Links between environmental change and its impacts on river flow regime and quality in urbanising catchments

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5 August, 2013

Declaration of Own Work

I declare that this thesis, “Links between environmental change and Its impacts on river flow regime and quality in urbanising catchments” is entirely my own work and that where any material could be construed as the work of others, it is fully cited and referenced, and/or with appropriate acknowledgement given.

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Abstract

This study was undertaken to investigate the effects of urbanisation on the river flow regime and water quality. The links between environmental changes represented by rainfall and Urban Extent (URBEXT) with the changes in the river flow, river temperature and dissolved oxygen were explored. This thesis focuses on the following question “does urbanisation has an effect on the river water quantity and quality changes?”. Two urbanising catchments in the United Kingdom, the river Ray at Water Eaton and the river Cut at Binfield were selected for this study. As a comparison, nearby similar sized rural catchments, the river Enborne at Brimpton and the river Winterbourne at Bagnor were also selected.

There was no significant time-trend of rainfall found in all urban and rural catchments in all aggregations (annual, summer and winter). For river flow, positive time-trends were found in the two urban catchments in all aggregations with the exception of no significant trend was found in the winter in the river Cut at Binfield. The log-log regression analysis found that in the two urban catchments, URBEXT alone had a strong positive relationship with the changes in mean annual flow. When climate variability is included, the URBEXT signal was amplified. Contrasting results were found in all rural catchments where there was no significant evidence of time-trend in the river flow.

Increasing temperature and dissolved oxygen values were found in all aggregations in the river Ray, while in the river Cut these values increasing only in the winter. URBEXT had a significant positive relationship with temperature and dissolved oxygen in the river Ray. When rainfall and river flow are included, the URBEXT signal was reduced. This study also found a strong positive relationship between river flow and the increase of dissolved oxygen value in the river Ray. On the contrary, there was no significant time-trend in temperature and dissolved oxygen was found in all rural catchments.

Urbanisation was found to be a potential driver of the increase in river flow, which might lead to detrimental rather than beneficial effects. Nevertheless, the effect on water quality was somewhat spurious and showed mixed results. Despite not showing any significant trend, the present temperature and dissolved oxygen values in the more natural environment of rural catchments still showing a better state.

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1. Introduction

1.1 Statement of Problem

Water is fundamental to human life. It is the single most important commodity that each and every one of us needs, without it society and life itself comes to an end (Gray, 1994). There are growing concerns on how human manage their water environment could lead to environmental impacts. Rivers as one of the water stream in the environment had also faced with these concerning impacts as many studies had found. Wade et al. (2012) expressed that the chemical and ecological status of surface waters is an increasing concern worldwide as demand for water and food grows with population increases. Hilton et al. (2006) had also suggested that the spatial and temporal variations in stream water chemistry are highly complex and the links between these changes and the controlling factor are subject to intense study.

From a strictly human perspective, healthy rivers perform numerous “ecosystem services”, the processes carried out by natural ecosystems that benefit human societies and economies. According to Postel and Richter (2003), river and other freshwater ecosystems constitute part of the natural infrastructure that keeps a country economies humming. In United Kingdom (UK), there are several significant water management issues including flow alteration, urban development, diffused pollution and point source pollution. Environmental changes and variability are contributing to these issues, however, the large effects mostly due to human activities rather than natural processes.

One of the environmental changes contributing to these issues and had been largely debated since 1990’s is climate. In UK, weather is one of the most talked about topic and well known for its variability and can changes drastically in short period of time. The unusual weather condition of higher or lower temperature which human is often related to the effects climate change, however, the change also can be resulted from variability. Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (2007) reported that 1995-2006 has recorded to be among of the twelve warmest years in the instrumental record of global surface temperature (since 1850) and it is very likely that man-made greenhouse gas emissions caused most of the observed temperature rise since the mid 20th century. This study suggested that human activities will likely affected negative impacts to climate.

During pre-urbanised era where population was much less and land use had not developed significantly to residential and industrial area, river flow was in their more natural condition with minimum human interactions to satisfy their needs.

This condition are considered to have better impacts to water quantity and quality, as amount of pollutants being discharged to the river resulting from household, industrial and other activities were less than the urbanisation era. An example of long-term record of nitrate shows increasing patterns mainly resulted from runoff from agricultural land (Robinson et al., 2000). Since the Second World War, Britain has had a policy encouraging food production through grant aid, technical advice and price support, which might had trigger this increasing value.

Many human alterations in the river resulting from urbanisation, had changed its natural characteristic and water body condition e.g. land opening for agricultural industry, cutting trees along river banks for recreation area and point source pollutants discharge from sewage water treatment or industry. This condition leads to land opening and changing proportions of land use, clearance of original forest would have increased runoff and probably caused erosion of valley floors and head ward extension of channel (Robinson et al., 2000). However, recent environmental concerns and awareness by community and the government had tried to shift this thought.

Many studies and research had been conducted towards understanding the best condition of a river in supporting aquatic habitat and human health. Human activities altering river characteristics and water body is now planned to make better condition of river despite changing its natural variation. A question emerges whether natural condition without or with minimum human interactions during the pre-urbanised era will be better than present urbanised era with improved regulations and better understanding of environmental issues.

Series of long-term data related with these issues are routinely monitored and available from UK government research bodies such as the Centre for Ecology and Hydrology (CEH), the Natural Environment Research Council (NERC), the Environment Agency (EA) and other organisations. However, further processing and analysis of such data is needed to have better understanding of the links between various variables in specific location and water resources. This research will study how the climate and land use had changed over time and will explore the links between these variables and their impacts on water quantity and quality of the selected rivers in urban and rural catchments. Two urban catchments in the UK, the river Ray at Water Eaton and the river Cut at Binfield and two rural catchments, the river Enborne at Brimpton and the river Winterbourne at Bagnor were selected for this study.

1.2 Aim and Objectives

Aim of this research is to investigate the links between urbanisation and climate changes and variability with river water quantity and quality in two urbanised catchments, the river Ray at Water Eaton and the river Cut at Binfield and to compare the results with non-urbanised catchments the river Enborne at Brimpton and the river Winterbourne at Bagnor.

The objectives of this project are:

- To identify the annual and seasonal climate time-trends in both urban and rural catchments over a specific length of period.
- To identify long-term annual and seasonal time-trends of flow in the river Ray, river Cut, river Enborne and river Winterbourne.
- To identify the time-trends of selected water quality variables (river temperature and dissolved oxygen) in the river Ray, river Cut, river Enborne and river Winterbourne.
- Comparing the time-trends of river flow, climate, and selected water quality variables in all catchments.
- Using statistical models to investigate the significance of relationship between climate change and land use variables with river flow and selected water quality variables in study sites.
- Determining water quality variable(s) that has been significantly affected by climate, and urbanisation and identifying the negative impacts to provide recommendation and concerns need to be addressed for future improvement.

1.3 Study Sites

Catchments study sites are defined using specific codes from National River Flow Archive (NRFA). The study sites for this research are two urban catchments: Ray at Water Eaton (NRFA 39087) and Cut at Binfield (NRFA 39052) and two non-urban (rural) catchments: Enborne at Brimpton (NRFA 39025) and Winterbourne at Bagnor (NRFA 39033).

1.3.1 Ray at Water Eaton Catchment (NRFA 39087)

The first urban catchment study site is the river Ray Water Eaton, Cricklade (see Figure 1.1) within borough of Swindon and Wiltshire County in South West England. Located about 130 km west from London and 64km west of Reading, Borough of Swindon has total population of 209,156 (ONS census, 2011). From 2001 to 2011 the population had growth over 16% as a result from the growth of housing developments around the area which attracts more people coming to Swindon.

The catchment itself is located in north Wiltshire and has population of 4,132 with catchment area of 84.1 km^2. This town is drained by the river Ray which is also a tributary of river Thames, it rises at Wroughton to the South of Swindon and runs to the west of the town via Shaw. It joins river Thames on the Southern bank near Cricklade upstream Water Easton House Bridge. This catchment area is mainly impervious with largely agricultural land use.

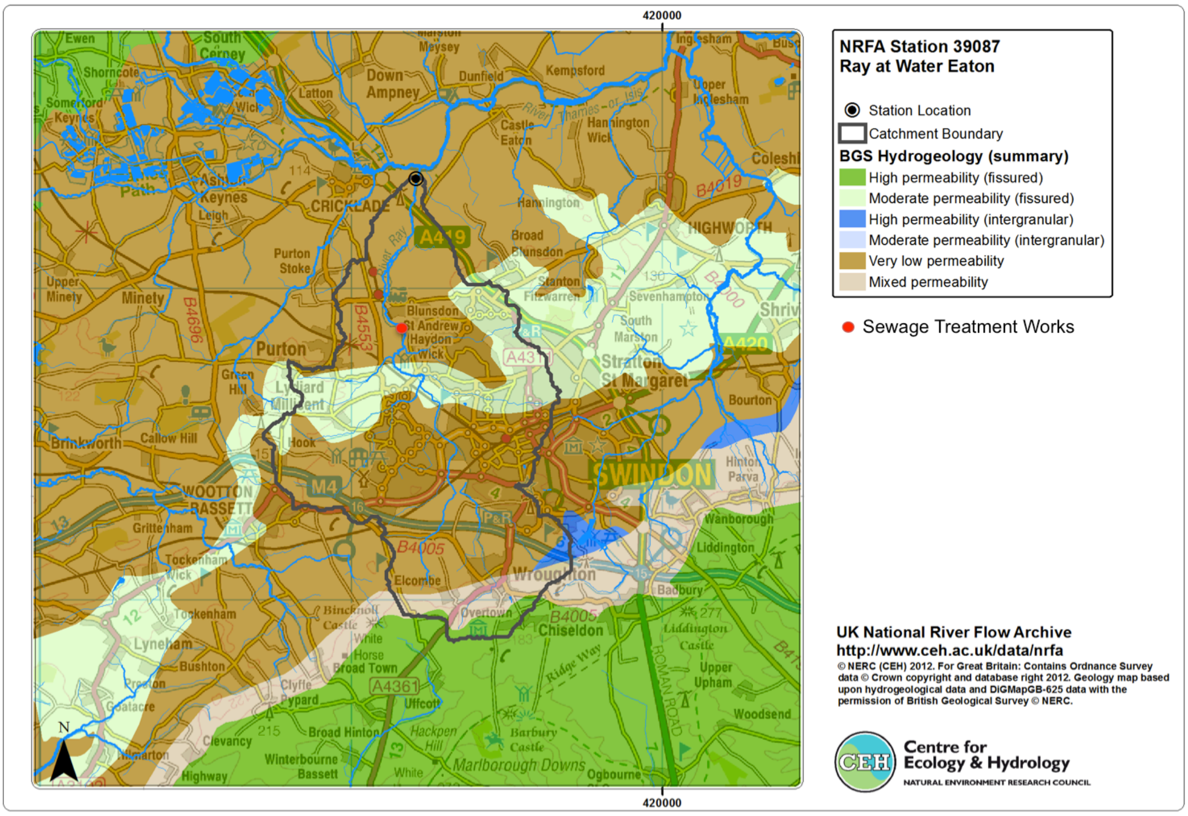

Figure 1.1 Ray at Water Eaton catchment location map; retrieved from www.ceh.ac.uk

1.3.2 The Cut at Binfield Catchment (NRFA 39052)

The second urban catchment study site is Cut at Binfield situated in Berkshire in the Bracknell Forest borough, South East England about 48 km west of central London and 16 km of southwest of Windsor (see Figure 1.2). After the Second World War, in 1949 Bracknell was designated as a new town under the New Towns Act 1946 which was planned to disperse population following the aftermath. This first wave of new towns was intended to improve the housing shortages around the designated area. Originally planned to accommodate 25,000 people, Bracknell attracts a lot more population than intended. The recent population of Bracknell is 113,200 (ONS census, 2011), the highest growth of over 33% in the last 25 years compared to any other cities in England.

Despite the huge rise of population, Bracknell is still a small borough, which will increase the density of the area. The catchment itself is located on the North West of Bracknell with population approximately 7,475 people and catchment area of 50.2 km^2. The river Cut flow rises in North Ascot, Berkshire and flow around 23 km through several areas including Winkfield, Warfield in Bracknell Forest borough before it meets the river Thames above Queens Eyot Island below Bray Lock. The Cut at Binfield is an impermeable catchment largely covered with London Clay.

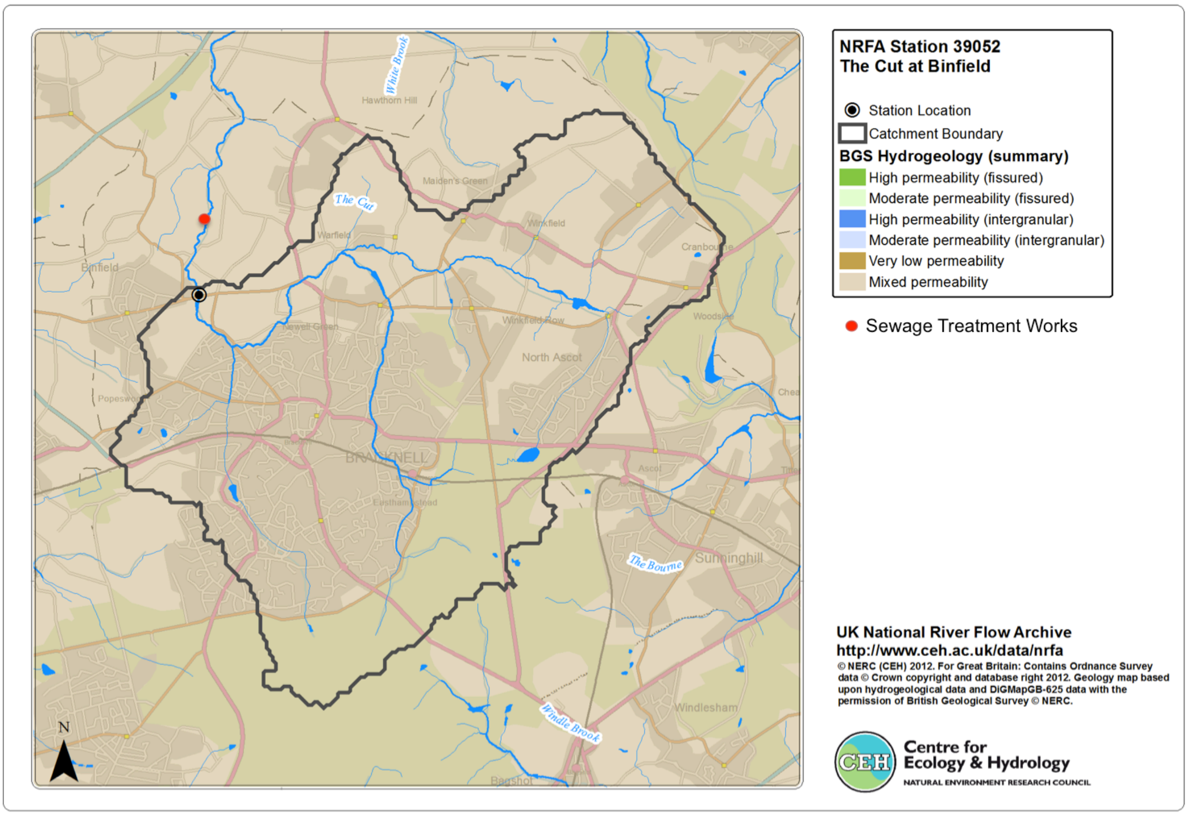

Figure 1.2 The Cut at Binfield catchment location map; retrieved from www.ceh.ac.uk

1.3.3 Enborne at Brimpton Catchment (NRFA 39025)

The third study site is Enborne at Brimpton catchment located in West Berkshire, South East England (see Figure 1.3), approximately 55 kilometers South East of Ray at Water Eaton catchment. The environmental change, river flow and water quality data from this site will be analysed and compared with Ray at Water Eaton urban catchment data. This site has a total area of 147.6 km^2 and was chosen due to its rural characteristic with very low population in comparison with Ray at Water Eaton urban catchment. This catchment drained by the river Enborne which rises near the Inkpen and West Woodhay villages and flows East towards Newbury. Enborne at Brimpton catchment land use is mainly agricultural (arable and grassland).

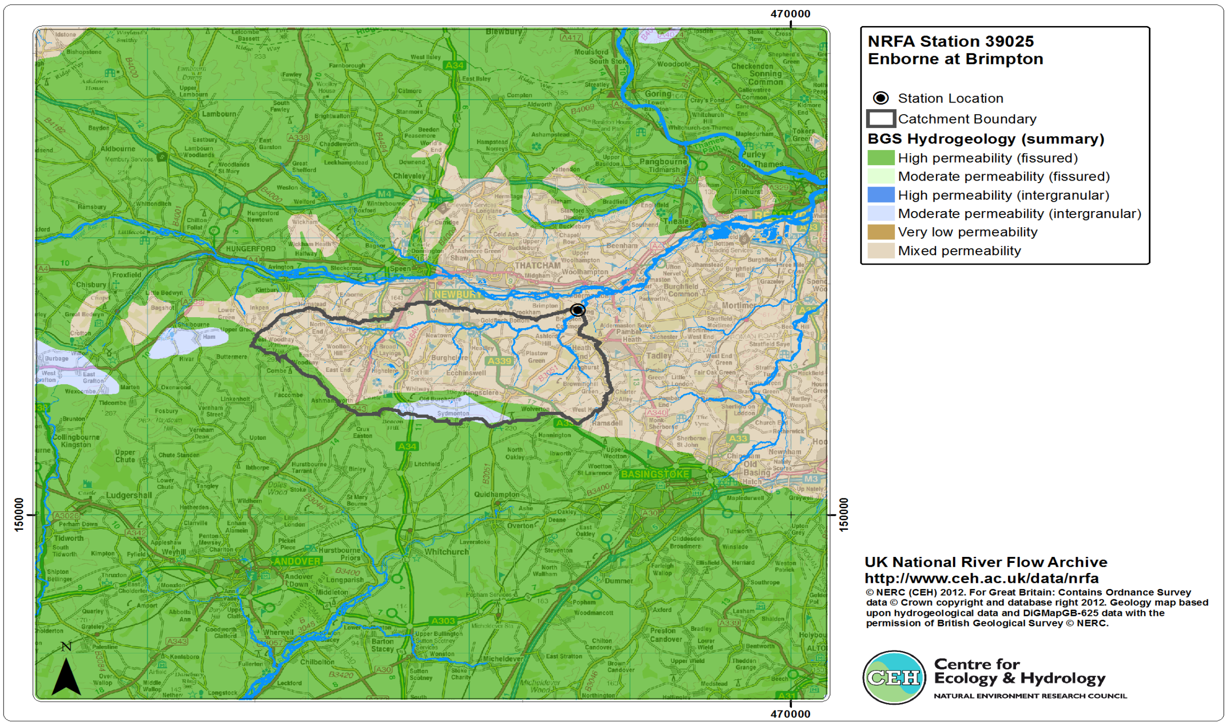

Figure 1.3 Enborne at Brimpton catchment location map; retrieved from www.ceh.ac.uk

1.3.4 Winterbourne at Bagnor Catchment (NRFA 39033)

Figure 1.4 shows the fourth study site in Winterbourne St at Bagnor, a 49.2 km^2 catchment located in West Berkshire, South East England approximately 38 kilometers West of Cut at Binfield catchment. This catchment chosen due to very rural characteristic and the environmental change, flow and selected water quality data observations will be use to compare the results obtained from the Cut at Binfield urban catchment.

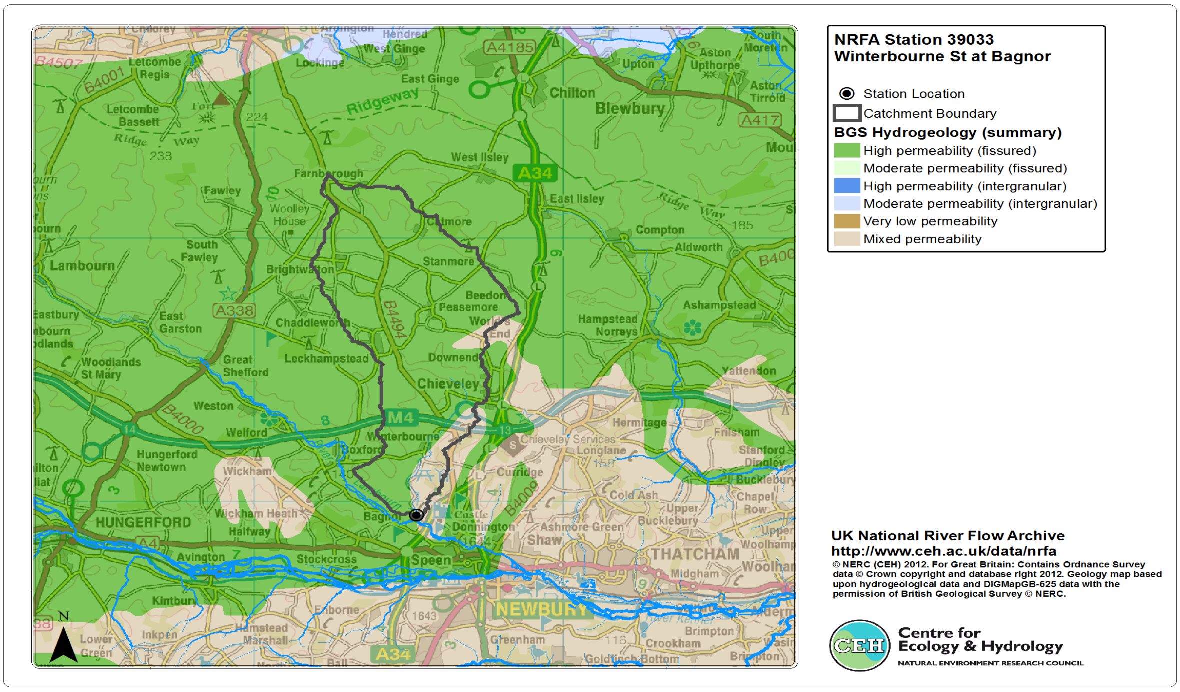

Figure 1.4 Winterbourne at Bagnor catchment location map, retrieved from www.ceh.ac.uk

2. Literature Review

2.1 Environmental Changes

In river, the volume of water storage and rates of exchange between them are controlled by multitude of factors; these include climate, land use, catchment development and channel engineering (Acreman, 2000). This research will study two factors of the environmental changes and variability including rainfall and urbanisation extent.

Growing industries and economy in Bracknell and Swindon attracted population from surrounding and other area, which leads to concentration of human population growth in areas resulting from rural migration. This condition had transformed land to satisfy human personal needs for residential, industrial, transportation and commercial purposes. Human action to satisfy their need will demand more land and lead to numerous condition of land clearing which interfering with the original condition of environment. According to Robinson et al. (2000), change of land use, both cover and management, will affect river flow river flows and the water balance.

Large-scale intensive agricultural processes that are not properly managed will lead to negative impacts to the environment. In addition, deliberate and unintentional human activity polluting the environment during the land development such as oil spill, improper waste discharge often caused decline in water quality. The clearance of forest for residential or agricultural development will also increase runoff and erosion, which will bring pollutants into the water body. Many of the problems for river management today relate to a complex sequence of land use changes, water resource development and industrial expansion which have altered the pattern of runoff, the quality of river discharge and the size distribution and load of sediment transported (Calow & Petts, 1994).

Although it is difficult to draw a clear distinction, climate change can be interpreted as resulting from change in the variables forcing climate (radiation inputs, for example). Despite UK long records of both rainfall and temperature at many sites across the country, the pattern still showing large degree of variability and with clear patterns of increasing temperature.

Defining trends in rainfall is harder to find, other parts of the world have also experienced changes in rainfall pattern over the last few decades, but the global average precipitation, unlike global average temperature, shows no clear pattern (Arnell & Reynard, 2000). Correspondingly, recent IPCC Fourth Assessment Report (2007) stated that the nature of precipitation is complex and that patterns of precipitation vary somewhat from year to year.

From Figure 2.1, the graph of long-term mean annual rainfall recorded across UK from 1910 showing great variability and did not exhibit any visible trend.

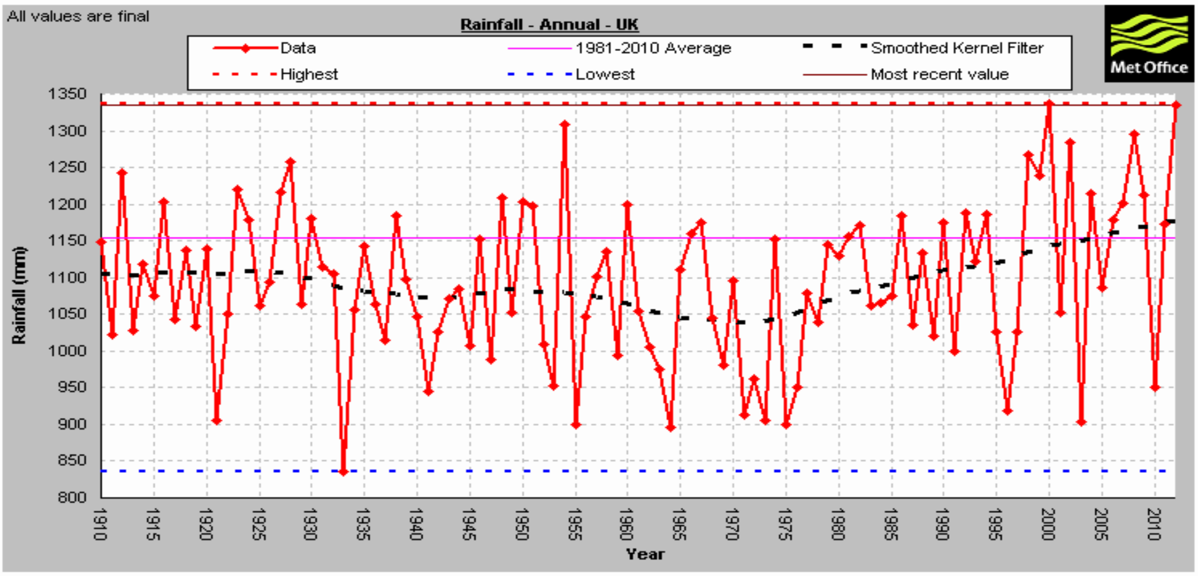

Figure 2.1 Long-term annual rainfall observations in United Kingdom in 1910-2012 retrieved from http://www.metoffice.gov.uk/climate/uk/actualmonthly

Land-use data as the second stressor is described using the urban extent (URBEXT) index. There were two different URBEXT indexes ($URBEXT_{1990}$ and $URBEXT_{2000}$) used to described urban extent, however, they are not comparable since the mapping technique has changed (Defra, 2006). A new dataset was developed to overcome the problem with URBEXT outlined. The new index was developed using equation comprising value reflecting both fraction of urban and suburban land cover within catchment.

A weight of 0.5 was added to suburban fraction, this due to type of suburban land cover which compromised a mixture of built-up land and permanent vegetation, on average of one half (Fuller et al., 1994). From the Table 2.1 it is evident that URBEXT index was continuously increasing from 1960 with highest index in Bracknell (0.24) in 2010.

These stressors of environmental changes are interrelated and linked to each other. Understanding the links of land use with climate changes are more complex and operate in a large scale. This complex relation between the stressors will likely to have a spurious cause and effects on the catchments.

Decade	Swindon			Bracknell		
	Sub urban (%)	Urban (%)	URBEXT	Sub urban (%)	Urban (%)	URBEXT
1960	13.3	4.4	0.11	8.5	0.3	0.05
1970	16	4.5	0.12	20.1	1	0.11
1980	17.6	5.5	0.14	24.7	2	0.14
1990	20	5.7	0.16	28.4	1.9	0.16
2000	22.7	6.7	0.18	35.7	2.7	0.21
2010	29.3	7.3	0.22	41.8	3.2	0.24

URBEXT = Urban fraction + (0.5 x Suburban fraction)

Table 2.1 URBEXT index in Swindon and Bracknell from 1960-2010,
reproduced with the permission from James Miller, Centre for Ecology and Hydrology (CEH)

2.2 Hydrological Parameter

Hydrological parameter of a river assessed by measuring river flow in different part of water body upstream and downstream. The greatest number of hydrological studies into the effects of climate change had concentrated on potential changes on stream flow and runoff (MacCarthy, 2001). In global context, rivers in UK are mere streams, being characteristically short, shallow and subject to considerable man-made disturbance (Marsh et al., 2010), which leads to more concern should be addressed in urbanizing area. River flow changes significantly in short amount of time due to many factors. Rainfall and snowmelt can effects river flow, in contrary, continuous high temperature during summer season will also effects the value.

Measuring river flow is considered to be crucial as it help to forecast future flood which might l cause damage to the environment and economic loss or even casualties. In the last century natural flow regimes have been heavily modified by different anthropogenic impacts (Malmqvist & Rundle, 2002; Schneider et al., 2013). Main cause of river flow alteration mostly to generate hydroelectric power, control floods and supply for drinking water and irrigation. Schneider et al. (2013) found that many rivers have also been artificially altered by construction works such as channelization, embanking, straightening, widening or deepening with further impacts on flow and flow velocity.

A recent study in United States found that flows were altered in nearly nine of ten river segments and compare with eight other variables-including water temperature, nitrogen and phosphorus pollution, and the loss of the riverside land to farming or urban uses-stream-flow alteration was the primary predictor of a river's biological integrity (Carlisle et al., 2010). Correspondingly, in UK only less than 15% of the flow regime in river can be considered as natural (Marsh et al., 2010).

In highly urban areas, the concerns are growing as the river water quality might be overlooked by the needs to accommodate human energy demand. In UK, variations of runoff with time are often studied using flow values for calendar time intervals (days, weeks, months, years) rather than for runoff events of non-uniform duration. In the case of major continental rivers, where the passage of flood peaks through the system may take several months, weekly flow values are usually suitable, however for small drainage basins that respond rapidly to precipitation or melt events, hydrographs of daily flow values may be more appropriate (Robinson & Ward, 2011). Large section of this research will consist of understanding the trends and variation in annual and seasonal data of stream flow in the river Ray, river Cut, river Enborne and river Winterbourne

River data measurement and hydrometric data collection area in UK are normally organized on a catchment or basin basis. It is maintained in NRFA which primary function is have an overview of network evolution in order to identify the trends, monitor drought extent and severity and help to develop tools to improve engineering design for river and water management. In the 1930's the Surface Water Survey designated which resulted a map of total 107 Hydrometric Areas across UK. The river Ray, river Cut, river Enborne and river Winterbourne are located in Thames Hydrometric Area number 39 as defined by NRFA and measured by Environment Agency-South East measuring authority, additional low measurement are carried out by other public and private bodies including CEH. Long-term river flow data series from selected gauging stations in will be assessed for this research.

2.3 Water Quality

Water quality, which consist of many different parameters are important factors to determine the condition of a river. It refers to biological, chemical and physical and characteristic of the water body. They area valuable indicators to assessed if water quality in river is improving to a better condition or falling. It is measured as a reference in relation to requirements of biotic species in the water environment and for human need purposes. To date, efforts to restore and protect rivers have focused primarily on two goals-improving water quality, and establishing minimum flow requirements so that rivers and streams do not run completely dry (Postel & Richter, 2003).

Most standards of water quality parameters are used as a guideline to process drinking water and it become more important to maintain the river water quality in good condition since further process to clean polluted river water will cost more for the government and water industries. In contrary, many studies have explored the potential effect of climate change for river flows in the UK and elsewhere, but very few studies have looked either groundwater recharge or water quality (Arnell & Reynard, 2000).

As many rivers in UK will meet with the river Thames, which provides two-third of London's drinking water (Environment Agency, 2007), it is become more apparent that river water quality assessment is needed in UK. In addition, rivers and path along it are often become attraction for tourist and local community, which would likely provide an income for the borough, thus the aesthetic factor of the river should be considered as it often influenced by other water quality parameter in this study.

Many studies has been done and still being carry out to understand the how water quality parameters influence each other and to determine the acceptable level for each parameter to formulate a standard for water quality parameters. For the last twenty years, UK used General Quality Assessment (GQA) to assess river water quality in term of biology, chemistry and nutrients. More sophisticated way of assessing the whole water environment by using The European Water Framework Directive (WFD) is now used to help the government with direct action. River flow as hydrological parameter and selected water quality parameters will be assessed in this research to understand their trends and relationship with environmental changes.

2.3.1 River Temperature

One of the water quality parameters that have a fundamental influence on aquatic organism is temperature. Smith (1979) implies that the thermal regime of a river is one of the most important of all water quality parameter. It has direct and indirect effects on many aspects of the river water including the viability of aquatic habitat. It also influences other water quality parameter such as dissolve oxygen and also ecological processes and potency of many pollutants. Changes in temperature determine which organism will live and which will diminish in the water body. Parmesan (2006) studied that ecological response to the changes in thermal regime vary according to species resilience and resistance but can include local extinction, migration and changes in behavior and physiology.

Temperature varies during the day and season and is influenced by many factors including air temperature, shading and also human interaction. Water temperature does not follow air temperatures exactly due to complex atmospheric and hydrological controls (Hannah et al., 2008). Each aquatic animal and plants have certain thermal point in which they can no longer survive, many of the organisms cannot live under high temperature condition, the threshold is stated in River Basin District Typology Standard (Water Framework Directive, 2010) which created the high standard of river temperature of 20-25 °C as an annual "98-percentile standard" which mean this standard would failed if the measure value of the parameter to which standard refers is greater than standard for 2 or more of the time. Any value above 30 °C is considered to be in poor condition.

This research analyses long-term river water temperature data monitored and stored by EA, part of more than 30,000 sites across England and Wales starting from 1980's and has been archived from 2007. The surface water temperature archive, created by the EA has direct measures of water temperature at broad spatial and temporal scales and could be used to improve our understanding and predictive capacity of thermal regimes of surface water. With this long-term temperature data, the thermal regime and variation of the rivers could be assessed. According to Orr et al. (2010), developing information on thermal regimes would advance our ability for more interactive approach to understand and predict the impacts of climate change on water quality variables, particularly dissolved oxygen levels, ecological processes and community composition.

2.3.2 Dissolved Oxygen

Dissolved oxygen shows how much oxygen dissolved in the water. The oxygen found in water comes from different sources but mainly comes from oxygen absorbed from atmosphere and aquatic plants. The suitability of natural waters for many types of organism, including fish is often characterized by the concentration of dissolved oxygen (Hemond & Levy, 2000). Dissolved oxygen is greatly influenced by water temperature. Warmer water will lead to lower dissolved oxygen in comparison with colder water. It is important to assess the amount of dissolved oxygen in the river as it is also influenced by anthropogenic activities besides natural sources.

As in the normal natural condition, higher dissolved oxygen will be expected during winter season and tends to be lower during spring and summer as the temperature gets higher. Human activities surrounding the river will likely to affect the condition of dissolved oxygen in the water. Waste discharge will likely to deplete the amount of oxygen in the water thus there will be less oxygen can be consumed by aquatic animal.

This condition has to be monitor continuously to avoid having river water condition that does not support fish life and to have minimum treatment of water before it can be consume as a drinking water. As for river temperature, the standards for dissolved oxygen in the rivers set up in The River Basin Districts Typology, Standards and Groundwater Threshold Value (WFD, 2010). The standards are specific for different type of fish and defined as a “10-percentile standard” which mean the standard would fail if the measure value of parameter to which standard refers is less than standard for more than 10% of the time. Values for dissolved oxygen in the river are considered to be a high standard if the values being 80 percent saturation or higher, any value below 50 percent saturation are considered to be poor.

3. Research Methodology

This chapter describes the methodology used in this study and explained the sources of the data and how the data were collected, classified, processed and analysed. Correlation analyses methods and statistical models were used to determine the strength of relationships between the environmental changes, river flow and selected water quality variables.

3.1 Data Collection and Classification

This research is a desktop based study and all the data analysed in this research primarily made available from the EA and the NERC's Centre for Ecology and Hydrology. Recent data series developed for land-use data in Swindon and Bracknell were made available from CEH. River flow and rainfall data were obtained from NRFA and water quality data from selected monitoring stations were made available by the EA.

List of all variables and the sources in this study are listed in table 3.1:

Classification	Name	Unit	Source
Environmental changes variables	Land-use data (URBEXT)		CEH
	Catchment average rainfall	mm	NRFA hosted at CEH
Hydrological variable	Catchment average daily flow	m^3/s	NRFA hosted at CEH
Water quality	River water temperature	^oC	EA
	Dissolved oxygen	mg/l	EA

Table 3.1 List of variables

3.2 Data Quality Control

The measurement of average daily flow by NRFA is archived at national level and followed the British and International Standards as far as possible in the design, installation and operation of gauging stations. This standard includes a section devoted to accuracy to reduce uncertainties. All of the river flow and rainfall monitoring data assessed in this research available with minimal missing values and are considered representative to be analysed.

Long-term water quality data from urban and rural catchments acquired from EA for this research has limited availability with notable gaps and missing values between observations. For purpose of this research, data was filtered with below conditions:

- Data with less than six observations from different months (<50%) in a calendar year was removed from statistical analysis. This was done to have to best possible data that can be a representative of mean annual value in a particular year.
- Data collected by EA conducted with various monitoring purposes. Statistical analysis excluded measurements that not fit for use in this assessment, which is to investigate trends and relationships from normal water quality. All data from non-regular monitoring purpose e.g. unplanned reactive monitoring due to pollution incidents was removed from the analysis as it could have extreme high or low peak values that might contributed unrepresentative background values in analysed period. The water quality data that was removed from the analysis are with these monitoring purposes: UI (unplanned reactive monitoring, pollution incidents) and UF (unplanned reactive monitoring formal, pollution incidents)

3.3 Data Processing and Analysis

3.3.1 Time Trend and Regression Analysis

The processing of data will start by plotting data as time series using univariate linear regression model. It will continue with the analysis of long-term river flow and water quality data to see how the data changed over the years to spot any trend or shift. Visual graphs are essential for to main reason: provide insight for the analyst into the data under scrutiny and to illustrate important concepts when presenting result to others (Helsel & Hirch, 2002). River flows and selected water quality variables are plotted in graphics with different aggregations of annual and seasonal to investigate the temporal trend during the period assessed

Time series is a sequence of data in successive order and occurring in uniform interval in certain period of time e.g. daily, monthly and yearly. It is a useful analysis to investigate how data change over time and how the change compared to other variables over the same time period. This technique used by many researchers in earth science and environmental topic. The analysis of time series will be used to provide meaningful representation and of data being observed, for this research the data will look at the selected environmental parameter changes over the years and trend analysis will be taken to spot a pattern in the long-term movement of the information. Justified the tendencies in the data or the trends are important steps in data analysis before further method or processes applied to the data.

One of the statistical methods to determine trend is regression analysis and will be used in this research. It is an analysis technique in statistic use for estimating and measuring the links and relationship between variables and assumes one variable is the predictor and the other is the response. This method draws a line as close to all data as possible. Regression analysis is widely used for prediction and forecasting the future trends and help to understand how the value of the dependent variables change if one or more independent variables varies or changes.

The term multiple linear regression was intended to learn more about relationship between several independent and dependent variables. This model is widely used in scientific research since it allows researcher to ask the question of what is the best predictor resulting a condition, in this particular research this question could lead to the answer on what the likely caused of flow and water quality changes. Many techniques are used in regression analysis, for this research, linear regression primarily will be used.

Simple linear regression combines a single response measurement to a single regressor or explanatory variable and has an equation below:

$$Y = \beta_0 + \beta_1 X + \varepsilon$$

In many problems, more than one predictor will be available thus multiple linear regression model is used. Multiple linear regression has an equation of:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_n X_n + \varepsilon$$

Where

Y = response variable

β_0 = intercept

$X_1, X_2, \ldots, X_n$ = explanatory variables

$\beta_1, \beta_2, \ldots, \beta_n$ = slope

ε = error

3.3.2 Data Transformation

The principal of linear regression is provided that data follow the assumption of: normally distributed and linear. To make the assumption to use linear model, data have to be normally distributed and the variance is not homogenous. In summary the error terms are assumed to be Independent and Identically Distributed (I.I.D), which means data shows that each random variable has the same probability distribution (randomly distributed) and not showing specific patterns or in other word is mutually independent of each other.

Whenever data is not I.I.D, other model or data transformation needed to have the best model fitted t data. This process conducted to ensure a correct and best possible model applied to the available data. Logarithmic transforming in regression model is a common way to handle data if there are non-linear relationship between independent and dependent variables. It is also a convenient way of transforming a highly skewed variable into one that is more approximately normal. Linear log transform model can be described in four possible combinations as follow:

Y	X	log X
Y	linear	linear-log
	$Y = \beta_0 + \beta_1 X$	**$Y = \beta_0 + \beta_1 . \log X$**
log Y	log linear	log-log
	$\log Y = \beta_0 + \beta_1 X$	**$\log Y = \beta_0 + \beta . \log X$**

Table 3.2 Four varieties of logarithmic transformation

In this thesis, tendency to find "best" transformation will be avoided. It is probably better to find one transformation works reasonably well for all, rather than using slightly different ones for each (Helsel & Hirsch, 2002). All of the "log" terms in this study refer to the natural logarithm or the logarithm to the base *e*, where *e* is a Euler's constant approximately equals to 2.71828183

3.3.3 Experiment Design

Figure 3.1 illustrates the experiment design in applying regression models of selected variables. The experimental design was developed to provide as much as confidence in checking the variables individually or in conjunction that could act as potential driver(s) to the changes in river flow and water quality. By analyzing all the models, the significance levels from urban and nearby rural catchments can be determined and then compared. This design would be able to provide extra checks of the validity of the hypothesis testing results on individual catchments.

	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)**
$\log Q = \beta_0 + \beta_1.\text{time}$	+	+	+	+
$\log Q = \beta_0 + \beta_1.\log U$	+	÷	+	÷
$\log Q = \beta_0 + \beta_1.\log P$	+	+	+	+
$\log Q = \beta_0 + \beta_1.\log U + \beta_2.\log P$	+	÷	+	÷
$\log F = \beta_0 + \beta_1.\text{time}$	+	+	+	+
$\log F = \beta_0 + \beta_1.\log U$	+	÷	+	÷
$\log F = \beta_0 + \beta_1.\log P$	+	+	+	+
$\log F = \beta_0 + \beta_1.\log Q$	+	+	+	+
$\log F = \beta_0 + \beta_1.\log U + \beta_2.\log P$	+	÷	+	÷
$\log F = \beta_0 + \beta_1.\log U + \beta_2.\log Q$	+	÷	+	÷

Variables:

Q = river flow

F = selected water quality variables

U = urban extent (URBEXT)

P = rainfall

Figure 3.1 Experiment design

The different time aggregations in analysis defined as follows:

- Annual analysis: twelve calendar months starting from January and ending in December in a particular year
- Summer analysis: six calendar months starting from April and ending in September in a particular year
- Winter analysis: six calendar months starting from October and ending in March in the following year

3.4 Sample Site Location

River flow, rainfall and selected water quality variables data for this research were taken from gauging and monitoring stations covering urban and rural catchments. Table 3.2 listed the stations and length of record analysed in this research.

	Swindon		Bracknell	
Data	**Ray at Water Eaton** *(urban catchment)*	**Enborne at Brimpton** *(rural catchment)*	**The Cut at Binfield** *(urban catchment)*	**Winterbourne at Bagnor** *(rural catchment)*
Water course	***Ray***	***Enborne***	***Cut***	***Winterbourne***
River flow, rainfall	NRFA catchment 39087 gauging station	NRFA catchment 39025 gauging station	NRFA catchment 39052 gauging station	NRFA catchment 39033 gauging station
Length of record	1974 - 2010	1968-2010	1961 - 2010	1963-2010
Water quality	Ray at Seven Bridges, Cricklade PT Code : PTHR 0128	Enborne at gauging station, Brimpton PT Code : PKER 0016	Cut at Pitts Bridge, Binfield PT Code : PUTR 0071	Winterbourne at gauging station, Bagnor PT Code : PKER 0089
Length of record	1980 - 2010	1980-2010	1980 - 2010	1980-2009

Table 3.3 List of gauging and monitoring stations

3.5 Hypothesis

One of the most important scientific notions is that absence of evidence is not evidence of absence. Null hypothesis says “nothing’s happening”. The essential point in null hypothesis is that it is falsifiable and we reject the null hypothesis when our data show that the null hypothesis is sufficiently unlikely (Crawley, 2005). To estimates the significance of the result, *p*-value will be calculated and used to weigh the strength of evidence toward accepting or rejecting null hypothesis. *p*-value is the estimated probability of rejecting the null hypothesis (H_0) when the hypothesis is true. If *p*-value is less than chosen significance, null hypothesis will be rejected, a small *p*-value is an indication that the null hypothesis is false with certain confidence limit.

The predetermined significance level of 0.05 used as a standard to determine if null hypothesis can be rejected or not i.e. *p*-value<0.05 meaning strong evidence to reject the null hypothesis in favour for alternative hypothesis and *p*-value>0.05 meaning lack of evidence to reject the null hypothesis.

In statistic interpretation there are 2 mistakes that can be resulted in the interpretation of the statistical models, which would be likely to occurred in this study and can be defined as follows:

- Rejecting null hypothesis when it is true
- Accepting null hypothesis when it is false

	ACTUAL SITUATION	
Null hypothesis	TRUE	FALSE
Accept	**correct decision P**	**type II**
Reject	**type I**	**correct decision**

Table 3.4 Type I and type II error, adapted from Crawley (2005)

3.5.1 Hypothesis for Trend Analysis

The *p*-value from regression statistic would be use to determined whether the null hypothesis of true slope being zero can be rejected or accepted.

This process will determine if there is actually a trend or the slope in linear model just happened by chance which defined in null hypothesis below:

Null hypothesis

H_0: *true slope being zero* ($\beta = 0$)

Alternative hypothesis:

H_1: *true slope is not zero* ($\beta \neq 0$)

Result from statistical treatment using analytical tool of the data then will be interprets to find the likely answer according to each statistical model applied and whether to accept and to reject null hypothesis.

3.5.2 Hypothesis for Relationship Between Variables

Main hypotheses were to test the relationships between variables defined as follows and will be defined in more details using specific variables and sites in the specific chapter and sub-chapter.

Null hypothesis to test the environmental changes relationships with mean annual river flow defined as follow:

Null hypothesis

$H_{0;}$ The environmental changes and variability in urban/rural catchments did not have an effect on the changes in mean annual river flow ($\beta = 0$)

Alternative hypothesis:

$H_{1;}$ The environmental changes and variability in urban/rural catchments affected on the changes in mean annual river flow ($\beta \neq 0$)

Null hypothesis to test the environmental changes and mean annual flow relationships with changes in water quality defined as follows and will be defined in specific variables and sites in the next sub-chapter.

Null hypothesis

H_0: The environmental and mean annual river flow changes did not have an effect on the mean annual water quality data ($\beta = 0$)

Alternative hypothesis:

H_1: The environmental and mean annual river flow changes affected on the mean annual water quality data ($\beta \neq 0$)

4. Data Analysis

This chapter will start with a time-trend detection of river flow, rainfall and selected water quality variables during a specified period in both urbanising and rural catchments. It will continue with the analysis of relationship between variables using univariate and multivariate regression models, and tested hypotheses, which will be defined in more detailed in the specific sub-chapter. Arnell (1998) found that in the absence of climate change, the quantity and quality of water will be affected by changes in land use (such as urbanisation and agricultural changes), which expressed that greater effects to river water course would likely occurs in urban catchments. The general perception of major urban developments impacts in a catchment on watercourse as studied by Shaw (1983) can be identified as follows:

1. There is higher proportion of rainfall appearing as surface runoff, and so the total volume of discharges is increased;
2. For a specific rainfall event, the response of the catchment is accelerated, with a steeper rising limb of the flow hydrograph;
3. The combined effect of perception 1 and 2 is that flood magnitude is increased;
4. Water quality in streams and rivers draining urban areas is degraded by effluent discharge, increased water temperature and danger from other forms of pollution.

4.1 Rainfall and River Flow Trend and Relationship in Urban Catchments

Trends of rainfall and river flow in urban catchments were analysed in this section, as well as testing the null hypothesis for trend analysis as defined in chapter 3. From general perceptions, it can be expected that the results would exhibit statistically significant time-trend for water quantity and quality in urban catchment in contrast with rural catchment where human interference is still minimal. For rainfall data, a large variability of observations is expected without showing a significant trend. Additionally, the trend in rainfall is not expected to vary between urban and rural catchments.

4.1.1 Rainfall and River Flow Time Trend in Urban Catchments

Log-transformed mean annual rainfall data in Ray at Water Eaton from 1974-2010 was analysed to see if any evidence of trend occurred. Figure 4.1 shows the rainfall data varied widely over the period. With a log-linear model fitted for the dataset, a large *p*-value of 4.17E-01 suggested that there is lack of evidence to reject the null hypothesis of the true slope being zero i.e. there is no trend in mean annual rainfall during the period. For seasonal rainfall trend analysis, mean summer and mean winter values show similar results without sufficient evidence to reject the null hypothesis. *p*-values obtained for summer and winter months' analysis were 5.49E-01 and 8.16E-01 respectively.

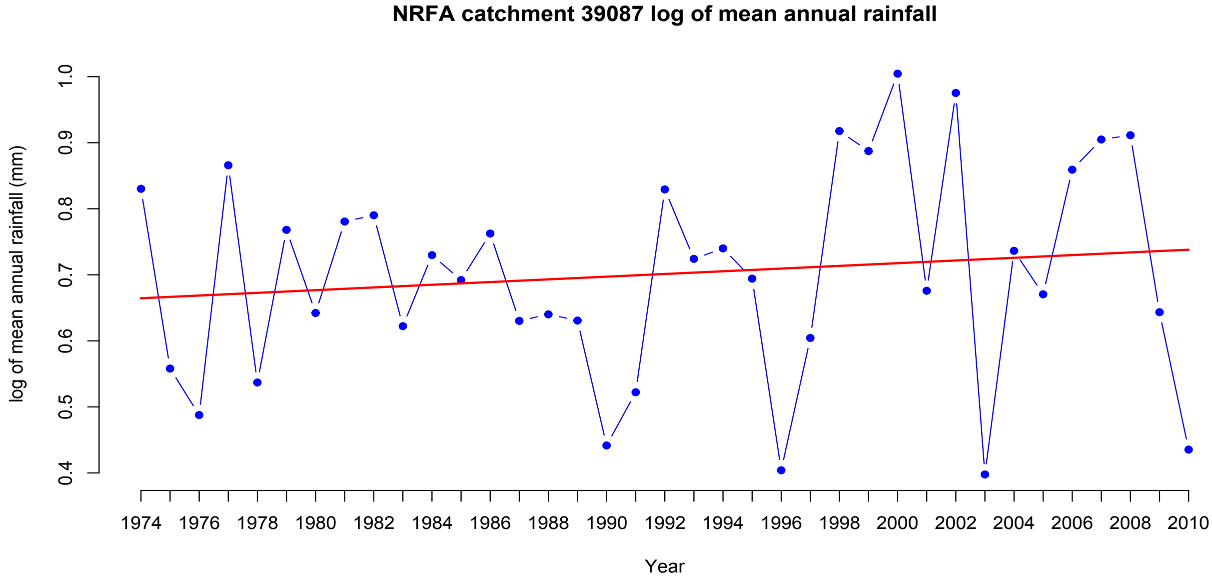

Figure 4.1 NRFA 39087(Ray at Water Eaton) log of mean annual rainfall in 1974-2010

For the river Cut at Binfield catchment, the mean annual rainfall data from the longer period between 1961–2010 showed similar large variability as at Ray at Water Eaton (see Figure 4.2). The *p*-value result from this model showed a large value of 8.57E-01, which also suggested that there is not enough evidence that null hypothesis of true slope being zero can be rejected i.e. there is no trend in the Cut at Binfield mean annual rainfall data. Seasonal mean rainfall time trend analysis shows similar results insufficient evidence to reject the null hypothesis (*p*-value for summer: 1.62E-01 and winter: 2.48E-01), leading to the conclusion that there is no trend in the mean annual rainfall exhibited during summer and winter.

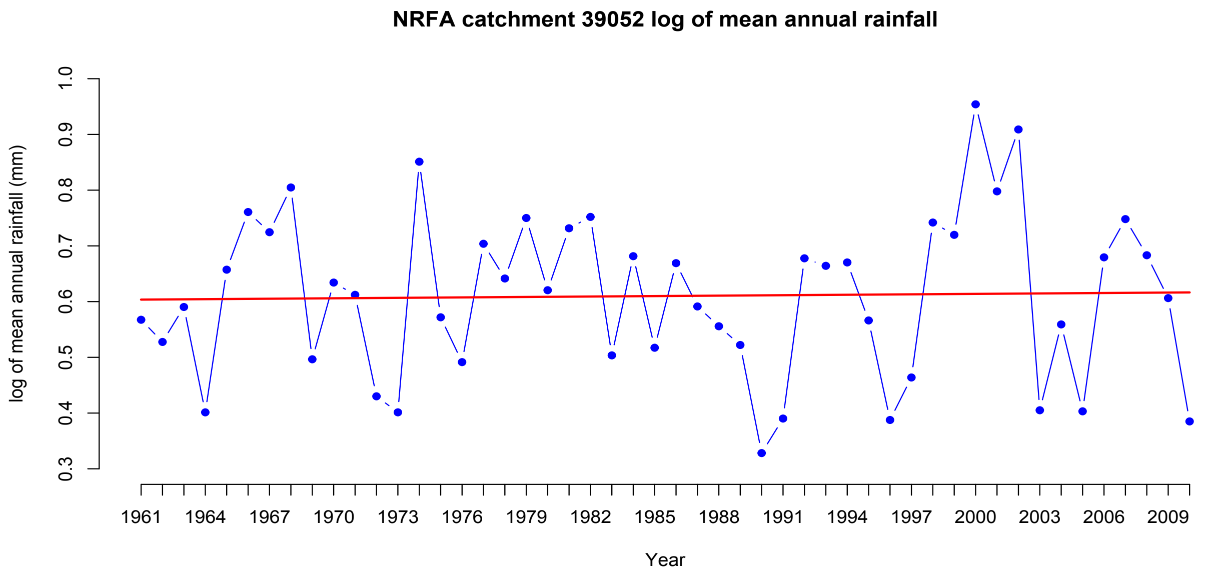

Figure 4.2 NRFA 39052(Cut at Binfield) log of mean annual rainfall in 1961-2010

According to Shaw (1983) 20-30 years flow records are required to provide representative pattern. A representative graphs were expected to obtained from river flow record in both catchments which has been measuring river flow for more than two decades. Using log-linear regression analysis, log of mean annual flow values from Ray at Water Eaton to 1974-2010 were plotted against time in Figure 4.3 to investigate if there has been any trend in mean annual flow observation over the years.

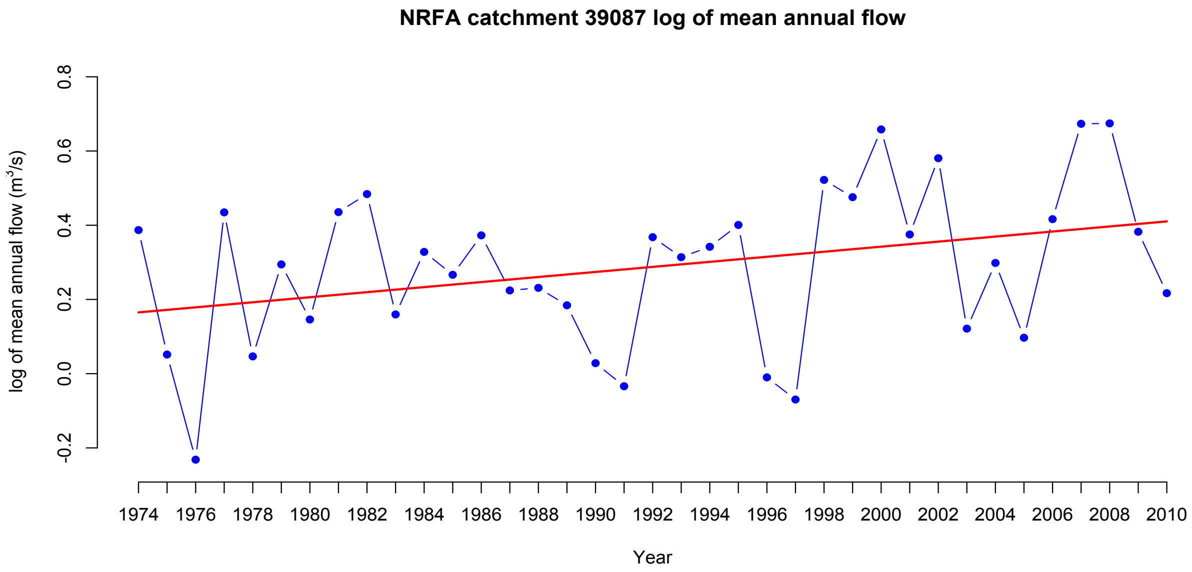

Figure 4.3 NRFA 39087(Ray at Water Eaton) log of mean annual flow in 1974-2010

The graphs of log transformed mean annual flow plotted from Ray at Water Eaton against time indicated visually increasing values during the period. Regression statistics for this model result in a *p*-value of 3.77E-02 and β_1=0.006, meaning that there is strong evidence that the null hypothesis can be rejected with greater than 95% confidence, and it can therefore be concluded that there is a positive trend in the mean annual flow data. Seasonal analysis for this catchment also found statistically significant evidence to reject the null hypothesis for mean value in summer months (*p*:1.86E-02, β_1=0.009) but lack of evidence to reject the null hypothesis for mean value in winter months as can be seen in Figure 4.4 (*p*:2.39E-01), i.e. there is positive trend with for mean summer flow while no trend in the winter season.

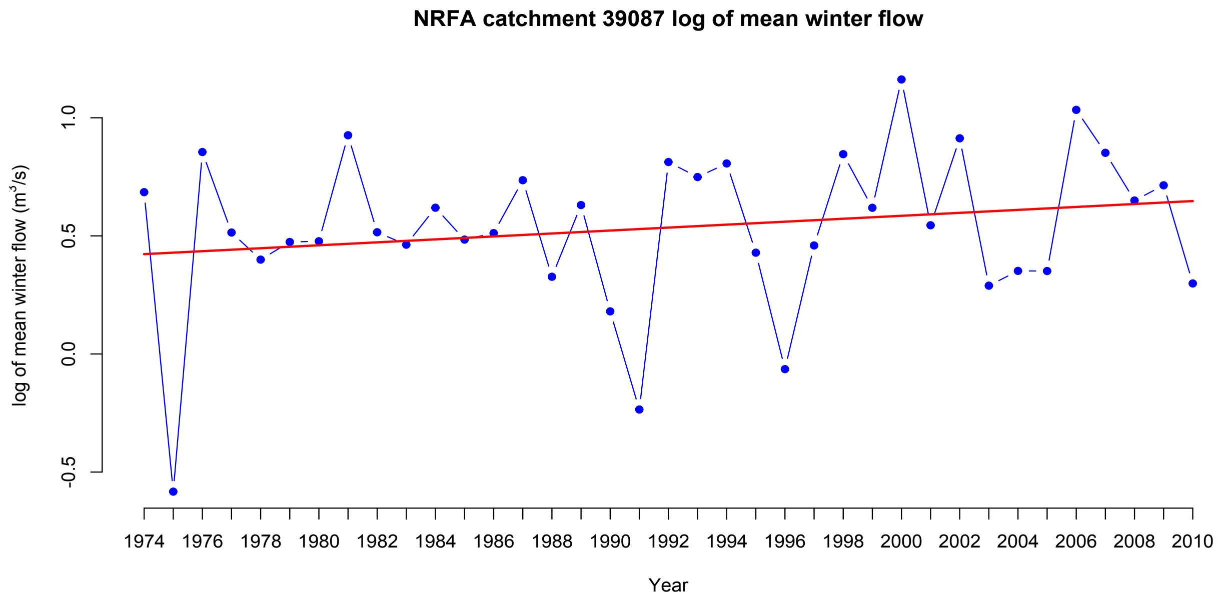

Figure 4.4 NRFA 39087(Ray at Water Eaton) log of mean winter flow in 1974-2010

For Cut at Binfield catchment, the graph of log transformed mean annual flow data against time also displayed a positive trend (see Figure 4.5). The regression statistics of this model resulted in a *p*-value of 2.97E-04, meaning that there is strong evidence that the null hypothesis can be rejected in favour of the alternative hypothesis and it can be concluded that there is a trend in the data. Mean river flow trend analysis in summer and winter also showed similar results. The small *p*-value of 3.80E-03; β_1=0.009 for summer and 4.29E-02;β_1=0.007 for winter suggested that the null hypothesis should be rejected with 95% or greater confidence i.e. there are positive trends in mean summer and mean winter flow in Cut at Binfield.

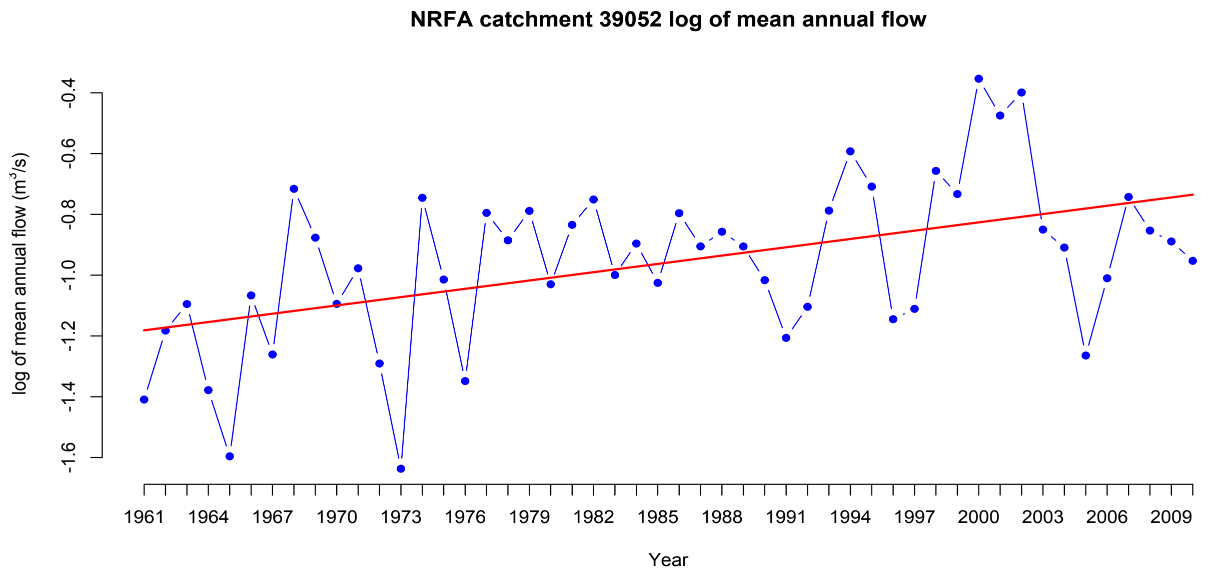

Figure 4.5 NRFA 39052(Cut at Binfield) log of mean annual flow in 1961-2010

Table 4.1 summarises the regression statistics of trend analysis in urban catchments. From the results, Ray at Water Eaton catchment, which had a higher URBEXT index in 2010, showed stronger evidence of a trend in mean annual river flow, compared to the urban catchment Cut at Binfield. Further analysis of URBEXT index changes effects on river flow will be assessed in the next sub chapter.

Model	*p*-value					
	NRFA 39087 (Ray at Water Eaton)			NRFA 39052 (Cut at Binfield)		
	annual	summer	winter	annual	summer	winter
$\log(\text{mean rainfall}) = \beta_0 + \beta_1 .\text{time}$	4.17E-01	5.49E-01	8.16E-01	8.57E-01	1.62E-01	2.48E-01
$\log(\text{mean flow}) = \beta_0 + \beta_1 .\text{time}$	3.77E-02	1.86E-02	2.39E-01	2.97E-04	3.79E-03	4.29E-02

Table 4.1 Regression statistics of rainfall and river flow time trend analysis in urban catchments

4.1.2 Relationship Between River Flow and Environmental Changes

The relationship between mean annual flow in the river Ray and river Cut takes into account environmental changes and variability, i.e. URBEXT and rainfall, which were approximated using log-log linear regression models where both variables were log transformed to obtain best fit of the data and distribution, as close to normal as possible. For the relationship between URBEXT and river flow the null hypothesis is defined as below:

H_0: URBEXT changes in catchment did not have an effect on changes in mean annual river flow ($\beta_1 = 0$)

H_1: URBEXT changes in catchment affected the changes in mean annual river flow ($\beta_1 \neq 0$)

Figure 4.6 illustrates the relationship between URBEXT index and the mean annual river flow in Ray at the Water Eaton catchment. The regression statistics of the log-log regression model resulted in a low *p*-value of 3.87E-02; R^2:0.1165, strongly suggesting that that the null hypothesis should be rejected in favour of the alternative hypothesis i.e. URBEXT index changes in Swindon were related to and affected the mean annual flow in the river Ray. The non-transformed relationship of the model could be used to estimate that each 1 percent increase in the URBEXT index could be expected to increase the mean annual river flow value by 0.47 percent.

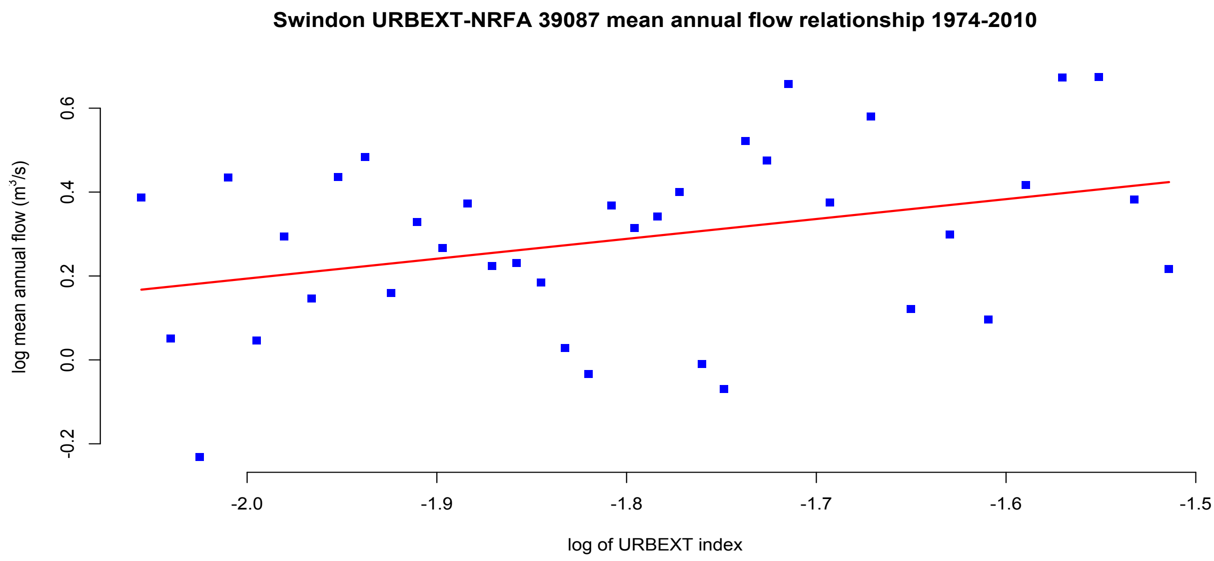

Figure 4.6 NRFA 39087(Ray at Water Eaton) log of URBEXT – log of mean annual flow relationship in 1974-2010

For the river Cut at Binfield catchment, the regression statistics of log-log regression model resulted in a lower *p*-value of 6.64E-05; R^2:0.2845, suggesting that there is strong evidence for the rejection of the null in favour of the alternative hypothesis i.e. the URBEXT index changes in Bracknell were related to and affected the mean annual flow in the river Cut. This result also suggested that URBEXT has a stronger effect that can be associated with the changes in mean annual river flow compared to time as an explanatory variable alone. Figure 4.6 illustrates the relationship between these variables.

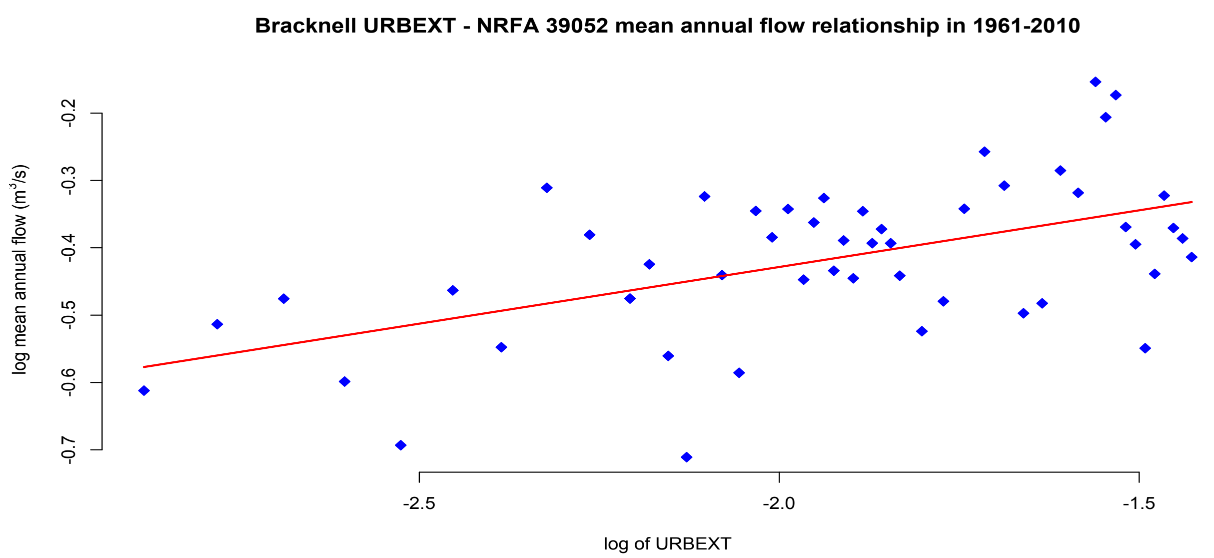

Figure 4.7 NRFA 39052(Cut at Binfield) log of URBEXT – log of mean annual flow relationship in 1961-2010

The non-transformed value of the model estimates that every 1 percent increase in the URBEXT index in Bracknell expected to increase the mean annual flow value of the River Cut by 0.16 percent. This result also suggested that URBEXT had a stronger effect associated with changes in mean annual river flow value in comparison with the function of time.

The relationship between rainfall and river flow was also analysed. The log transformed value of mean annual flow and log transformed value of mean annual rainfall at Ray at Water Eaton and Cut at Binfield was fitted using log-log regression models to investigate the relationship between rainfall and river flow and their statistical significance. The mean of annual river flow would likely be a function of mean annual rainfall. The changes of water quantity in the river were usually related to a change in rainfall for the area; higher rainfall values are often related to higher water quantity in the river. Shaw (1983) studied that over a brief period, the complex interrelationship between rainfall and runoff is not easily defined, but as the time period is extended, the connection becomes simpler until on an annual basis, a straight line correlation may be obtained.

The null and alternative hypotheses for this test are defined as follows:

H_0: Changes in mean annual rainfall at an urban catchment did not have an effect on changes in mean annual river flow ($\beta_1 = 0$)

H_1: Changes in mean annual rainfall in urban catchments affected the changes in mean annual river flow ($\beta_1 \neq 0$)

Figure 4.8 illustrates the relationship between mean annual river flow and mean annual rainfall of Ray at Water Eaton. The statistics from the log-log regression model presented strong evidence to reject the null hypothesis (p:3.58E-12, R^2: 0.753) suggesting there a relationship between mean annual rainfall data and mean annual flow. The model estimates that every 1 percent change in mean annual rainfall can be associated with a 1.16 percent increase in mean annual flow of the river Ray. The model also suggested that rainfall data presents stronger evidence of a relationship with flow in comparison with URBEXT.

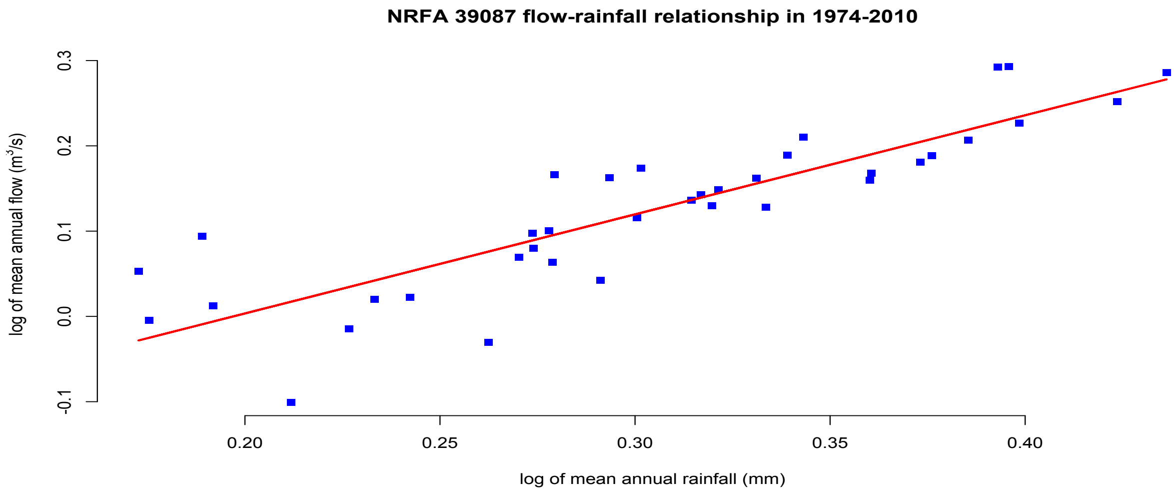

Figure 4.8 NRFA 39087(Ray at Water Eaton) log of mean annual rainfall – log of mean annual flow relationship in 1974-2010

Correspondingly, analysis from the river Cut at Binfield catchment showed similar results as illustrated in Figure 4.9. A *p*-value of 7.86-E07 presented strong evidence to reject the null hypothesis in favour of alternative hypothesis i.e. that there is a relationship between mean annual rainfall and mean annual river flow. The model can be used to estimate that every 1 percent increase in mean annual rainfall is expected to increase the mean annual river flow by 1.17 percent. Similarly to the Ray at Water Eaton catchment, the model also suggested that mean annual flow has a stronger correlation to mean annual rainfall in comparison with URBEXT.

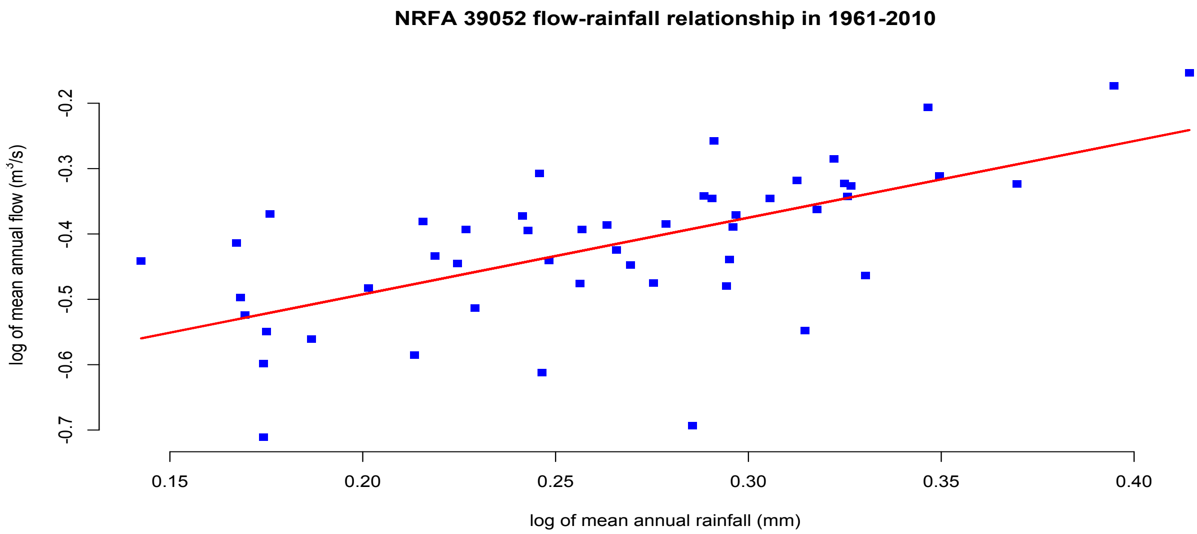

Figure 4.9 NRFA 39052(Cut at Binfield) log of mean annual rainfall – log of mean annual flow relationship in 1961-2010

From the results, both urbanised catchments seemed to exhibit a similar pattern of having statistically significant relationship of URBEXT and mean annual rainfall affecting the changes in mean annual river flow. When comparing the variables affecting mean annual river flow in both urbanised catchments, a stronger relationship was found in Ray at Water Eaton for URBEXT effects on mean annual flow, while mean annual rainfall had a stronger correlation with mean annual river flow in Cut at Binfield.

Individual mean annual flow assessment against URBEXT had shown strong evidence of a correlation. By taking into account environmental changes represented with mean annual rainfall as a second explanatory variable, a much clearer effect of urbanisation was found. Stronger evidence of the relationship was presented by smaller *p*-values for URBEXT (3.43E-03; 7.22-E06) for Ray at Water Eaton and Cut at Binfield respectively

Model	NRFA 39087 (Ray at Water Eaton)					NRFA 39052 (Cut at Binfield)				
	p-value		β_1	β_2	R^2	p-value		β_1	β_2	R^2
log(mean annual flow) = $\beta_0 + \beta_1$ log(URBEXT)		3.87E-02	0.47		0.12		6.64E-05	0.16		0.28
log(mean annual flow) = $\beta_0 + \beta_1$ log(mean annual rainfall)		3.58E-12	1.16		0.75		7.86E-07	1.17		0.4
log(mean annual flow) = $\beta_0 + \beta_1$ log(URBEXT) + β_2 log(mean annual rainfall)	URBEXT	3.43E-03	0.33	1.12	0.81	URBEXT	7.22E-06	0.61	1.16	0.61
	mean annual rainfall	7.64E-13				mean annual rainfall	1.13E-08			

Table 4.2 Regression statistics of the relationship between river flow, URBEXT and rainfall in urban catchments

4.2 Water Quality Time Trend in Urban Catchments

In this section, selected water quality variables were analysed individually against time to investigate how they had changed over the observed period and to see if any significant trend occurred. The monitoring stations selected to obtain the water quality data were listed in chapter 3. Selected long-term series water quality data available from the period between 1980 and 2010, with the exception of some water quality data observations missing during specific periods, will be explained in the sub chapter. The null hypothesis for trend analysis as defined in chapter 3 was used.

4.2.1 River Temperature Time Trend in Urban Catchments

The temporal trend of river temperature in the river Ray was estimated using a log-linear regression model of temperature against time to see how the trends had changed over the 1980-2010 period.

An upward trend can be observed in Figure 4.10. 1980 has the lowest value for mean annual flow recorded with a non-transformed value of 9.6 ^{0}C during the 1980-2010 period. The *p*-value calculated from the model was 4.26E-03;β_1:0.005, thus indicating that there was strong evidence to reject the null hypothesis of the true slope being zero, leading to the conclusion that there is a positive trend in temporal river temperature in the river Ray.

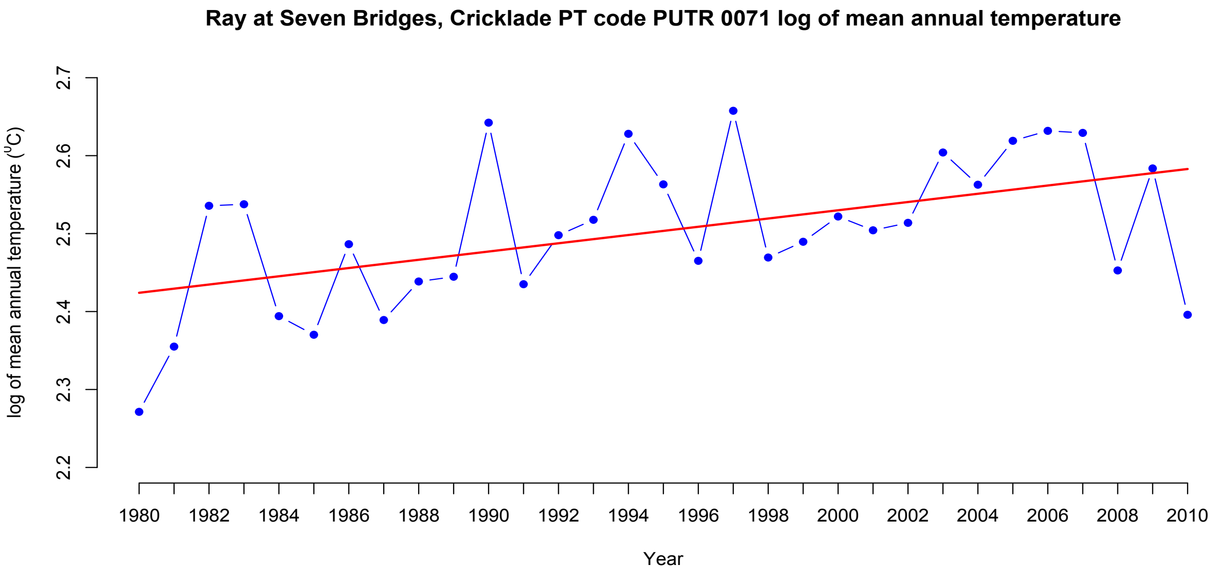

Figure 4.10 River Ray at Seven Bridges, Cricklade log of mean annual temperature in 1980-2010

The trends in river temperature during the summer and winter periods were also investigated. For the summer periods in 1980-2010, there was strong evidence to reject the null hypothesis (*p*:3.56E-03;β_1:0.003) and conclude that there is a positive trend in the data. Correspondingly, the analysis for the winter periods between 1981 and 2010 presented a similar result of strong evidence against the null hypothesis (*p*:1.63E-04, β_1:0.009) i.e. that there is a positive trend in the mean winter river temperature data. The smallest *p*-value obtained from the winter season suggested that the temporal river temperature trend was more statistically significant for the winter period compared to the annual and summer periods.

For the river Cut, different results were achieved. The log-linear regression model function of time suggested pointed to a lack of enough evidence to reject the null hypothesis of the true slope being zero with *p*-value 1.41E-01 then conclude that there was no trend in the river Cut mean annual temperature data during the 1980-2010 period. Seasonal trend analysis for the river Cut also showed different results without enough evidence to reject the null hypothesis for mean summer temperature (*p*-value:609E-01) and with strong evidence against the null hypothesis for mean winter temperature (*p*-value:1.9E-03; β_1:0.007).

This result suggested that there was no trend for mean summer temperature, however there was a statistically significant positive trend for the winter season. Figure 4.11 illustrates the graph of log mean annual temperature function of time in the river Cut.

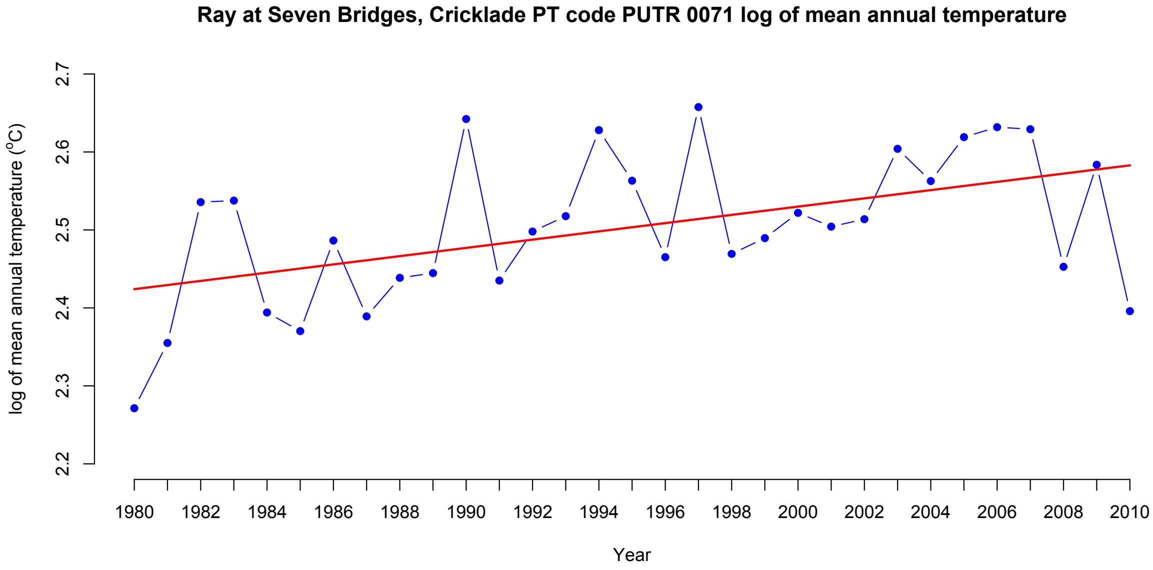

Figure 4.11 River Cut at Pitts Bridge, Binfield log of mean annual temperature in 1980-2010

Table 4.3 summarised the regression statistics for temporal trend river temperature analysis. Results in the river Ray presented identical results in different aggregations, whereas in the river Cut results varied.

Model		*p*-value NRFA 39087 (Ray at Water Eaton)	*p*-value NRFA 39052 (Cut at Binfield)
	Annual	4.26E-03	1.41E-01
log(mean temperature) = $\beta_0 + \beta_1 .time$	Summer	3.56E-03	6.09E-01
	Winter	1.63E-04	1.93E-03

Table 4.3 Regression statistics of river temperature time trend analysis in urban catchments

4.2.2 Dissolved Oxygen Time Trend in Urban catchments

Mean annual values of dissolved oxygen in the river Ray were plotted with univariate regression against time to see how the trends had changed over the 1980-2010 period (see Figure 4.12). Mean annual dissolved oxygen values fluctuated over the period with the lowest observed in 1988 and showing an increasing trend from this year onward. The latest observations, in 2010, showed the highest mean values during the period. The most fitting line for the log-linear model showed an upward trend.

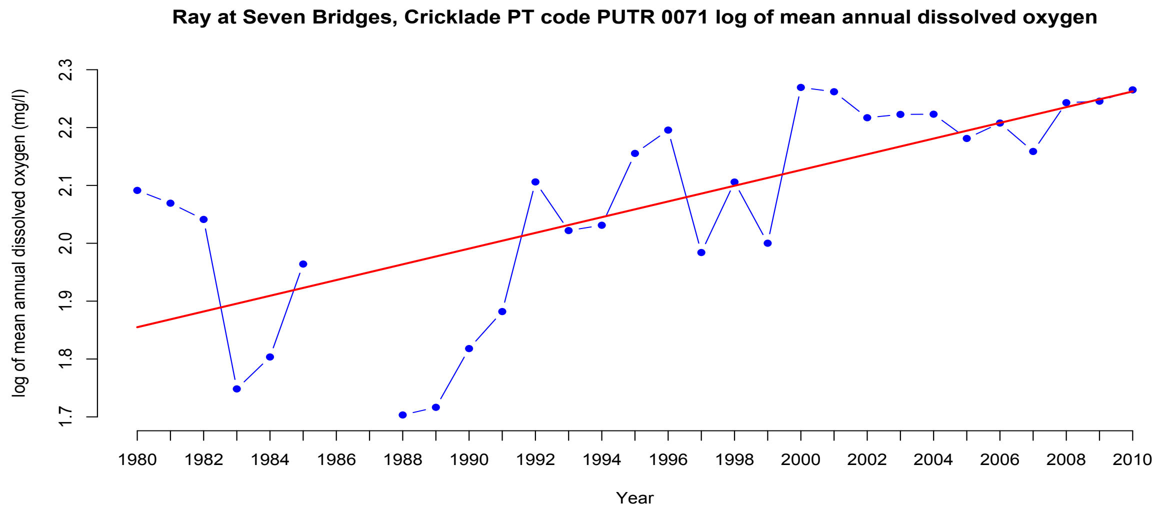

Figure 4.12 River Ray at Seven Bridges, Cricklade log of mean annual dissolved oxygen in 1980-2010

A small *p*-value of 2.17E-05; β_1:0.013 suggested strong evidence that the null hypothesis could be rejected in favour of the alternative hypothesis and it can then be concluded that there is a positive trend in the river Ray mean annual dissolved oxygen values. Summer and winter dissolved oxygen analysis for the river Ray also presented strong evidence against the null hypothesis with the *p*-value, resulting from the regression statistic, being 4.07E-04: β_1:0.014 and 9.11E-05; β_1:0.014 respectively, i.e. there were positive trends in both summer and winter mean values.

In contrast with the river Ray, trend analysis for mean annual dissolved oxygen value in the river Cut did not present sufficient evidence to reject the null hypothesis (*p*-value: 2.73E-01) for mean annual value, leading to the conclusion that there was no trend in the data during 1980-2010. .

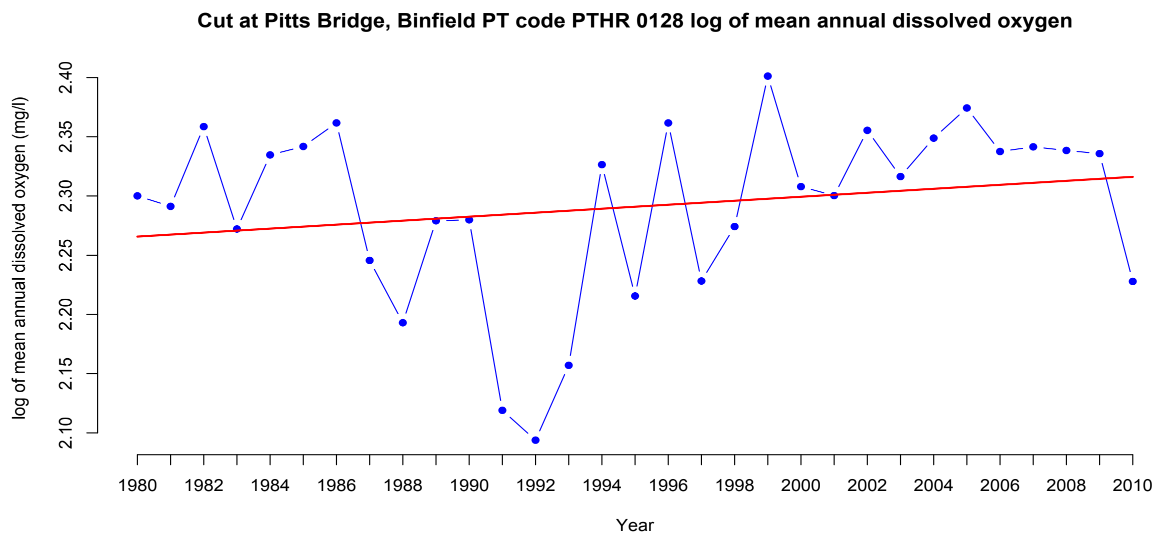

Figure 4.13 River Cut at Pitts Bridge, Binfield log of mean annual dissolved oxygen in 1980-2010

Figure 4.13 illustrates the log-of mean annual dissolved oxygen value of river Cut in 1980-2010. Mean summer and winter values were also assessed with different results. There was an insufficient evidence to reject the null hypothesis for summer (*p*-value:3.75E-01), however strong evidence was found for the mean winter value (*p*-value:5.46E-03, β_1=0.005) i.e. there was no trend in mean summer dissolved oxygen value, while a positive trend was found for the mean winter dissolved oxygen value. Table 4.4 summarises the regression statistics of dissolved oxygen time-trend analysis in urban catchments rivers.

Model		***p*-value**	
		NRFA 39087 (Ray at Water Eaton)	**NRFA 39052 (Cut at Binfield)**
	Annual	2.17E-05	2.73E-01
log(mean dissolved oxygen) = $\beta_0 + \beta_1 .time$	Summer	4.07E-04	3.75E-01
	Winter	9.11E-05	5.46E-03

Table 4.4 Regression statistics of dissolved oxygen time trend analysis in urban catchments

4.3 Relationship Between Variables Affecting Water Quality in Urban Catchments

This section analyses the relationship between rainfall, urbanisation and river flow in association with changes in selected water quality variables. Rivers exhibit complex chemical interactions with many factors including relevant natural and manmade factors. This is the general perception in urban areas. Periods of extreme (and non-natural) high flows, however, imply increased hazards for water quality because various pollutants can be washed into the river from otherwise non-flooded ground. If increased high flow is caused by heavy rain, effluents may be collected from yet larger areas (Chang and Carlson 2005). It can be assumed that in the rivers the effect of urbanisation is evident in sewage discharge or power plant waste.

4.3.1 Variables Affecting Water Temperature in Urban Catchments

The temperature of water in lakes, rivers and streams has a fundamental influence on aquatic organisms, ecological processes and the potency of pollutants. Many "natural" environmental factors affect the variation of water temperature between and within rivers, and thermal properties are also modified by anthropogenic impact (Orr et al., 2010).

The relationship between river flow, rainfall and URBEXT with changes in river temperature was investigated using the log-log regression model by assessing the three separately, as explanatory variables. For Ray at Water Eaton, The model suggested that there was a lack of evidence to reject the null hypothesis when applying river flow and mean annual rainfall as individual explanatory variable (*p*: 9.68E-01 and 8.40E-01), while strong evidence for mean annual river temperature function against URBEXT (*p*:7.14E-03, R^2:0.22) suggested that the null hypothesis could be rejected in favour of the alternative hypothesis (see Figure 4.14).

In summary, there is no significant interaction between river flow and rainfall that can be associated with changes in river flow, while it is statistically evident that the rises in URBEXT index during the period have a positive correlation to river temperature. It can be estimated from the model that every 1 percent increase in the URBEXT index in Swindon is associated with a 0.345 percent increase in river temperature.

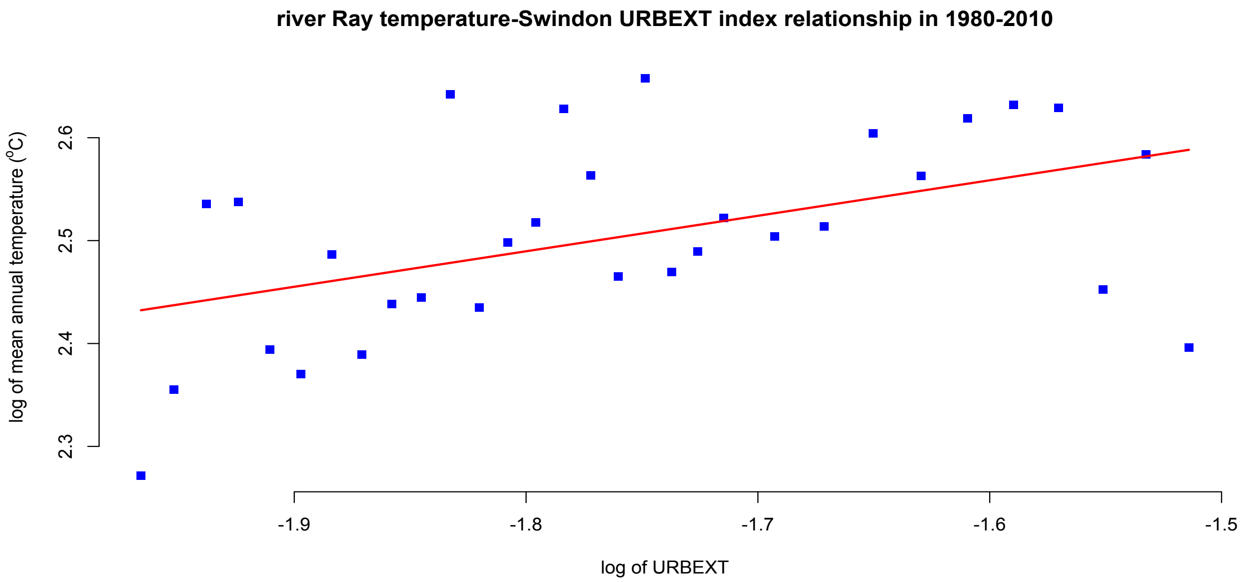

Figure 4.14 River Ray log of URBEXT – log of mean annual river temperature relationship in 1980-2010

By adding flow and rainfall separately as secondary explanatory variables, the effect of URBEXT on river temperature changes. A much clearer effect of URBEXT in Swindon on the river Ray temperature was shown by taking mean annual flow into account (*p*:6.05E-03;R^2:0.2339). A weaker effect was found (*p*:8.38E-03; R^2:0.2244) when rainfall was taken into account, suggesting that variability in mean annual rainfall with no trend observed in earlier analysis, was likely to decrease the positive relationship between URBEXT and river temperature. Table 4.5 summarised the regression statistics of the relationship in the river Ray.

Model		*p*-value	β_1	β_2	R^2
log(mean annual temperature) = β_0 + β_1.log(mean annual flow)		9.68E-01	0.0036		0.0001
log(mean annual temperature) = β_0 + β_1.log(mean annual rainfall)		8.40E-01	0.0225		0.0014
log(mean annual temperature) = β_0 + β_1.log(URBEXT)		7.14E-03	0.3450		0.2242
log(mean annual temperature) = β_0 + β_1.log(URBEXT) + $\beta 2$.log(mean annual flow)	**URBEXT :**	6.05E-03	0.8520		0.2396
	mean annual flow :	4.57E-01		-0.0614	
log(mean annual temperature) = β_0 + β_1.log(URBEXT) + $\beta 2$.log(mean annual rainfall)	**URBEXT :**	8.38E-03	0.3450		0.2244
	mean annual rainfall :	9.37E-01		-0.0079	

Table 4.5 Regression statistics of the relationship between temperature, river flow and URBEXT in the river Ray at Water Eaton catchment

For the river Cut, different results were found. Relationship analyses resulted in a lack of sufficient evidence to reject the null hypothesis for all models. Regression statistics from the model showed a large *p*-value for the relationship between mean annual temperature and mean annual flow (4.04E-01), mean annual rainfall (9.70E-01) and URBEXT(1.35E-01). The result suggested that there was no relationship between the assessed variables i.e. the changes in mean annual flow, mean annual rainfall and URBEXT index could not be statistically associated with changes in river Cut temperature. A summary of regression statistics of this relationship is presented in Table 4.6.

Model		*p*-value	R^2
log(mean annual temperature) = β_0 + β_1.log(mean annual flow)		4.04E-01	0.0242
log(mean annual temperature) = β_0 + β_1.log(mean annual rainfall)		9.70E-01	0.0241
log(mean annual temperature) = β_0 + β_1.log(URBEXT)		1.35E-01	0.0752
log(mean annual temperature) = β_0 + β_1.log(URBEXT) + β_2.log(mean annual flow)	**URBEXT :**	1.81E-01	0.0857
	mean annual flow :	5.75E-01	
log(mean annual temperature) = β_0 + β_1.log(URBEXT) + β_2.log(mean annual rainfall)	**URBEXT :**	1.42E-01	0.0755
	mean annual rainfall :	9.30E-01	

Table 4.6 Regression statistics of the relationship between temperature, river flow and URBEXT in the river Cut at Binfield catchment

4.3.2 Variables Affecting Dissolved Oxygen in Urban Catchments

Factors affecting the mean annual dissolved oxygen value in the river Ray are analysed in this sub-chapter. Dissolved oxygen values are affected by changes in river flow. The concentration would increase, where the water flow became more turbulent, which suggested that the higher flow would increase the dissolved oxygen value. Urbanisation was also linked to the changes in dissolved oxygen value. The transformation of lands along the river streams changes the natural variation of river water body. One simple example is that removing the vegetation could lead to depletion of dissolved oxygen as it would minimise the shading, which in turn would increase temperature in the river thus decreasing the water body's ability to hold oxygen. Other factors could also lead to degradation of dissolved oxygen. These include sewage water discharge and other point source pollution.

Analysis in the river Ray presented strong evidence to reject the null hypothesis for mean annual dissolved oxygen-mean annual river flow relationship (*p*-value:2.91E-02; β_1:0.3426, R^2:0.1645) as indicated in Figure 4.15, while a lack evidence was found for dissolved oxygen-rainfall analysis (*p*-value:2.16E-01). It can be estimated from the model that every 1 percent increase in mean annual river flow is associated with a 0.34 percent increase in dissolved oxygen value.

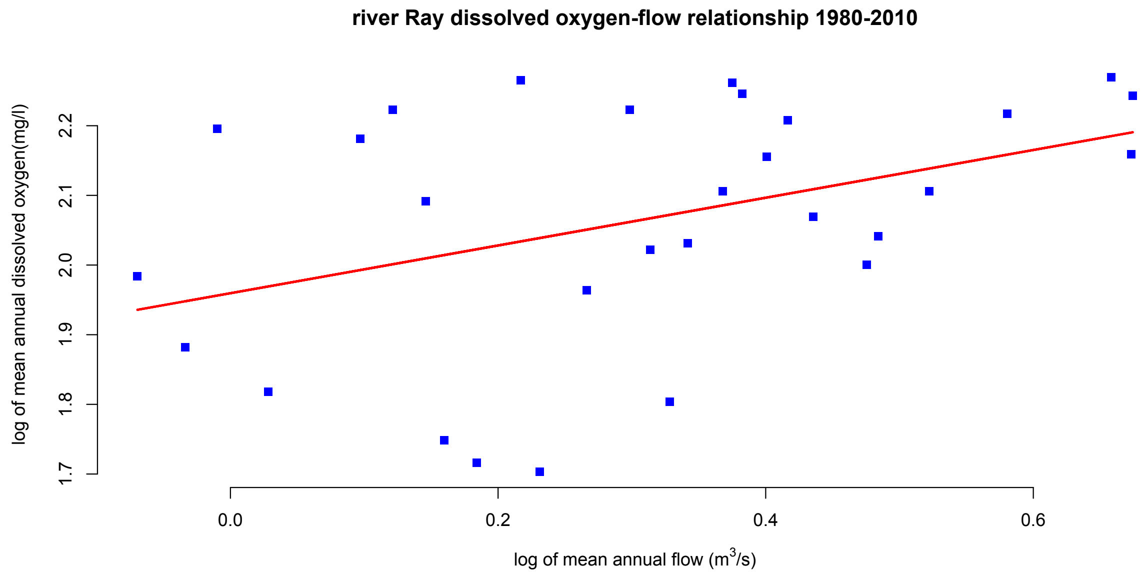

Figure 4.15 River Ray log of mean annual flow – log of mean annual dissolved oxygen relationship in 1980-2010

Strongest evidence of a positive relationship was found in dissolved oxygen-URBEXT analysis with *p*-value:3.17E-05, β_1:0.9165, R^2:0.4792 (see Figure 4.16). This result suggested that there was a positive relationship of dissolved oxygen and it can be estimated that every 1 percent increase in URBEXT index is associated with a 0.91 percent increase in the mean annual dissolved oxygen value. Table 4.7 summarised the regression statistics for the relationships in the river Ray.

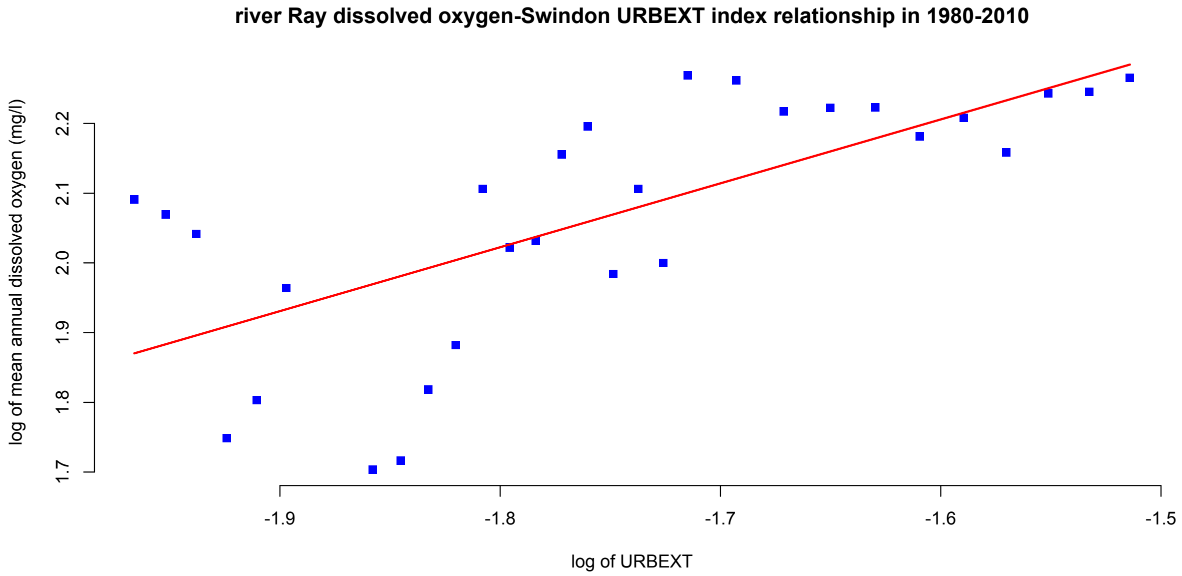

Figure 4.16 River Ray log of URBEXT – log of mean annual dissolved oxygen relationship in1980 -2010

Model		*p*-value	β_1	β_2	R^2
log(mean annual dissoved oxygen) = β_0 + β_1.log(mean annual flow)		2.90E-02	0.3426		0.1645
log(mean annual dissolved oxygen) = β_0 + β_1.log(mean annual rainfall)		2.16E-01	0.2507		0.5611
log(mean annual dissolved oxygen) = β_0 + β_1.log(URBEXT)		3.17E-05	0.9165		0.4792
log(mean annual dissolved oxygen) = β_0 + β_1.log(URBEXT) + β_2.log(mean annual flow)	**URBEXT :**	1.29E-04	0.8317		0.5294
	mean annual flow :	1.08E-01		0.1968	
log(mean annual dissolved oxygen) = β_0 + β_1.log(URBEXT) + β_2.log(mean annual rainfall)	**URBEXT :**	4.83E-05	0.8929		0.5052
	mean annual rainfall :	2.49E-01		0.1730	

Table 4.7 Regression statistics of the relationship between dissolved oxygen, river flow, rainfall and URBEXT in the river Ray at Water Eaton catchment

For river Cut analysis, no significant relation between variables was found. Log-log regression applied to estimate variables effecting mean annual dissolved oxygen data resulted in small *p*-values for mean annual flow (1.92E-01), mean annual rainfall (2.19E-01) and URBEXT (1.77E-01). These results suggested a lack of evidence to reject the null hypothesis i.e. there was no relation between mean annual flow, mean annual rainfall and URBEXT that could be associated with changes in mean annual dissolved oxygen value. The summary of regression statistics is presented in Table 4.8.

Model	*p*-value	
log(mean annual dissoved oxygen) = β_0 + β_1.log(mean annual flow)	1.92E-01	
log(mean annual dissolved oxygen) = β_0 + β_1.log(mean annual rainfall)	2.19E-01	
log(mean annual dissolved oxygen) = β_0 + β_1.log(URBEXT)	1.77E-01	
log(mean annual dissolved oxygen) = β_0 + β_1.(URBEXT) + β2.log(mean annual flow)	**URBEXT :**	2.63E-01
	mean annual flow :	2.86E-01
log(mean annual dissolved oxygen) = β_0 + β_1.log(URBEXT) + β2.log(mean annual rainfall)	**URBEXT :**	2.08E-01
	mean annual rainfall :	2.56E-01

Table 4.8 Regression statistics of the relationship between dissolved oxygen, river flow, rainfall and URBEXT in the river Cut at Binfield catchment

4.4 Detecting Rainfall and River Flow Time Trend in Rural Catchments

To compare trends in river flow, rainfall and selected water quality variables in urbanised catchments, Enborne at Brimpton (NRFA 39025) and Winterbourne at Bagnor(NRFA 39033) non-urbanised catchments were assessed. In contrast with urbanised catchments, river flow in rural catchments is expected to have more natural variation as the human interference is still minimal.

Mean annual river flow is expected to have greater variability in comparison with urban catchments. Figure 4.17 illustrates the log of mean annual rainfall in Enborne at Brimpton rural catchment in 1968 -2010. Mean annual rainfall data for Enborne at Brimpton showed a low *p*-value (4.20E-01) suggesting insufficient evidence to reject the null hypothesis and conclude that there is no trend in the mean annual rainfall data. The seasonal trend analysis showed similar results with insufficient evidence to reject the null hypothesis for mean summer rainfall (*p*:6.15E-01) and mean winter value (*p*:3.40E-01), meaning that there was no trend in the mean seasonal rainfall data.

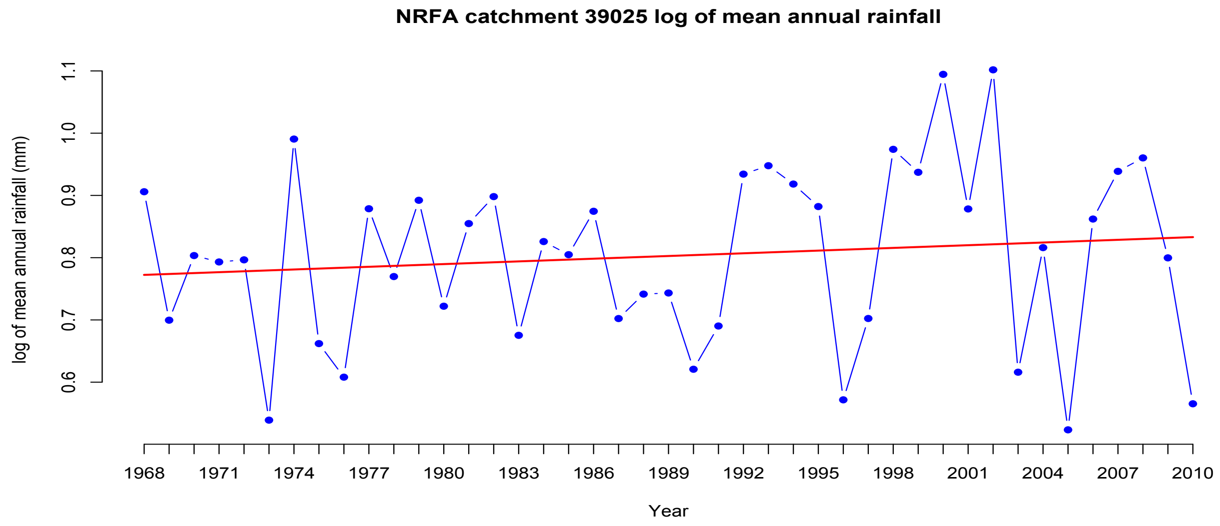

Figure 4.17 NRFA 39025(Enborne at Brimpton) log of mean annual rainfall in 1968-2010

Similarly, in Winterbourne at Bagnor catchment, mean annual rainfall data was fitted using log-linear model, presenting a lack of evidence to reject the null hypothesis (*p*:7.67E-01) and conclude that there was no trend in the data. Insufficient evidence against the null hypothesis was also obtained from the seasonal analysis with the *p*-values for mean summer rainfall and mean winter rainfall data being 1.88E-01 and 5.55E-01 respectively. The log of mean annual flow graph function of time is illustrated in Figure 4.18.

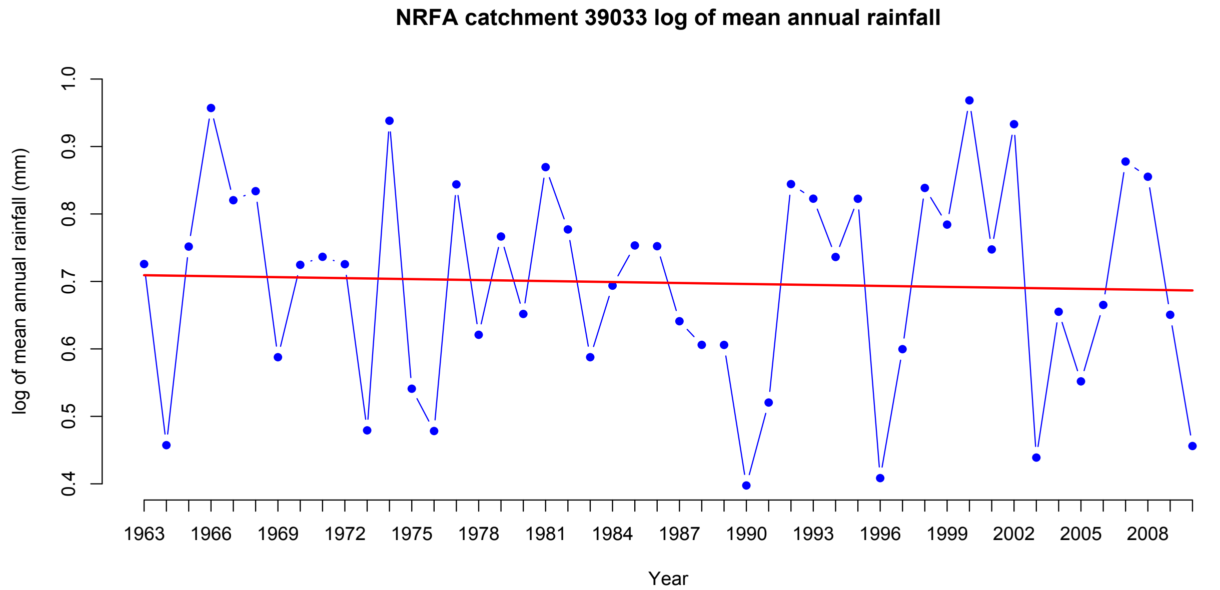

Figure 4.18 NRFA 39033(Winterbourne at Bagnor) log of mean annual rainfall in 1963-2010

Figure 4.19 illustrates the log of mean annual flow against time for the Enborne at Brimpton catchment for the 1968-2010 period. For mean annual river flow, data fitted with log-linear regression model resulted in a high *p*-value of 6.00E-01.

Seasonal analysis also found similar result with lack of evidence to reject the null hypothesis with the *p*-value for mean summer flow analysis at 7.91E-01 and mean winter flow analysis at 6.90E-01 and to conclude that there was no trend in mean annual, summer and winter flow data in Enborne at Brimpton.

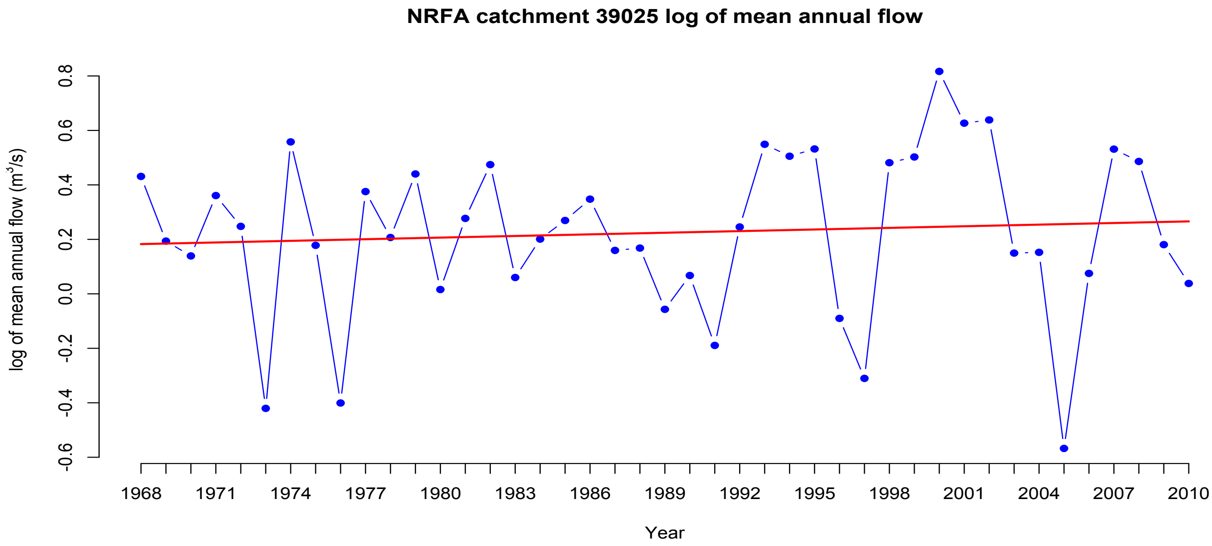

Figure 4.19 NRFA 39025(Enborne at Brimpton) log of mean annual flow in 1968-2010

A similar result was reached in the Winterbourne at Bagnor river flow mean annual trend analysis. Data from 1963-2010 was fitted into log-liner regression and resulted in a *p*-value of 6.25E-01, which suggested there was lack of evidence to reject the null hypothesis of the true slope being zero. Likewise, seasonal analysis also showed a lack of evidence to reject the null hypothesis with the *p*-value being 8.73E-01 for mean summer flow and 4.74E-01 for mean winter flow analysis. Figure 4.20 shows the log of mean annual flow in the river Winterbourne during the 1963-2010 period, while a summary of the regression statistics for the model is presented in Table 4.9.

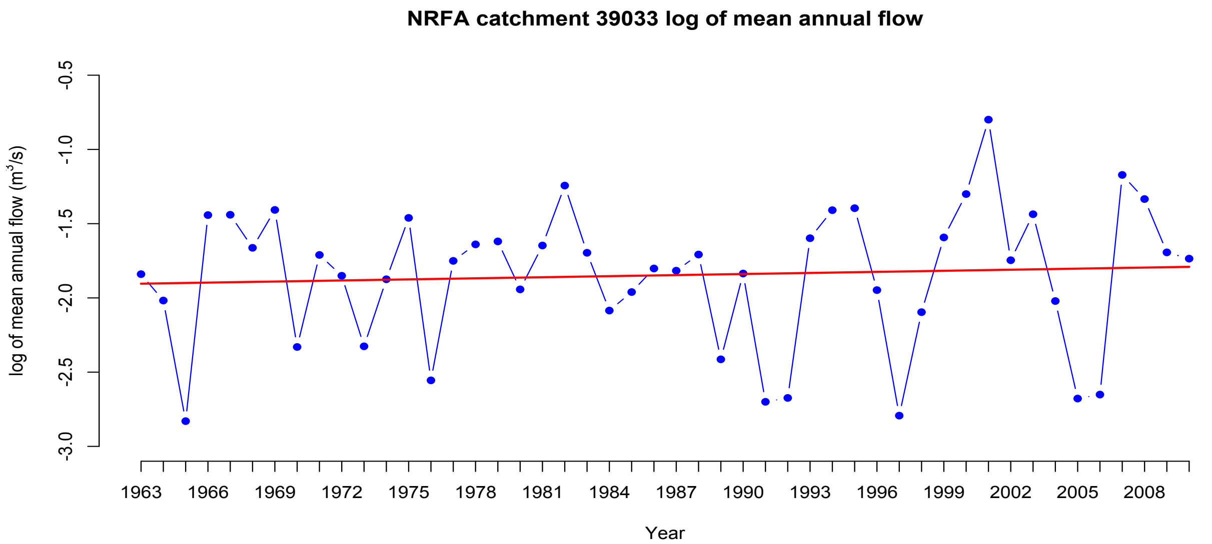

Figure 4.20 NRFA 39033(Winterbourne at Bagnor) log of mean annual flow in 1963-2010

Model	p-value					
	NRFA 39025 (Enborne at Brimpton)			NRFA 39033 (Winterbourne at Bagnor)		
	annual	summer	winter	annual	summer	winter
log(mean rainfall) = $\beta_0 + \beta_1$.*time*	4.20E-01	6.15E-01	3.40E-01	7.67E-01	1.88E-01	5.55E-01
log(mean flow) = $\beta_0 + \beta_1$.*time*	6.00E-01	7.91E-01	6.90E-01	6.25E-01	8.73E-01	4.74E-01

Table 4.9 Regression statistics of the rainfall and river flow time trend analysis in rural catchments

4.5 Relationship Between River Flow and Rainfall in Rural Catchments

In the absence of urbanisation, the relationship between river flow and rainfall was analysed. This section tested the null hypothesis defined as follows:

H_0: Changes in mean annual rainfall in rural catchments did not have an effect on changes in mean annual river flow ($\beta_1 = 0$)

H_1: Changes in mean annual rainfall in rural catchments affected changes in mean annual river flow ($\beta_1 \neq 0$)

Analysing effects of mean annual rainfall to the changes in mean annual river flow reveals strong relationships between these variables as illustrated in Figure 4.21.

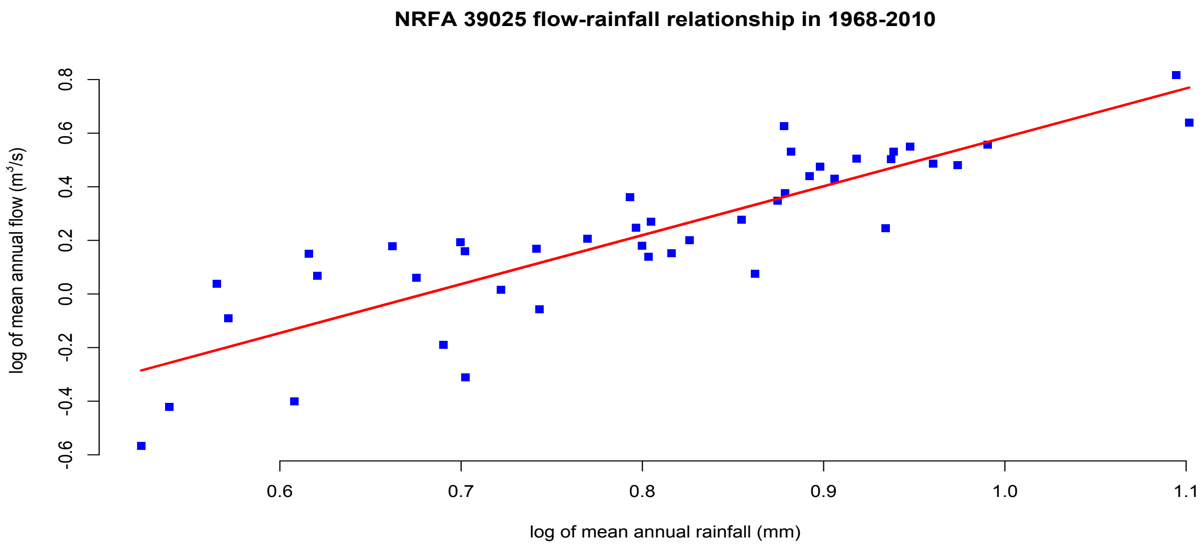

Figure 4.21 NRFA 39025(Enborne at Brimpton) log of mean annual flow - log of mean annual rainfall relationship in 1968-2010

The log-log regression model resulted in a low *p*-value 5.58E-14 (R^2:0.75,;β_1=1.83) for Enborne at the Brimpton catchment, suggesting that there was strong evidence that the null hypothesis could be rejected in favour of the alternative hypothesis and it could then be concluded that mean annual rainfall has a positive correlation to mean annual river flow. It can be estimated from the model that every 1 percent increase in mean annual rainfall is associated with a 1.83 percent increase in mean annual flow.

In Winterbourne at Bagnor, the analysis showed a similar result with strong evidence to reject the null hypothesis (*p*-value:2.25E-02;R^2:0.11;β_1=1.00) i.e. there was a relationship between mean annual rainfall and mean annual flow in this catchment as illustrated in Figure 4.22. The model estimated that every 1 percent increase in mean annual rainfall was associated with a 1 percent increase in mean annual flow.

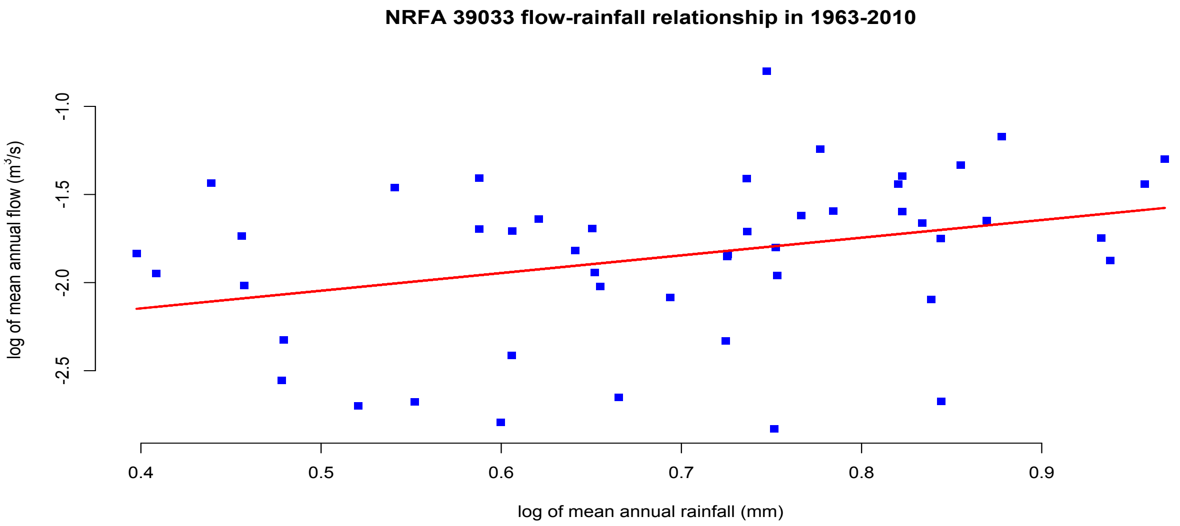

Figure 4.22 NRFA 39033(Winterbourne at Bagnor) log of mean annual flow-log of mean annual rainfall relationship in 1963 – 2010

The summary of regression model statistics is shown in Table 4.10. Comparing the *p*-value in rural catchments, the regression model in Enborne at Brimpton shows stronger relationship in comparison to Winterbourne at Bagnor and the model estimates a higher increase in mean annual flow for every 1 percent increase in mean annual rainfall.

Model	NRFA 39025			NRFA 39033		
	p-value	β_1	R^2	p-value	β_1	R^2
log(mean annual flow) = $\beta_0 + \beta_1$ *log(mean annual rainfall)*	5.81E-14	1.83	0.75	2.25E-02	1.00	0.11

Table 4.10 Regression statistics of the river flow-rainfall relationship in rural catchments

4.6 Detecting Water Quality Time Trend and Relationship in Rural Catchments

4.6.1 River Temperature Time Trend and Relationship in Rural Catchments

Using a log-linear regression model of mean annual temperature function of time, the water temperature temporal trend in river Enborne during the 1980-2010 period was investigated with the exception of observations from 1983-1987 due to a lack of available data (see Figure 4.23). The high *p*-value (9.53E-01) suggested a lack of evidence to reject the null hypothesis of the true slope being zero and conclude that there was no temporal trend of river water temperature during the period. Seasonal trend analysis presented a similar result with a lack of evidence to reject the null hypothesis for the mean summer value (*p*:7.69E-01), and mean winter value (*p*:4.06E-01).

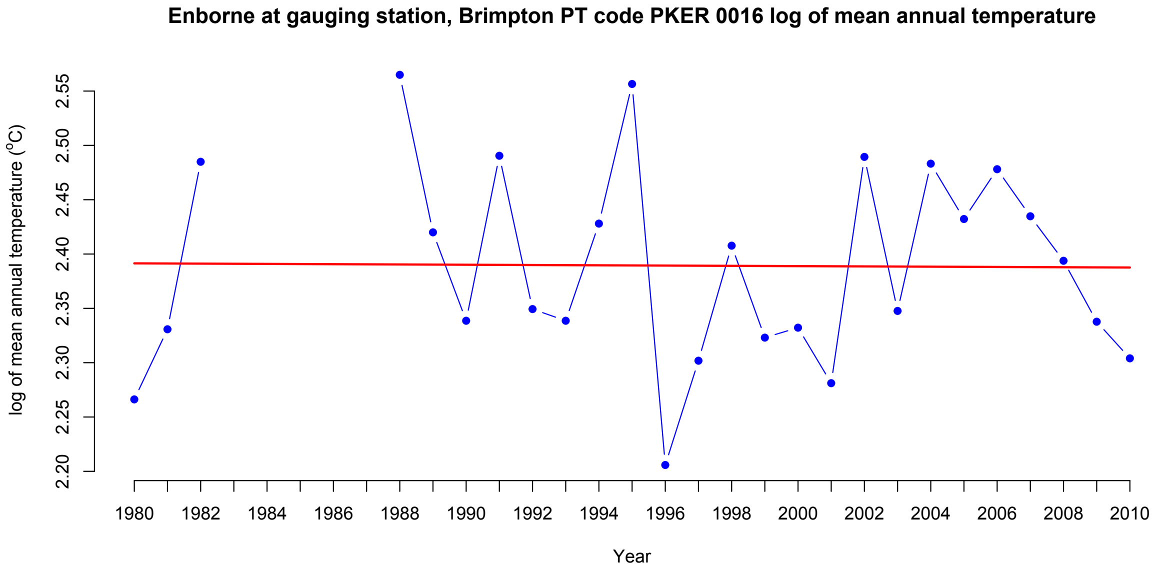

Figure 4.23 River Enborne at gauging station, Brimpton log of mean annual temperature in 1980-2010

Figure 4.24 illustrates the log-linear regression of the mean annual temperature function of time in river Winterbourne. The trend analysis presented insufficient evidence to reject the null hypothesis for mean annual value(*p*:4.90E-01), mean summer (*p*:9.58E-02) and mean winter (*p*:3.09E-01) and concluded that there was no trend in the river Enborne data for all aggregations (annual, summer and winter) mean temperature value.

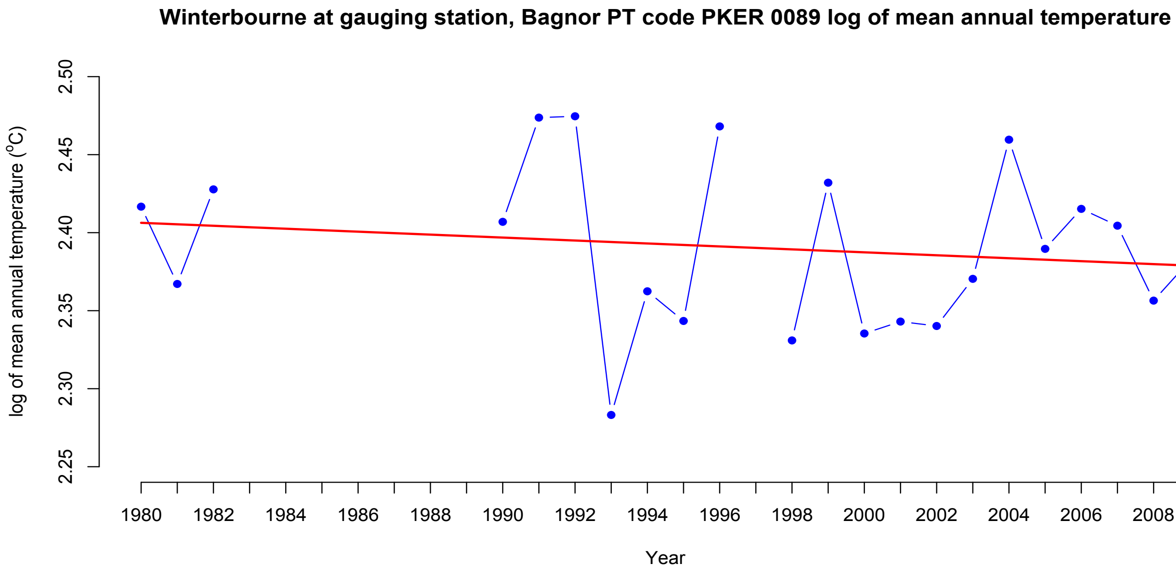

Figure 4.24 River Winterbourne at gauging station, Bagnor log of mean annual temperature in 1980-2010

The summary statistics for log-linear regression of river temperature function of time are shown in table 4.11 below.

Model	*p*-value					
	NRFA 39025			NRFA 39033		
	annual	summer	winter	annual	summer	winter
log(mean temperature) = $\beta_0 + \beta_1 .time$	9.53E-01	7.69E-01	4.06E-01	4.90E-01	9.58E-02	3.09E-01

Table 4.11 Regression statistics of the river temperature time trend analysis in rural catchments

To investigate the relationship between mean annual river temperature with mean annual flow and mean annual rainfall, the dataset were fitted into log-log regression model. The model suggested similar result with urban catchment and finding no correlation of changes in mean annual temperature that can be associated with mean annual rainfall in Enborne at Brimpton catchment (*p*:2.41E-01). Conversely, in Winterbourne at Bagnor rural catchment, a strong evidence to reject null hypothesis was found (*p*:2.76E-02 β_1=0.15), leading to conclusion that there is a relationship between mean annual rainfall that can be associated with the changes in mean annual temperature (see Figure 4.25). The model estimate that every 1 percent changes in mean annual rainfall in Winterbourne at Bagnor catchment can be associated with 0.15 percent decrease in mean annual temperature in the river Winterbourne.

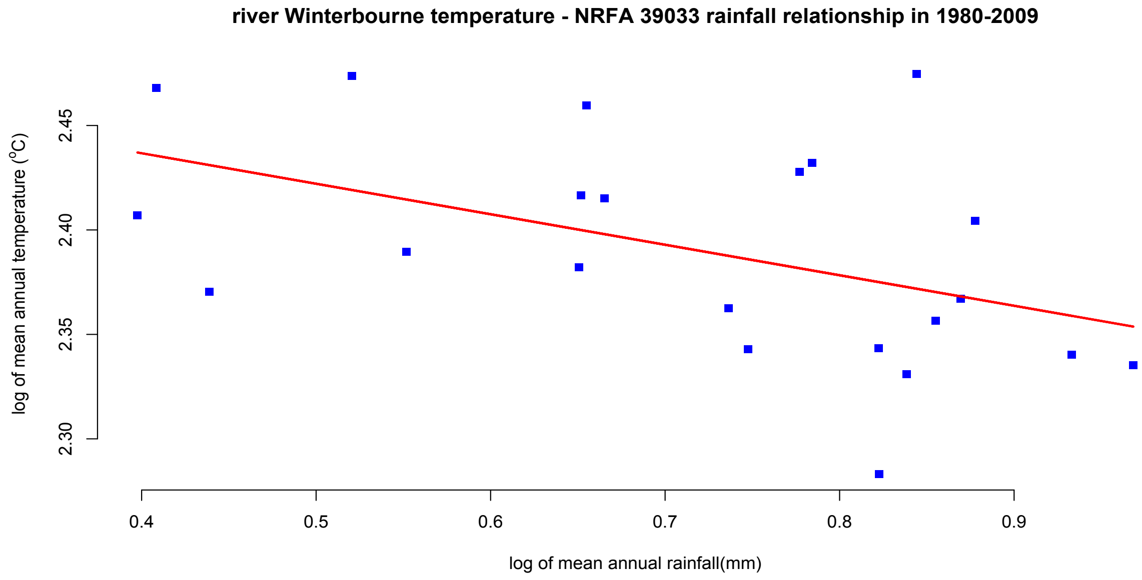

Figure 4.25 River Winterbourne log of mean annual temperature – log of mean annual rainfall relationship in 1980-2009

Relationship analysis between mean annual flow and mean annual temperature assessed for rural catchment showing insufficient evidence to reject the null hypothesis for river Enborne analysis(*p*:6.23E-01) i.e. there is no relationship between mean annual flow and mean annual temperature. Different result was achieved for river Winterbourne. The regression statistics displayed strong evidence to reject the null hypothesis (*p*:1.48E-02, β_1=0.05) and suggested that there is a relationship between mean annual river flow and the changes in mean annual river flow (see Figure 4.26). From the model it can be estimated that every 1 percent increase in mean annual river flow can be associated with 0.05 percent decrease in water temperature in the river Winterbourne. Table 4.12 summarised the regression statistics of river temperature model in rural catchments.

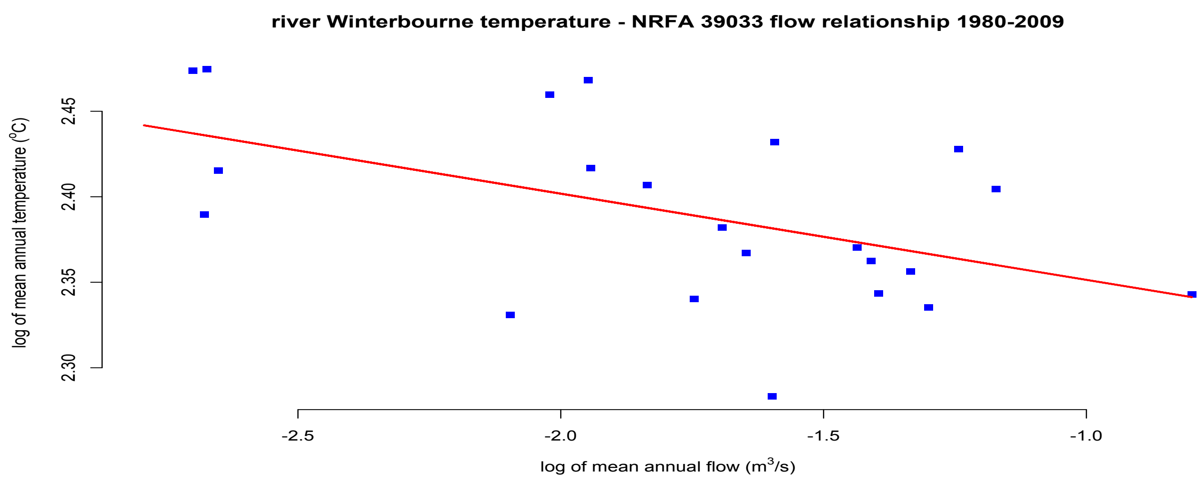

Figure 4.26 River Winterbourne log of mean annual temperature – log of mean annual flow relationship in 1980-2009

Model	River Enborne NRFA 39025	River Winterbourne NRFA 39033	
	p-value	***p-value***	
log(mean annual temperature) = β_0 + β_1.log(mean annual rainfall)	2.41E-01	2.76E-02	R^2 = 0.22 β_1 = -0.15
log(mean annual temperature) = β_0 + β_1.log(mean annual flow)	6.23E-01	1.48E-02	R^2 = 0.21 β_1 = -0.05

Table 4.12 Regression statistics of the river temperature-rainfall and flow relationship in rural catchments

4.6.2 Dissolved Oxygen Trend and Relationship in Rural Catchments

Figure 4.27 illustrates the log of mean annual dissolved oxygen in river Enborne function of time in 1980-2010. The result suggested insufficient evidence to reject the null hypothesis (*p*:5.05E-01). Correspondingly, there is also insufficient evidence to reject the null hypothesis for mean summer and mean winter value (*p*:7.95E-01; 6.87E02). Similar results were also found in river Winterbourne with lack of evidence to reject the null hypothesis for all aggregations. The *p*-values resulted from this model were 1.23E-01;2.80E01 and 1.73E01 for mean annual, mean summer and mean winter respectively. The regression statistics of log-linear regression model function of time are shown in Table 4.13.

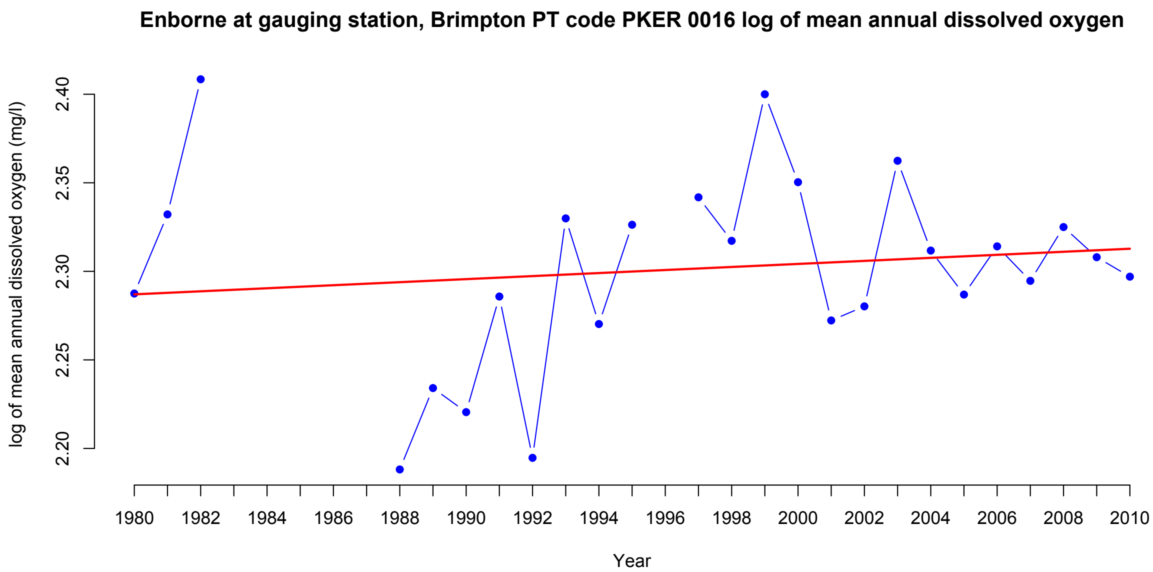

Figure 4.27 River Enborne at gauging station, Brimpton log of mean annual dissolved oxygen in 1980-2010

Model	*p*-value					
	NRFA 39025 (Enborne at Brimpton)			NRFA 39033 (Winterbourne at Bagnor)		
	annual	summer	winter	annual	summer	winter
log(mean dissolved oxygen) = $\beta_0 + \beta_1$ *.time*	5.05E-01	7.95E-01	6.87E-02	1.23E-01	2.80E-01	1.73E-01

Table 4.13 Regression statistics of the dissolved oxygen time trend analysis in rural catchments

Relationship between variables that affecting the changes in mean annual dissolved oxygen value was also assessed to investigate their correlation and significance. The log-log regression model fitted with mean annual river flow data as the explanatory variable found insufficient of evidence that the null hypothesis can be rejected (*p*:2.22E-01) then conclude there is no relationship between mean annual river flow and changes in mean annual dissolved oxygen value in river Enborne.

The lack of evidence was also found when the log-log regression model fitted with mean annual rainfall as the explanatory variable (*p*:2,94E-01). Similar result was found in river Winterboune analysis. Log-log regression of mean annual dissolved oxygen function of mean annual rainfall and mean annual flow that was assessed separately did not found any significant evidence to reject the null hypothesis of no relation, with *p*-value being 7.00E-01 for the former and 5.86E-01 for the later. The regression statistics for these models are summarised in Table 4.14.

Model	River Enborne NRFA 39025	River Winterbourne NRFA 39033
	p-value	*p-value*
ln(mean annual dissolved oxygen) = $\beta_0 + \beta_1$*.(mean annual rainfall)*	2.94E-01	7.00E-01
ln(mean annual dissolved oxygen) = $\beta_0 + \beta_1$*.(mean annual flow)*	2.22E-01	5.86E-01

Table 4.14 Regression statistics of the dissolved oxygen relationship with rainfall and flow in rural catchments

5. Discussions

This section summarises the results and interprets the findings obtained from the data analysis and will explain the likely causes that might have contributed to the trends and relationships between assessed variables. Literature references and previous studies are used as a theoretical comparison, particularly results obtained from similar scientific researches. Limitations during this research are also expressed for the improvement of future study.

Main findings of this study are as follows:

Rainfall and river flow:

- *No significant trend of rainfall found in any of the urban or rural catchments*
- *Positive trends of flow in the river Ray at Water Eaton (urban) found in annual and summer months*
- *Positive trends of flow in the river Cut at Binfield (urban) found in all aggregations*
- *No significant trend of river flow found in the two rural catchments*
- *URBEXT has a strong positive relationship with mean annual flow, when climate variability is included, the URBEXT signal is amplified*

Water quality:

- *Temperature and dissolved oxygen in the river Ray at Water Eaton (urban) are increasing in all time aggregations*
- *Temperature and dissolved oxygen in the river Cut at Binfield (urban) are increasing in the winter months*
- *River flow has a positive relationship with dissolved oxygen in the river Ray at Water Eaton (urban)*
- *No significant trends of temperature and dissolved oxygen found in the two rural catchments*
- *URBEXT has a strong positive relationship with temperature and dissolved oxygen in the river Ray at Water Eaton (urban), when rainfall and river flow included, the URBEXT signal is reduced*
- *Rainfall and flow has a negative relationship with temperature in the river Winterbourne at Bagnor (rural)*

5.1 Environmental Changes and River Flow Trends and Relationships

5.1.1 Rainfall Time Trends

Mean annual rainfall analysis in study sites showed no statistically significant evidence of mean annual rainfall trends in either urban or rural catchments. At the regional scale, there has long been controversy as to whether vegetation cover could influence rainfall via its effects on evaporation losses (Robinson & Ward, 2000), which might suggest that the trend and relationship difference between urban and rural catchment still remains a debatable topic.

Correspondingly, a recent report found that annual mean precipitation over England and Wales has not changed significantly since records began in 1766 (Met Office, 2006). The Met Office report in 2006 also found seasonal rainfall is highly variable, but appears to have decreased in summer and increased in winter. However this tendency was not found in the seasonal analysis of all catchments, suggesting that the variability might come from naturally occurring variation, rather than merely from human interaction. A study from Marsh et al. (2000) also expressed that river systems are always in natural transition and many of their characteristics may not reflect contemporary climate conditions.

5.1.2 River Flow Time Trends and Relationship

The analysis of river flow time-trends in both urban catchments showed expected positive trends. A notable result was found in winter mean river flow analysis of Ray at Water Eaton where the result showed lack of evidence of trend occurred despite having statistically significant evidence for both annual and summer analysis. The mean river flow during the winter periods was mainly observed with above $1m^3/s$ value. This notable winter result might have been caused by some very dry winter year observations, for example in 1975, 1991 and 1996 with mean winter value being $0.55m^3/s$, $0.79m^3/s$ and $0.94m^3/s$ respectively. A previous study from Robinson (2000) supports these findings. This author implies that UK rivers are especially sensitive to regime changes resulting from climate variation or the net effect of anthropogenic factors i.e. development of land use and heavy abstraction rates.

In the river Cut at Binfield, the log-log regression with URBEXT as the explanatory variable showed more sufficient evidence of relationship in comparison with the time-trend analysis. However, in Ray at Water Eaton catchment the result rather similar and not showing significant difference. The log-log regression model of mean annual flow function of mean annual rainfall proved to be a significantly better model that can be associated with changes in mean annual river flow. This model has the strongest evidence to reject the null hypothesis of no relationship from all urban catchments in comparison with other models, especially for the Ray at Water Eaton catchment, where the model explained more than 75% of the variance.

Urban development is expected to affect a wide range of environmental changes including soil quality and water runoff, thus increasing the speed of water flowing from land to river stream. The geology and relief of urban catchments would also have major influence on this condition. 76.7% of Ray at Water Eaton and 60.9% of Cut at Binfield urban catchment areas are covered with low permeability bedrock, which most likely increase the speed of runoff when water flows into the surface, due to its smaller infiltration capacities.

Results supported this condition, with a strong positive relationship between URBEXT and mean annual river flow in both urban catchments. Correspondingly, Marsh et al. (2000) expressed that the geology is an important factor, with spates being more common in mountainous, impermeable catchments than in rivers, draining more subdued permeable catchments.

The result was that Cut at the Binfield catchment displayed a better model with stronger evidence of URBEXT-mean annual flow positive relationship in comparison with Ray at Water Eaton. The larger area of Ray at the Water Eaton catchment in comparison with Cut at Binfield might be attributed to this different strength of statistical evidence. Wheater and Evans(2009) expressed that in larger catchments the effects of urbanisation on runoff in relation to flood peaks are more complex, as the location of development within the catchment will affect the response.

In general, every river goes through natural changes of rhythm in river flow, including high and low flows, which in extreme conditions both would hold disadvantages for the environment. In contrast with low flow that might cause imbalance and problems in the dry season, high flow conditions could result in problems during extreme weather where rainfall intensity is at its highest. With the positive trend found in mean annual river flow and strong relationship with mean annual rainfall there are concerns of risks of flooding during periods of extreme weather with high rainfall intensity. There has been a psotive action from the community. Nearby Peatmoor lagoon and woodland owned by local authority and managed under agreement by a local community group could mitigate the risks. The lagoon, which has been managed since 1988, was designed to manage the increased water runoff from the surrounding urban development.

In this particular research the tendency of changes in river flow is towards positive value over time and statistically significant in both urban catchments. Wheater and Evans (2009) expressed that urban development resulted a greater volume of runoff, discharging in a shorter time, potentially leading to dramatically increased flood peaks, but also reduced low flows and less groundwater discharge. The study also found that the size of the effect will depend on the natural response of the catchment and will be greatest where natural runoff is low, in catchments with permeable soils and geology.

A much better model was obtained when taking mean annual rainfall as a second explanatory variable to URBEXT function. The bivariate log-log regression model resulted in approximately tenfold smaller *p*-values compare to when taking URBEXT as a single explanatory variable.

This result suggested that the continuous increase of urban development in an area would have stronger effects in mean annual river flow changes when environmental variability is taken into account. It could be argued that development in both urban catchments, leading to increased value of mean annual river flow, could provide better condition to aquatic life. However in the event of extreme weather, the risk of flooding that could result to environment and economic loss is inevitable.

River flow assessment in rural catchments showed expected results of no significant trends in all aggregations. In a catchment where vegetation dominated the majority of the area, the amounts of precipitation transferred to main channel would likely be intercepted and stored by the structure thus decreasing the sensitivity of water flowing directly from the surface to the river. The majority of Enborne at Brimpton (91%) and Winterbourne art Bagnor (96%) catchment areas are covered by vegetation including arable land, woodland and grassland. Large variability of river flow is anticipated due to this condition.

Although lack of trends in rural catchments suggested that natural variability of the river might have contributed in large part to river flow over human interaction, the possibility that the rainfall large interception might alter the water balance into an unfavourable condition must be taken into consideration. A previous study (Robinson and Ward, 2000) had expressed this concern; this author found that in some cases the interception loss may be quite large and can have a significant impact of water balance.

Climate variability in all rural catchments also showed strong positive relations with mean annual flow. Understanding the relationship between rainfall and flow would require further research as it involves complex and details vegetation and land characteristic analysis that impacts runoff.

From the comparison of the results in urban and rural catchments, it can be summarised that in urban catchments there is a positive trend in mean annual river flow value over time that can be associated with the increase of urban development, whereas in the absence of urbanisation in rural catchments, the trend was not spotted.

5.2 Water Temperature Trends and Relationships

The importance of river water temperature is predominantly associated with its effect on aquatic life and could be a result of either natural or anthropogenic impact. Changes in water temperature are linked to the changes in other water quality variables (e.g. dissolved oxygen and nitrogen levels) and also affect the chemical reactions of many pollutants.

Urbanised catchments are expected to have increasing water temperature due to human interference. The effects could come from discharges from power plants, which increase water temperature or simply from moving vegetation and shrubs around the river, which act as a canopy that would decrease the water temperature. Other causes could be the heat transfer between runoff and the heated impervious surface in contact with runoff (Espinosa et al., 2001).

As expected, time-trend analysis of water temperature showed a significant positive trend in the Ray at Water Eaton catchment for mean annual, mean summer and mean winter observation. The monitoring station for the river Ray is located further downstream from Sewage Treatment Works (STW), which might explain the increase of temperature - it could be the result of the sewage discharges.

This study did not find a significant relationship between temperature and rainfall and flow, but found a significant positive relationship when taking URBEXT as the explanatory variable. When climate variability and flow was taking into account as an individual second explanatory variable, the URBEXT signal decreased. In summary, in the Ray at Water Eaton catchment, the log-log regression analysis of mean annual temperature function of URBEXT proved to be the most appropriate model that could be used to explain the changes in mean annual temperature.

On the contrary, there is no statistically significant evidence of temperature trends found in all aggregations in nearby rural catchment Enborne at Brimpton, suggesting the value in river Enborne remains stable over assessed period with large variability. In the absence of URBEXT, the log-log regression model using rainfall and flow as explanatory variables did not result in enough evidence to conclude that a relationship existed. It could be argued that there were not enough observations to be directly compared with WFD “98-percentile” temperature threshold. However, individual observation during the assessed period found that the maximum water temperature recorded for both river Ray and river Enborne was never exceeded 22^{o}C, therefore this can be considered to be a good standard to would support fish life, according to WFD.

As can bee seen in Figure 5.1, the overall mean annual value in the river Ray in urban catchment is noticeably higher than in the river Enborne. It demonstrated that in the rural catchment with very minimum human interaction, the mean annual temperature remain stable in good condition. Despite recent good status according to WFD standard, with the increasing trend in the river Ray, the effects of urbanisation might cause problems in the future if no improvement made.

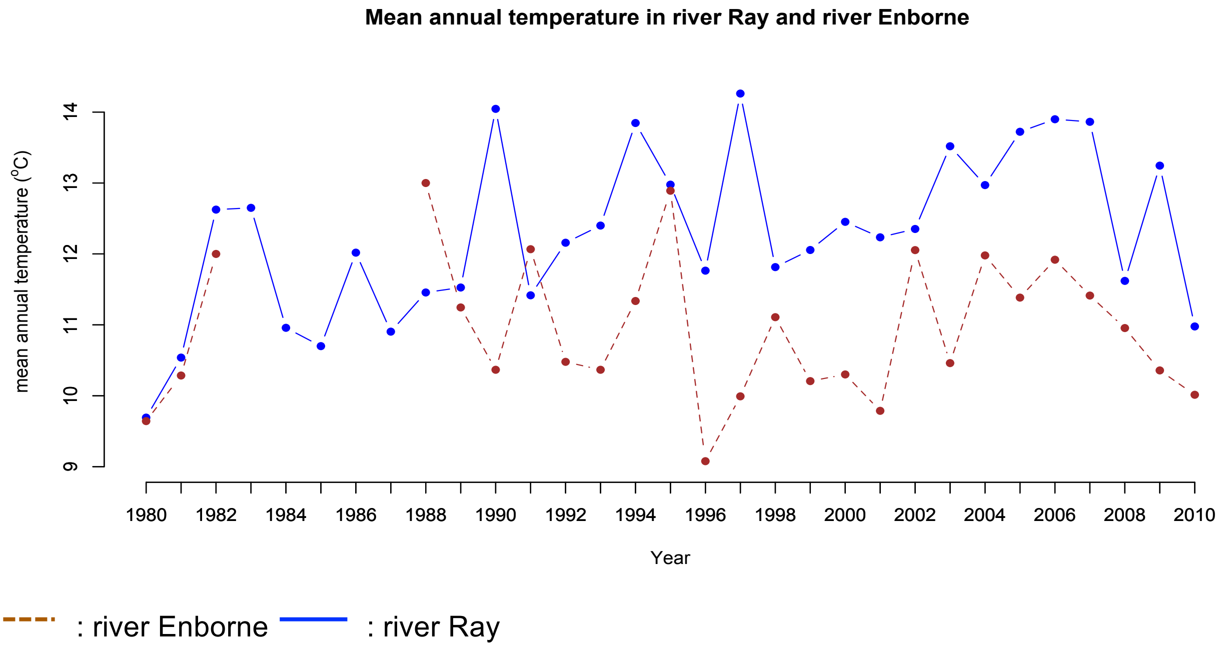

Figure 5.1 Mean annual temperature in river Ray and river Enborne

For the river Cut at Binfield, no significant time-trend was found in annual and summer analysis, however during the winter season there is statistically strong evidence of rising temperature. The log-log regression analysis of mean annual rainfall, mean annual flow and URBEXT in relation to the changes in mean annual temperature also did not find any significant evidence of trend. Comparing the models in this catchment, time-trend analysis in the winter months was the only significant model. This result might suggested that despite the urban development in this area, the changes in mean annual temperature could predominantly influenced by natural variability rather than anthropogenic impacts.

Analysis in the nearby rural catchment in Winterboune at Bagnor also did not find any significant trends of river water temperature during assessed period. These results were expected to be obtained from rural catchment, as the characteristic of the area would likely provides a better condition to maintain a cooler river water temperature e.g. minimum interference from heated surface runoff. In the absence of URBEXT, mean annual rainfall and mean annual flow variables were used to investigate the relationship that can be attributed to the changes in mean annual temperature in river Winterbourne. The results for both analyses showed strong relationship between variables.

The increase of mean annual rainfall in relation to a decrease in mean annual water temperature might need more complex research to be explained, however, the influence of mean annual rainfall that contributed to the increasing of mean annual flow could explain this condition.

The negative relationship between flow and temperature supported the study from Brown (1972). This author found that for a given level of solar radiation heat, stream temperature is inversely proportional to stream discharges. This suggests that the lower the discharge, the lower the capacity for stream heat storage, thus increasing the water temperature.

Despite an arguable lack of observation in Winterbourne at Bagnor rural catchments to be directly compared with WFD 98 percentile temperature threshold, individual observation during the assessed period found that maximum water temperature recorded for both river Cut and river Winterbourne never exceeded 22°C and 18.5°C respectively, therefore these can be considered to be good standards according to WFD and would support fish life.

Bates et al (2008) expressed that inland water temperature is expected to be significantly altered by future climate change with potential impacts on freshwater ecosystem. Developing detailed thermal regime would advance the ability for more interactive approach to understand and predict the impacts of climate change to water quality (Orr et al, 2010). The concerns of warming river and the needs to measure changes in water temperature, for example, had lead to the commissioned of Water Research Centre (WRc) by the EA to provide recommendations for the design of an efficient river temperature monitoring networks across England and Wales.

5.3 Dissolved Oxygen Time Trends and Relationships

Dissolved oxygen influenced by several factors including water temperature, salinity, altitude stream structure an aquatic organism living in the stream. Urban development often related to the degradation of dissolved oxygen values e.g. land clearing that might send excess organic material from land into water body and development of riparian areas that might decreased the amount of shade.

In the river Ray, the location of monitoring station is further downstream of STW and was expected to have a decreasing trend due to the possibility of oxygen depletion that might be caused by organic material in the sewage discharge. On the contrary, the result shows significant increasing trends in all aggregations (mean annual, mean summer and mean winter). The mean annual dissolved oxygen values observed in 1980-2010 were remained stable above 8 mg/l with the lowest mean annual value observed in 1988 (5.5 mg/l).

The log-log regression model of mean annual dissolved oxygen with URBEXT as the explanatory variable showed a positive relation with stronger evidence in comparison with when taking mean annual flow as the explanatory variable.

This might suggest that despite the high urban development in Swindon area, the mean annual dissolved oxygen value had showed improvement and is moving towards positive direction. There has been restoration works led by Wiltshire Wildlife Trust in conjunction with Swindon Borough Council, EA, Thames Water and local communities conducted along 1.2 km stretch of the river involving re-meandering and other habitat improvements. This positive human alteration might contribute to the positive trend of mean annual dissolved oxygen value.

The assessment from nearby rural catchment in Enborne at Brimpton showed different result with no trend observed in all aggregations. This result could suggest that in more natural environment with very minimum human interferences, the mean annual dissolved oxygen value tends to have wide variability in the data without showing any specific positive or negative trends. Relationship analyses between mean annual dissolved oxygen with mean annual rainfall and mean annual flow also not demonstrated a representative model. Despite an arguable lack of significant trend, the dissolved oxygen value in this catchment was showing better overall condition in comparison with urban catchment. The mean annual dissolved oxygen observation for all periods was 11.12 mg/l with the lowest mean annual value of 8.9 mg/l observed in 1988.

Figure 5.2 illustrates the mean annual dissolved oxygen value from the river Ray (urban) and nearby river Enborne (rural). From the graph it is evident that despite not having any significant trend, the overall mean annual value was showing better condition in comparison with significantly increasing trend in the river Ray.

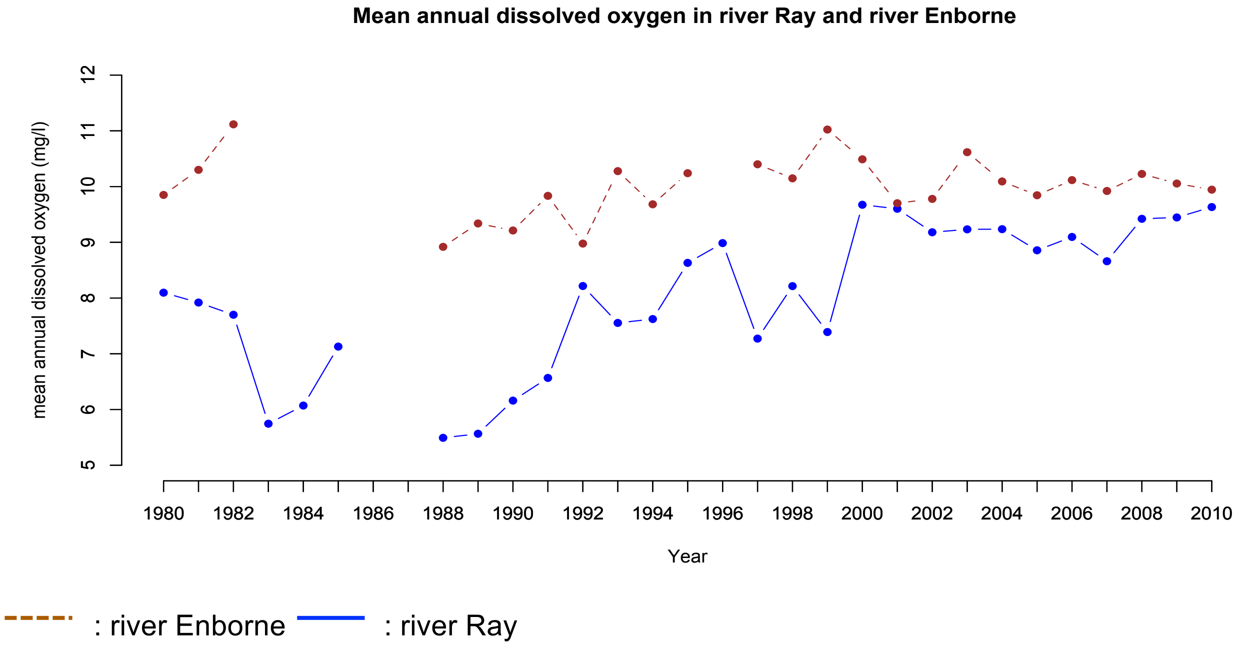

Figure 5.2 Mean annual dissolved oxygen in river Ray and river Enborne

In river Cut time-trend analysis, the value of dissolved oxygen was expected to have better condition as the location of monitoring is further upstream before STW. The mean annual dissolved oxygen value in all assessed period was 9.91 mg/l with lowest value of 8.12 mg/l observed in 1992. As expected, these values displayed better condition in comparison with the river Ray observation, which was obtained from further downstream after STW.

There was no significant trend was found in this catchment in annual and summer months. A noteworthy result was found during the winter. Time-trend analysis showed significant evidence of increasing mean value in the winter months despite no trend in annual and summer period.

In general perception, the positive trend of river water temperature would likely to be associated with decreasing value in dissolved oxygen, on the contrary, the result in river Cut shows the opposite. The investigation of variables that could explain the changes in mean annual dissolved also did not found significant relationship. The log-log regression model of mean annual dissolved oxygen by separately taking the mean annual rainfall, mean annual flow and URBEXT as explanatory variables was proved not to be an appropriate model to explain the changes in mean annual dissolved oxygen in river Cut.

For Winterbourne at Bagnor catchment, there was not a single regression model using assessed variables that proved to be a representative in explaining the changes in dissolved oxygen value in river Winterbourne. Similarly with Enborne at Brimpton rural catchment, the result might suggest that the natural variation in the river Winterbourne had contributed the large variability in the data. Mean annual dissolved oxygen (10.61 mg/l) for all periods was also showing better condition compared to the observation in river Cut in urban catchment with the lowest mean annual value of 9.62 mg/l observed in 1988.

5.4 Prediction Using the Model

For both urban catchments, the bivariate log-log regression model of mean annual river flow model function of URBEXT and mean annual rainfall resulted in a statistically strong evidence to reject the null hypothesis and suggesting a strong relationship between variables. This model will be used to predict the changes in mean annual river flow that can be associated with the increased in URBEXT with taking account of mean annual rainfall as second explanatory variable.

The non transformed model for this relation are shown below:

$$\log(\boldsymbol{mean\ annual\ flow}) = \boldsymbol{\beta_0} + \boldsymbol{\beta_1}.\log(\boldsymbol{URBEXT}) + \boldsymbol{\beta_2}.\log(\boldsymbol{mean\ annual\ rainfall})$$

which leads to the unstransformed relationship of:

$$\boldsymbol{Q} = \boldsymbol{exp}(\boldsymbol{\beta_0}) \times \boldsymbol{U}^{\boldsymbol{\beta_1}} \times \boldsymbol{P}^{\boldsymbol{\beta_2}}$$

where

Q = mean annual flow (m^3/s)

U = URBEXT

P = mean annual rainfall (mm)

Figure 5.3 shows the regression equations with the coefficients obtained from the regression statistics.

for the river Ray at Water Eaton urban catchment

$$\boldsymbol{Q} = \boldsymbol{1.10} \times \boldsymbol{U}^{\boldsymbol{0.33}} \times \boldsymbol{P}^{\boldsymbol{1.12}}$$

for the river Cut at Binfield urban catchment

$$\boldsymbol{Q} = \boldsymbol{0.60} \times \boldsymbol{U}^{\boldsymbol{0.61}} \times \boldsymbol{P}^{\boldsymbol{1.16}}$$

Figure 5.3 Regression equations to predict the mean annual flow in urban catchments

As the category for catchment urbanisation for the new developed URBEXT index has not been published, the prediction will use constant values of 0.40 and 0.60 to estimate the changes if urban exten rise to an approximately two and three times from the latest 2010 index. This specific contant value also described as “very heavily urbanised” and “extremely heavily urbanised” in previous $URBEXT_{1990}$ and $URBEXT_{2000}$ categorisation (Defra, 2006). The mean annual rainfall value was obtained from the linear interpolated dataset using actual minimum, mean and maximum annual rainfall data from observed period in each catchment.

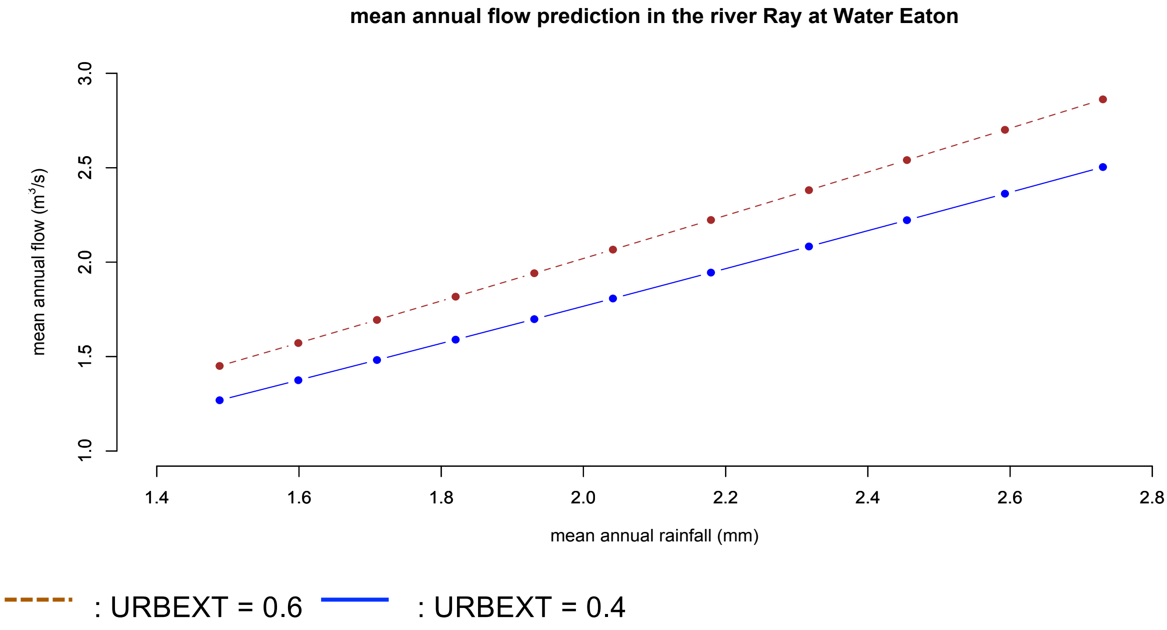

Figure 5.4 Mean annual flow prediction in the river Ray at Water Eaton (NRFA 39087) using log-log regression model

Figure 5.4 illustrates the mean annual flow prediction in the river Ray at Water Eaton. It is evident from the model that the higher the URBEXT index associated with higher mean annual flow rates. The actual mean annual flow value in the river Ray when the mean annual rainfall observed at its highest was 1.93 m^3/s. The model predicts the mean annual flow will rise to 2.50 m^3/s if URBEXT index is approximately doubled (0.4) and will rise to 2.86 m^3/s if URBEXT approximately rise three times (0.6) from the recent 2010 Swindon's URBEXT index value (0.22).

Mean annual flow in the river Cut at Binfield also predicted will rise to 1.04 m^3/s and 1.33 m^3/s with URBEXT index being 0.4 and 0.6 respectively (see Figure 5.5). The actual observed mean annual flow in the river Cut when the mean annual rainfall at its highest was 0.70 m^3/s. This prediction shows that with urban catchment surface characteristic that would likely to increased runoff and the uncertainty of rainfall trend, there are concerns during the highest intensity of rainfall that might caused flood problem which lead to the environment and economic loss.

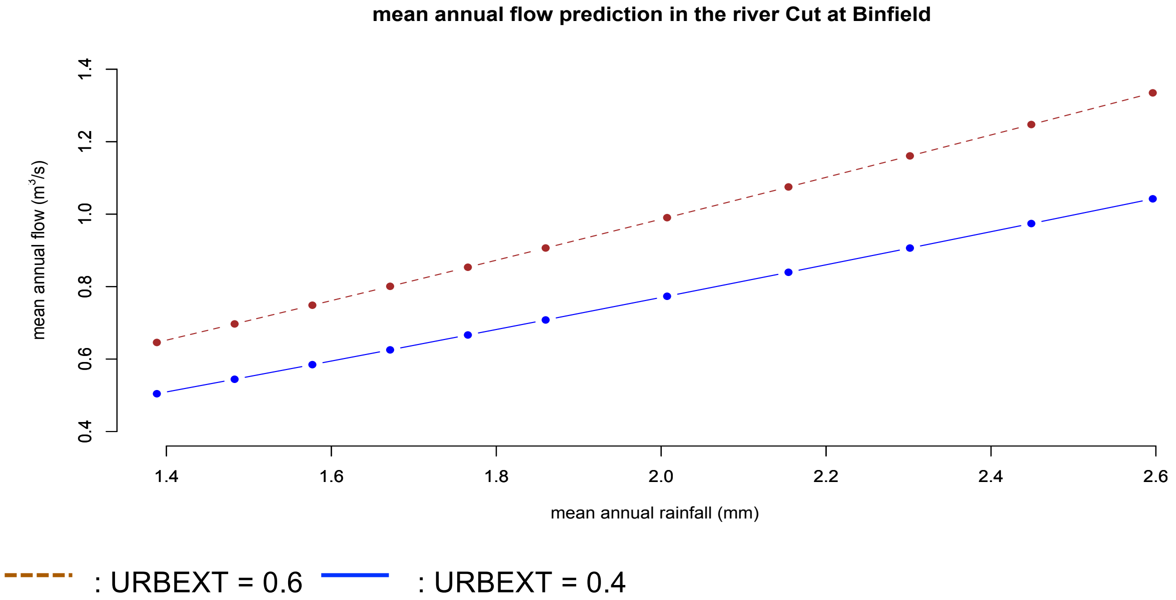

Figure 5.5 Mean annual flow prediction in the river Cut at Binfield (NRFA 39052) using log-log regression model

5.5 Limitations

This research had several limitations. Although river flow and rainfall data had provided representative amount of for the observed period, there would be likely a tendency for inaccurate flow measurement. The development of weir near the gauging station in the river would alter the flow rate and could result a reduced flow measurement. Water quality data shown great variability, however, there were notable gaps of missing data during the period which resulted several annual analysis had to be removed. Analysis may resulted a better model to explain the changes could the amount of data had been larger. The different time of measurement for water quality data could have resulted a biased outcome to the analyses.

6. Conclusions and Recommendations

6.1 Conclusions

The study was set out to investigate time-trends and explores the links between environmental changes, river flow and selected water quality variables in urban catchments the river Ray at Water Eaton and the river Cut at Binfield and nearby similar sized rural catchments in Enborne at Brimpton and Winterbourne at Bagnor. This research also focused in sought the best possible model to investigate potential driver(s) that can be associated to the changes in river flow and selected water quality variables. The general literature is that the urban development would have more drawbacks than the advantages. On contrary, some noteworthy results were found that might suggest the changes are towards positive improvements.

Based from the results and findings from the analysis, this study can be drawn into these conclusions:

- The long-term mean annual rainfall data for both urban and rural catchments were not indicated any trends. Different characteristics of each urban and rural catchment were not appeared to affects the rainfall trend during the periods. Lengthier period of rainfall observations might be useful to address the concerns that climate changes would create trend in precipitation and rainfall towards negative impacts.
- The 37-50 years of river flow measurements proved to be a considerable and representative data to investigate trends. Annual, summer and winter mean of annual flow in Cut at Binfield showed strong evidence of positive trends. However lack of evidence of trend during the winter season in Ray at Water Eaton catchment whereas positive trends were found in annual and summer analysis still remain unexplained. On contrary with the nearby similar sized rural catchments, there were no trends spotted for both Enborne at Brimpton and Winterbourne at Bagnor.
- In all urban catchments, URBEXT in conjunction with mean annual rainfall were found to be the most representative explanatory variables which could act as potential drivers that can be associated with the changes in mean annual flow in the river Ray and the river Cut. The log-log regression model found significant relationships, which explain 81% and 61% of the variance in Ray at Water Eaton and Cut at Binfield respectively.
- In the absence of URBEXT, rainfall was the only potential driver that could be assessed in this study to investigate the relationship with river flow. Expected results were found. The log-log regression model of mean annual flow with mean annual rainfall as the explanatory variable resulted a strong evidence of relationship and proved to be a good model to explain the relationship.

- This study also found that despite concerns of oxygen depletion from anthropogenic impacts in urban catchments, positive trends were found in the river Ray in all different time aggregations, and only during winter months in the river Cut. These results suggested that there might have been positive human impacts contributing to this condition.
- In general, the river temperature and dissolved oxygen relationship analysis in rural catchments showed no significant evidence during the periods. A notable relationship was found in mean annual temperature when taking mean annual rainfall and mean annual flow as an individual explanatory variable. From an arguably lack of observations of river temperature and dissolved oxygen in Enborne at Brimpton and Winterbourne at Bagnor, conclusions were drawn from period with 5 to 7 years gaps in between. The result might not be the best representative to investigate the trends and relationship and could have resulted better model using a lengthier datasets.
- In general, despite some low values observed in mean annual selected water quality data, the recent observation was considered to be a good and high standard according to Water Framework Directive.

6.2 Recommendations

The following recommendations are offered for related future research that could be important for a more in depth assessment of the urbanisation effects on river flow regime and water quality:

- Further in depth investigation in the urban area to determine to magnitude of increased runoff during high intensity of rainfall is needed to understand and minimise the possible negative impacts of flooding.
- Air temperature data in specific study sites location would also be useful variable to understand how it might impact the river water temperature data
- Other parameter of water quality such as nitrogen species, phosphorus species and pH could be also be assessed to understand the wider effects of urbanisation on water quality
- The current overall condition of river water temperature showing good condition. Special attention needed to be addressed to the rising river temperature in urban catchments, which would likely to cause problems in the future.

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Appendix A.

Computer program

Data in this research was processed and plotted using the aid of R software. R is a free software environment used for statistical computing and graphics. It provides an open source route for its users. Evolved from the idea to provide a powerful software tool for professionals that combine comprehensive graphics and model fitting capability, this software now used by more variety level of users. Developed at Bell Laboratories by John Chambers and colleagues, R provides a wide variety of statistical modeling and graphical techniques. Reason for choosing R is its capability to perform data manipulation, calculation and graphical displays which includes effective data handling, simple and effective programming language and a large, coherent, integrated collection of intermediate tools for data analysis.

This software works in popular platform including Windows and Macintosh. In this research R GUI software under 32-bit Macintosh's platform version 2.15.3 for Leopard operating system was used to analyzed selected variables.

Appendix B

Images of the gauging stations

Image 1. The river Ray at Water Eaton (NRFA 39087) gauging station retrieved from http://www.geograph.co.uk. Image ©Copyright Des Blenkinsopp and licensed for reuse under Creative Commons Licence.

Image 2. The river Cut at Binfield (NRFA 39052) gauging station Environment Agency. retrieved from http://www.environment-agency.gov.uk

Image 3. The river Enborne at Brimpton (NRFA 39025) gauging station
Environment Agency. retrieved from http://www.environment-agency.gov.uk

Image 4. The river Winterbourne at Bagnor (NRFA39033) gauging station
Environment Agency. retrieved from http://www.environment-agency.gov.uk