3.

For the 4 sites where paired records existed, the different regression equations were applied to the existing air temperature data to estimate the water temperature data. These data were then compared with the existing water temperature data. Estimation error was assessed by calculating the maximum, minimum and range of the differences

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[7] http://www.metoffice.gov.uk/climatechange/science/monitoring/ukcp09/

between observed and estimated, and by calculating the standard error of the estimate (Table A.3).

The results of this analysis suggest that:

- the estimation error range is high across the sites (4.4–12.8°C)
- there is a greater difference between sites than between approaches, especially for estimation error range
- the factor and literature regressions give poor estimations relative to the other approaches
- site-specific seasonal equations provide the best estimation, although the error is still high

All approaches give very similar estimation error, which is of similar magnitude to the range in water temperature variability. Using the seasonal average parameters (Approach 5) gives the best, generally applicable results, with the standard error of the estimate (SEE) between 1.05 and 1.48 and range between 4.95 and 10.65 across sites. This compares favourably with the site-specific seasonal values (Approach 7) of 0.75 to 1.25 and 4.38 to 10.49.

Approach 5 was therefore used in the analysis, acknowledging that this is a limitation of the study. Furthermore, the range in error is not spread evenly around 0 error, resulting in distortions in temporal patterns, which will adversely affect the timing of threshold attainment. These results are for the 5-day rolling average of air temperature; this improves both the strength of regressions and estimation error compared with using raw daily values. Further work to improve temperature estimations and assess temperature sensitivity is necessary. Once improved estimations become available, it will be possible to assess how temperature change affects results. This analysis confirms that such approaches can only give indicative values for water temperature.

Table A.3 Comparison of regression model parameters and SEE for different approaches to estimating water temperature from air temperature

Approach	Time period	a	b	Thames (39001)		Stour (43007)		Avon (43021)		Severn (54001)	
				SEE	RANGE	SEE	RANGE	SEE	RANGE	SEE	RANGE
1	Annual	0.90	0.00	3.32	5.54	2.6	12.45	1.87	7.27	2.81	8.58
2	Annual	0.75	5.00	1.87	7.03	1.99	12.75	2.58	8.05	2.19	10.18
3	Annual	0.86	4.29	1.6	5.93	2.25	12.53	2.89	7.46	2.16	8.84
4	Annual	0.95	1.66	1.43	5.1	1.52	12.44	1.65	7.31	1.39	8.49
5	Winter	0.53	3.36	1.30	4.95	1.29	10.65	1.48	6.24	1.05	7.92
	Spring	0.95	2.15								
	Summer	0.72	6.50								
	Autumn	0.89	1.82								

Approach	Time period	Thames at Kingston (39001)					Stour at Throop (43007)				
		a	b	R^2	SEE	RANGE	a	b	R^2	SEE	RANGE
6	Annual	1.01	1.82	0.97	1.11	4.84	0.88	2.40	0.90	1.47	12.5
7	Winter	0.47	4.07	0.82	0.75	4.38	0.45	4.14	0.60	1.25	10.59
	Spring	0.98	2.11	0.98			0.83	3.34	0.82		
	Summer	0.73	7.71	0.90			0.62	7.85	0.57		
	Autumn	0.85	3.59	0.90			0.90	1.87	0.93		

Approach	Time period	Avon at Knapp Mill (43021)					Severn at Bewdley (54001)				
		a	b	R^2	SEE	RANGE	a	b	R^2	SEE	RANGE
6	Annual	0.90	1.26	0.91	1.34	7.27	1.02	1.16	0.94	1.33	8.98
7	Winter	0.56	2.71	0.73	0.97	5.29	0.63	2.52	0.91	0.98	8.14
	Spring	0.90	2.03	0.86			1.08	1.13	0.89		
	Summer	0.71	5.13	0.55			0.81	5.30	0.66		
	Autumn	0.90	0.26	0.90			0.92	1.58	0.64		

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