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An empirical investigation of climate and land-use effects on water quantity and quality in two urbanising catchments in the southern United Kingdom

[1]Putro, B., [2]Kjeldsen, T. R., [3]Hutchins,M. G. and [3]Miller, J.

[1] Department of Earth Sciences, Royal Holloway, University of London, Egham, Surrey TW20 0EX, United Kingdom

[2]Department of Architecture and Civil Engineering, University of Bath, BA2 7AY, Bath, United Kingdom

[3]Centre for Ecology & Hydrology, Maclean Building, Crowmarsh Gifford, Wallingford, OX10 8BB, United Kingdom

Abstract

Using historical data of climate, land-use, hydrology and water quality from four catchments located in the south of England, this study identifies the impact of climate and land-use change on selected water quantity and water quality indicators. The study utilises a paired catchment approach, with two catchments that have experienced a high degree of urbanisation over the past five decades and two nearby, hydrologically similar, but undeveloped catchments. Multivariate regression models were used to assess the influence of rainfall and urbanisation on runoff (annual and seasonal), dissolved oxygen levels and temperature. Results indicate: (i) no trend in annual or seasonal rainfall totals, (ii) upward trend in runoff totals in the two urban catchments but not in the rural catchments, (iii) upward trend in dissolved oxygen and temperature in the urban catchments, but not in the rural catchments, and (iv) changes in temperature and dissolved oxygen in the urban catchments are not driven by climatic variables.

Key-words: hydrology, water quality, urbanisation, climate

1. Introduction

A combination of changes in seasonal rainfall patterns and increased evapotranspiration as a result of raised temperatures, will result in changes in the United Kingdom with respect to future river flows, river water temperature and river water quality (Watts et al., 2015). To achieve sustainable utilisation of water resources, these pressures have to be balanced against the needs of a growing population and attendant pressures on land management. The population of the United Kingdom is projected to increase from 62.3M in 2010 to 72.3M by 2035 (ONS, 2011). The majority of this 16% growth is forecast for England and is likely to change the size and internal structure of urban areas. Such expansion and densification of urban areas is shown to have adverse impacts on the downstream aquatic environment downstream of the urban areas due to both changes in water quality and alterations of the natural flow regimes (Schuster et al., 2005). Detection of temporal changes in water quantity and quality provide the scientific basis for providing early warning signs of a potentially deteriorating aquatic environment and attribution of trends in long-term series of observations to concurrent changes in climate and development pressures provides the evidence basis for decision-makers to steer towards more effective policy interventions (Burt et al., 2008). However, the confounding influence of multiple stressors and the general lack of reliable and systematic long-term data makes this a challenging scientific task (Hering et al., 2015).

Reviewing the available literature, it appears that studies assessing the effect of urbanisation on water quantity have mainly adopted a modelling based approach (Cuo et al. 2008; Haase, 2009; Chu et al., 2013, Miller et al., 2014 among many others) and mostly agree that urbanisation will increase both peak flow and annual runoff volumes. Relatively fewer studies have attempted to detect and attribute urbanisation effects through use of long-term observed records of river flows and coincidental urban development. In the US, Rose and Peters (2001) analysed historical streamflow data and found statistically significant differences between streamflow in an urbanised Atlanta watershed and six other less developed watershed. This study found that peak flows are between 30% to more than 100% greater in the urbanised area than in other streams. In contrast, Steinschneider et al. (2013) reported little or no relationship between annual runoff coefficients and urbanisation in 19 catchments located in North East USA. In a study of observed flood events from catchments in the United Kingdom, Kjeldsen et al. (2013) found that urbanisation tend to reduce lag-time and increase runoff volumes, resulting in higher peak flow values, with the lag-time reduction being the most important process. Lerner (2002) discusses the sources of groundwater recharge in urban areas, including complications caused by contributions from the leaking water supply systems and imported water from outside the catchment.

There is extensive evidence from spatial surveys to make a positive link between metrics of urban land cover and water quality parameters in terms of nutrients (N, P, C), DO and suspended sediment (Chang, 2008). However it is important to understand how development patterns in specific watersheds affect water quality (Fu et al., 2009). Aside from a concentrated source of BOD, warmer waters originating from urban areas will lower the oxygen carrying capacity of urban rivers and accelerate processes of chemical degradation threatening fish survival. Comprehensive data on the impacts of urbanisation are available in the largest cities in the world and these have been the subject of overarching review (Duh et al., 2008). Yet such an approach rather than confirm the negative impacts of urbanisation reveals inconsistent trends in biological oxygen demand (BOD) and dissolved oxygen (DO) between one major city and another, highlighting confounding influences most notably that growth stimulates resilience by prompting technological improvements (e.g. increased efficiency of wastewater treatment). Pinpointing the effects of urban growth on water quality at a small scale can be realistically quantified using scenario modelling but for interpretative purposes this approach has the restrictions of site-specific conditions. Studies have considered combined sewer systems and identified for example relationships between changes in spill volume (an indicator of population growth) and incidence/duration of undesirable DO conditions (Lau et al., 2002), yet much recent urban development is founded on separate storm and foul sewer systems. Therefore alongside deterministic modelling studies an empirical approach is very valuable and is the subject of this study on two growing towns largely characterised by separate sewer systems in which flood events have been mitigated against at the planning stage by the construction of balancing ponds. Although moderated by site-specific factors combined and separate sewer systems can have very different impacts on receiving water quality (Brombach et al., 2005). Whilst a move to separate systems will likely increase the overall storm water volume and pollutant load it should be beneficial as much of the organic matter reaching receiving waters will be of lower concentration and less biodegradable and therefore less likely to lower oxygen levels (Thorndahl et al., 2015).

The detection and attribution of effects of urbanisation on water quantity and quality has been hampered by the lack-of concurrent and consistent long-term historical records of relevant datasets on urban extent and associated indicators of urban development such as impervious cover. However, the recent development of a method to map the spatial-temporal development of urban areas by Miller and Grebby (2014) that does not rely upon limited remote sensing imagery but instead utilises historical maps from the UK Ordnance Survey provides a new opportunity for attribution of long term changes in water quantity and quality. The objective of this study is to utilise the method developed by Miller and Grebby (2014) to map long term change in urban cover to attribute observed trends in river water quantity and quality to urbanisation and climate variability.

Using a statistical approach the present study aims to detect and attribute stressors affecting the changes of river flow and water quality in the study sites. In selected catchments within the Thames basin (South England) for the period 1960-2010, use will be made of historic rainfall data coupled with the new information on spatio-temporal urban development to attribute the impact of climate and land-use change on both water quality and quantity. Daily rainfall, runoff and water quality data will be collated, but will be aggregated to annual and seasonal (winter, summer) metrics for the purposes of statistical analysis. The results will then compared to those from similar analyses conducted using data from two rural control catchments chosen on the basis of proximity and similar size. By considering water temperature and DO, key direct indicators of the health of waterbodies as well as other important indicators of nutrient enrichment (soluble reactive phosphorus (SRP)), we will investigate whether the confounding conclusions regarding impacts of urban growth drawn at the scale of mega-cities (Duh et al 2008) are reflected in smaller areas where the process of detection and attribution is more tractable. The following research questions will be addressed:

- Can statistically significant trends be detected in rainfall, river flow and selected water quality data obtained from two urban catchments?
- How does the observed trend in the urban catchments compare with the trend found in data from two nearby and similar sized, but rural, catchments?
- Is urbanisation the main cause of the changes in river flow and water quality in urban catchments?

2 Study sites

The experimental approach adopted in this study required identification of two medium-sized catchments where a significant transformation from rural to urban land-cover has taken place, and coincide with the availability of good-quality long-term hydrological data covering the same time period. For each of the two urban catchments a nearby and hydrologically similar, but undeveloped rural, catchments, also with a long and high quality hydrological records, should be available. Finally, for each of the four study sites, good quality long-term records of comparable water quality measurements should also be available. Based on these criteria two sets of paired urban and rural catchments were selected as shown in Table 1 where the urban catchment 39052 (Cut at Binfield) is paired with the rural 39022 (Winterbourne at Bagnor), and the urban catchment 39087 (Ray at

Water Eaton) is paired with the rural catchment 39025 (Enborne at Brimpton). The locations of the four study sites are shown in Figure 1.

FIGURE 1:

2.1 Spatial-temporal development of urban land-use

Urban land-use in this study is represented as 50m grids squares of either undeveloped land (Rural) or is assigned the classification of *Urban* and *Suburban*. These classifications are based on the descriptions used in the UK Land Cover Mapping products (Fuller et al. 2002) whereby *Urban* is areas of near continuous development with little vegetation (e.g. industry or high density developments) and *Suburban* is mixed development and green space. The proportions of these land-use cells within each catchment is then used to calculate a catchment index of urban extent, URBEXT, developed by Bayliss (1999) and utilised in the UK Flood Estimation Handbook (FEH) methodology (Institute of Hydrology, 1999):

$$URBEXT = Urban + \left(0.5 \times Suburban\right)$$

whereby *Urban* and *Suburban* are the proportions of Urban and Suburban grid cells within each catchment, respectively, and 0.5 is the Suburban weighting factor. The temporal changes in URBEXT across the selected urban catchments were mapped using the method of Miller and Grebby (2014). The method utilises digitised topographic maps produced by the UK Ordnance Survey updated each decade to represent significant changes in land cover such as urbanisation or deforestation. These provide comparable images of land cover change in an urban areas. The images are transformed first into *i* binary maps and then into gridded maps of Urban and Suburban land-use grids at a 50m resolution for each decade. The index is intended as a broad classification urban development and does not include specific information on local hydraulic and water management features affecting water quality and quantity at specific sites.

FIGURE 2

2.2 Hydrometric Data

Continuous time series of mean daily runoff and catchment average daily rainfall were obtained from the National River Flow Archive (NRFA). The catchment average rainfall data were available for each of the four catchments derived from a national dataset of long-term daily rainfall gauges (Keller et al., 2015). As the catchments analysed in this study are of relatively modest size and with only limited topographic features influencing rainfall regimes, the use of catchment average data was assumed to provide a homogeneous representation of rainfall across the catchments. A summary of the river flow series is shown in Table 1.

TABLE 1

With the exception of the gauging station located on the River Cut at Binfield (39052), the river flow series cover a shorter period than the 1961-2011 period covered by the catchment average rainfall data. The daily records of rainfall and runoff were aggregated into time series of average seasonal (summer and winter) and annual rainfall and runoff series. These aggregated series were used in the subsequent trend studies.

2.2 Water quality observations

Water quality data were obtained from four monitoring stations in each water course as shown in Table 2. Data from monitoring close to or at NRFA gauging stations (see above) were selected for analysis in preference to other monitoring locations. The water quality observations comprise Soluble Reactive Phosphorus (SRP), Dissolved Oxygen (DO) and temperature data

TABLE 2: Summary of water quality monitoring stations

The long-term water quality data from urban and rural catchments acquired from the Environment Agency for this research has limited availability with notable gaps and missing values between observations. To improve the data quality and homogeneity, a number of decisions were taken as outlined below:

- Data with less than six observations from different months (<50%) in a calendar year was removed to ensure that spurious data unrepresentative of mean annual value did not influence the analysis.
- All data from non-regular monitoring purposes - i.e. those classified as unplanned reactive monitoring, pollution incidents, unplanned reactive monitoring formal, and pollution incidents - were removed from the analysis as they could have extreme high or low peak values that might contribute unrepresentative background values.

3. Detection and attribution of change signals

The links between the two primary environmental drivers, climate and land-use, and the resulting impacts on the downstream water quantity and quality variables were investigated using a statistical framework based on multivariate regression models. A predetermined significance level of α = 0.05

was used as a standard for whether or not a null hypothesis of no impact could be rejected. The analysis was developed to provide as much checking as possible, by analysing each variables and drivers individually and in conjunction. A time series of a response variable, e.g. annual runoff, consisting of *n* observations is denoted Y_t $t=1,....n$. A set of concurrent covariates, e.g. annual rainfall or level of urbanisation in year *t* or simply time, are denoted $x_{i,t}$ where *i* denotes the class of the variable. The link between the response variable and the covariates is defined as:

$$Y_t = \beta_0 + \mathbf{x}^T\boldsymbol{\beta} + \varepsilon_t \ , \quad \text{with} \quad t = 1,\ldots,n$$

Where β_0 is the model intercept, $\boldsymbol{\beta}$ is a vector of model parameters, $\boldsymbol{x}^T$ is a transposed vector containing the values of the covariates (e.g. time, land-use and climate at time *t*) at time *t*, and ε_t is the model residual assumed to be normally distributed with zero mean and equal variance. In some cases it was necessary to use a natural log-transformation of the response variable and the covariates to ensure that that the assumption of variance homogeneity of the regression residuals was reasonable. For each series, the distributional assumptions were assessed through visual inspection of quantile-quantile (Q-Q) pots. The different time aggregations were defined as annual (January to December in a particular year), summer (six calendar months from April to September) and winter (six calendar months from October to March the following year). The statistical analysis was organised as a sequence of increasingly complex statistical models, and trend analysis was carried out in both the urban and the associated rural control catchments. The experimental setup is illustrated in Figure 3.

FIGURE 3

This dual approach allows the impact of urbanisation to be assessed both by contrasting: i) the performance of increasingly complex models in the urban catchments, and ii) results obtained in the urban catchments and the corresponding rural control catchments. Starting from a null-hypothesis of no-impact (slope of regression model equals zero), the rejection of this hypothesis indicates that a strong (statistically significant) link has been identified between the response variable and the covariate. The level of significance is reported as a p-value, with a p-value is less than the significance interval (here defined as $\alpha = 0.05$) taken to indicate a significance impact (i.e. rejection of the no-impact hypothesis).

However, care should be exerted when interpreting the p-values as exact measures of statistical significance as some of the fundamental assumptions of the linear regression models are unlikely to be meet in all cases. In particular, some degree of auto-correlation between values in successive years and seasons is inevitable (e.g. Peel et al., 2005). To assess the likely influence of auto-correlation, initial numerical experiments were undertaken where lagged values of the response variable, Y_{t-1}, was included as a covariate. The lagged values were generally found to be highly non-significant with little impact on the p-values of the other covariates. It was therefore decided that using p-values as an indicator of strength between the response variables and the covariates is a reasonable approach.

4. RESULTS

The analysis found several key findings for rainfall, river flow and selected water quality variables; temperature and dissolved oxygen.

4.1 Rainfall

Using log-transformed annual and seasonal rainfall total, the results of a regression analysis of rainfall totals against time in each of the four catchments was conducted. The results of the analysis are shown in Table 3.

TABLE 3: Results from regression analysis of log-transformed rainfall total against time. Numbers in table are p-values associated with regression slope parameter. Strong links (as signified by $p<0.05$) are highlighted.

The results in Table 3 show that no significant trend was identified in rainfall totals, including both seasonal and annual aggregations, in either the urban or the rural catchments. Consequently, should any trend subsequently be found in other hydro-chemical variables, they are less likely to be a result of changing rainfall totals.

4.2 Runoff

The investigation of trend in runoff was conducted using a hierarchy of regression models as detailed in Figure 3 and a summary of the regression models are shown in Table 4

TABLE 4

The results in Table 4 show that in the two rural catchments no significant trend was detected for any of the seasonal runoff volumes or for the annual runoff. In contrast, an upward trend was detected for annual and summer runoff in both urban catchments, and also for winter runoff in catchment

39052. In the urban catchments the upward trends observed in the summer season is more significant than both the annual and winter runoff, suggesting that the upward trend observed in the annual runoff totals are caused by increases observed during the summer season. The reason for this could be an increase in dry weather flow from wastewater treatment plant which becomes increasingly more dominate over time during the summer low flow season. This flow is expected to be the closest representation of domestic and industrial sewage flows, with minimal additional flows due to surface runoff (Starr, 2006), and therefore expected to increase as urbanisation increases.

Next, a set of models with a more hydrological interpretation was developed by relating runoff total to urban extend (URBEXT), rainfall totals, respectively, and, finally, a model relating runoff model to both rainfall total and URRBEXT. A summary of the three different regression models when applied to each of the four catchments is shown in Table 5. Note that the models including URBEXT were not applied to the rural catchments.

TABLE 5: Slope parameter of regression models of log-transformed annual runoff against different covariates. Numbers in () refer to p-values, with $p<0.05$ suggesting a a strong link.

The results in Table 5 show that a positive upward trend is found for annual runoff in all urban catchments, and that using URBEXT as the only covariate provides no better description of the year to year variation in runoff than using time in catchment 39087, but appears to be a better descriptor than time in catchment 39052. In contrast, using rainfall as a covariate has a very significant influence of the variation in runoff volume. This is of course to be expected as rainfall and runoff are closely related. However, as rainfall was previously found not to increase significantly with time, the upward trend in runoff in the urban catchments cannot be explained by rainfall alone.

The last model uses both rainfall and URBEXT as covariates to describe annual runoff. For both of the urban catchments, the level of significance of both URBEXT and rainfall increased when compared to the two previous univariate models using the two covariates independently.

When considering all the results shown in Tables 3, 4 and 5, the analysis shows that the influence of urbanisation on runoff volume is evident, but is masked by a strong year to year variability of rainfall. The comparison between the results obtained in the urban catchments, where trend in runoff was observed, and in the two rural control catchments, where no trend was observed, further emphasise the importance of increasing urbanisation when considering water resources assessments.

4.3. Water quality

Changes in dissolved oxygen and water temperature were investigated using log-transformed regression models. A simple model using only time as a covariate was used to investigate if any trend occurred during a specific period. A second model using: rainfall, runoff and URBEXT covariates to investigate the significance of relationship between each driver.

Interventions

The water quality in the receiving rivers can be impacted by significant interventions such as the implementation of new treatment facilities for waste water. In the presence of such major interventions, it is no longer valid to look for long-term smooth patterns of trend in the water quality data. Specifically, the Cut is influenced by two STWs (Bracknell and Ascot serving 97500 and 25500 people equivalents, respectively) both of which will have required tertiary treatment under the EU Urban Waste Water Directive (91/271/EEC) (Halliday et al., 2015). Spot samples of DO and SRP since 1980 illustrate that downstream of Bracknell STW at Buck Bridge (NGR: 485610 174580) SRP concentrations have become much lower since 2001, particularly since 2006 (Figure 4). Upstream of Bracknell STW at Pitts Bridge (NGR: 485350 171240) which is only influenced by Ascott STW concentrations only came down since 2006 (Figure 5). These step changes, very likely directly reflecting the dates of likely implementation of STW upgrades, are not apparent in DO which acts as a more integrative indicator of river water quality and ecological health.

Figure 4

Figure 5

In comparison with Figure 4, the plot in Figure 5 shows the values of SRP and ammonia downstream the Bracknell STW. The value of DO and BOD seems not to be significantly affected after water passing through the STP. In contrast, it can be seen that there has been a shift that led to the decrease of SRP recently, with values recorded below 1 mg/l. There has been some STP improvement over the years, for example at Binfield in 2001. There were also upgrades in upstream Ascot STP in 2006 and installation of P stripping in 2007, which would likely to be the caused of this shift.

Drawing conclusion from the figures, it is evident that the changes were likely directly influenced by the STP upgrades rather than long term changes in either land-use or rainfall over the period. For this particular reason, the study will not be focused on the long-term change in nutrient, but instead looked at dissolved oxygen and water temperature, which are only indirectly linked to such upgrades.

Dissolved Oxygen

The time trend analysis of dissolved oxygen against time in Table 6 shows upward trends in all aggregations in the river Ray draining the urban catchment 39087. For this catchment, the seasonal upward trend signal is more significant in the winter than in the summer. In the river Cut, draining the 39052 urban catchment, dissolved oxygen only increased in the winter months. Conversely, there is no statistically significant results to suggest the existence of any trend for both of the rural catchments (39025 and 39033).

TABLE 6: p-values for Dissolved Oxygen time Trend in all rivers

Next, the links between DO and the physical drivers (rainfall, runoff and urbanisation) were investigated. The results in Table 7 show that the three regression models each using either: rainfall, runoff or URBEXT as the sole covariate, found a positive relationship when URBEXT and runoff. When URBEXT is considered jointly with either rainfall or river flow, then the significance of URBEXT is slightly reduced, though it remains a significant covariate. In contrast, in the river Cut no trend was identified in any of the aggregations.

TABLE 7: Slope parameter of regression models of log-transformed mean annual dissolved oxygen against different covariates. Number in () refer to p-values, with $p<0.05$ suggesting a significant trend

Temperature

For temperature, a similar trend pattern to that observed for DO was detected. The water temperature in the river Ray is increasing in all aggregations, in the river Cut the upward trend only detected in the winter months. For both rural catchments, there is no statistically significant results (see Table 8), suggesting no trends occurred. For river Enborne at WInterbourne, the result shows as similarity with dissolved oxygen, showing no trend for both rural rivers. The lesser human interference affecting the river would likely be the caused for this.

TABLE 8: p-values for water temperature time trend in all rivers

The analysis of relationship between water temperature, rainfall and runoff found a positive relationship between temperature and URBEXT in the river Ray. Despite the increasing urbanisation, when rainfall was taken into account, the signal is reduced.

In the river Enborne draining catchment 39025 no evidence was found to suggest that there is correlation between water temperature with rainfall or runoff. In contrary, in the river WInterbourne a negative relationship was identified between temperature and rainfall and runoff.

TABLE 9: Slope parameter of regression models of log-transformed mean annual river temperature against different covariates. Number in () refer to p-values, with $p<0.05$ suggesting a significant trend.

From Table 9, the water quality analysis shown mixed results for urban catchments, however for rural catchments the result showed the high variability. The increasing trend of temperature and dissolved oxygen in all aggregations only can be found in 39087.

5. Discussion

5.1 Hydrology

Based on the analysis of water quantity and quality data from two urbanised catchment in the UK, the impacts of urban development on annual and seasonal average runoff and selected water quality variables were found to be complex. Seasonal and annual rainfall is highly variable, but no significant trends were identified in the catchment average rainfall series. The impacts of urbanisation are more apparent on the average flow values, where the majority of results showed upward trends. The exception is the river Ray at Water Eaton (39087) where no trends occurred in winter runoff. This could be the result of some very dry winter year observations, for example in 1975 and 1991, where runoff mean value recorded its lowest at $0.55m^3/s$ and $0.79m^3/s$ respectively. Urbanisation, as measured by URBEXT, was found to have strong relationship with the changes in river flow in both urban catchments, especially for the summer and annual aggregations. When removing the influence of the climate variability but including both rainfall and URBEXT as covariates in the regression model, the significance of the urban impact was even greater, suggesting that the more subtle signal from the urban impact can be masked by the large variability in rainfall from year to year and from season to season. A similar result was reported by Prosdocimi et al. (2015) investigating the impact of urbanisation on flood peaks in an urbanising catchment located in the north of England using a point process model. As no trend was found in rainfall totals in neither annual nor seasonal aggregations, it is likely that the upward trend in runoff is caused by increasing flow during the relatively dry summer season. The actual cause of this increase is not known, but added contribution to dry weather flow from increased discharge from waste water treatment facilities is suggested asd a possibility.

5.2. Water quality

Increasing river water temperature in rivers draining urban catchments could come from discharges from sewer treatment plans increasing the temperature during the winter season. Espinosa et al. (2001) suggested higher temperature could lead from heat transfer between runoff and heated impervious surface (e,g. roads, roofs) in contact with runoff. The effects on the dissolved oxygen are showing more variability. In the river Ray where water quality data obtained from further downstream of sewage treatment, DOE was expected to have decreasing trend due to sewage discharge depleting the oxygen. On the contrary the results from this study show increasing dissolved oxygen value. This might suggest some improvements had been made to intercept the impact of sewage discharge on water quality. The demonstrated lack of influence that hydrological factors have on this trend would appear to reinforce the likelihood of improvement in sewage treatment being the driver of the increase in dissolved oxygen concentration.

With the advent of improved sewage treatment in the urban catchments, loads of nutrients and organic matter to receiving waters has thereby been reduced despite the increase in effluent volumes which will occurred due to population growth. A reduced load of organic matter means that oxygen becomes less depleted as there is less demand from microbial decay both in the water column and in the bed sediment. Indeed in Swindon, treatment of sewage has become so advanced (activated charcoal) that now it actually dilutes the river BOD load and improves river water quality. Decreases in the concentration of ammonium, which alongside SRP are also synchronous with improved sewage treatment, mean that the in-river nitrification flux is also reduced and less oxygen is consumed by this route as well. Restoration works by local Swindon Borough Council and local communities along river stretches (involving re-meandering and habitat improvements) could also have benefitted the water quality in tandem with ecological improvements.

Improvements to water quality are less apparent in the summer. Despite the long-term increases seen in water temperature, during warm seasons the reduced nutrient load will increasingly have served to limit primary productivity, a process which elevates DO during daytime photosynthesis. This effect may moderate the benefits seen in terms of DO resulting from a lessening in the BOD load. It should be stressed that despite the long term improvements in DO seen in the urbanising rivers, levels are still lower than in the rural control catchments.

Finally, it should be noted that the statistical significance cannot be interpreted as evidence of an actual physical linkage between drivers and response variables. More detailed processes based studies should be undertaken to further examine and explain the links identified in this study.

7. Conclusions

This study was set out to explore the links between environmental changes, and a subset of water quantity and quality variables. It sought the best possible model to investigate the potential driver(s) that can be associated with the changes in river flow and selected water quality variables. By combining historical observations in land-use, climate, hydrology and water quality for paired urban and rural catchments in the south of England, the study has identified strong impact of urbanisation on downstream water quality and quantity. From the assessment, this study can be drawn into these conclusions.

- The long-term annual rainfall observed in both the urban and the rural catchments did not indicate the existence of any trends.
- Upward trends in summer and annual runoff were found in both urban catchments, while no trend in runoff (annual or seasonal) was observed in any of the rural catchments. For the urban catchments, increases in winter flows were observed in the Cut, but not in the river Ray.
- An index of urban land-cover extent (URBEXT) as well as annual rainfall totals were found to be the most representative covariates, which could act as potential drivers to changes of river flow in urban catchments. In particular, the URBEXT signal becomes stronger once the effect of rainfall variability is accounted for. In the absence of URBEXT in rural catchments, rainfall was the only potential driver that can be associated with the changes.
- Temperature and dissolved oxygen have been rising in urban catchments particularly in winter. These trends are not explained by hydrological drivers but are thought due to be improvements in sewage treatment despite the increased effluent load to the rivers brought about by increasing population.

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TABLES

Table 1: Summary of available daily runoff data

NRFA number	**River**	**Location**	**Catchment area (km^2)**	**State**	**Start of record**	**End of record**
39052	Cut	Binfield	50.2	Urban	1961	2010
39033	Winterbourne	Bagnor	49.2	Rural	1963	2010
39087	Ray	Water Eaton	84.1	Urban	1974	2010
39025	Enborne	Brimpton	147.6	Rural	1968	2010

Table 2: Summary of water quality monitoring stations

Code	Monitoring station name/location	State	Length of record
PTHR 0128	Ray at Seven Bridges, Cricklade	Urban	1980-2010
PKER 0016	Enborne at gauging station, Brimpton	Rural	1980-2010
PUTR 0071	Cut at Pitts Bridge, Binfield	Urban	1980-2010
PKER 0089	Winterbourne at gauging station, Bagnor	Rural	1980-2009

Table 3: Results from regression analysis of log-transformed rainfall total against time. Numbers in table are p-values associated with regression slope parameter. For $p<0.05$ a significant trend is reported.

Catchment	State	Annual	Summer	Winter
39087	Urban	0.417	0.549	0.816
39025	Rural	0.420	0.615	0.340
39052	Urban	0.875	0.162	0.248
39033	Rural	0.767	0.188	0.555

Table 4: Results from regression analysis of log-transformed runoff total against time. Numbers in table are p-values associated with regression slope parameter. For $p<0.05$ a significant trend is reported and highlighted in grey cells.

Catchment	*State*	*Annual*	*Summer*	*Winter*
39087	*Urban*	***0.038***	***0.019***	*0.239*
39025	*Rural*	*0.600*	*0.791*	*0.690*
39052	*Urban*	***0.000***	***0.004***	***0.043***
39033	*Rural*	*0.625*	*0.873*	*0.474*

Table 5: Slope parameter of regression models of log-transformed annual runoff against different covariates. Number in () refer to p-values, with $p<0.05$ suggesting a significant trend and are highlighted in grey cells.

NRFA	*39087*	*39025*	*39052*	*39033*
URBEXT	**0.47 (0.039)**		**0.16 (0.000)**	
Rainfall	**1.16 (0.000)**	**1.83 (0.000)**	**1.17 (0.000)**	**1.00 (0.023)**
URBEXT	0.33 (0.003)		0.61 (0.000)	
Rainfall	1.12 (0.000)		1.13 (0.000)	

Table 6: p-values for Dissolved Oxygen time Trend in all rivers. For p<0.05 a significant trend is reported and highlighted in grey cells .

River	*State*	*Annual*	*Summer*	*Winter*
Ray	Urban	**0.000**	**0.000**	**0.000**
Enborne	Rural	0.505	0.795	0.069
Cut	Urban	0.273	0.375	**0.005**
WInterbourne	Rural	0.123	0.280	0.173

Table 7: Slope parameter of regression models of log-transformed mean annual dissolved oxygen (DOE) against different covariates. Number in () refer to p-values, with p<0.05 suggesting a significant trend and are highlighted in grey cells

River	*Ray*	Enborne	Cut	WInterbourne
URBEXT	**0.91 (0.000)**		0.103 (0.1.77)	
Rainfall	0.25 (0.216)	0.0773 (0.294)	0.109 (0.219)	-0.021 (0.700)
Runoff	**0.34 (0.003)**	0.0416 (0.222)	0.082 (0.192)	-0.009 (0.586)
URBEXT	**0.89 (0.000)**		0.095 (0.208)	
Rainfall	0.17(0.249)		0.1 (0.256)	
URBEXT	**0.83 (0.000)**		0.086 (0.263)	
Runoff	0.19 (0.108)		0.068 (0.286)	

Table 8: p-values for water temperature time trend in all rivers. For $p<0.05$ a significant trend is reported and highlighted in grey cells.

River	State	Annual	Summer	Winter
Ray	Urban	**0.004**	**0.004**	**0.000**
Enborne	Rural	0.953	0.769	0.406
Cut	Urban	0.141	0.609	**0.002**
WInterbourne	Rural	0.490	0.096	0.309

Table 9: Slope parameter of regression models of log-transformed mean annual river temperature against different covariates. Number in () refer to p-values, with $p<0.05$ suggesting a significant trend and are highlighted in grey cells.

River	*Ray*	Enborne	*Cut*	Winterbourne
Urbext	**0.345 (0.007)**		0.124 (0.135)	
Rainfall	0.022 (0.840)	0.137 (0.241)	0.003 (0.970)	**-0.15 (0.0028)**
Runoff	0.003(0.968)	0.028 (0.623)	0.058 (0.404)	**-0.05 (0.015)**
Urbext	**0.345 (0.008)**		0.124 (0.142)	
Rainfall	-0.007 (0.937)		-0.008 (0.930)	
Urbext	**0.852 (0.006)**		0.114 (0.181)	
Runoff	-0.061 (0.457)		0.039 (0.575)	

FIGURES

FIGURE 1: Locations of the two urban and two rural test catchments within the Thames Basin (Inset United Kingdom)

FIGURE 2: Increase in Urban (black) and Suburban (Grey) land-use grid-cells within the two urban test catchments (39052 and 39086) for each decade during 1960-2010

FIGURE 3: Summary of regression models deployed to detect impact of environmental drivers. The variables are: runoff (Q), water quality (F), rainfall (P) and urbanisation (U). In addition, β_0 and β_1 are regression model parameters.

FIGURE 4: Time series of DO and SRP values measured in the river Cut downstream of Bracknell STW.

FIGURE 5: Time series of DO and SRP values measured in the river Cut upstream of Bracknell STW

Figure 1

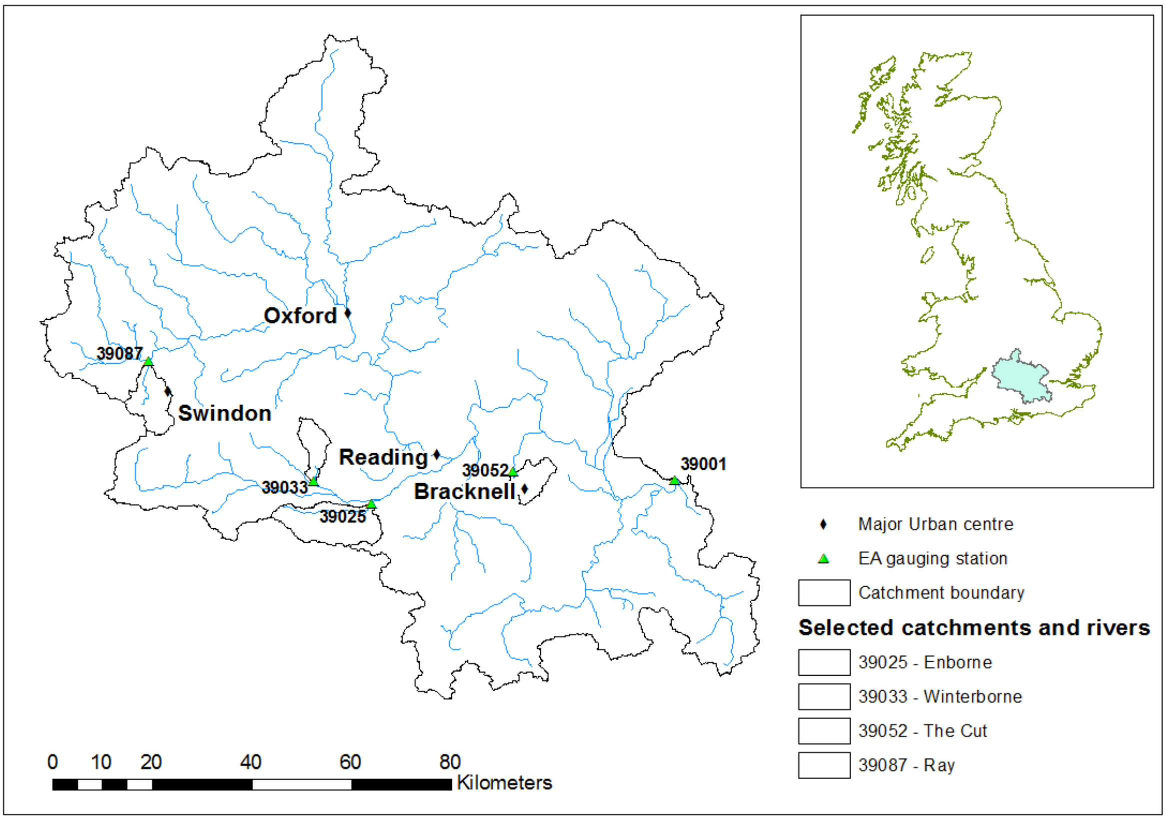
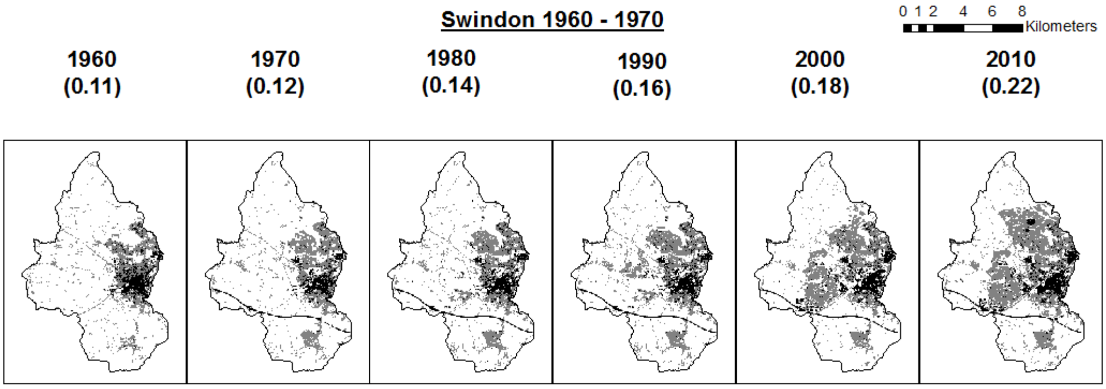
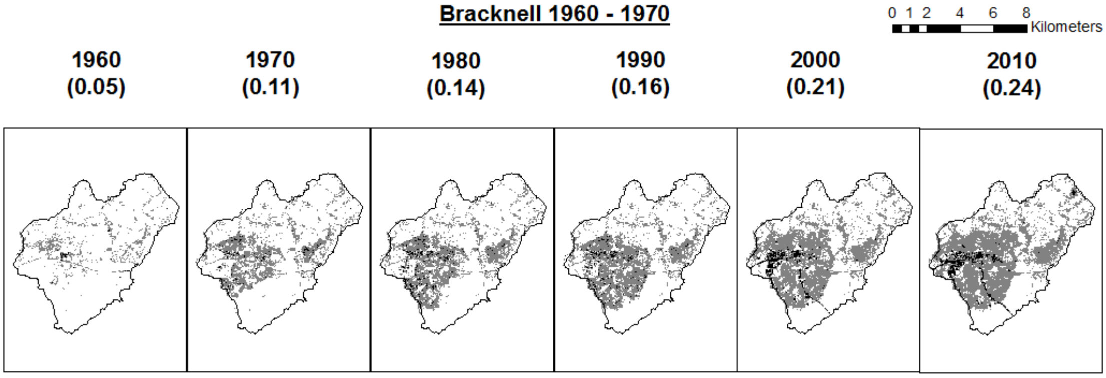

Oxford
Swindon
Reading
Bracknell
39087
39033
39025
39052
39001
0 10 20 40 60 80
Kilometers
Major Urban centre
EA gauging station
Catchment boundary
Selected catchments and rivers
39025 - Enborne
39033 - Winterborne
39052 - The Cut
39087 - Ray

Figure 2



Swindon 1960 - 1970



Bracknell 1960 - 1970

Figure 3

	Swindon		Bracknell	
Model	The River Ray at Water Eaton (NRFA 39087)	The River Enborne at Brimpton (NRFA 39025)	The River Cut at Binfield (NRFA 39052)	The River Winterbourne at Bagnor (NRFA 39033)
$\log Q = \beta_0 + \beta_1.\text{time}$	+	+	+	+
$\log Q = \beta_0 + \beta_1.\log U$	+	÷	+	÷
$\log Q = \beta_0 + \beta_1.\log P$	+	+	+	+
$\log Q = \beta_0 + \beta_1.\log U + \beta_2.\log P$	+	÷	+	÷
$\log F = \beta_0 + \beta_1.\text{time}$	+	+	+	+
$\log F = \beta_0 + \beta_1.\log U$	+	÷	+	÷
$\log F = \beta_0 + \beta_1.\log P$	+	+	+	+
$\log F = \beta_0 + \beta_1.\log Q$	+	+	+	+
$\log F = \beta_0 + \beta_1.\log U + \beta_2.\log P$	+	÷	+	÷
$\log F = \beta_0 + \beta_1.\log U + \beta_2.\log Q$	+	÷	+	÷

Figure 4

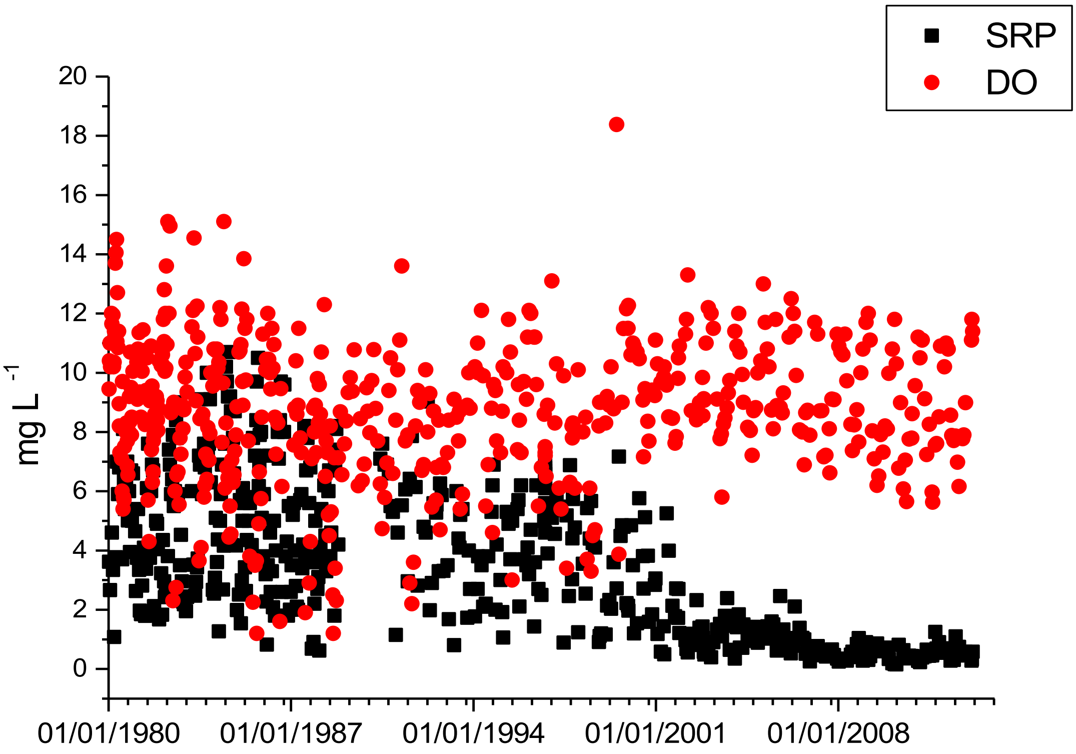
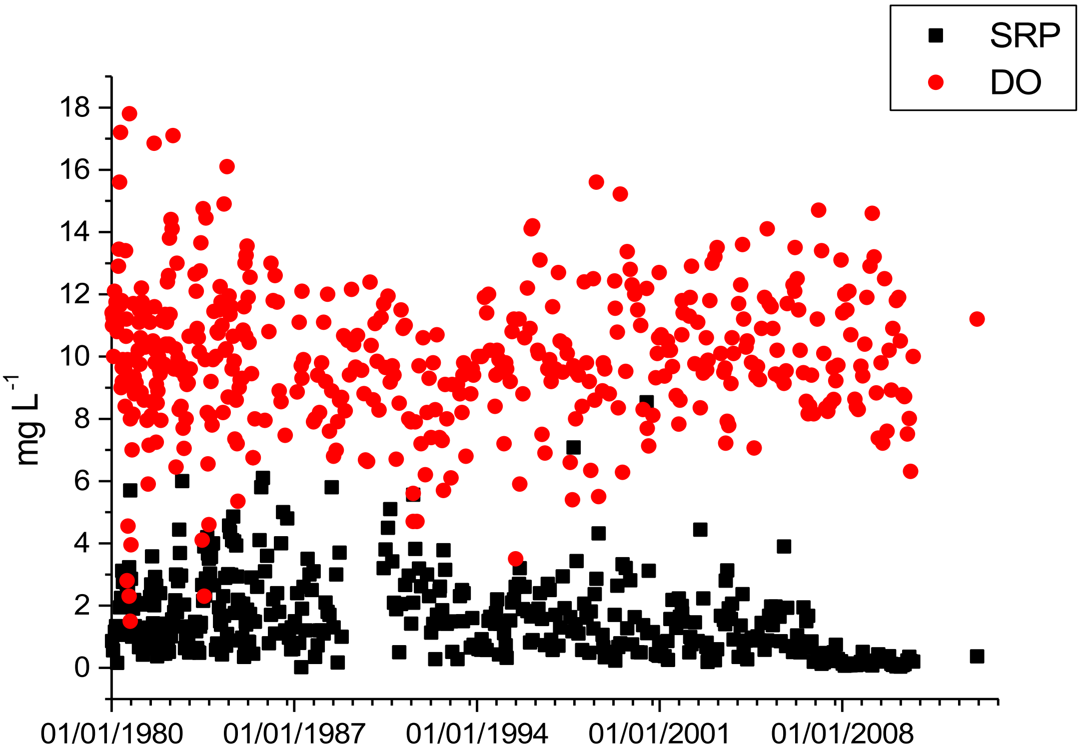

SRP
DO
20
18
16
14
12
10
8
6
4
2
0
mg L -1
01/01/1980
01/01/1987
01/01/1994
01/01/2001
01/01/2008

Figure 5


SRP
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18
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