Short-term domestic water demand: estimation, forecasting and management

by
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Submitted in accordance with the requirements for the degree of Doctor of Philosophy

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July 2001

The candidate confirms that the work submitted is her own and that appropriate credit has been given where reference has been made to the work of others.

Abstract

In the UK, the water resource problems during the droughts of 1988-1992 and the well-publicized problems of 1995-1996, serve to highlight the finite nature of the potable water resource. Demand management is increasingly considered a fundamental tool in promoting a sustainable water resource strategy. However, of equal importance is the development of accurate water demand forecasts that work in parallel with demand management measures. These forecasts should predict all components of water use on different planning horizons. Presently, water plc's have a very limited understanding of factors influencing short-term domestic water demands and rely upon crude methods of forecasting. However, no precise definition of 'short-term' exists within the water industry. Previous research defined 'short-term' to be between twenty-four hours and seven days ahead. It was argued that effective weather prediction and operationally useful forecast times were the determining factor in the definition.

The domestic water consumption data used in this research is derived from two different methods: (i) zonal metering and (ii) individual household metering. Welsh Water and Yorkshire Water provided zonal metering data, which refers to the flow to a zone that has many households. Essex and Suffolk Water, Thames Water and Yorkshire Water provided individual household metering data, which is a measure of consumption in single households. These data were used in the determination of: (i) underlying factors that influence the demand for water in both the short- and the medium- to long-term and (ii) factors that influence short-term demands. The influential factors aided in the exploration of modelling strategies to forecast short-term domestic water demands. Approaches explored included a pragmatic approach, based on a form of accounting using a series of 'lookup tables', and advanced approaches, including stepwise regression, both with and without k-means cluster analysis, and univariate and multivariate ARMA time-series modelling. The most successful approach was then used to determine how future scenarios such as changes in the population base, climate, culture and technology might influence the characteristics of short-term domestic water demands.

Household size and property type appears to exert the greatest underlying influence on medium- to long-term domestic water demands. In the short-term, domestic water demand appears to be influenced by the two days antecedent and the prevailing day's weather conditions, day of the week, calendar effects, school holidays and demand management measures. No single approach provided the best overall prediction of short-term domestic water demands. However, the pragmatic approach emerged as one of the most promising techniques. The pragmatic approach, used to determine how future scenarios might change the characteristics of short-term domestic water demand, suggests that increases in demands are associated with changes in the population base, climate and culture. However, changes in technology associated with the widespread implementation of demand management measures have the potential to suppress the increases and indeed reduce demands to less than those of the present day.

Table of Contents

List of Figures

List of Tables

Acknowledgements

This research would not have been possible without the help, support and advice of many people to whom I am eternally grateful. Prof. Adrian McDonald from the School of Geography has been a wonderful source of inspiration, enthusiasm and advice during all stages of my research. Not only did he give me confidence to believe in myself but he also provided financial support for this research. Sincere thanks must also go to Dr Linda See from the School of Geography. Her expert advice and knowledge of forecasting systems was invaluable to this research.

I would like to thank Claire Ridgewell and Helen Canswick from Essex and Suffolk Water, Sue Craddock from Thames Water, John Morrison and Hussain Rab from Welsh Water, and Andrew Iveson and Rachel Evans from Yorkshire Water, for providing me with their domestic water use data. I would also like to thank David Appleyard from the Graphics Unit at the University of Leeds.

There are many others who provided their time, advice and friendship. Many thanks go to Marcus Powers, the girls in the office (past and present), Kyoko Fukasawa, my parents and of course Linda See. An extra special thank you must go to Gary Beasley for his essential contributions and abundant support during my time at both Manchester and Leeds. This research would certainly not have been completed without his unbelievable ability to solve problems.

1. Introduction

1.1 Introduction

Water is arguably the world's most precious resource. In developed countries such as the UK, society expects, and legislates for, a clean and reliable supply of potable water. Scientific investigation of potable water quality in the UK started in the 18th Century and is now claimed to be set at a standard far higher than necessary to safeguard health (Department of the Environment, 1994). Despite this, immediately following the privatization in 1989 of the water industry in England and Wales, the focus was on potable water quality. However, since the water resource problems during the droughts of 1988-1992 and the well-publicized problems of 1995-1996, the supply of potable water has received increased attention. It is considered that at a global scale there should be enough water to meet human needs into the foreseeable future (Golubev, 1993 in Haughton and Hunter, 1994). However, these resource problems associated with specific droughts, in conjunction with unevenly distributed, poorly managed, wasted and inappropriately consumed water supplies (Haughton and Hunter, 1994) along with recognized increases in demand primarily due to population growth (Haughton and Hunter, 1994; Schutte and Pretorius, 1997) and climate change-induced uncertainty over supply (Gleick *et al.*, 1997; Stakhiv, 1998; Arnell, 1999; Mitchell, 1999; Loucks, 2000; Loucks *et al.*, 2000), serve to highlight the finite nature of the potable water resource. In fact, UK water resources are considered closer to sustainability limits than ever before (Mitchell, 1999).

Demand management is increasingly considered a fundamental tool in promoting a sustainable water resource strategy. This undoubtedly stems from the publication of the Bruntdland Commission report *Our Common Future* (World Commission on Environment and Development, 1987), which gained international credence. In this report, demand management accords with the concept of sustainability and underpinned many of the principles outlined in the UNCED Earth Summit in Rio in 1992 (National Rivers Authority, 1995). In January 1994, the UK Government published *Sustainable Development – The UK Strategy,* which outlined challenges to be tackled over the next twenty years to achieve sustainable development. Included in that report is the aim to ensure that adequate water resources are available to meet consumer needs and to manage and meet the demand for water from households, agriculture and industry. Within these overall goals it was recognized that maximizing the effectiveness of existing resources will require demand management (economic instruments, selective metering, improved abstraction charges), and day to day management measures (leakage, waste minimization). Then, in March 2000, one hundred and fifty countries agreed the Ministerial Declaration on Water Security in the 21st Century, which focused in part on resource efficiency. The sustainable use of water had been reaffirmed publicly, by almost every country and global agency (Soussan *et al.*, 2000).

Without question demand management is a vital component of a sustainable water resource strategy. However, of equal importance is the development of accurate water demand forecasts that work in parallel with demand management techniques. These forecasts should predict all components of water use (e.g. domestic, industrial, agricultural) on different planning horizons (e.g. the short-, medium- and long-term). Much attention has been given to the forecasting of water demand in the medium- to long-term (e.g. Rees and Rees, 1972; Batchelor, 1975; Archibald, 1983; Herrington, 1996; Clarke *et al.*, 1997) primarily because the premature development of unnecessary water resources, e.g. surface reservoirs, impacts on valued countryside, wildlife and livelihoods. However, a major and seemingly forgotten factor in the sustainability debate would include the potential to predict water demand in the short-term and thereby optimize water management.

Over-estimation of water demand in the short-term can induce detrimental environmental impacts. One such impact results from river over-abstraction. This problem may be exacerbated further during summer months and drought periods when low river flows prevail. At these times unnecessary over-abstraction can compromise the integrity of aquatic systems, particularly their waste disposal and ecological life-support functions (Mitchell, 1999). For example, forty rivers were identified as suffering from low flow problems due to continued abstraction during the drought of 1988-1992 in the UK. As a result, wildlife habitats were damaged and pollution problems became more apparent due to the lack of effluent dilution (National Rivers Authority, 1995). Continued over-abstraction of surface reservoirs and groundwater can also induce low river flows and in some cases can result in the drying up of perennial streams (e.g. Owen, 1991). The increased risk of subsidence, spring failure, and saltwater intrusion into coastal aquifers can also result from continued abstraction of groundwater resources. Such detrimental impacts resulting from unnecessary river, groundwater and surface reservoir over-abstraction could be alleviated if accurate forecasts of short-term water demand were available. In turn, this would help to promote the sustainability of water resources for all time-scales from the short- through to the long-term.

1.2 Why forecast short-term domestic water demand?

In the UK, water plc's have a requirement, set both internally and externally, to estimate water demand: externally by the Office of Water Services (OFWAT) and internally to provide a cost effective and efficient service. At present, water plc's have a very limited understanding of factors affecting short-term unmetered domestic water demand and rely upon crude methods of forecasting. Gaining this understanding and being able to undertake short-term forecasting will undoubtedly have several benefits besides the mitigation of detrimental environmental impacts. In particular the following would be of benefit:

(i) Under section 145 of the Water Industry Act, 1991, water plc's were required to change their method of charging from a property's rateable value by the 31st March, 2000. Although this deadline was deferred in April 1995, water plc's are still faced with devising a different charging mechanism for consumers. It would be extremely valuable to the water plc's if they had more information about the factors that influence domestic water consumption in order that a fairer mechanism for charging consumers could be established and demonstrated.

(ii) When factors that influence unmetered domestic water consumption have been identified, these factors could be used to aid forecasting of unmetered domestic water demand for all time-scales e.g. the short-, medium- and long-term.

(iii) The short-term operation of water supply and distribution systems in response to demand variations would result in system optimization therefore minimizing costs (particularly energy) for the water plc's.

(iv) Determination of the factors that influence unmetered domestic water consumption has the potential to be used as an aid in resource needs forecasting. If a new housing estate were going to be built, it would be possible for the water plc's to determine how much water the estate would use and whether new resources were required. With the proposal of 4.4 million houses to be built between 1991 and 2016 (Department of the Environment, 1994), resource needs forecasting would be an invaluable tool. Asset design requirements usually focus on peak demand. This is in many respects an attribute of the short-term, a local peak generated by a partial combination of short-term characteristics.

1.3 Aims of the research

This thesis is concerned with the demand for water and in particular the short-term demand for potable water for domestic use. The aim of this thesis is to develop estimations and forecasts of short-term domestic water demands that can be used as a tool for sustainable water resource management.

This aim can be subdivided into six main objectives:

(i) To examine the underlying factors influencing unmetered domestic water demands in the medium- to long-term (Chapter 4 and 5).

(ii) To determine the factors that influence unmetered domestic water demands in the short-term (Chapter 4 and 5).

(iii) To investigate whether influential factors differ on a spatial scale, in urban/rural areas, in areas where demand management measures have been introduced and so on (Chapter 4 and 5).

(iv) To use the results from the aforementioned objectives to develop an appropriate technique to forecast short-term domestic water demands (Chapter 6).

(v) To determine how future scenarios might influence the characteristics of short-term domestic water demands (Chapter 7).

(vi) To provide recommendations for future avenues of research (Chapter 9).

Note that in this research the term 'demand' refers to the quantity demanded or just water use. This is the conventional definition used by water resource planners and engineers, rather than the stricter definition of the relationship between price and quantity.

1.4 Thesis structure

The thesis structure follows a logical progression from problem identification (Chapter 1) to future research needs (Chapter 9). A detailed synopsis of each chapter is presented below.

Chapter 2 examines domestic water demand within the context of water demand as a whole and provides appropriate definitions and time horizons for this research. A review and synthesis of approaches used (i) to make current estimates of domestic water demand and (ii) to forecast short-term water demand, are provided. The final section of this chapter outlines current and proposed domestic water consumption studies undertaken within the UK water industry.

Chapter 3 describes the sources of data used in this research and provides a rationale for using these data. This chapter also specifies the analytical methodology for determining the factors that influence domestic water consumption in both the short- and the medium- to long-term.

Chapter 4 investigates the way in which domestic water demand is influenced, in both the short- and medium- to long-term, by the aggregate of the water using behaviour of the individuals in the zonal meter studies undertaken by Welsh Water and Yorkshire Water. The data from Yorkshire Water also provided the opportunity to evaluate the influence of demand management practices on domestic water demands.

Chapter 5 investigates the way in which domestic water demand is influenced, in both the short- and medium- to long-term, by the water using behaviour of individuals in the household studies undertaken by Essex and Suffolk Water, Thames Water and Yorkshire Water.

Chapter 6 is an exploratory chapter which seeks to investigate the ways in which short-term domestic water demands can be forecast. Approaches investigated range from simple pragmatic approaches, using a form of accounting, to more complex advanced approaches, such as multivariate ARMA time-series modelling.

Chapter 7 applies the findings from Chapters 4, 5 and 6 to determine how changes in the population base, climate, culture and technology might influence the characteristics of short-term domestic water demands.

Chapter 8 seeks to explain the findings of the research into the demand for domestic water presented in earlier chapters. The results are compared to the findings of similar research reported in the literature and reviewed in Chapter 2. The wider implications of this research, in particular the potential it has to be used as a vital component of a sustainable water resource strategy in the 21st Century, is also discussed. Limitations of this research are also identified and examined.

Chapter 9 concludes the thesis by summarizing the research findings and emphasizing the main discoveries with reference to the aims and objectives of the research. This chapter also recommends future avenues of research to further improve our understanding of domestic water demands.

2. A Review of the Literature: Water Resources and Demand Estimation and Forecasting

2.1 Introduction

This chapter examines *domestic* water demand within the context of water demand as a whole and provides appropriate definitions and time horizons for this research. In order to forecast short-term unmetered domestic water demands, the underlying influential factors must be identified. This is accomplished through a review and synthesis of approaches used in the literature, based on estimates of demand from various water use studies. This is followed by a review of approaches to forecasting short-term water demand. The final section of this chapter outlines current and proposed approaches to estimating unmetered domestic water consumption within the UK water industry.

2.2 Components of water demand

The water industry is required to meet the consumer's demand for water for domestic, industrial, agricultural and public purposes. However, many of these components of demand are unmeasured. In the UK, for example, only about 14% of domestic supplies in England and Wales were metered in 1999 (Twort *et al.*, 2000). To derive components of water demand, the water industry must subtract known demands from the total amount of water supplied and often uses the residual to estimate other components of demand. However, a distinction must be made between how much water must be supplied from the service reservoir or treatment works and how much is demanded by the households. The difference between the two figures is unaccounted for water usage, some of which are legal, some of which are illegal, and some of which are unknown.

This research focuses on the true demand for domestic water, not the supply (or works demand). Domestic water use represents the single largest consumption of water in the UK (Figure 2.1). The largest part of domestic water supply is for unmetered households (Figure 2.2). As it was beyond the scope of this research to study different components of water usage on different time-scales, short-term fluctuations in water demand for the largest consumer of water, unmetered households, were studied.

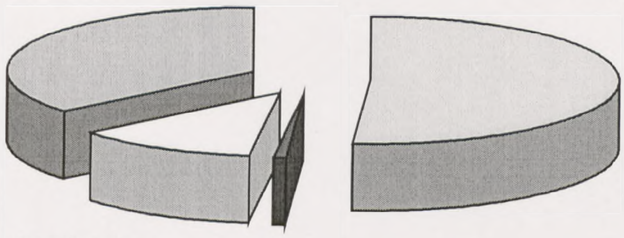


Figure 2.1: Water abstraction by purpose (non-tidal water and groundwater only) (Source: National Rivers Authority, 1995)

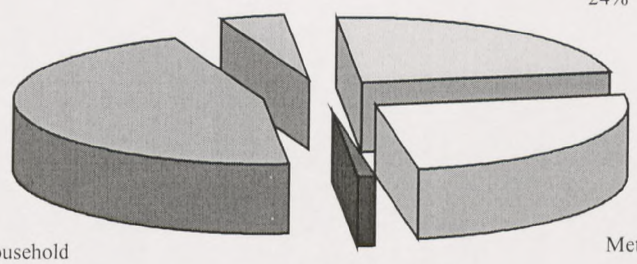


Figure 2.2: Components of the public water supply (by volume) (Source: National Rivers Authority, 1995)

2.3 Definition of time horizons

The water industry employs a range of time horizons. For strategic purposes, such as bids for licence renewal, the industry is required by OFWAT to make estimates of demand and resource availability on a twenty-five year horizon. Intermediate time horizons, for example in the planning, commissioning and implementation of new major works, is in the order of ten to fifteen years. Management time horizons are in the order of three to five years but tactical management ranges from a few months to a year. Operational management is in the order of weeks.

Figure 2.3 illustrates the range of time horizons employed and, since there is no consistent nomenclature on which to draw, attempts a logical characterization of time horizons.

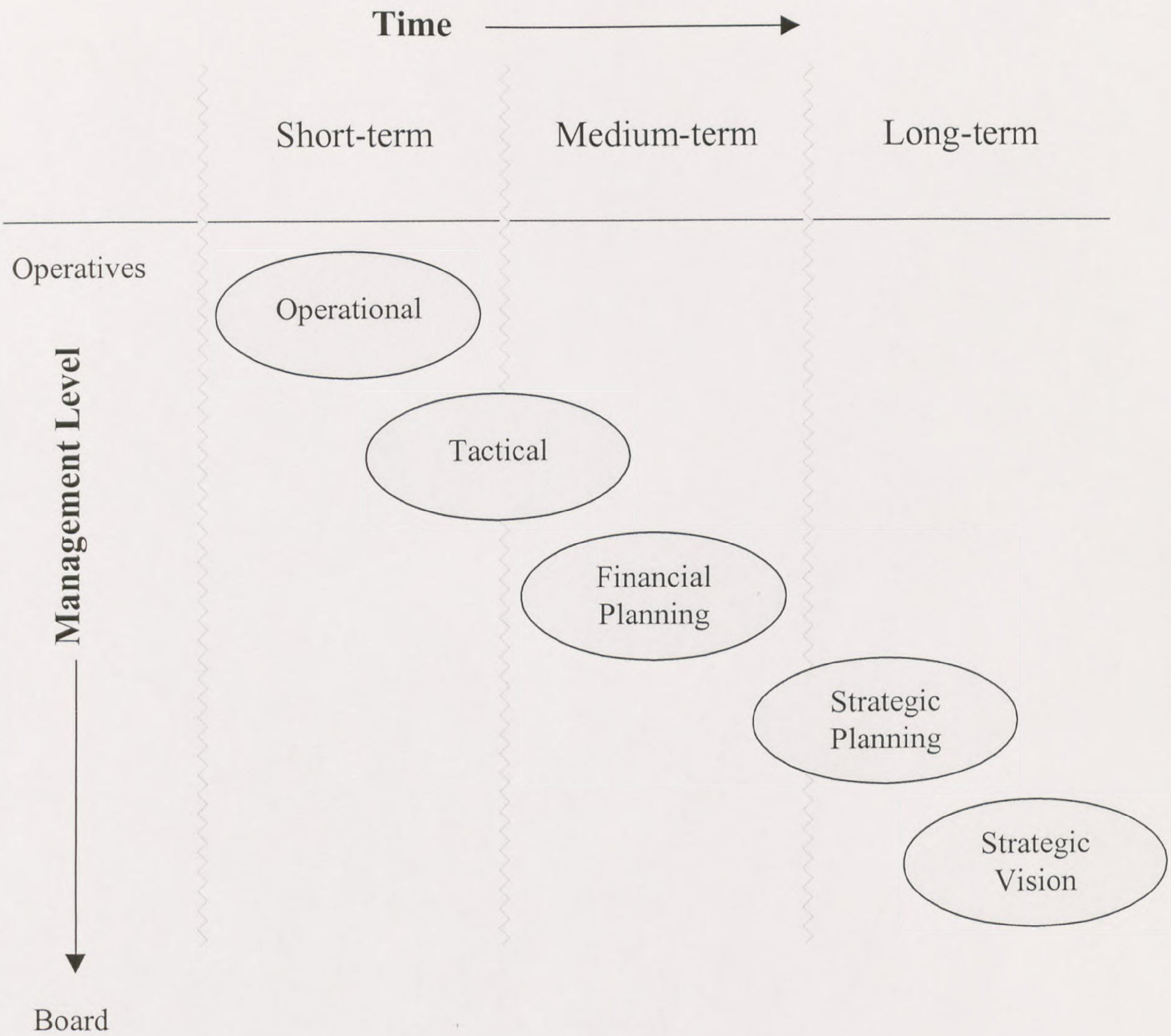


Figure 2.3: Time horizons employed in the UK water industry

Many definitions of the short-term exist within the water demand literature. DeKay (1985) defined the short-term to be between five and seven years ahead. While perhaps extreme, this definition appears to be reasonable, particularly when long-term is often defined as twenty to twenty-five years ahead (Rees and Rees, 1972; Batchelor, 1975; Archibald, 1983). Others have defined short-term as anything from instantaneous demand (Buchberger and Wu, 1995), to hours (Chen, 1988; Shvarster *et al.*, 1993; Guhl *et al.*, 1998; Oshima and Kosuda, 1998) days (Coulbeck, 1985; An *et al.*, 1996, 1997), weeks (Carnell, 1986) and months ahead (Maidment and Parzen, 1981; Maidment and Parzen, 1984a,b; Franklin and Maidment, 1986). As this research aims to inform the optimization of the water distribution system, short-term is defined here to be between twenty-four hours and seven days ahead. The determining factor in this definition is that it complies with effective weather prediction and provides operationally useful forecast times. It would be of no benefit to the water industry if they could forecast water demand a few hours ahead but were unable to alter the amount of water fed into the distribution system within that time.

2.4 Approaches to estimating water demand

A review of approaches to estimating water demand has revealed a number of estimates based on various time scales or cross-sections of the population. Some studies have based estimates of water demand at the municipal level (Wong, 1972; Berry and Bonem, 1974; Morgan and Smolen, 1976; Cochran and Cotton, 1985). As these studies include many components of demand, the estimates are therefore much less sensitive to variations in water demand from the individual components. Other studies have estimated water demand for individual components. Industrial demand, for example, was estimated by Thackray and Archibald (1981), Smith (1986), Renzetti (1992), Mitchell and Wattage (1998) and Mitchell *et al.* (2000). As this research is primarily concerned with the domestic component of water demand, a more detailed synopsis of estimates of domestic water demand is undertaken.

2.5 Approaches to estimating domestic water demand

The review of approaches to estimating domestic water demand concluded that most estimates have generally relied upon cross-sectional or time-series analysis. Cross-sectional analysis is utilized to estimate the quantity of water used by a cross-section of several residential areas at a given time whereas time-series analysis is utilized to estimate the quantity of water used by residential areas as a function of variables changing over time. The data are derived using (i) zonal metering studies (ii) individual household studies (iii) component studies or (iv) a combination of the above. The scale, design and purpose of these studies vary significantly although all estimate demand. The most common technique of using these estimates to determine underlying factors influencing domestic water demands is through multiple linear regression analysis. Large proportions of these studies use price as one of the key independent variables affecting demand. However, the selection of independent variables varies in each individual study. In the UK, for example, most domestic water demand is unrelated to price because the majority of households are unmetered and, therefore in any given household, the variation in demand is unrelated to the (constant) price.

2.5.1 Cross-sectional approach using zonal metering studies

Earlier work used cross-sectional data from zonal metering studies to estimate water demand (Turnovsky, 1969; Foster and Beattie, 1979). Regression analysis used by Turnovsky (1969) and Foster and Beattie (1979) found that price explained a significant percentage of variation in domestic water demand. However, other variables found to influence domestic water demand differed, probably due to the geographical location of the data sources. Turnovsky (1969) found that uncertainty, as measured by supply variance, and housing space also influenced demand. These variables were not included in the regression analysis undertaken by Foster and Beattie

(1979). Instead, they found that the best estimates of household water demand were provided when using price, income, rainfall and number of persons per meter as independent variables.

2.5.2 Cross-sectional approach using individual household studies

Primeaux and Hollman (1974) used cross-sectional data from a random selection of individual households to estimate demand. Thirteen variables, including price of water, socio-economic and weather factors were used in the analysis. Multiple linear regression demonstrated that all thirteen variables explained only 56.26% of the total variation in water demand. The primary determinant was number of residents per household, with various other factors having a small but significant explanatory effect. However, Foster and Beattie (1979) revealed some interdependency between explanatory variables, particularly with house value, lawn area, level of education and number of bathrooms. Consequently, it was impossible to determine the specific effect of any one of the highly correlated variables. Furthermore, correlation between the independent variables, whilst not invalidating such multivariate approaches, compromises the associated test/diagnostic statistics, raising doubts over the explained variables in Primeaux and Hollman (1974).

2.5.3 Time-series approach using zonal metering studies

Several studies have used time-series rather than cross-sectional data to estimate demand (Headley, 1963; Hanke, 1970; Thackray *et al.*, 1978; Russac *et al.*, 1991; Rhoades, 1995; Water Research Council, 1997). The importance of studying time-series data has been strongly advocated by many researchers (Hanke, 1970; Danielson, 1979; Carver and Boland, 1980). Hanke (1970) concluded that significantly more confidence could be placed on estimates of demand using time-series data as the 'rival' cross-sectional data are devoid of any dynamic influences.

As in previous cross-sectional studies, Headley (1963) and Hanke (1970) recognized the importance of economic variables. Headley (1963) focused on the relationship between family income and water use, while Hanke (1970) concentrated on the relationship with water price. Using regression analysis, significant relationships were observed between these two variables and water use. In the remaining studies, although some economic variables or surrogates of economic variables were considered, no real emphasis was placed on the price of water. Instead, the influence of factors such as household size, property type, the classification of residential neighbourhoods (ACORN) and number of water using appliances were assessed. The percentage of explained variance ranged from 53% (Water Research Council, 1997) to 61% (Thackray *et al.*, 1978). However, as Thackray *et al.* (1978) observed, a wide variation in water consumption exists, even in groups with common characteristics. Figure 2.4, for example, shows that a reasonable linear trend exists between domestic water consumption and the rateable value of properties, but overall, there is a large degree of dispersion in the data.

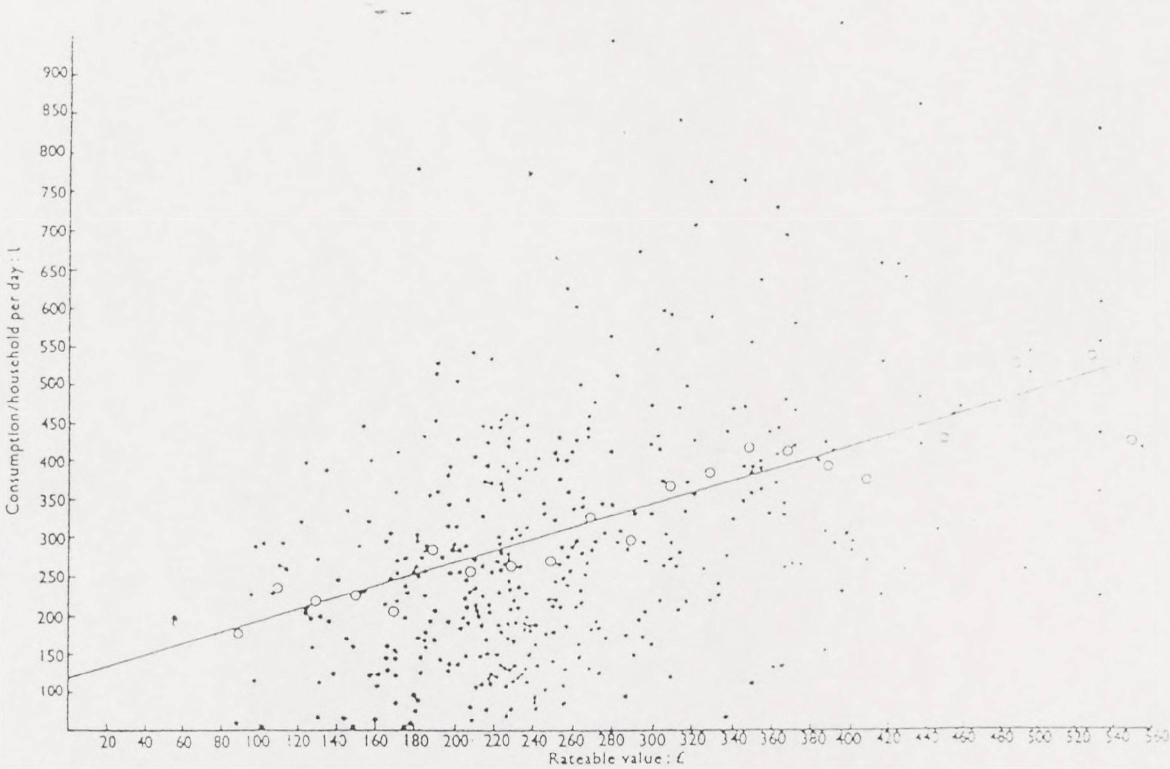


Figure 2.4: The relationship between consumption and rateable value in Malvern (Source: Thackray *et al.*, 1978)

2.5.4 Time-series approach using individual household studies

Time-series data from individual household studies have also been used to estimate water demand (Morgan, 1973; Turton and Smith, 1976; Danielson, 1979; Power *et al.*, 1981; Agthe *et al.*, 1988; Edwards and Martin, 1995). All studies demonstrated that household size consistently exerts the greatest influence on water demand, with water consumption per person reducing with greater household size (Figure 2.5). Danielson (1979), for example, found that household size explained 74% of the variation in household water demand. Other factors found to influence household water demand included housing type, socio-economic groupings and the rateable value of properties. However, only Danielson (1979) attempted to assess the influence of weather on household water consumption. Danielson (1979) observed a weak negative relationship between household water consumption and rainfall and a slightly stronger positive relationship with temperature.

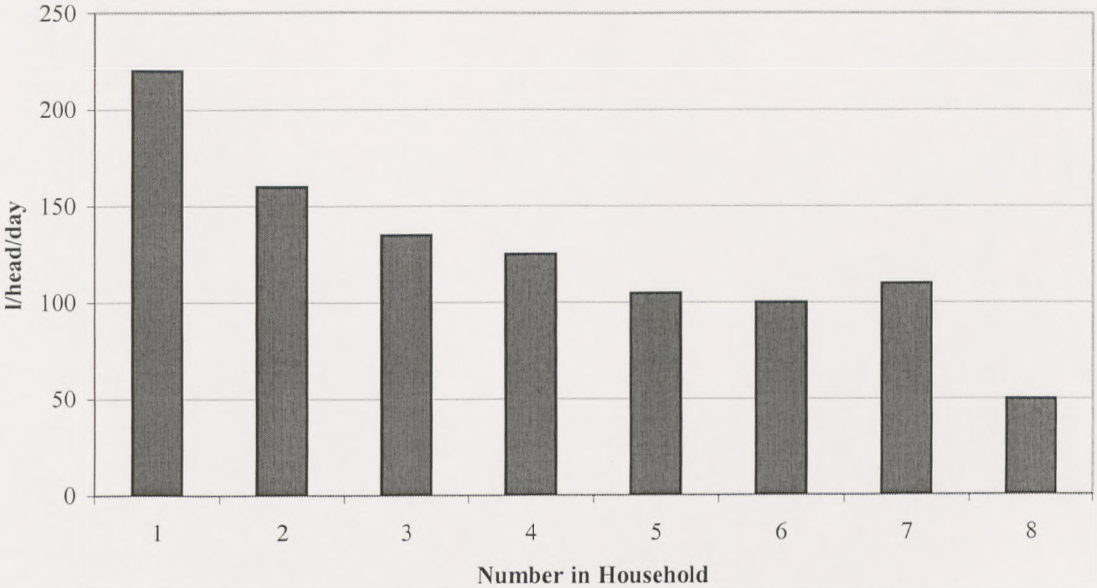


Figure 2.5: Mean per capita consumption by household size (Source: Edwards and Martin, 1995)

2.5.5 Time-series approach using component studies

Components of domestic water use have also been studied to estimate demand (Thackray *et al.*, 1978; National Water Council, 1982; Hall *et al.*, 1988; Edwards and Martin, 1995; DeOreo *et al.*, 1996). The main strength of using the component approach is that each main item of domestic water consumption, such as personal washing, toilet flushing, clothes washing and garden watering is identified and treated separately. Earlier work in this field generally relied upon the co-operation of participating households to keep daily records of water use (Thackray *et al.*, 1978; National Water Council, 1982; Hall *et al.*, 1988). However, a more advanced technique, developed in the United States, used flow traces that were so precise, signatures associated with all major water use categories could be identified (DeOreo *et al.*, 1996).

Household water demand in the component studies is estimated by summing the volume of water used by each appliance by the frequency of use. However, many of the studies observed large variations in the frequency of appliance usage. Edwards and Martin (1995) compared appliance usage of two individual households to highlight this variation (Figure 2.6). This makes it extremely difficult to extrapolate demand estimates to the wider population. Water use may also be influenced significantly by a metering effect, particularly in the diary studies, as customers are reminded constantly that they are being monitored. This questions the validity of the component study data.

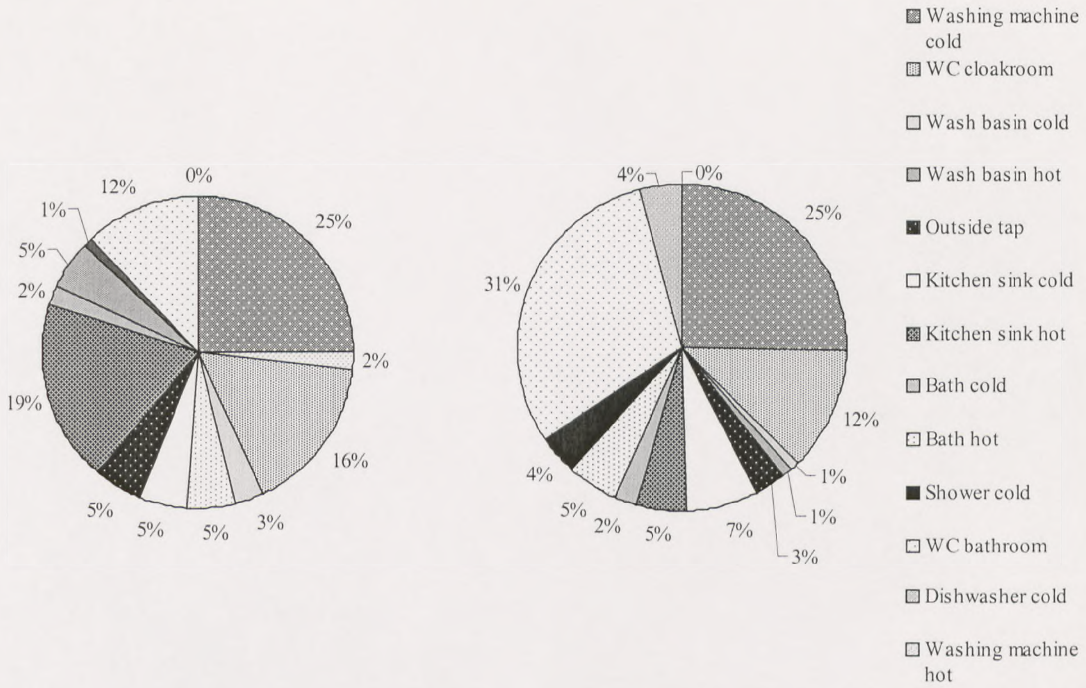


Figure 2.6: Examples of water use by individual properties (November 1992 - October 1993) (Source: Edwards and Martin, 1995)

2.6 Summary of approaches to estimating domestic water demand

Although there is a substantial literature concerning the estimation of domestic water demand, the applicability of the results, particularly to the UK, must be questioned. One of the foremost reasons for this is the absence of the price variable in the UK. The major exception is Malvern, in Worcestershire, where individual households have been charged by meter since 1871 (Archibald, 1983). It is also unclear how representative many of these studies were to the wider population. In many cases, only a few hundred households were included in the studies (Morgan, 1973; Turton and Smith, 1976; Danielson, 1979). As water consumption varies significantly among households with similar and different characteristics, an adequate cross-section of the population is required to capture variations in domestic water use. Many of the studies only monitored water consumption over a relatively short time period, typically a few months (Morgan, 1973; Thackray *et al.*, 1978; Hall *et al.*, 1988; Russac *et al.*, 1991). Results from these studies may be influenced severely by metering effects, seasonal effects, abnormal weather patterns or restrictions imposed by water companies, such as hose-pipe bans. The validity of this data for estimating demand over a longer time period is therefore questionable. Some of these studies were also undertaken in areas with distinct socio-economic attributes (e.g. Russac *et al.*, 1991). Again it is unclear whether this data is representative of the population as a whole. It is also particularly misleading to apply estimates of demand from one country to another due to environmental, technological and cultural differences. In the UK for example, distinct seasonal weather patterns occur, unlike in many parts of the world. This seasonal weather pattern undoubtedly influences water demand.

2.7 Approaches to forecasting water demand

Many estimates of domestic water demand and the associated key influential variables have been applied to the forecasting of demand in the medium- to long-term (Rees and Rees, 1972; Batchelor, 1975; Archibald, 1983; Herrington, 1996; Clarke *et al.*, 1997). Other studies have applied estimates and key influential variables to the forecasting of water demand on much shorter time scales, such as year on year (Miaou, 1990), month on month (Maidment and Parzen, 1981; Maidment and Parzen, 1984a,b; Franklin and Maidment, 1986), hour on hour (Chen, 1988; Shvarster *et al.*, 1993; Guhl *et al.*, 1998; Oshima and Kosuda, 1998) or instantaneous demands (Buchberger and Wu, 1995).

In many parts of the world, the water distribution system typically consists of multi-reservoir networks incorporating pipes, pumps and valves, to supply varying water demands (Coulbeck, 1993). Optimization of these systems relies upon the minimization of electricity tariffs and associated costs for the complete network. This requires the control of pumping and storage while catering for consumer demand and addressing risk and reliability by maintaining desired reservoir levels. Consequently, the successful application of optimization methods depends significantly upon the formulation of accurate predictions of water demand in the short-term, typically between twenty-four hours and seven days ahead. A review of approaches to estimating and forecasting short-term water demand is therefore undertaken.

2.8 Approaches to forecasting short-term water demand

Operations of the water distribution system are typically controlled by human operators at a central pumping station (An *et al.*, 1996, 1997) or at least a central management or operational control centre which may not be remote from the pumping station. In Yorkshire Water for example, some six-hundred pumps are in operation for which only three-hundred have performance monitors. The operators use heuristics or rules of thumb to minimize power costs, to make demand forecasts and to maintain the water level of reservoirs, aquifers and rivers within reasonable ranges. In fact, Gistau (1993) considers the operation of the distribution system more of an art than a science. Heuristics are usually based on several economic, environmental and sociological variables. An example heuristic is:

> If the weather in the last three days is hot and dry, and the weather in the next three days is expected to be hot and dry, and the time before high demand is expected to be less than or equal to eight hours, then use a large pump and run it for a short time.

Documenting heuristics is one method of optimizing the distribution system. However, even the experts, who approximate daily water demand based on their experience, have a limited understanding of the prediction of water demand. This lack of knowledge in the prediction of water demand often results in inaccurate estimations and a gap in the expert systems knowledge base. An *et al.* (1996, 1997) therefore concluded that manual knowledge acquisition by itself is inadequate for handling all the situations that can arise in a complex engineering application.

During the last few decades, increased emphasis has been placed on the development of more standardized techniques to forecast short-term water demand and hence to optimize the distribution system. This review of approaches to forecasting short-term water demand concluded that most forecasts relied upon extrapolation, time-series regression or time-series analytical algorithms, often with an added element of subjective analysis.

2.8.1 Forecasting short-term water demand using extrapolation techniques

Some forecasts of short-term water demand are based upon extrapolation from the most recent 'equivalent' day (Coulbeck *et al.*, 1985; Coulbeck, 1993). The most recent 'equivalent' day is a day that displays similar characteristics to the day being forecast. For example, both days must occur on the same day of the week and experience similar weather conditions. These studies aim to provide a demand prediction program that could process telemetered data to remove detectable errors, predict for the next period ahead using a minimum of past data and allow for transient changes in demand influencing parameters (e.g. weather and holiday influences). Coulbeck *et al.* (1985) based forecasts of short-term water demand on these requirements and the results of other studies (namely DeMoyer and Horwitz, 1973; Fallside *et al.,* 1974; Moss, 1975; Perry, 1981) to indicate the essential components of a demand prediction process (Figure 2.7). When this process was applied to a set of real data, Coulbeck *et al.* (1985) considered that overall prediction accuracy is likely to be consistent with the presently envisaged needs of optimized control schemes. Although this method appears to provide adequate results, the process of error detection and rejection appears dubious. Significant fluctuations in water consumption occur (Thackray *et al.*, 1978; Russac *et al.*, 1991). Rejection of such fluctuations reduces confidence in the demand prediction process.

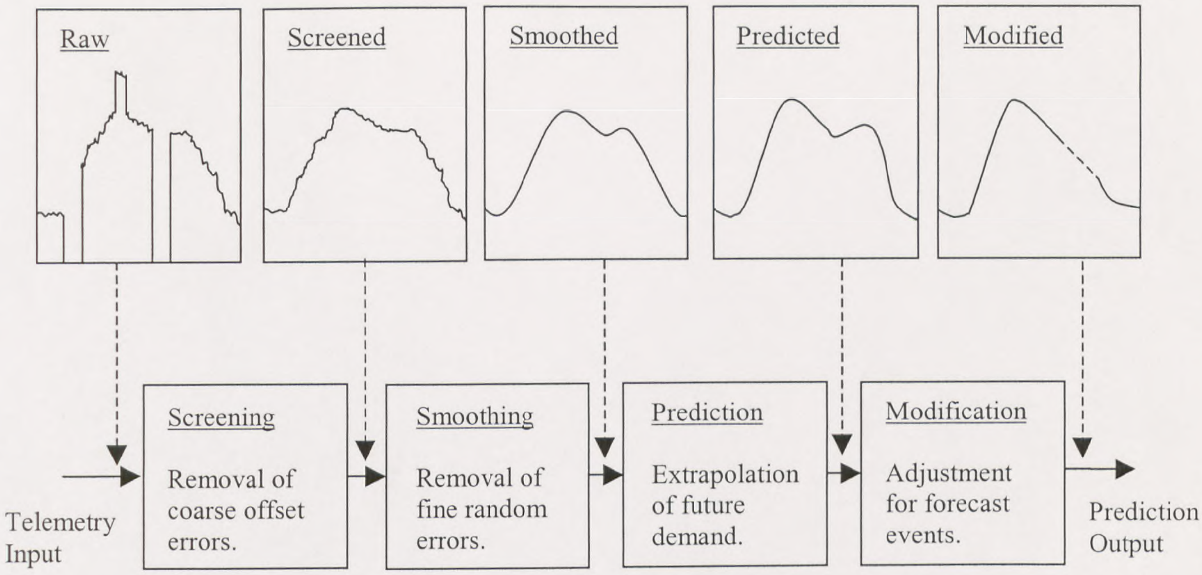


Figure 2.7: Block diagram of a demand predictor (Source: Coulbeck *et al.*, 1985)

2.8.2 Forecasting short-term water demand using time-series analytical techniques

Many studies have used time-series regression to forecast short-term water demands (Graeser, 1958; Howe and Linaweaver, 1967; Weeks and McMahon, 1973; Oh and Yamauchi, 1974; Anderson *et al.*, 1980; Hughes, 1980; Viswanathan, 1981; Steiner and Smith, 1983; Steiner, 1984; Carnell, 1986). Most of these studies have focused on municipal water demand in the United States and have used temperature, rainfall and/or the number of preceding dry days as explanatory variables. Some studies identified a threshold value above which daily maximum temperature or rainfall will affect water use (Graeser, 1958; Steiner, 1984). Others observed a lag effect, typically of one day, between maximum temperature, rainfall and water consumption (Graeser, 1958; Viswanathan, 1981). Other significant explanatory variables were also identified, including day of the week (Steiner and Smith, 1983), weekly pan evaporation (Weeks and McMahon, 1973) and soil moisture deficit (Carnell, 1986). However, in all cases, the percentage of explained variance was not very strong. Miaou (1990) also recognized four problems associated with the use of time-series regression analysis: (i) generally the length of time-series data is relatively short (ii) a large set of candidate explanatory variables need to be considered (iii) input variables can be highly correlated with each other (multi-collinearity problem) and (iv) model error series are often highly autocorrelated or even nonstationary. As a result, many potential input variables do not have the opportunity to be evaluated properly.

A number of forecasting algorithms have been developed to forecast short-term water demand on the basis of a purely mathematical view (Maidment and Parzen, 1984a,b; Maidment *et al.*, 1985; Sterling and Bargiela, 1985; Sastri, 1987; Chen, 1988; Smith, 1988; Jowitt and Xu, 1992). The mathematical algorithm used in many of these studies was based on an ARMA (Auto Regressive Moving Average) method developed from the original Box Jenkins model (Box and

Jenkins, 1976). The ARMA uses a time-series of past data and then fits the model to this time-series. Maidment *et al.* (1985) and Maidment and Parzen (1984a,b) also included linear regression analysis to identify trends in water use.

Many studies have observed a cyclic pattern in the time-series data. These cyclic patterns occur on a yearly (seasonal) and weekly cycle. Some of these analytical algorithms have been shown to be effective in modelling the regular cyclic variations observed in a typical water demand time-series. However if this cyclic pattern is disrupted by a sudden abnormal demand event, such as a bank-holiday, then a purely mathematical approach will fail to model accurately this deviation. Quevedo and Cembrano (1988) demonstrated that adequate predictions are initially made using a purely mathematical approach. However, as soon as a large deviation of demand from the predicted value occurred, the prediction accuracy deteriorated. A periodic seven-day pattern was observed in the prediction errors, which showed a non-decreasing sequence of errors in successive seven-day periods after an abnormally large prediction error (Quevedo and Cembrano, 1988). In a real water network, such deviations are not uncommon and hence optimization schemes that are based on a purely mathematical prediction are unlikely to result in a true optimization of the network operation (Hartley and Powell, 1991).

2.8.3 Forecasting short-term water demand using heuristic techniques

Rahman and Bhatnagar (1988) proposed a demand forecasting method that adopts a purely heuristic approach. The approach was demonstrated using daily power consumption as this is considered similar to forecasting daily water use. Both are utility services supplied to customers throughout a city, both exhibit seasonal trends and both are affected by weather conditions (Maidment *et al.*, 1985). Rahman and Bhatnagar (1988) subdivided total demand into a number of components identified as contributing to the whole i.e. base load, temperature related load etc. Values for each of these components were estimated for the prediction period and added together to give a total demand prediction. Such methods appeared to deal well with abnormal days as the additional component causing the abnormality could be incorporated easily in the final prediction. However, Hartley and Powell (1991) noted that in a water distribution network, the relative scarcity of metering points makes it extremely difficult to identify correctly the quantities of water used for particular domestic, commercial or industrial purposes. This suggests that neither a purely mathematical nor a purely heuristic approach to demand forecasting is appropriate in a water network application.

2.8.4 Forecasting short-term water demand using time-series analytical techniques with heuristic techniques

A number of studies have attempted to improve the accuracy of short-term water demand forecasts by combining a mathematical approach with a knowledge base of information relating to non-cyclic abnormal demand occurrences (Quevedo and Cembrano, 1988; Hartley and Powell, 1991; Saporta and Munoz, 1995). Again, ARMA models were the mathematical algorithms used in all of these studies. Intervention variables, which are supplementary information about the characteristics of the day in which the water demand is predicted, were also incorporated into the algorithm. These intervention variables provide the knowledge base of information relating to non-cyclic abnormal demand occurrences. Intervention variables included calendar related effects such as bank-holidays, public holidays and school holidays, weather related effects such as temperature, rainfall patterns and sunshine amounts, and network related effects such as re-zoning of an area or the introduction of water usage restrictions in an area. Results indicated that the methodology of combining a mathematical approach with a knowledge base of information provides significant improvements in prediction accuracy, even when the normal cyclic demand pattern is disrupted.

2.8.5 Forecasting short-term water demand using intelligent techniques

Intelligent techniques such as fuzzy logic, artificial neural networks, knowledge-based and case-based reasoning have also been used to forecast short-term water demand (Canu *et al.*, 1990; Cubero, 1991, 1992; An *et al.*, 1996, 1997; Iokibe *et al.*, 1997; Tuck, 1998; Lertpalangsunti *et al.*, 1999). The major advantage of using these techniques over mathematical modelling such as linear regression and the Box Jenkins method is that both quantitative and qualitative variables are considered in the automated learning process. In comparison, mathematical models focus on quantitative information alone. All the neural network studies found that when these models were provided with supplementary information about the characteristics of the day in which the water demand is predicted, the prediction performance of the models increased significantly. Supplementary information included indicators of public and bank-holidays (Cubero, 1991, 1992) and indicators of day of the week, maximum and minimum temperatures, average humidity, rainfall, snowfall and average wind speed (An *et al.*, 1996, 1997). Lertpalangsunti *et al.* (1999) found that when using similar variables to An *et al.* (1996, 1997) the neural networks over fitted the training data, increasing errors. However, when the data were separated into multiple data sets based on temperature and day of the week, prediction performances improved significantly while errors were reduced.

When prediction performances were compared with other techniques, Cubero (1991, 1992) found that the resulting error was the same order as that obtained by Quevedo and Cembrano

(1988) using the Box Jenkins approach. However, Cubero's (1991, 1992) approach appears more satisfactory as no prior filtering or statistical treatment of the data was required. Lertpalangsunti *et al.* (1999) also compared the prediction performance of the neural networks with case-based reasoning and linear regression. Neural networks provided significantly better predictions and fewer errors than the other two approaches.

Although advances in the forecasting of short-term water demand have been made, the applicability of these forecasts to the UK must be questioned. Many of these studies were undertaken in cities such as Barcelona, Spain (Cubero, 1991), the city of Regina, Canada (Lertpalangsunti *et al.*, 1999) and moderate sized cities in North America (An *et al.*, 1996, 1997). Environmental, cultural and technological differences will therefore exist between these cities and those in the UK. There was also a paucity of literature concerning forecasts of different components of water demand in the short-term. To optimize the distribution system, short-term forecasts of the different components of demand are essential.

2.9 Domestic water demand studies in the UK

Over the past few decades, pressure on water authorities to gain an understanding of household water use (Turton and Smith, 1976) resulted in a series of domestic water use studies. Figure 2.8 shows the growth in interest in the subject over the years. A number of the current domestic consumption monitoring studies have been in place since the mid 1970s and can reveal valuable time-series information. These studies were primarily designed to establish unmeasured per capita domestic water consumption. Momentum for these studies was generated by a series of public enquiries concerning the development of major new resources and licenses for abstractions, notably for Roadford, Broad Oak and Teddington Weir (Turton, 1995). In such enquiries the companies had to demonstrate publicly that they had researched current and future trends in water use. Water companies in areas with potential water resource shortages therefore tended to put most effort into domestic water consumption studies. There were no major reservoir enquiries in the mid to late 1980s and approaching privatization reduced the impetus for new experimentation or the extension of existing studies.

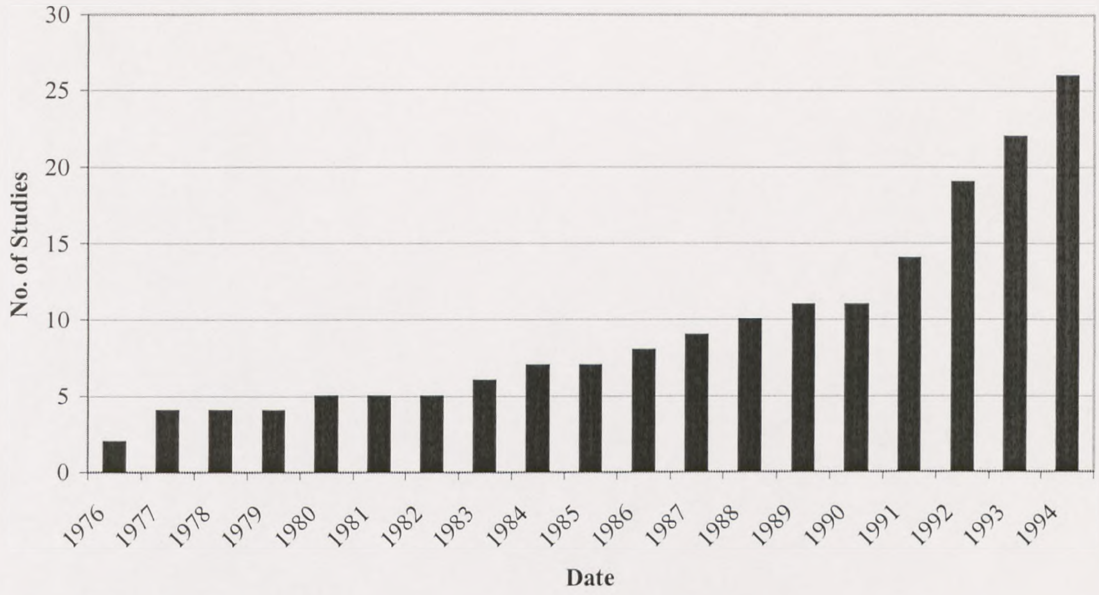


Figure 2.8: Number of studies 'up and running' 1975 to 1994 (Source: Turton, 1995)

Following the establishment of the National Metering Trials, the momentum for domestic consumption monitoring increased again. Some of the earlier established studies have been rejuvenated and upgraded while several studies have begun since 1991. Today, most of the water companies in England and Wales together with the Scottish Office and Department of the Environment (Northern Ireland) have conducted, are conducting or are planning their own individual domestic consumption studies. The scale, design and purpose of these studies vary significantly from company to company.

2.10 Naming conventions, boundaries and zones

In the UK water industry, two main approaches are used in current and proposed studies of domestic water use. The first main approach is zonal metering, where the flow of water to a group of households is measured (Figure 2.9). These groups of households are typically in a cul-de-sac, a small water supply area or a district meter area. The number of households included in these studies therefore varies from company to company, depending on the chosen location of the zonal meter. In general, cul-de-sacs include about thirty households, small water supply areas include less than one hundred households, and district meter areas can include up to two thousand households.

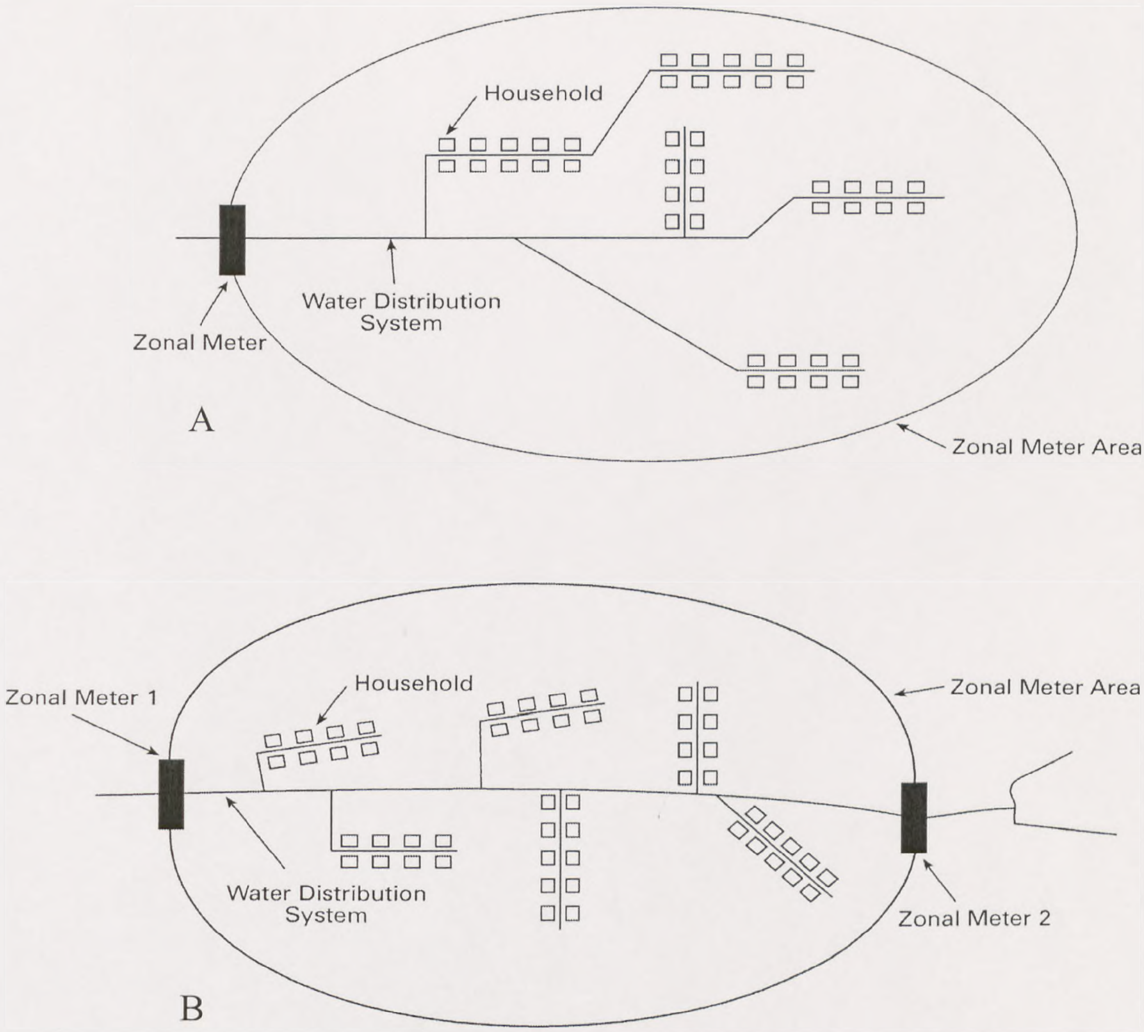


Figure 2.9: Schematic diagram of two zonal meter areas: (A) is an end of pipe or discrete zonal meter area; (B) is a subsection of an urban agglomeration differentiated into a zonal meter area by valving.

Bournemouth and West Hampshire Water, Hartlepool Water, Welsh Water, York Water Works company and Mid Kent Water have all adopted zonal metering as their approach to monitoring domestic water consumption. Mid Kent Water monitors domestic water consumption using cul-de-sac type areas, Welsh Water and York Water Works Company use district meter areas, and the remaining companies monitor water consumption for small water supply areas. The group of households selected in the zonal metering studies aim to represent water consumption for each of the water company areas. Selection procedures for these areas vary from company to company. Bournemouth and West Hampshire Water, for example, selected randomly twenty enumeration districts that aimed to represent the ACORN type profile for the Bournemouth and West Hampshire area (MacFarlane, 1998, pers. comm.). The distribution systems within the twenty enumeration districts were studied using geographical information systems to identify discrete areas of approximately fifty households that could be metered easily. As these discrete areas did not cross the enumeration district boundaries, the households were assumed to have similar characteristics according to ACORN type. In comparison, Hartlepool Water concluded that the zonal meter areas should represent one of the principal types of housing stock within

Hartlepool. Five principal housing stock types were identified using local knowledge (Table 2.1).

Table 2.1: The five principal housing stock types in Hartlepool (Source: Norman, 1998, pers. comm.)

Type	*Description*	*Site Name*
1	Terraced housing with back yards	Hurworth Street
2	Smaller properties including flats, starter homes and sheltered accommodation	Bakers Mead
3	Pre 1950 semi-detached and larger terraced properties with gardens	Southbrooke Avenue
4	Modern housing development, post 1950, usually on developer built estates	Springston Road
5	Executive housing	Millston Close

The second main approach used to study domestic water consumption is through individual household metering. Individual meters can be placed at the boundary of the property where the communication pipe from the distribution main enters the property boundary and becomes the supply pipe of the customer, or they can be installed inside the property at the stop tap position. Yorkshire Water, Thames Water, Essex and Suffolk Water, Anglian Water, South West Water and Portsmouth Water have adopted an individual household metering approach. The number of individual households included in these studies is typically between one and two thousand. As in the zonal metering studies, the individual household studies aim to represent the company area as a whole. Most of the other water companies, including Yorkshire Water, Thames Water and Anglian Water, selected individual households that were representative of ACORN types in the company area. However, Portsmouth Water selected individual households on the basis of a representative sample by property type (e.g. detached, semi-detached, terraced) (Hedges, 1998, pers. comm.). Within both the individual household and zonal metering studies, the frequency of monitoring domestic water consumption is typically at fifteen-minute intervals. The exception is Hartlepool Water, where consumption is monitored weekly, and Essex and Suffolk Water, where consumption is monitored at three-month intervals.

2.11 Summary

This chapter has provided the appropriate definitions and time horizons for this research, reviewed and synthesized approaches used to make current estimates of domestic water demands, and outlined the approaches used to predict short-term water demands. This chapter has highlighted the paucity of domestic water demand literature from the UK. The majority of research making current estimates of domestic water demand and predicting short-term water demands has been undertaken outside the UK. However, these findings cannot be applied to the UK. Domestic water demands in the UK are unique because of: (i) the absence of the price variable and (ii) the seasonality factor in the UK climate. Furthermore, forecasts of short-term water demands focused on aggregates of demand rather than individual components of demand. Chapter 3 outlines the data sources that were available for this research from the current domestic water use studies undertaken in the UK water industry. A critique of these studies is provided together with a statement/commentary on the mode of analysis to be used as the basis of forecasting short-term domestic water demands.

3. Data Sources, Data Validation and Analytical Methodology

3.1 Introduction

The way in which domestic water demand fluctuates depends on the aggregate of the water using behaviour of the individuals in the population. Ideally, a domestic water consumption study would cover a range of people, houses, climatic conditions etc., to capture such behaviour. Within the UK water industry there is a relatively short history of domestic water consumption studies, and only since 1999 has there been a protocol to manage such studies.

Each year OFWAT requires water companies to estimate unmetered domestic water demand. The methods employed vary from company to company as all water companies in the UK are under different ownership. Different time periods and structures are used in the estimations. As many water companies are still in the process of developing and refining their domestic water use studies, and due to the perceived commercial sensitivity of the data, it was impossible to obtain domestic water consumption data across the whole of the UK.

This chapter:

(i) Describes and evaluates the methods of monitoring domestic water consumption,

(ii) Outlines the data that were available for this research,

(iii) Explains the analytical methodology for determining underlying factors influencing domestic water demands in both the short- and the medium- to long-term.

3.2 Methods of monitoring domestic water consumption

Determination of domestic water consumption requires one basic item - the ability to measure the volume of water entering or consumed within a property. As outlined in section 2.5, three approaches can be adopted to measure the volume of water entering or consumed within a property:

(i) Zonal metering - the flow of water to a group of properties is metered.

(ii) Household metering - the volume of water entering a property is measured by individually metering the flow to that property.

(iii) Component metering - the water use of individual appliances within a property are metered.

3.3 Assessment of component, household and zonal metering

Several advantages and disadvantages are associated with each metering technique. The major advantage of individual household and component metering relates to the direct measurement of water consumption (with internal meters). This means that unlike zonal meters, leakage in the distribution system and communication pipe work does not affect the measured water consumption; however, supply pipe leakage remains a factor. Zonal metering relies upon accurate determinations of leakage, usually by taking the minimum night flow and distributing it throughout the day as a leakage rate per hour. The minimum night flow is the flow taken at night and a figure is derived by averaging the low flow values from 2.00am to 4.00am, although the precise period varies between different companies. From this figure the measured consumption of industrial usage at this time is subtracted. It is recognized that some legitimate use of water may be taking place at night and is largely arbitrary but an industry agreed figure of 1.75 litres per household is also subtracted from the flow. The final figure is leakage volume, which is divided by the number of households in the measured area to yield a figure for leakage per household. Clearly this calculation requires accurate information about the number of households and the metered consumption in the area.

When using individual household or component metering, it is probable that the true figure for household water consumption is obtained for the households sampled. However, the value of the data depends very much on the extent to which the sample is representative of the population as a whole. Several forms of bias may have affected these consumption rates which influence the value for the true population. These include:

(i) Selection of households and self-selection.

(ii) The Hawthorne Effect.

(iii) Financial advantage bias.

(iv) Sample decay and monitor maintenance.

These are discussed in the sections that follow.

3.3.1 Selection of households and self-selection

The greatest potential source of bias in any water use study may be introduced if the sample households are not representative of the wider population. Component or individual household studies demonstrate the greatest risk of being unrepresentative of the wider population. However, no work exists which evaluates whether an area or zonal meter is representative. Per capita consumption can range enormously for properties in the same area or street (Russac *et al.*, 1991). This makes it extremely difficult to select typical households for individual and component studies that are representative of the wider population. It is estimated, for example, that probably less than 10% of households regularly use a hose-pipe or a garden sprinkler. A very large number of households would therefore be required to participate in the study to ensure that the sample was representative with respect to hose-pipe and sprinkler use. If a classification such as ACORN is being used to profile water use, it is possible that an individual household will not be typical of the ACORN class for the enumeration district in which it is situated. Water companies use different measures to stratify their samples – property type, ownership type, head of household's occupation etc (see section 2.10 for details). The same concern, the representation of the sample in relation to the population, exists for all measures. However, this form of bias is not the only one that water plc's face when selecting households to participate in their study.

Further bias may also be introduced as installation of individual household and component monitors requires the agreement of the householder. Therefore, a degree of 'self-selection' is inevitable; for example, customers who use excessive amounts of water (or who ignore restrictions) will be unlikely to agree to take part in such a study. This will tend to bias the sample in favour of low water users. Also, there is a strong possibility that customers agreeing to participate in the study will be in the same socio-economic grouping, probably well educated middle-class citizens who realize the objectives of such studies. Self-selection may therefore result in a disproportionate cross-section of the population included in the domestic consumption study who are low water users. In comparison, zonal metering produces more accurate and representative estimates of the population (i) because they do not require the agreement of the householder and (ii) as a group of households are monitored, the individualistic behaviour of single households is smoothed out.

3.3.2 The Hawthorne Effect

Bias may arise because occupants are aware that they are being monitored. Demand may be suppressed resulting in the underestimation of overall per capita consumption. Even if meter installation has no impact on the householder's water bill, the presence of a meter may encourage householders to deal more quickly with dripping taps for example. Also, householders are more likely to comply with regulations set by the water company such as hose-pipe bans. This is known as 'the Hawthorne Effect'. The Hawthorne Effect is named after a study performed in the 1930's in Hawthorne, Illinois in which it was discovered that the act of merely studying individual behaviour could impact upon that behaviour (Greinder *et al.*, 1998; DeAmici *et al.*, 2000; Wickstrom and Bendix, 2000). Thackray *et al.* (1978) suggested that this effect is temporary; however, during meter readings, customers are reminded that they are being monitored, particularly when using internal household meters which require the permission of the householder to be read. This effect may be exacerbated further during component studies where the occupants record their own water use and hence, are reminded constantly that they are being monitored. In a zonal meter however, customers will probably be unaware that their water consumption is being monitored and, therefore, there can be no question of the presence of a meter directly influencing the results. Even if householders are aware that their property is included in a consumption study, metering on a group rather than an individual basis will be less likely to suppress demand.

3.3.3 Financial advantage bias

A specialized form of 'self-selection' is where there is a preferential uptake of domestic consumption monitor 'opportunity' because of perceived financial advantage. Financial advantage bias is inevitably also the prime reason for customers leaving domestic water use studies. Some customers realize that it is more financially viable to opt for a meter, rather than paying for water according to the rateable value of properties. Often these customers only agree to participate in water use studies for confirmation that they are low water users. They perhaps also wish to adopt the preferential meter installation rates frequently available through water use studies. In turn, there may be a disproportionate number of high water users remaining. Some water plc's have attempted to solve this problem by offering financial incentives to householders (e.g. Essex and Suffolk Water) in the form of funds which could otherwise be spent on recruiting more households to participate in such studies.

3.3.4 Sample decay and monitor maintenance

The perception among domestic consumption monitor administrators is that it is becoming increasingly difficult to recruit new volunteers for household studies (Iveson, 1999, pers. comm.; Ridgewell, 1999, pers. comm.). As already identified in section 3.3.3, the prime reason for leaving such a study is due to the financial viability of opting for a metered tariff. However, there will be further losses from the study due to factors such as death or relocation. With reference to relocation, the average residence time in a property in the UK is approximately ten years; therefore, it is possible that more than 10% of some domestic consumption monitor studies will change each year based solely on relocation. Average residence time is based on the gross migra-production rate (GMR) calculated using the 1981 census of population, which states that over a lifetime, a person in the UK moves 6.5 times. If the average life expectancy of seventy years is used, the average time in one place is 10.77 years (Stillwell, 2000, pers. comm.). Typically the characteristics of the individual households which make up the domestic consumption studies were surveyed only once, at the start of the monitoring programme. Thus factors such as family growth, deaths, unemployment or new employment, divorce etc., will all reduce the validity of the original data. In recognition of these problems, several companies have introduced household re-surveys into their domestic consumption monitoring programme. However, this complicates the handling of the domestic water consumption data.

Regular maintenance of water meters is essential to the success of any domestic consumption study whether it be a zonal study, an individual household study, or a component study. Without regular maintenance, the potential for errors in the water consumption data will undoubtedly increase.

3.4 Frequency of monitoring water consumption

If domestic water consumption data were to be used to forecast water demand in the medium- or long-term, monthly or quarterly meter readings would be sufficient as seasonal variations etc., would be smoothed out. However, if the domestic water consumption data were used to analyse or predict water consumption in the short-term, this frequency of monitoring would not be adequate. For example, it would be impossible to say accurately what would happen to water consumption if there was a heat wave induced surge in demand lasting only a few days or weeks. In many companies the domestic consumption monitoring data are logged every fifteen minutes. Thus for a domestic consumption monitor with 1,000 households, there are approximately 100,000 items of consumption data daily or approximately 35,000,000 items annually. For the researcher therefore, the aggregation, or more specifically the degree of aggregation, of the data is a compromise between constraints of analysing large data sets and the frequency needed to resolve a particular question.

3.5 Summary of component, household and zonal metering

Each approach used to determine domestic water consumption has several advantages and disadvantages. For a given expenditure, an individual component study provides a significantly smaller sample than a household study, which provides a far smaller sample than a zonal study. Far fewer zonal meters are therefore required, resulting in reduced set up and meter reading costs. If the household and zonal metering studies have been established and maintained correctly, it can be assumed that these studies provide a better estimation of domestic water consumption compared to component studies. Data from component studies in the UK are sparse. Where data has been collected, only a relatively small number of households are included. This makes it virtually impossible to determine whether these households are representative of the wider population. Much of the component study data in the UK are for short periods (typically less than three months). The data will therefore fail to cover different climatic conditions. This time period could also increase the susceptibility of the data to the Hawthorne Effect. The Hawthorne Effect may be exacerbated further when householders record their own water use and hence, are aware that they are being monitored constantly. As many component studies also rely on householders to record their correct frequencies of use, potential errors in the data may increase if frequencies of use are not documented accurately. Due to these problems and because no component metering data were available from any water plc's, it appeared justifiable not to pursue component metering data. However, it is extremely difficult to determine whether zonal or household metering provides the best estimation of domestic water consumption. It was therefore decided to use data from both of these sources.

3.6 Data sources

It was impossible to obtain domestic water consumption data across the whole of the UK: (i) due to the perceived commercial sensitivity of water consumption data and (ii) because many water companies are still in the process of designing and developing their water use studies. Irrespective of these problems, data collection was extremely successful. Zonal metering data were obtained from Welsh Water and Yorkshire Water's small water supply areas, while individual household metering data were obtained from Essex and Suffolk Water, Thames Water and Yorkshire Water. As the water companies believe that households included in their zonal meter and individual household studies are representative of the company area as a whole (the exception is Yorkshire Water's small water supply areas which were never developed to be representative), it can be assumed that the water consumption data in this research represents approximately twenty million people, therefore managing to capture over one-third of the population of England and Wales.

Water consumption data from these sources represent a good cross-section of the population, both spatially (Figure 3.1) and socio-economically. The data sources range from highly concentrated urban areas in the Thames Water study, to highly rural areas in the Welsh Water study; from very affluent areas in the South East of England, to poor rundown communities in the coal field areas of Yorkshire. In addition to a good cross-section of the wider population, the data sources had the following advantages:

(i) The water plc's had a well-established and suitable method of monitoring domestic water consumption.

(ii) Each of the studies had been ongoing for at least eighteen months.

(iii) All data except those from Essex and Suffolk Water were daily data, vital for any analysis of water demand in the short-term. However, the Essex and Suffolk Water data were not discounted as they could be used in the determination of underlying factors influencing domestic water consumption in the medium- to long-term.

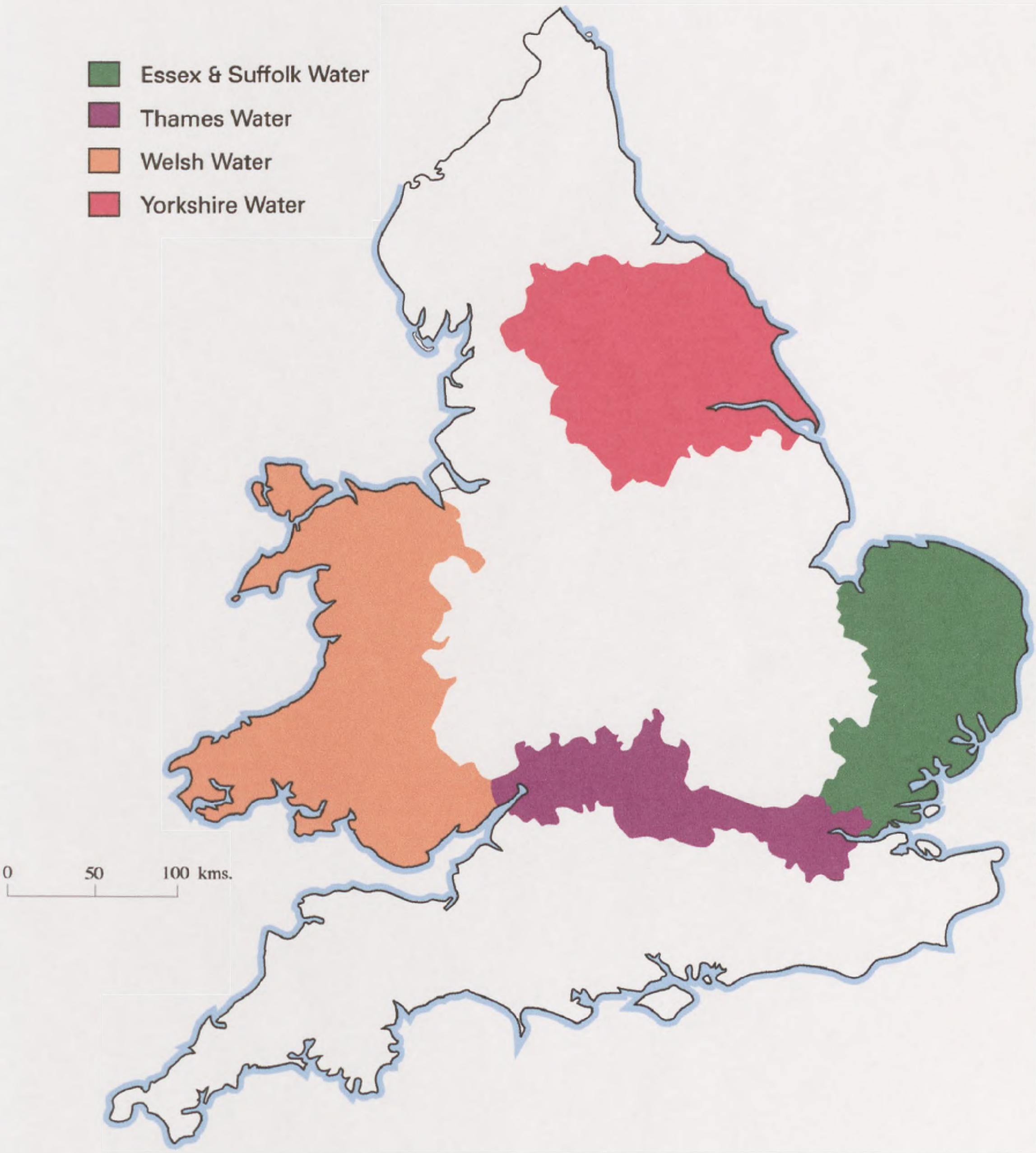


Figure 3.1: Location of the data sources

3.7 *Zonal metering*

3.7.1 *Estimating domestic water consumption in Wales*

In their study of domestic water consumption, Welsh Water opted for zonal metering using thirty-six district meter areas (Figure 3.2 and Appendix 3A).

In each of the district meter areas, Welsh Water adopted a three-step process to estimate domestic water consumption:

(i) Leakage in each of the district meter areas was estimated.

(ii) Water use, other than that of households paying on an unmetered tariff, were metered or estimated.

(iii) Leakage and non-household water use were subtracted from the gross demand.

3.7.1.1 *Welsh Water's determination of leakage*

Welsh Water used the minimum night flow to estimate leakage. The minimum night flows are distributed throughout the day as a leakage rate per hour (Morrison, 1998, pers. comm.). For the small district meter areas (50 to 300 properties), leakage estimates are based on the minimum night-line with no allowance for customer night use. In the larger district meter areas (300 plus properties), customer night use is accounted for and the resulting leakage is split between burst and background losses. There is no obvious logic to the different treatment of legitimate night use. These procedures have the effect of depressing 'demand'.

3.7.1.2 *Welsh Water's determination of non-household water consumption*

Water consumption for non-household properties was either measured or estimated by Welsh Water. No indication was given of the basis on which this estimation was established.

Both leakage and non-household water consumption were subtracted from the flow data in each of the district meter areas, providing an estimate of daily domestic water consumption. These daily data were provided by Welsh Water for thirty-six district meter areas from September 1997 to March 1999 (see Appendix 3B for details). The weak specification of the data processing reduces the confidence in the absolute value of demand although relative values will be more secure.

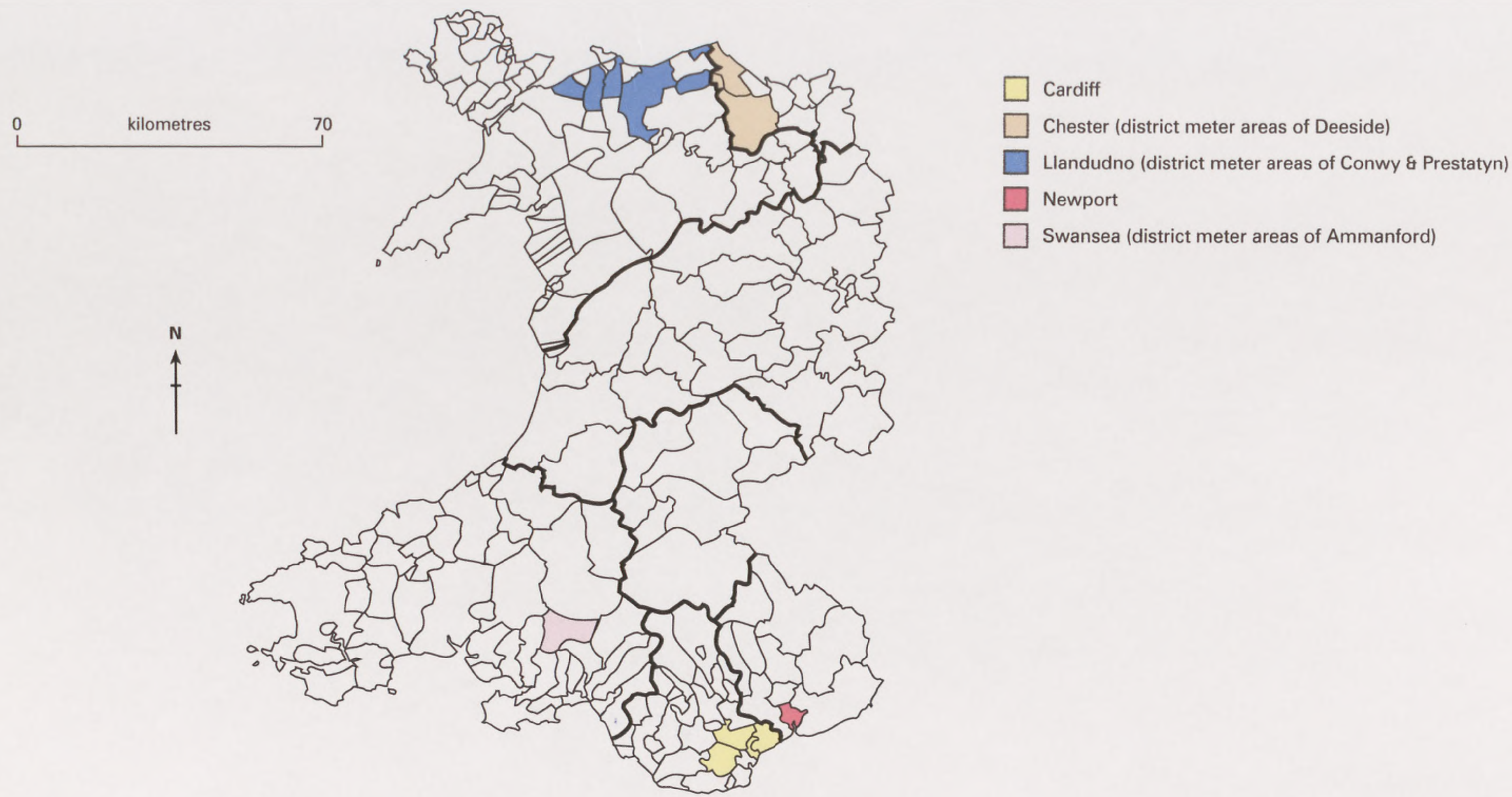


Figure 3.2: The postal districts where Welsh Water's district meter areas are located

3.7.2 Estimating domestic water consumption in Yorkshire Water's small water supply areas

Yorkshire Water provided the average flow of water (m^3/day) and the minimum average flow of water (litres/second) through the zonal meter from the 1st of July 1995 to the 30th of June 1998 for Kettlewell, from the 1st of July 1995 to the 16th of July 1998 for Starbotton and Buckden, from the 1st of July 1995 to the 31st of July 1998 for Conistone, and from the 1st of December 1996 to the 30th of June 1998 for Malham (Figure 3.3).

To calculate the correct levels of domestic water consumption in these areas several procedures were undertaken (Figure 3.4). Firstly, the minimum average flow of water was converted from litres per second to litres per hour. Legitimate water use per hour in each area was then calculated by multiplying the number of households in each small water supply area by 1.75 litres (which is the figure used by Yorkshire Water). Legitimate water use was then subtracted from the minimum average flow of water to give leakage in the area. Leakage (converted to m^3/day) was subtracted from the average flow of water, giving the actual domestic water consumption for each area (see Appendix 3C for details). The ability to specify the nature of the processing of the raw data gives much increased confidence in the data. Nevertheless there remains several generic problems associated with such data sources (see section 3.3 for details).

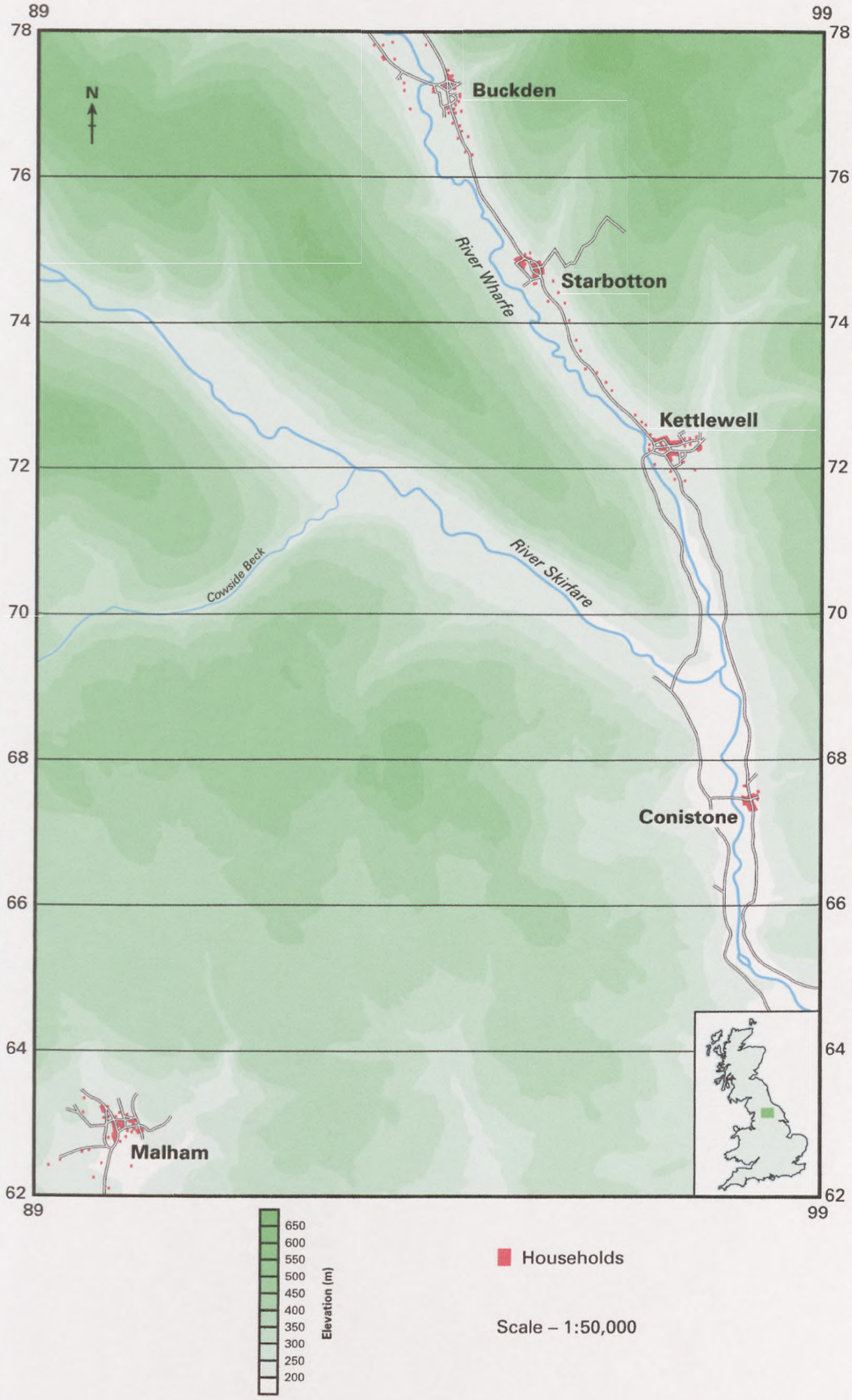


Figure 3.3: The location of Yorkshire Water's small water supply areas

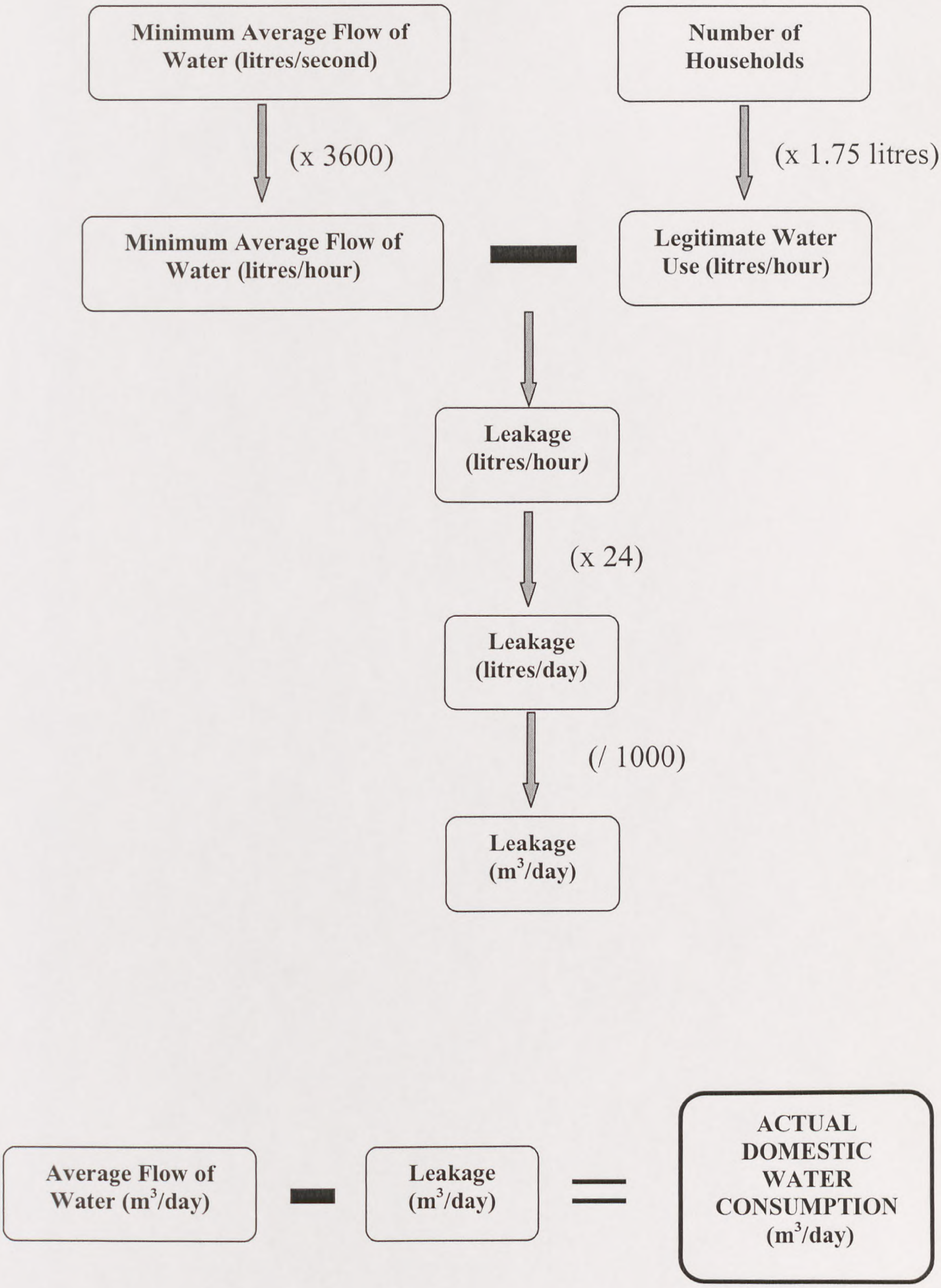


Figure 3.4: The procedure used to calculate domestic water consumption in each small water supply area

3.8 Individual household metering

3.8.1 Estimating domestic water consumption in Yorkshire

In April 1996, Yorkshire Water commissioned a programme to estimate unmetered domestic water consumption, monitoring 1,581 households throughout Yorkshire and Humberside including Bradford, Doncaster, Halifax, Huddersfield, Hull, Leeds, Sheffield, Wakefield and York (Figure 3.5). All participants in the study were selected at random. For those households wishing to partake in the study, a meter and logger, monitoring water consumption at fifteen-minute intervals, were installed inside the property at the stop tap position. Yorkshire Water provided daily average water consumption data (litres/day) for each of the 1,581 households from April 1996 to August 1999 (see Appendix 3D for details).

3.8.2 Estimating domestic water consumption in and around the London area

Thames Water established an individual household water consumption study in 1994. A total of 1,984 randomly selected households are included in the study. These households are located throughout central and greater London as well as other districts outside London including Oxfordshire, Gloucestershire, Swindon and Reading (Figure 3.6). Meters, monitoring water consumption at fifteen-minute intervals, were installed inside the property at the stop tap position. Thames Water provided daily average water consumption data (litres/day) for each of the 1,984 households from April 1994 to September 1999 (see Appendix 3E for details).

3.8.3 Estimating domestic water consumption in Essex, Suffolk and Norfolk

Essex and Suffolk Water began to monitor the aggregate domestic water consumption on a quarterly basis (every three months) from March 1994. The number of properties monitored has increased steadily so that now 1,760 households participate in the domestic consumption study, of which 1,109 are from Essex, 167 from Norfolk, 19 from Outer London, and 465 from Suffolk (Figure 3.7). The households selected all had existing meter chambers (to reduce expenditure) and a single supply pipe. Once selected, the households were sent a letter, a leaflet and a questionnaire, requesting their assistance. If the householder complied, a meter was fitted within the existing meter chamber. This means that all meters are installed externally at the property boundary. When the meter was fitted, and at subsequent meter readings, the supply was checked for leakage. If a leak is suspected, a logger is fitted to the meter to measure the volume of water lost. Essex and Suffolk Water provided a spreadsheet containing each household's aggregate quarterly consumption figure divided by the number of days monitored to give the daily average consumption figure for each household in litres per property per day from March 1994 to March 1998 (see Appendix 3F for details).

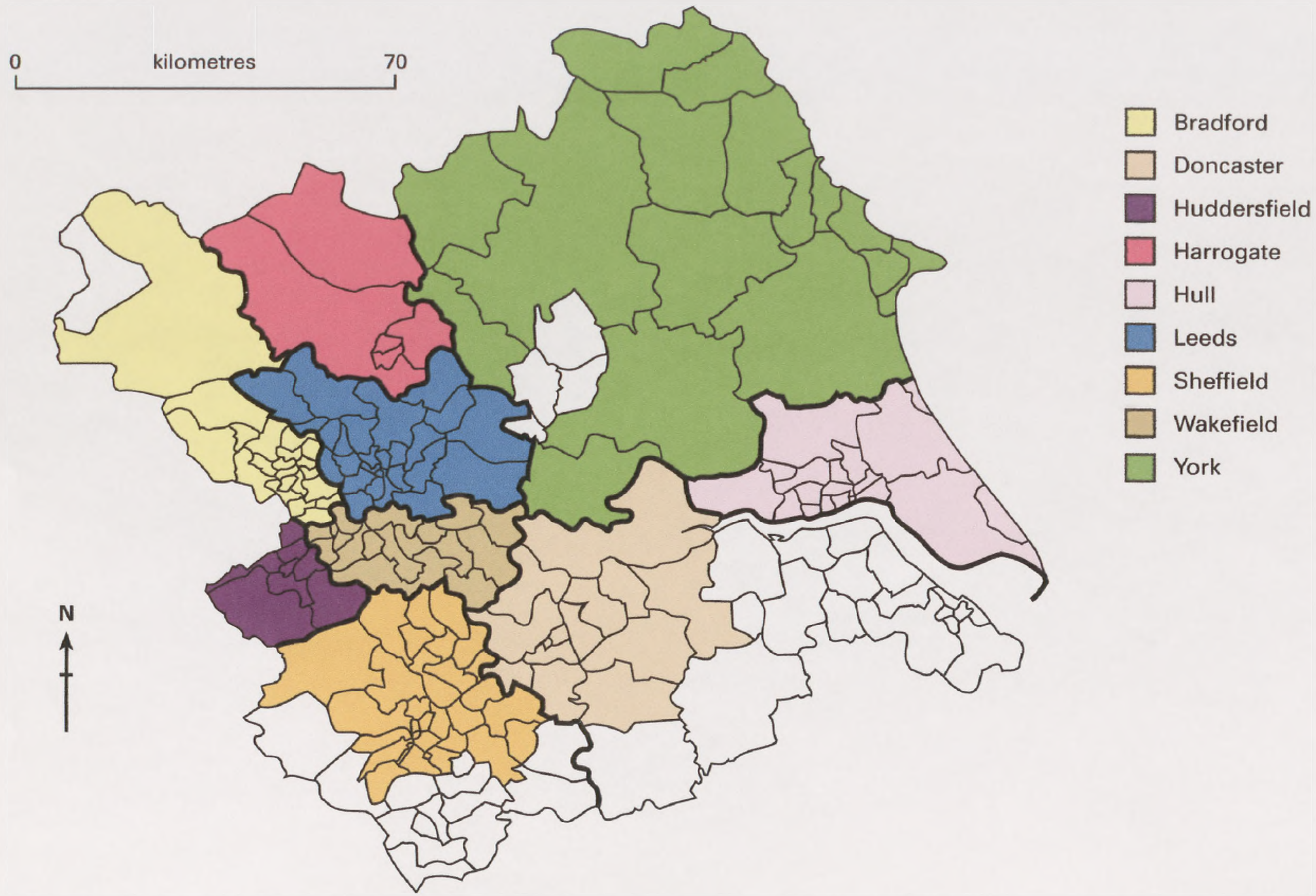


Figure 3.4: The postal districts where households in the Yorkshire Water consumption programme are located

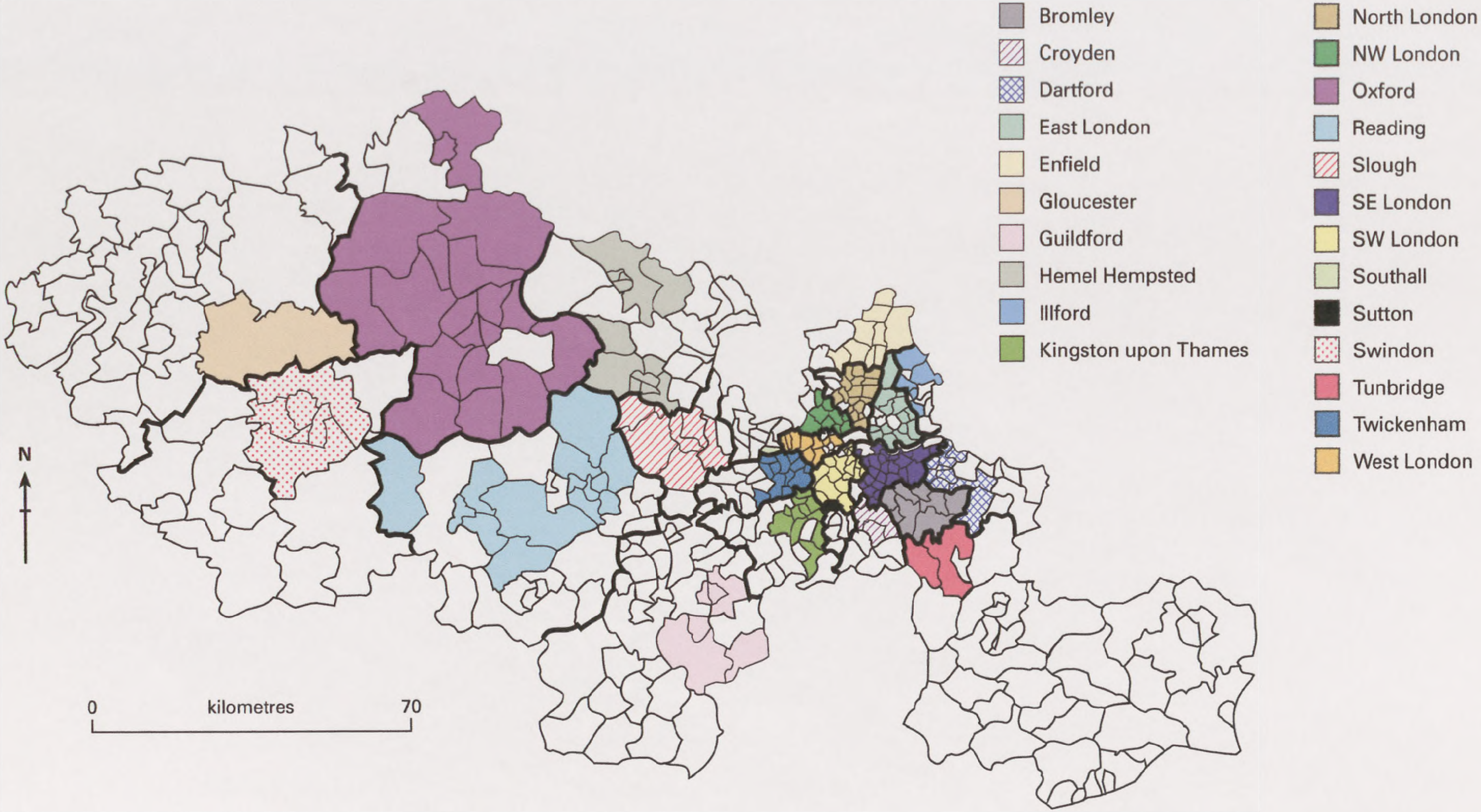


Figure 3.5: The postal districts where households in the Thames Water consumption programme are located

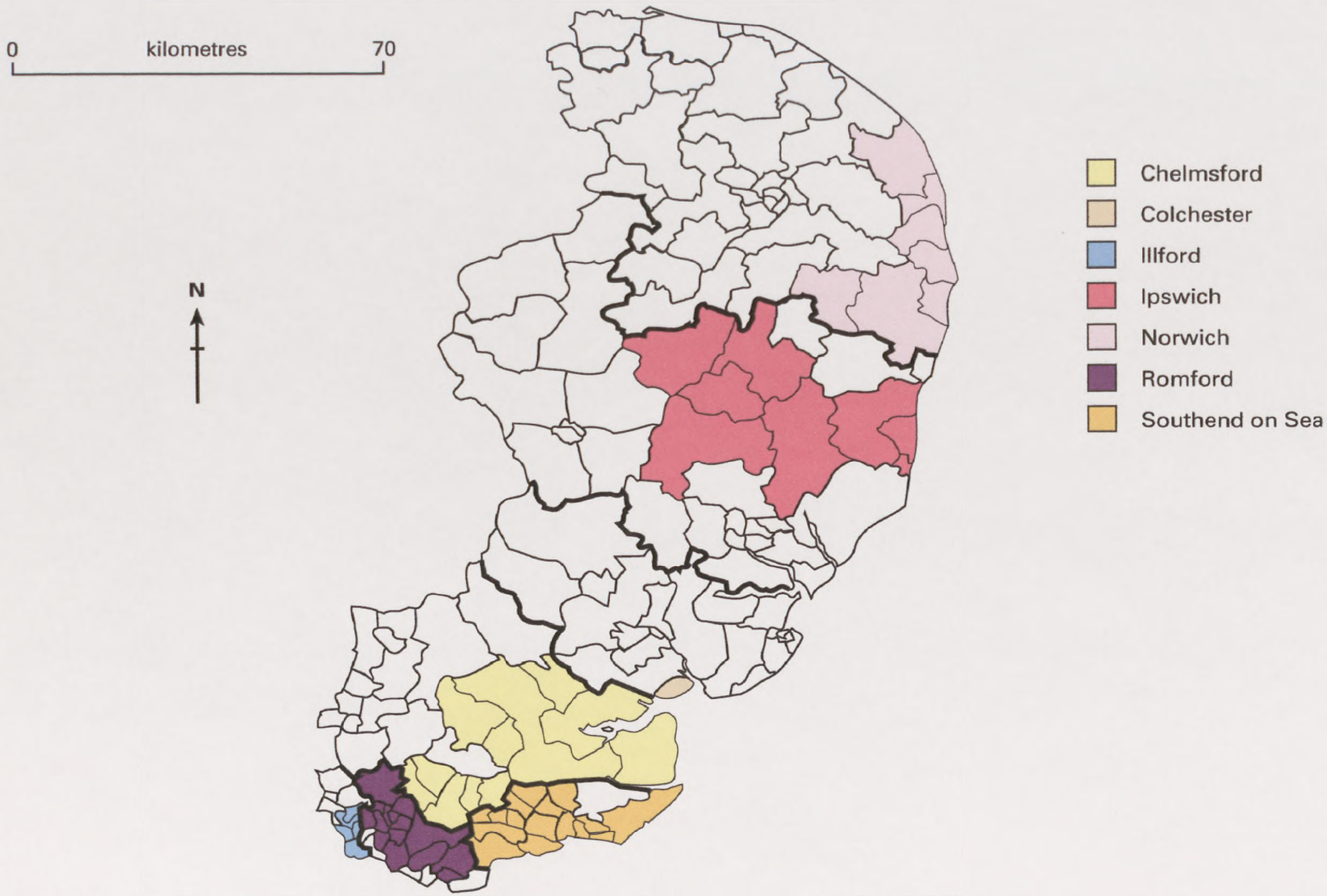


Figure 3.6: The postal districts where households in the Essex and Suffolk Water consumption programme are located

3.9 Estimating average daily domestic water consumption in the individual household studies

In the individual household studies, only water consumption data from the Thames Water and Yorkshire Water studies were used to calculate the 'true' daily average. Data from the Essex and Suffolk Water study were omitted due to the low frequency of meter readings. Average daily domestic water consumption in the Thames Water and Yorkshire Water studies was calculated by averaging individual household water consumption for each day over the study period.

3.10 Data cleaning

Domestic water consumption data in both the zonal meter studies and the individual household studies were plotted as a time-series. This allowed the detection of anomalous consumption values. Anomalous values can be introduced into the data by meter or logger failure or leakage. Such suspect values were removed from the analysis and the daily averages were recalculated (see section 3.8 for details). Obvious leakage events were also removed from the analysis. Although it is virtually impossible to determine which anomalous values are caused by leakage, it was highly likely that significant, large increases in water consumption during the winter months were caused by leakage as minimum temperatures fall below zero degrees and inevitably cause pipes to burst. It is recognized that leakage must be accounted for when supplying water from the service reservoir or treatment works to meet demands. However, in this research, the removal of leakage events was justified to permit a more accurate picture of how household characteristics influence water usage.

In the individual household studies, empty properties were also removed. These properties were identified where zero consumption values existed for more than three consecutive months. In the zonal meter studies, empty properties were included in the data as it was impossible to identify how many properties were empty and what their typical consumption values would be at any one time. This introduces a degree of error in the zonal metering data. Some water consumption data for individual households in both the Thames Water and Yorkshire Water studies appeared suspiciously low. A typical example is a property in Yorkshire whose water consumption fluctuates between 0.4 and 10 litres/day for much of the study period. Such low consumption values are extremely dubious, particularly when it takes approximately 10 litres to flush a toilet (Hamer, 1992 in Haughton and Hunter, 1994). Several reasons may account for some excessively low water consumption values in the Thames Water and Yorkshire Water studies:

(i) Meter or logger failure - some of the water consumption data in Yorkshire appeared to be out by at least a factor of 10. A critical review of the data held by Yorkshire Water and forming the basis of the domestic consumption monitor identified possible errors in the data. When checked, the majority was due to incorrect 'scale' settings on the loggers. Based on this review (McDonald, 1995), national guidelines for checking values in new domestic consumption monitors were established but these were never applied retrospectively and significant amounts of poor quality data remain.

(ii) Questionnaire error – as noted in section 3.3.4, the average residence time in a property in the UK is approximately ten years; therefore, it is possible that more than 10% of some domestic consumption studies will change each year based solely on relocation. There will also be several births and deaths within the studies. However, since the Thames Water and Yorkshire Water studies were commissioned in 1994 and 1996 respectively, only one questionnaire has been undertaken. As a result, the questionnaire data are substantially out of date. Such errors in the questionnaire data may generate under or overestimations of per capita domestic water consumption.

(iii) Householders on holiday.

Excessively low consumption values were removed from this analysis. Even if some of these values result from householders on holiday, their removal is justified as this research is focused on the behavioural response of water use and not the holiday response. To aid identification of anomalously low consumption values, the water consumption data were subdivided into the number of residents per household. The number of residents per household was obtained from the individual household questionnaires commissioned by Thames Water and Yorkshire Water when the monitoring programmes began (see section 3.10.1 for details).

As Table 3.1 suggests, it would be extremely atypical for a person to sustain a water use of less than 50 litres/day.

Table 3.1: Typical water usage for household appliances (Source: Hamer, 1992 in Haughton and Hunter, 1994)

Component of Water Use	*Water Use (litres)*
Toilet Flushing	10 litres
Shower	30 litres
Washing Machine	100 litres/cycle
Dishwasher	50 litres/cycle
Bath	80 litres

As a result, a threshold of 50 litres/person/day was set to filter out excessively low consumption values. For example, if a household contains two residents and has a water consumption of less than 100 litres/property/day, the water consumption value was removed from the analysis.

3.11 Protocol for determining socio-economic attributes of households in the zonal and individual metering studies

Socio-economic attributes of the households in the studies were required: (i) to determine their influence on domestic water consumption and (ii) to validate whether the consumption studies are representative of the wider population. The method of determining socio-economic characteristics differed for the individual household and zonal metering studies.

3.11.1 Socio-economic attributes of households in the individual metering studies

When Essex and Suffolk Water, Thames Water and Yorkshire Water commissioned their individual household water use studies, questionnaires were issued to all participating households (see Appendix 3G, 3H and 3I for details). The contents of the questionnaires were similar in that all requested information about the property, householders and appliances. However, much of the detail between the questionnaires differed as different categorizations were used. Essex and Suffolk Water and Thames Water, for example, categorized properties as detached, semi-detached and terraced properties and flats whereas Yorkshire Water further subdivided these categories into houses and bungalows. Garden size is another example in the questionnaire where different categorizations were used. Essex and Suffolk Water categorized garden size on a qualitative scale from one to four (small, medium, large and extra large) with no quantitative measures of what constitutes a small, medium, large or extra large garden. A more quantitative approach, based on measurements, was used by Thames Water to categorize garden size. As different categorizations were used throughout the questionnaires, the data could not be integrated for analysis and the information revealed has to be thoughtfully interpreted.

3.11.2 Socio-economic attributes of households in the zonal metering studies

In the zonal metering studies, no questionnaires were issued to the participating households. Information about the properties and householders included in the zonal metering studies was therefore inferred using the 1991 census of population. The census of population is the single most important source of detailed social information in the UK at the small level (Martin *et al.*, 1998). Over 9,000 items of information are available for each enumeration district, typically containing around 200 households. Unfortunately, the census does not ask questions about a number of household and individual attributes that are expected to determine, in part, levels of household water consumption, including garden size and ownership of washing machines and dishwashers. Instead it is assumed that household attributes such as property type (detached, semi-detached, terraced, flat) and size (number of residents) act as at least a partial proxy for this variable.

Two limitations can be associated with using the 1991 census of population as a source of information about properties and householders in the zonal metering studies:

(i) Foreseen changes in the 1991 census of population.
(ii) The degree of randomness incorporated into the 1991 census of population for confidentiality purposes (Cole, 1994).

As this research was undertaken prior to the 2001 census of population, the 1991 census of population was the only feasible source of information about properties and householders in the zonal metering studies. The incorporated degree of randomness and the question of whether the households in the postal code or enumeration district are representative of the area as a whole, is recognized, but impossible to quantify.

GB Profiler and Small Area Statistics (SAS) are based on the 1991 census of population. The GB Profiler System, developed by Blake and Openshaw (1995), identifies the geodemographic group in each postal code. GB Profiler is a small area classification system based on eighty-five variables from the 1991 census of population and uses both a conventional clustering and a neural network approach to classify areas. The classification is hierarchical. At the highest level, there are five classes: struggling, aspiring, established, climbing or prosperous. The second level provides a description of the residents of the area, typically including information about age, ethnicity, family status, occupation and housing tenure. These descriptions can be found in Appendix 3J.

The SAS are a predefined set of cross-tabulations of two or more census variables. These cross-tabulations have been aggregated into a series of tables. These summary tables cover all topics from the 1991 census of population and provide a detailed source of comparable statistics relating to demographic characteristics, housing conditions, household composition and economic activity (Cole, 1993). In this analysis, information about household size, property type and household composition, i.e. the number of adults and number of children in an enumeration district were extracted from SAS.

3.11.2.1 Socio-economic attributes of the small water supply and district meter areas using GB Profiler

Welsh Water and Yorkshire Water provided the street names and numbers of all properties included in the district meter and small water supply areas. Postal codes were obtained using 'postcode finder' on the Royal Mail web page. Postal codes were then entered into the GB Profiler System. GB Profiler not only produces a classification of the area but also indicates to which enumeration district that postal code belongs.

3.11.2.2 Socio-economic attributes of the small water supply and district meter areas using SAS

Casweb, launched in 1998, is a WWW-based interface to 1991 census area statistics (Martin *et al.*, 1998). The system is based on a large relational database containing the entire SAS for Great Britain at several geographical aggregations. The interface comprises a series of tools, enabling queries to be formulated. These queries are then passed to the database where they are processed.

In Casweb, the queries were formulated using enumeration districts as the scale of geographical aggregation. Enumeration districts are the smallest aggregation level available through SAS. Results in the form of tables with counts of the attributes selected for each enumeration district were then downloaded. However, two problems were encountered when applying the enumeration district data to the zonal meter areas: (i) zonal meter boundaries did not coincide with enumeration district boundaries and (ii) several enumeration districts often lay in the same zonal meter area. A stylized typical example is shown in Figure 3.8.

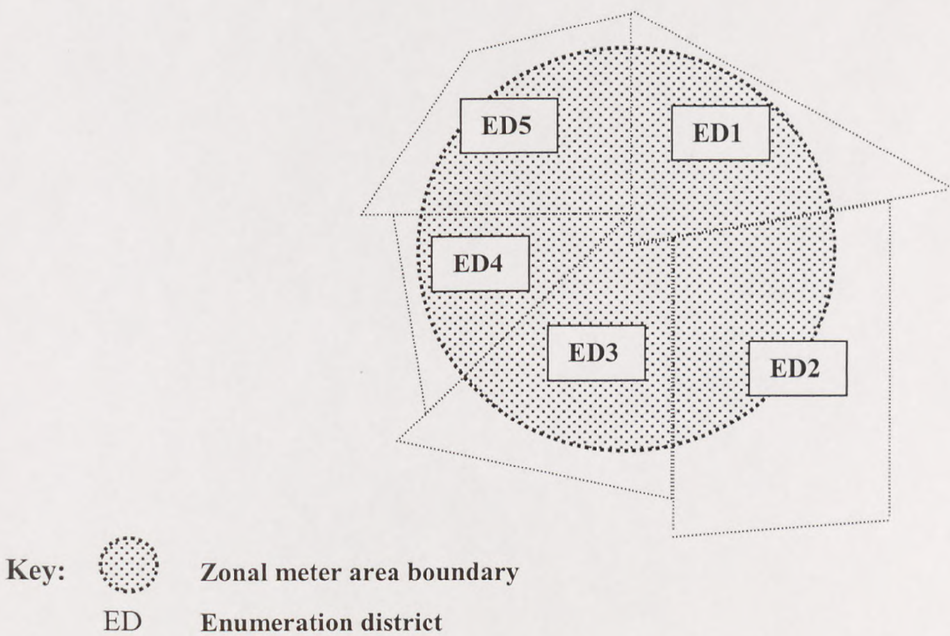


Figure 3.8: A typical example of a zonal meter area overlaying enumeration district boundaries

To determine socio-economic attributes of the zonal meter areas, disaggregation of the enumeration district data was necessary. The Centre for Computational Geography at the University of Leeds recommended the technique used to disaggregate the enumeration district data. As the total number of households from each enumeration district that are included in the zonal meter area could be calculated using the postal code information, the following formula, using total number of one-person households as an example, was used:

$$N_y^{x1} = N^{x1} \times N_y / N^x \tag{1}$$

where N^x is the total number of households in enumeration district 1, N_y is the total number of households in enumeration district 1 that are included in the zonal meter area, N^{x1} is the total number of one-person households in enumeration district 1, N_y^{x1} is the total number of one-person households in the zonal meter area in enumeration district 1.

This formula was repeated for each enumeration district lying in the boundary of the zonal meter area. The results were then summed to give the total number of one-person households in the zonal meter area. Values were rounded to the nearest whole number. The percentage of one-person households in the zonal meter area was calculated by dividing the total number of one-person households in the zonal meter area by the total number of households in the zonal meter area and multiplying by 100. This whole procedure was then repeated for two, three, four, five, six and seven or more person households.

Disaggregation of enumeration district data relating to household counts was accomplished easily, as the total number of households in the zonal meter areas was known. However, when disaggregating enumeration district data relating to person counts, the number of persons in the zonal meter area had to be inferred using results obtained previously about household size. In College Street, Ammanford, for example, the following results about household size for each enumeration district in the district meter area were obtained (Table 3.2):

Table 3.2: Household size in College Street, Ammanford

	Total Number of Households Inside the District Meter Area – College Street						
Enumeration District ID.	*1-person households*	*2-person households*	*3-person households*	*4-person households*	*5-person households*	*6-person households*	*7 or more person households*
49SNFA02	55	75	29	35	7	3	2
49SNFA03	33	27	16	13	3	1	0
49SNFL03	2	2	1	1	0	0	0
49SNFU01	9	11	5	3	2	0	0
49SNFU03	9	8	4	4	1	0	0
49SNGA03	19	20	14	12	5	1	0

A simple multiplication and summing procedure was used to calculate the number of persons in enumeration district 49SNFA02 that are included in the district meter area. The number of one-person households that are included in enumeration district 49SNFA02 and the district meter area was multiplied by one, the number of two-person households by two, and so on, producing the number of persons per household size. By summing the number of persons according to household size, the number of persons in enumeration district 49SNFA02 that are included in the district meter area of College Street, Ammanford was found (Table 3.3). This procedure was then repeated for each enumeration district in the district meter area of College Street, Ammanford.

Table 3.3: Total number of persons in enumeration district 49SNFA02 that are included in the district meter area of College Street, Ammanford

Number of Persons Per Household	*Total Number of Persons Per Household*	*Total Number of Persons Per Household Size*
1	55	55
2	75	150
3	29	87
4	35	140
5	7	35
6	3	18
7 or more	2	14
		499

Once the number of persons in each enumeration district in the district meter area of College Street, Ammanford was obtained, the numbers were summed to give the total number of persons in College Street, Ammanford. This procedure was repeated for all district meter and small water supply areas. To determine other characteristics of the zonal meter areas (namely the types of property and the age of the population), it was assumed that the characteristics of the enumeration district lying in the zonal meter area were representative of the characteristics of the enumeration district as a whole.

3.12 *Validation of the domestic water use studies*

3.12.1 *Validation of the individual household water use studies*

Examination of the sample size and structure used in the individual household water use studies was necessary to determine whether the households selected were representative of the wider population. Validation of the sample size was achieved by determining the percentage of the population included in the individual water use studies from each postal district area. The population of Bradford included in Yorkshire Water's domestic water use study, for example, was calculated from the individual household questionnaires. SAS was then used to determine the total population of Bradford. The percentage of the total population included in the domestic water use study from Bradford was then established. This technique was applied to each individual household water use study. The process was then repeated to determine the percentage of different property types included in each study, and the percentage of different household sizes.

The structure of the individual household water use studies was examined by determining the number of one-person households, two-person households, flats, semi-detached bungalows, number of adults and children etc., within each area from the individual household questionnaires. These same characteristics were then determined for the wards, districts and counties in which they are situated using SAS. The student t-test was used to determine whether there was any significant difference between the structure of the individual household water use studies and the wards, districts and counties in which they are situated.

3.12.2 *Validation of the zonal metering studies*

The validity of the sample size and structure of the zonal metering studies was determined by comparing the socio-economic characteristics calculated using the enumeration district data, with the data obtained from SAS for the wards, districts and counties in which they are situated. The socio-economic attributes of Myddnfych, a district meter area in Ammanford, for example, was compared to the socio-economic attributes of Ammanford as a whole. The same approach used in the validation of the individual household studies was then applied to validate the sample size and structure of the zonal metering studies.

3.13 *Determination of underlying factors influencing domestic water demand in the medium- to long-term*

It was hypothesized that underlying factors influence domestic water demand in the medium- to long-term. The underlying factors investigated included household size, property type, number of adults, number of children, socio-economic grouping, garden size, etc. Initially, principal components analysis was proposed to determine the most influential set of variables affecting domestic water demands in the medium- to long-term. However, some of the data, such as the socio-economic grouping data, are categorical, and hence unsuitable for principal components analysis.

The zonal meter area data and the individual household data were used in the investigation of underlying factors influencing medium- to long-term domestic water demands. In the zonal meter areas, average per capita consumption over the study period was calculated by dividing average domestic water consumption for each zonal meter area by the population count. Relationships between average per capita consumption and the socio-economic attributes of each area were examined using descriptive statistics.

A more in-depth analysis of underlying factors was possible using the individual household data. Data were subdivided into factors thought to have an underlying influence on domestic water demand, e.g. household size. Descriptive statistics were calculated and average per capita and per property water consumption were plotted to examine the factors' influence on domestic water demands. Further subdivisions of the data were then undertaken. The aim was to determine whether, for example, an eight-person detached property with a large garden consumes the most water.

3.14 Determination of factors influencing domestic water demand in the short-term

3.14.1 Environmental variables

Environmental variables were hypothesized to influence domestic water demands in the short-term. Daily data were imperative for compliance with the definition of short-term (see section 2.3 for details). Environmental variables selected for analysis were daily maximum, minimum and average air temperatures, daily rainfall totals, and daily sunshine amounts. These weather variables were selected, primarily because there is a clear conceptual and supportable link between the variables and expected influence on demand. There was also a pragmatic basis for the selection namely because daily data are available for numerous weather stations throughout England and Wales. Other environmental variables, such as soil moisture content found to influence industrial water demand (Mitchell, 1999), were only available on a monthly basis, making it impossible to determine its effects on short-term domestic water demands.

The Meteorological Office supplied daily maximum, minimum and average air temperatures, daily rainfall totals and daily sunshine amounts for eight weather stations in Wales, for fourteen in Yorkshire and for one in London (see Appendix 3K for details). Significantly more weather stations were required in the Welsh Water and Yorkshire Water studies due to the geographical spread of the water consumption data. In Yorkshire, for example, the household consumption study extends from the Yorkshire and Humberside coast, to the upland areas of the Pennines. Hence, there can be no question that the weather data from a particular weather station is not representative of the weather in any particular zonal or individual household metering study.

As short-term domestic water demand is likely to be influenced by the antecedent as well as the prevailing day's weather conditions, the effects of weather variables from 24 hours to 7 days prior to a given demand day were investigated. This time scale was adopted because it conforms to effective weather prediction for forecasting short-term water demand and it provides operationally useful forecast times. Two methodologies, the lag and cumulative lag, were adopted to investigate this 'lag effect'. Table 3.4 demonstrates the first methodology whereby water consumption on day (x) is correlated with sunshine amounts on day (x) and then day (x^{-1}) and so on up until (x^{-7}). Table 3.5 demonstrates the second cumulative methodology whereby water consumption on day (x) is correlated with sunshine amounts on day ($x+x^{-1}$) and so on up until day 7 ($x+x^{-1}+x^{-2}+x^{-3}+x^{-4}+x^{-5}+x^{-6}+x^{-7}$). All correlation coefficients were evaluated at the 99% significance level.

Table 3.4: Technique 1 - The lag effect

Day	*Sunshine (hours)*	*Consumption (l/prop/day)*
x	5	120
x^{-1}	6	
x^{-2}	7	
x^{-3}	8	
x^{-4}	1	
x^{-5}	2	
x^{-6}	3	
x^{-7}	4	

Table 3.5: Technique 2 - The cumulative lag effect

Day	*Sunshine (hours)*	*Consumption (l/prop/day)*
x	5	120
$x+x^{-1}$	6	
$x+x^{-1}+x^{-2}$	7	
$x+x^{-1}+x^{-2}+x^{-3}$	8	
$x+x^{-1}+x^{-2}+x^{-3}+x^{-4}$	1	
$x+x^{-1}+x^{-2}+x^{-3}+x^{-4}+x^{-5}$	2	
$x+x^{-1}+x^{-2}+x^{-3}+x^{-4}+x^{-5}+x^{-6}$	3	
$x+x^{-1}+x^{-2+}x^{-3}+x^{-4}+x^{-5}+x^{-6}+x^{-7}$	4	

To determine which correlation technique to use in this analysis, weather and water consumption data were plotted as histograms and z-scores were calculated using the formula:

$$z = \frac{x - \bar{x}}{\sigma}$$

(2)

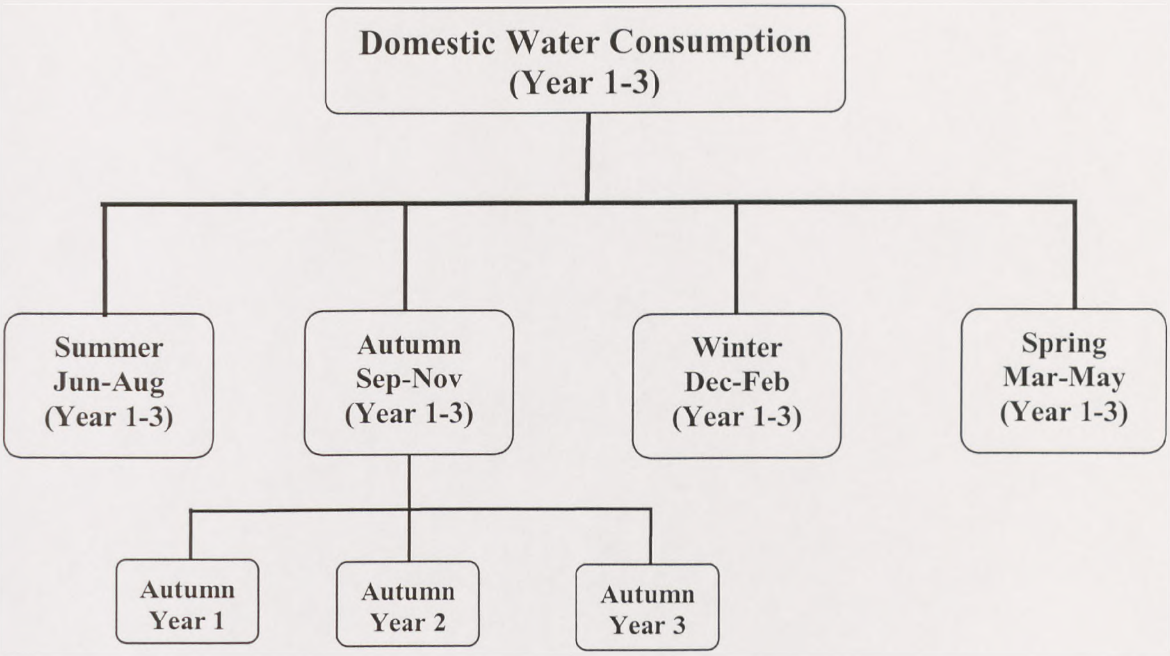
where x is the raw data, $\bar{x}$ is the mean of the data and σ is the standard deviation of the data. Typical examples of the histograms and associated z-scores are shown in Appendix 3L. As these examples suggest, the water consumption data for each of the study areas were approximately normally distributed but the weather data were not. A non-parametric technique, which makes no assumptions about the background data, was therefore required. The Spearman's Rank Correlation Coefficient was selected for this analysis which is denoted by r and is calculated as:

$$r_s = 1 - 6\left[\frac{\sum d_i^2}{n(n^2 - 1)}\right]$$

(3)

Further investigations were made to quantify the influence of weather variables on domestic water demand. Scatter graphs and associated statistical techniques were used to assess the response of water consumption to changes in weather variables. Multiple linear regression analysis was also performed using temperature, rainfall totals and sunshine amounts, in an attempt to explain variation in domestic water consumption.

Water consumption data for each area were first analysed as a whole and then separated arbitrarily into seasons, and then from seasons into years (Figure 3.9). Subdivision of the data from seasons to years can be justified as follows. Much of the domestic water consumption data covered the drought period of 1995-1996. If the data were simply analysed as a whole or subdivided into seasons, results may be influenced by the drought period, rather than represent the 'usual' behavioural consumption patterns.

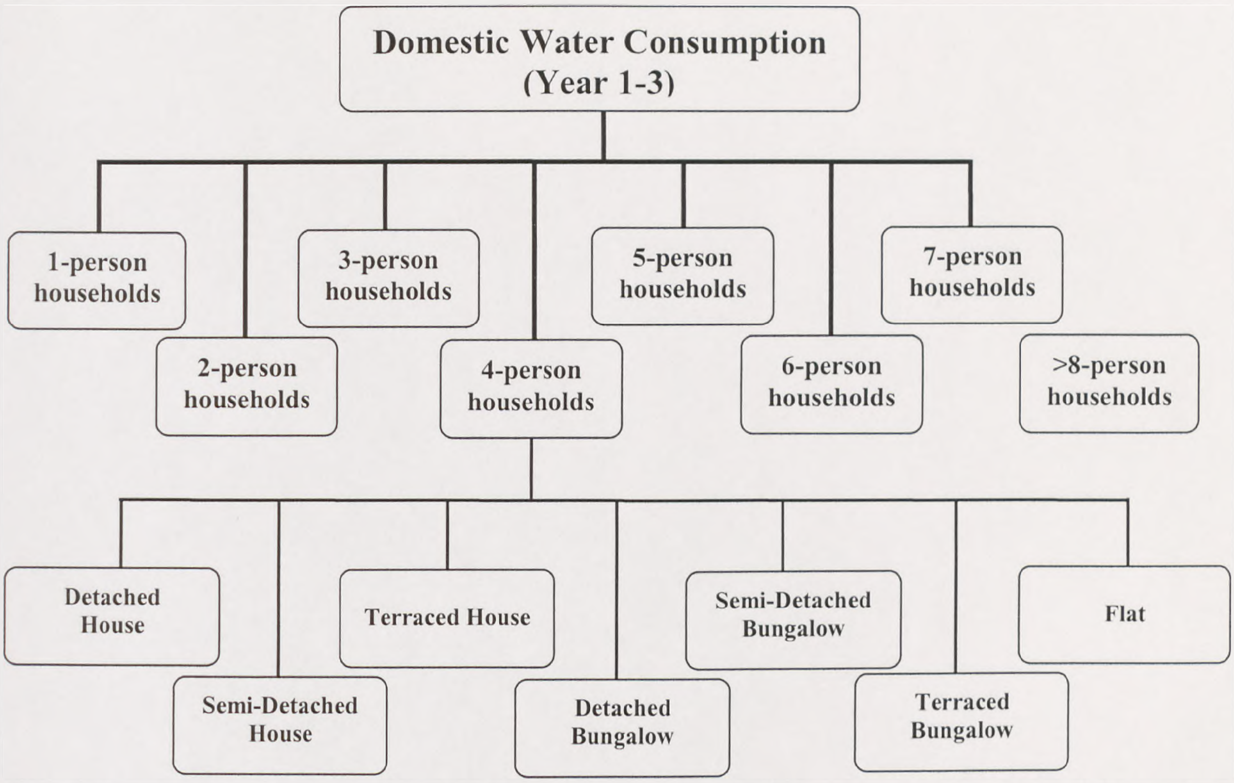


Note that in Figure 3.9, subdivision of data is only shown for autumn; the same process was followed for all seasons.

Figure 3.9: Methodology used to investigate the relationship between environmental variables and domestic water demands

3.14.2 Environmental and socio-economic variables

Household size and property types were found to exert the greatest underlying influence on medium- to long-term domestic water demands. The data were therefore subdivided by household size and property type (Figure 3.10). As this level of information was not available for the zonal meter areas, only the individual household data could be subdivided in this way. Once the data had been subdivided into household size and property type, daily average water consumption was recalculated using the procedure outlined in section 3.8. The relationship between water consumption, environmental variables and property type according to household size were then established (see section 3.13.1 for details).



Note that in Figure 3.10, subdivision of data is only shown for 4-person households; the same process was followed for all household sizes.

Figure 3.10: Methodology used to investigate the relationship between short-term domestic water demands, environmental variables, household size and property type

3.14.3 Temporal variables

To improve the explanation of variations in domestic water demand, factors other than environmental and socio-economic variables were investigated. These were temporal factors and included day of the week, calendar effects and school holidays.

3.14.3.1 Day of the week effect

Many authors have noted a 'day of the week' effect in previous water consumption studies; e.g. Maidment and Miaou (1986) showed evidence of a weekly cycle in municipal water use, usually manifested by higher water consumption on weekdays than weekends. Jowitt and Xu (1992) observed a difference in weekend and weekday consumption, while An *et al.* (1996, 1997) noted that day of the week and particular 'observed holiday days' influence water consumption.

It was hypothesized that water consumption would be higher on weekends than weekdays because more people are at home and hence are likely to consume more water. Water consumption data for each area were split into weekends and weekdays, and individual days of the week. The data sets were then compared using descriptive statistics. Analysis of the relationship between day of the week water consumption, environmental variables and socio-economic attributes was also undertaken.

3.14.3.2 School holidays

Analysis of the relationship between domestic water consumption and school holidays was undertaken using data obtained from Local Education Authorities in the areas studied. School holiday data were not available for every area, as some Local Education Authorities did not hold past school holiday data (undoubtedly due to changes in Local Education Authority boundaries). Public and state school holidays also differ. This analysis may therefore be subject to errors as some schools may be on holiday and some may not. The impact of school holidays on domestic water consumption focused on the February, May, Easter and October half-term holidays. For several reasons, the summer and Christmas holidays were omitted from this analysis. It would be unrealistic to compare the period prior and subsequent to the summer school holidays with those that occur during them because of the large variation in weather, i.e. the summer school holidays coincide with maximum air temperatures and maximum sunshine amounts. Summer school holidays also coincide with the main holiday season in the UK, factory shut down weeks, increased occupation of second homes, etc. It would therefore be impossible to determine whether the school holidays are the sole influence on variations in domestic water consumption. A similar situation is also evident during the Christmas school holidays, with the obvious exception of the weather effects although it may be more than compensated for by leakage effects uncorrected in the data.

3.15 Summary

This chapter has highlighted the success of data acquisition from domestic water consumption studies undertaken in the UK water industry. A critique of these studies has been provided together with an explanation of the approaches used to estimate: (i) daily unmetered domestic water use and (ii) the socio-economic characteristics of the households included in these studies. Chapters 4 and 5 apply the analytical methodology described in this chapter to determine factors that influence domestic water demands in both the short- and the medium- to long-term. Chapter 4 is based on zonal meter area data while Chapter 5 is based on individual household data.

4. Factors Affecting Short-Term Domestic Water Demand in the Zonal Meter Areas

4.1 Introduction

This chapter uses data from two areas, Wales and part of Yorkshire. At both sites the data refers to the flow to a zone which has many households. It is thus an aggregate flow and not a measure of a single household. However, the characteristics of the two data sources differ and to distinguish them, the term district meter is used for Wales and small water supply areas for Yorkshire (see section 2.10 for details). Many of the areas in Wales are subsections of an urban agglomeration differentiated into a district meter area by valving, whereas in Yorkshire, the sites are individually identifiable with Yorkshire Water.

While this chapter is concerned with factors that influence the demand for water in the short-term, there are a number of factors, hereafter underlying factors, that influence both short- and medium- to long-term demand. Data provided by Welsh Water, for the district meter areas of Wales, and Yorkshire Water, for the small water supply areas of Yorkshire, have been used to explore domestic water demands in both the short- and the medium- to long-term. These studies capture the water using behaviour of individuals from a wide geographical spectrum ranging from remote rural villages to relatively highly concentrated urban areas; from poor rundown communities with high unemployment to prosperous areas with low unemployment; and from areas with young families to areas comprised predominantly of pensioners. The data from Yorkshire Water also provided the opportunity to evaluate the influence of demand management measures on domestic water demands. Effectiveness of the demand management measures was assessed by comparison with control villages. Single mass curves were employed as the analysis technique as no monitoring period was established prior to these activities.

4.2 Characteristics of the zonal meter areas

When Welsh Water and Yorkshire Water commissioned their zonal meter studies, no information was collected about the characteristics of the participating households. Instead, information about the households was obtained from the 1991 census of population using small area statistics and GB Profiler (see section 3.11.2 for details). As the census of population does not ask questions about a number of household and individual attributes that are expected to determine, in part, levels of household water consumption, attributes believed to act as a proxy for variables influencing domestic water demand were used. These proxy variables are household size, property type, age of population and geodemographic variables.

4.2.1 Household size

In Welsh Water's zonal metering study, each of the six areas in Wales where the district meter areas are located (Ammanford, Cardiff, Conwy, Deeside, Newport and Prestatyn) display similar distributions in household size (Figure 4.1). Two-person households represent the most common size, accounting for 32.25% of the households in Ammanford to 37.25% in Conwy. A similar pattern was also observed in the small water supply areas of Yorkshire (Figure 4.2). The domination of two-person households ranged from 36.26% in Kettlewell to 52.00% in Starbotton.

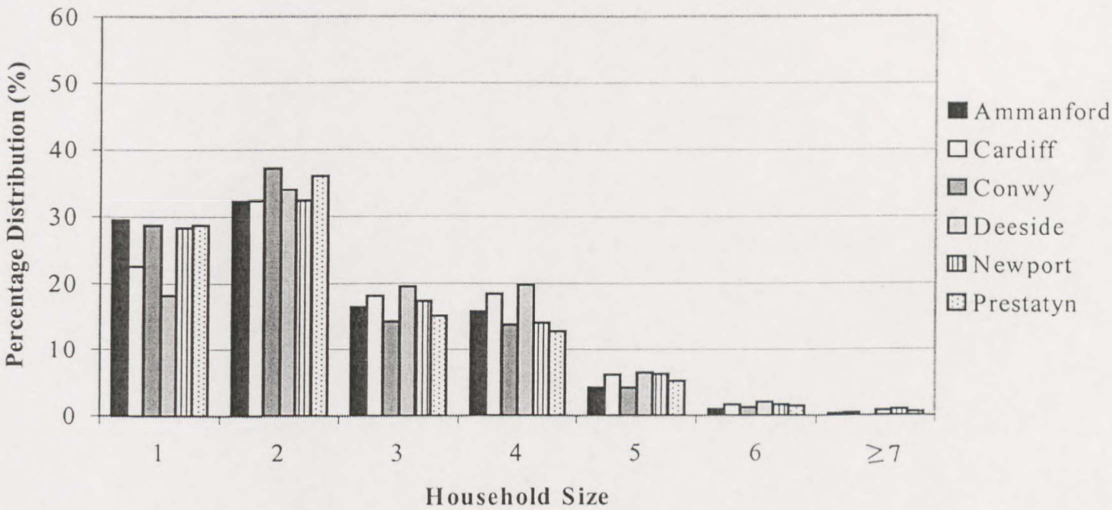


Figure 4.1: Distribution of household size in the district meter areas of Wales

One-person households are the second most common size in all areas except Deeside. In the six areas of Wales the percentage of one-person households ranges from 22.62% in Cardiff to 29.50% in Ammanford. In the small water supply areas the range in one-person households is slightly larger (15.52% in Malham to 30.77% in Kettlewell). In Deeside, although four-person households are the second most common size, accounting for 19.75% of all households, one-person households account for a similar proportion (18.25% of all households).

Figure 4.2: Distribution of household size in the small water supply areas of Yorkshire

A broadly similar distribution of three and four-person households was found in the six areas of Wales. The greatest variation in three and four-person households was recorded in Newport, but even in this case, the percentage difference was only 3.33%. In the small water supply areas, the percentage difference between three and four-person households was slightly larger, with the greatest variation of 13.80% observed in Malham. In both the district meter and the small water supply areas, there was a reduction in the number of five, six and seven or more person households. In fact, seven or more person households are extremely atypical with no representation in any of the small water supply areas and Conwy, and only 1.00% in Deeside, the area with the highest percentage of seven or more person households. However, within some of the individual district meter areas located in the six areas of Wales, slight variation in household size exists. In the district meter area of Glyn Rhosyn, Cardiff, for example, one-person households account for only 8.00% of the total households (see Appendix 4A for details). This compares to the district meter area of Star Street, Cardiff, where one-person households predominate and represent 38.00% of all households. As a result of such variation in household size in the individual district meter areas, data for the district meter areas in the six areas of Wales were not aggregated. Instead, it was hypothesized that a more detailed investigation of factors influencing domestic water demand in both the short- and the medium- to long-term could be made using data from each individual district meter area.

4.2.2 Property type

Significant variation in property type was found in the six areas of Wales where the district meter areas are located (Figure 4.3). Semi-detached properties dominate four of the six areas, representing approximately one-third of the housing stock in Newport, to over one-half in Ammanford. In the remaining two areas, Cardiff and Conwy, the representation of semi-detached properties is only 21.15% and 31.75%, respectively. Terraced properties (46.54%)

dominate Cardiff, while detached properties (41.75%) dominate Conwy. However, a wide variation in the percentage of detached and terraced properties was found between the six areas. The percentage variation is 32.42% for detached properties and 33.79% for terraced properties. In most areas, flats represent the smallest proportion of properties. The percentage of flats range from 1.25% in Deeside to 24.00% in Newport. However, as with household size, variation in property type does exist in some individual district meter areas, particularly in Cardiff (see Appendix 4A for details). No detached properties are evident in five of the thirteen district meter areas in Cardiff, while in Lower Craig, Cardiff, detached properties dominate (79.00% of the total). Another example is Star Street, Cardiff, where 41.00% of the total housing is flats. This compares to three other areas in Cardiff, where no flats are evident. As mentioned in section 4.2.1, variation in household size and property type in each of the district meter areas may result in a more detailed investigation of factors influencing domestic water demands if the data for each district meter area are analysed individually.

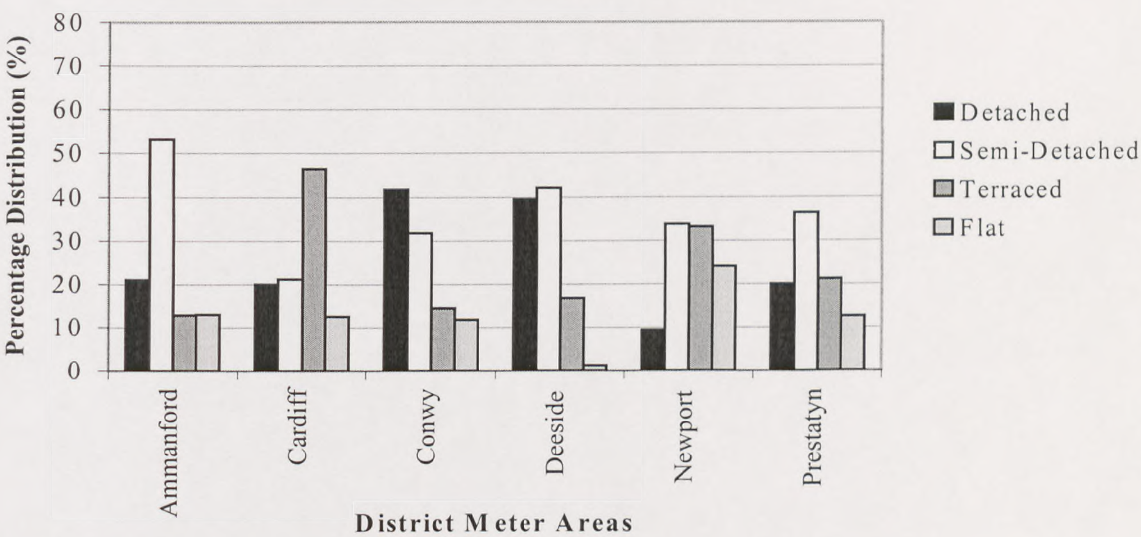


Figure 4.3: Distribution of property type in the district meter areas of Wales

The distribution of property type in the small water supply areas differs to that observed in the six areas of Wales (Figure 4.4). Detached properties are most common in the small water supply areas, representing 38.41% in Kettlewell to 66.67% in Malham. In all areas except Conistone, terraced properties represent the second most common type of housing. The proportion of terraced properties range from 18.06% in Malham to 37.09% in Kettlewell. In Conistone, semi-detached properties represent the second most common type of housing, accounting for approximately one-third of the housing stock. In the remaining four areas, the percentage of semi-detached properties ranges from 13.89% in Malham to 30.17% in Buckden. Flats represent the least common housing type. In fact, in all areas except Malham, no flats are evident. However, even in Malham, flats only represent 1.39% of the total housing.

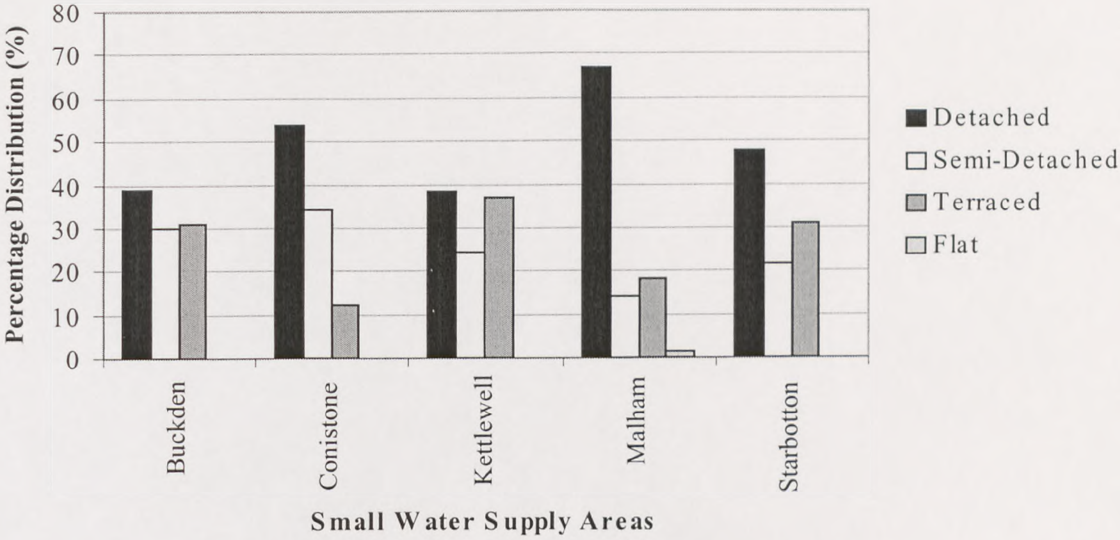


Figure 4.4: Distribution of property type in the small water supply areas of Yorkshire

4.2.3 Age of population

Both the district meter and small water supply areas display a significantly larger proportion of adults compared to children. In the six locations where the district meter areas are located, the percentage of population aged between 0 and 15 years varies from 17.50% in Ammanford to 22.31% in Cardiff (Figure 4.5). However, in some individual district meter areas, larger variation in the proportion of adults to children was observed (see Appendix 4A for details). In St Philomenia, Deeside, for example, 29.00% of the population is comprised of persons less than 15 years of age. In comparison, this age group only constitutes 11.00% of the total in Llanfair Road, Conwy.

In the small water supply areas, the ratio of children to adults is relatively small (Figure 4.6). The percentage of population aged between 0 and 15 years ranges from 10.71% in Starbotton to 17.20% in Malham. In areas where there is a relatively low proportion of children to adults, there appears to be a relatively high percentage of persons who are economically inactive due to retirement. In Starbotton, for example, 42.00% of the population are economically inactive, whereas in Malham, this figure is only 25.38%. GB Profiler clarified the assumption that areas with a low ratio of children to adults have a high percentage of retired persons. In St Philomenia, Deeside, GB Profiler indicated that the residents of this area are typically blue-collar and comfortable middle-class families. In comparison the residents of Llanfair Road, Conwy, were described as comfortable and prosperous pensioners (see Appendix 4B for details).

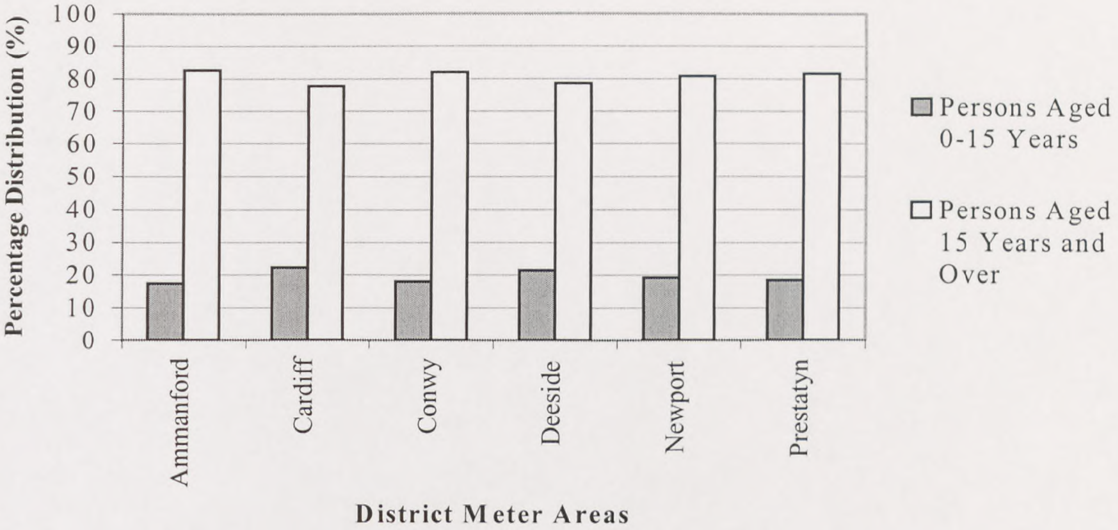


Figure 4.5: Distribution of children and adults in the district meter areas of Wales

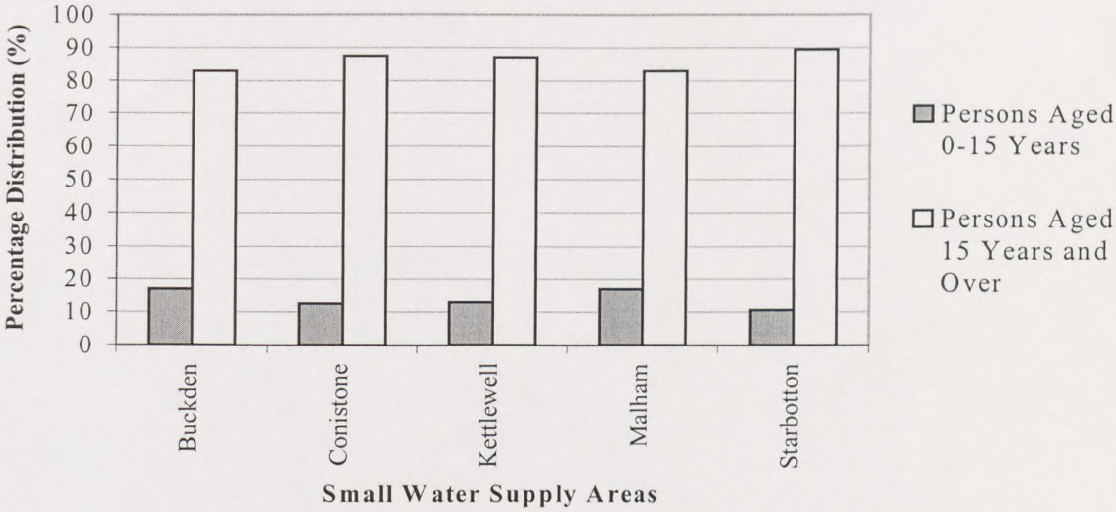


Figure 4.6: Distribution of children and adults in the small water supply areas of Yorkshire

4.2.4 Geodemographic characteristics

Welsh Water's district meter areas cover a number of households with different geodemographic characteristics, including households that are struggling, aspiring, established, climbing, or prosperous, households with different age groups, ethnicities, occupations, and family statuses, and households with a variety of tenure types (see Appendix 4B for details). However, in Yorkshire Water's small water supply areas, the geodemographic descriptions of the areas are similar. Households in the small water supply areas are classified as either established, well-off, middle-aged and retired residents, owning detached and semi-detached houses, or the areas are classified as prospering, with households containing prosperous pensioners and mature, educated, professional families, owning detached houses. It can be concluded that significant variation exists in the characteristics of households in each individual district meter and small water supply area. Due to this variation, it is hypothesized that a more detailed investigation of factors influencing domestic water demands in both the short- and the medium- to long-term could be made by analysing individually the data from each district meter and small water supply area.

4.3 Validation of the zonal meter studies

As Table 4.1 indicates, only a small fraction of the population and households from each of the water companies' supply areas are included in the water use studies, particularly in the Yorkshire Water study. This obviously raises questions concerning the application of the results to the wider population. However, the characteristics of the small water supply areas in Yorkshire are distinct and do not aim to represent Yorkshire as a whole. The district meter areas of Wales, however, aim to represent the wider population of Wales. Although the size of the sample used in the Welsh Water study is questionable, the student t-test revealed no significant difference (at the 99% significance level) between the distribution of household composition and type in the district meter areas and the wards, districts and counties in which they are situated.

Table 4.1: Percentage of the water companies' population and households included in the water use studies

Water Use Studies	*% of Population in the Water Use Studies*	*% of Households in the Water Use Studies*
Welsh Water	1.72	1.91
Yorkshire Water	0.03	0.03

4.4 Characteristics of the data in the zonal meter areas

4.4.1 Missing water consumption data

In each of the district meter and small water supply areas, some water consumption data were missing. Missing water consumption data almost certainly results from meter or logger failure. Table 4.2 shows the percentage of missing water consumption data for each area. Some 12.45% of the data are missing in the district meter areas and 24.31% in the small water supply areas. In the district meter areas, the percentage of missing data ranges from 0.00% in Cheriton Drive, Cardiff, and Meliden Estate, Prestatyn, to 29.60% in Lower St Asaph, Conwy. In the small water supply areas, the percentage of missing data ranges from 12.41% in Kettlewell to 34.44% in Starbotton. However, the percentage of missing data can be misinterpreted. The data set in Cheriton Drive and Meliden Estate, for example, is considerably smaller than that of other areas (6 times less in Cheriton Drive and 24 times less in Meliden Estate).

Table 4.2: Percentage of missing water consumption data in each zonal meter area

Area			*% of Missing Data*
Small Water Supply Areas		Buckden	29.32
		Conistone	18.19
		Kettlewell	12.41
		Malham	6.75
		Starbotton	34.44
District Meter Areas	Ammanford	College Street	2.39
		Margaret Street	23.02
		Myddnfych	11.05
		Wind Street	10.10
	Cardiff	Brynfedw West	25.00
		Chapelwood	6.94
		Cheriton Drive	0.00
		Courtney Road	8.63
		Excalibur Drive	10.84
		Glyn Rhosyn	4.14
		Lower Craig	6.53
		Oakwood	31.00
		Orchard Castle	8.83
		Pearl Street	7.91
		Penylan Hill	3.96
		Star Street	3.89
		The Farthings	15.79
	Conwy	Cathedral	1.44
		Glan Conwy	21.33
		Llanfair Road	23.56
		Lower St Asaph	29.60
		Uppergate	7.97
	Deeside	Chambers Lane	17.81
		Clay Lane	2.58
		Gronant	4.88
		St Philomenia	25.15
	Newport	Church Street	3.99
		Oakfield Road	1.99
		The Woodlands	8.45
	Prestatyn	High Street	25.06
		Jolly Sailor	1.82
		Kingsway	20.47
		Meliden Estate	0.00
		Meliden Church	26.84
		Nant Hall Road	24.38
		Sintras	20.74

4.4.2 Data cleaning

Although large surveys will contain erroneous data, the water consumption data are highly variable with genuine extreme values. The key, therefore, is to estimate a maximum value beyond which the data will be in error. In each of the zonal meter studies it was impossible to determine a single absolute value beyond which is deemed in error because each study contained different numbers of households. Instead, anomalous water consumption data were identified by visual inspection, aided by the time-series plots (see Appendix 4C and 4D for details). Anomalous values can be introduced into the data by meter or logger failure or leakage. The arrows in Figures 4.7 and 4.8 indicate typical examples of anomalous consumption values. The average percentage of anomalous consumption values in the district meter and small water supply areas were 15.12% and 27.36%, respectively.

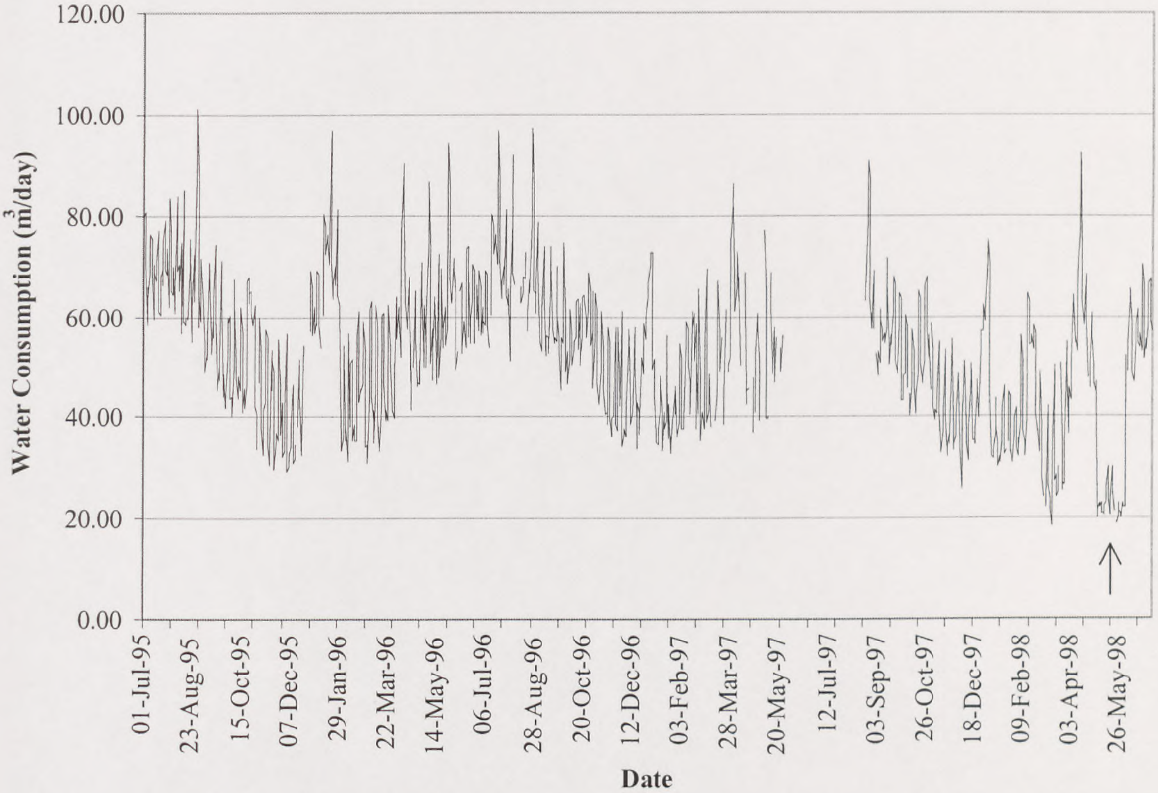


Figure 4.7: Anomalous water consumption data in Kettlewell

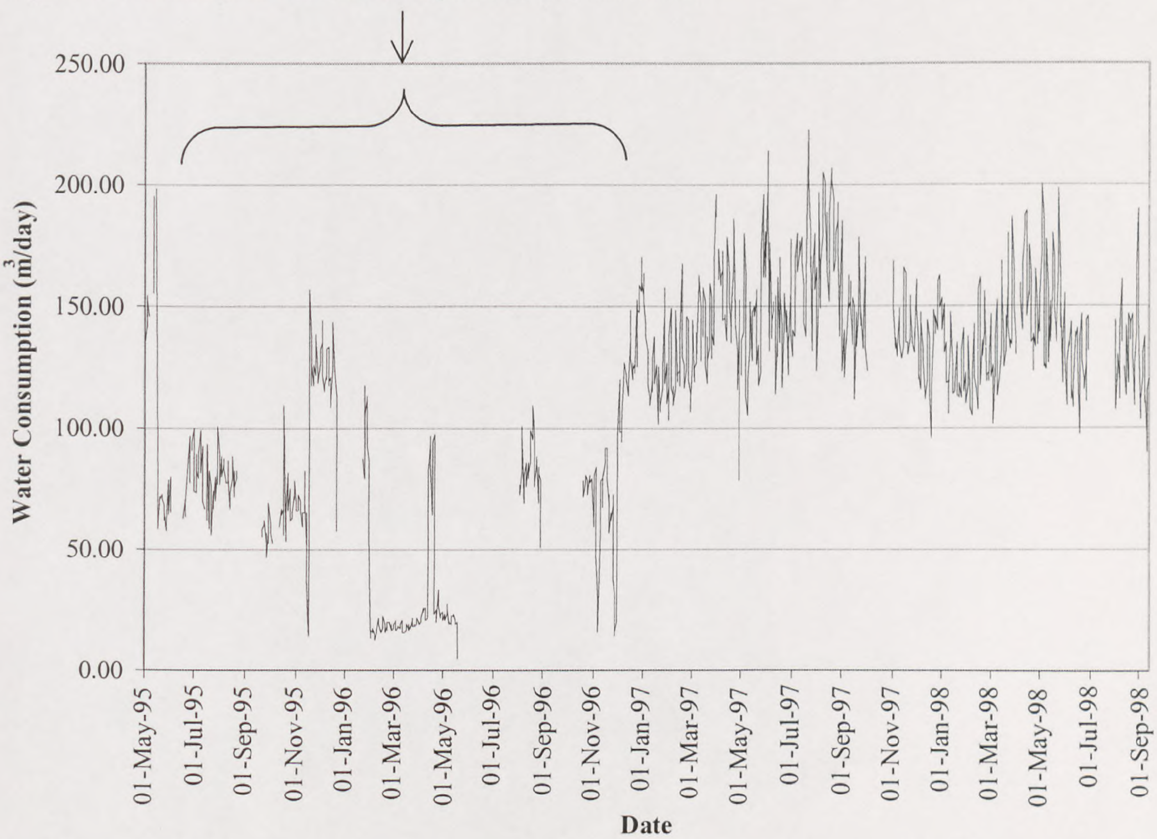


Figure 4.8: Anomalous water consumption data in Malham

4.4.3 Data interpolation

Data interpolation was investigated to reduce the amount of missing consumption data. Where only a few days data were missing (up to five consecutive days), consumption data could be imputed by using the data on either side of the missing values (Figure 4.9). The smaller consumption value would be subtracted from the larger value (Step 1) and the resultant figure divided by the number of missing values, plus one (Step 2). The resulting figure in Step 2 would then be added to the lowest consumption value (Step 3), and so on.

However, data interpolation was considered unrealistic. Where data interpolation was employed, improvements were only slight as many of the data gaps were too large for interpolation. In the small water supply areas, for example, improvements in the percentage of missing data only averaged 1.90%. It was also considered impossible to interpolate data accurately (i) due to the large variation in daily water consumption and (ii) because the factors that influence domestic water demand are unknown.

Day	*Domestic Water Consumption (m^3d^{-1})*
Day 1	120
Day 2	?
Day 3	?
Day 4	150

Step 1. 150 – 120 = 30
Step 2. 30 / 3 = 10
Step 3. 120 + 10 = 130
Step 4. 130 + 10 = 140

Day	*Domestic Water Consumption (m^3d^{-1})*
Day 1	120
Day 2	130
Day 3	140
Day 4	150

Figure 4.9: Interpolation of missing domestic water consumption data

4.4.4 Analysis of the time-series data – medium- to long-term water demand

The time-series data in thirty-five of the thirty-six district meter areas show a relatively constant demand for water throughout the year (Figure 4.10 and Appendix 4C). In the remaining area, the Jolly Sailor, Prestatyn, and in each of the small water supply areas, the time-series indicate a seasonal trend in domestic water consumption with peaks during summer and troughs during winter (Figure 4.11 and Appendix 4D). Significant increases in consumption are also observed during public holidays (Christmas and Easter) and bank-holidays (May Day and August bank-holiday). However, large increases in water consumption over the Christmas period may be influenced by increased leakage as minimum temperatures begin to fall below zero degrees and inevitably cause pipes to burst.

Several reasons may account for the lack of seasonal variation in domestic water consumption in the district meter areas of Wales:

(i) Water consumption for households within the district meter areas are unaffected by changes in weather.

(ii) Water consumption for only a small number of households within the district meter areas are influenced by weather, producing little variation in domestic water consumption.

(iii) Severe smoothing of the data may result from improper calculation of non-household consumption in a district meter area (see section 3.7.1.2 for details). Fluctuations in water use may be assigned to non-household rather than household use where estimates are used to determine non-household water consumption. However, if this assumption were true, seasonal variation would be expected in those district meter areas with few or no non-household properties (see Appendix 3A for details).

(iv) Leakage determinations may be inaccurate (see section 3.7.1.1 for details). Fluctuations in water use may be assigned to changes in leakage rather than changes in household water consumption.

No conclusions can be drawn about the unexpected lack of seasonal variation in domestic water consumption in the district meter areas. Further research revealed that a golf course was located in the Jolly Sailor, Prestatyn (the only district meter area displaying seasonal variation). Irrigation of the golf course is a possible explanation why water consumption in this district meter area displayed a seasonal trend (Morrison, 1999, pers. comm.; Rab, 1999, pers. comm.). However, Welsh Water was unable to provide a detailed methodological approach to calculating non-household water consumption and leakage in the district meter areas. It was therefore impossible to determine whether Welsh Water's method of calculating domestic water consumption influenced the lack of seasonal variation in the data.

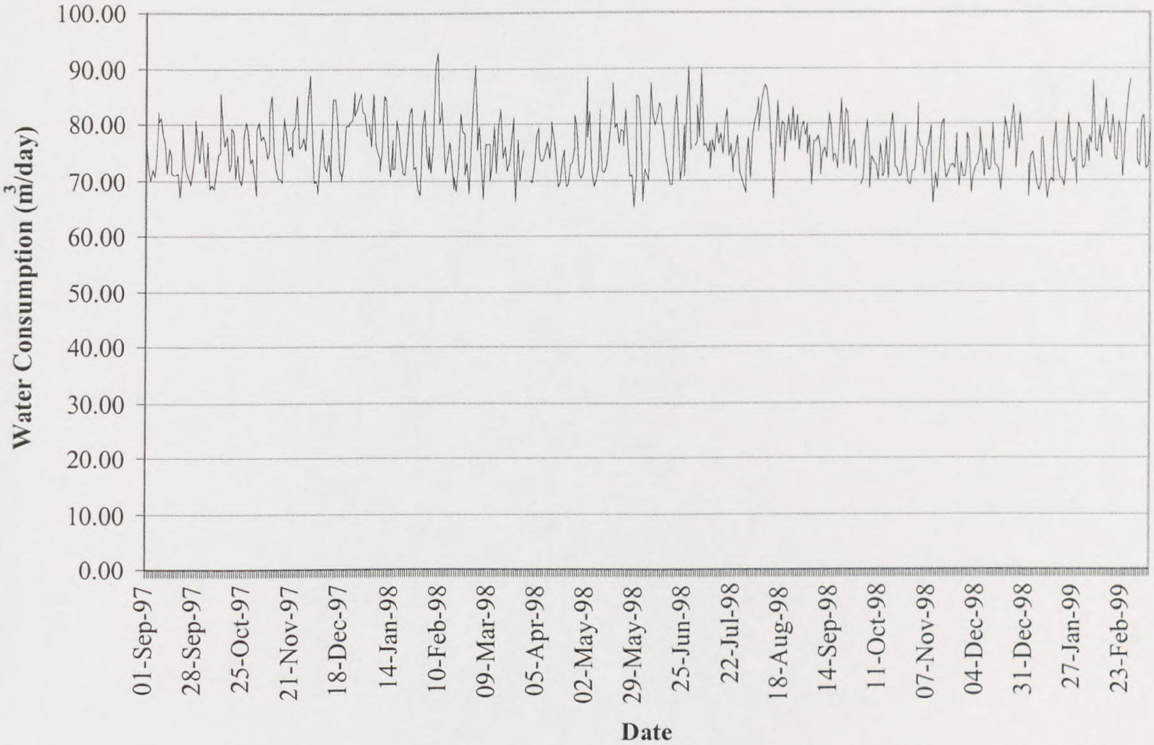


Figure 4.10: A typical example of a time-series plot from Welsh Water's district meter areas (Oakfield Road, Newport)

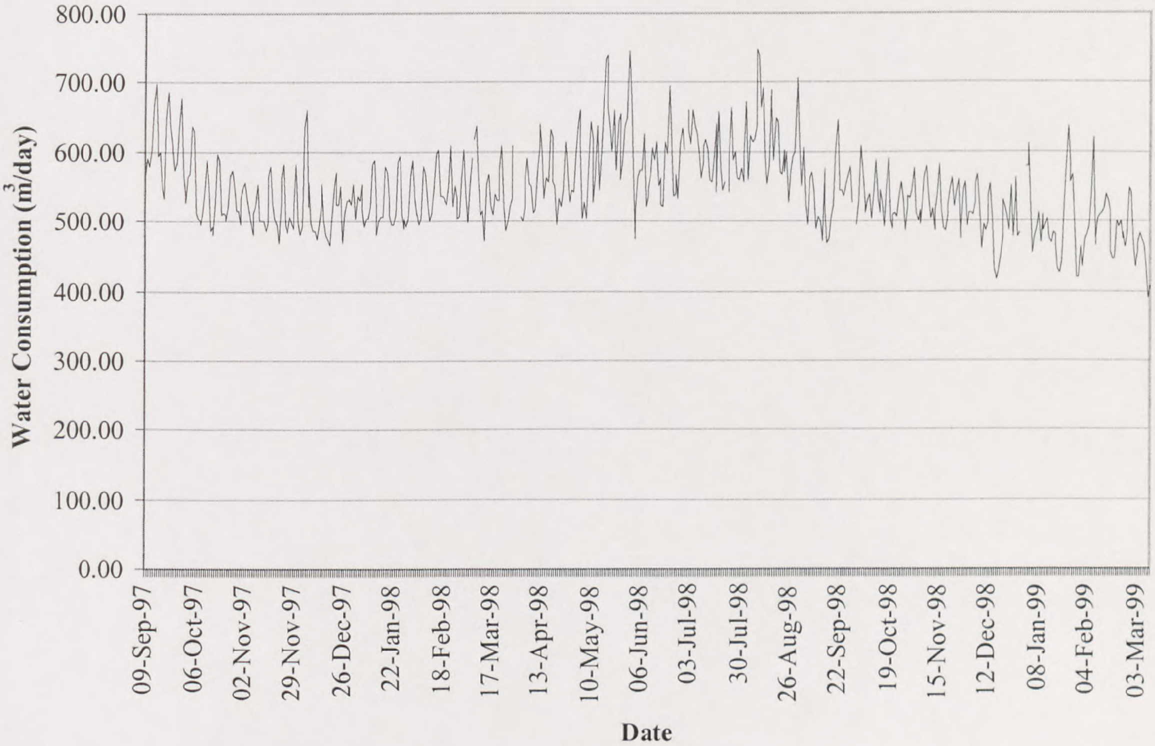


Figure 4.11: A typical example of a time-series plot displaying some seasonal variation in water demand (Jolly Sailor, Prestatyn)

4.5 Per capita consumption in the zonal meter areas

Average per capita consumption in the small water supply areas is generally higher than that observed in the district meter areas (see Appendix 4F for details). This may result from the large proportion of detached properties in the small water supply areas. Malham, the small water supply area with the highest percentage of detached properties, has the highest per capita consumption of 397.56 litres/person/day. Detached properties would be expected to have larger gardens than terraced properties and flats, and hence are likely to have a higher outdoor water use. However, Lower Craig in Cardiff, an area that displays a high proportion of detached properties, has an average per capita consumption of 203.06 litres/person/day less than that observed in Malham. This suggests that the characteristics of the population base may also influence per capita consumption. In Lower Craig, Cardiff, the majority of residents are educated professional families (see Appendix 4B for details) who will undoubtedly have limited time for water consuming activities such as garden watering due to employment. However, the small water supply areas are comprised predominately of retired residents and pensioners who have ample opportunity for water consuming activities such as garden watering. GB Profiler also indicates that the population of the small water supply areas in Yorkshire is more affluent than much of the population in the district meter areas of Wales (see section 4.2.4 for details). Many of these people will therefore have the potential to irrigate their gardens when it is hot and sunny. They also have no financial constraints that may limit heating costs for water consuming activities. It is highly probable, therefore, that the combination of detached properties with large gardens, high levels of affluence in the population, and residents with ample opportunity for water consuming activities result in high per capita consumption values.

Although there appears to be some relationship between property type, levels of affluence and economic activity, some district meter areas in Wales displayed very similar geodemographic characteristics but very different average per capita consumption values. Orchard Castle, Cardiff, for example, is dominated by climbing, affluent, executive, home-owning areas. Cheriton Drive, Cardiff, is also given this description, yet per capita consumption is 197.70 litres/person/day less than that in Orchard Castle. Similarly, some district meter areas displayed very similar average per capita consumption values but exhibited very different geodemographic characteristics. Average per capita consumption in Church Street and Oakfield Road, Newport, varies by only 1.38 litres/person/day. Struggling young blue-collar families and pensioners living in local authority rented terraced properties dominate Church Street, whereas prospering, affluent, mature, educated, professional families, owning and buying large semi-detached and detached properties dominate Oakfield Road. A similar situation was also observed in Deeside. Average per capita consumption in Chambers Lane, Clay Lane and Gronant varies by only 6.04 litres/person/day. Clay Lane is a prospering, affluent, rural, commuter area, with mature couples and families in mixed occupations, owning and renting large, detached properties. Gronant is an established, less-well-off, area with middle-aged mature blue-collar couples and pensioners renting and owning terraced and semi-detached properties from the local authority.

Several reasons may explain why some district meter areas in Wales: (i) have similar geodemographic characteristics yet different per capita consumption values and (ii) have similar per capita consumption values yet different geodemographic characteristics:

(i) Population counts used to calculate per capita consumption may be subject to error from:

- Random fluctuations introduced into the 1991 census of population to protect confidentiality (Cole, 1994).
- Changes in population and households since the 1991 census of population (see section 3.11.2 for details).
- Inference errors regarding the number of households and persons in a particular zonal meter area (see section 3.10.2.2 for details).

(ii) The domestic water consumption data may have incurred error from:

- Leakage calculations (see section 3.7.1.1 for details).
- Determinations of water use for non-household properties (see section 3.7.1.2 for details).
- Failure to maintain and calibrate water meters and loggers adequately.

4.6 The influence of environmental factors on domestic water demands

Observed seasonal variation in domestic water demands (Figures 4.7, 4.8 and Appendix 4D) in the small water supply areas of Yorkshire and fluctuations in domestic water demands in the district meter areas of Wales (Figures 4.10, 4.11 and Appendix 4C) suggests that demands may be influenced by environmental factors. To investigate the influence of environmental factors on domestic water demands, linear and multiple linear regression analysis were performed using temperature, sunshine amounts and rainfall as independent variables (see section 3.14.1 for details).

4.6.1 Linear regression analysis

Figures 4.12-4.14 and Appendix 4G and 4H suggest that domestic water demands in the small water supply areas of Yorkshire and the district meter areas of Wales are influenced by environmental factors. In all cases the trends are in the intuitively expected direction. When it is hotter/sunnier, more water is used and when it is colder/wetter, less water is used. However, there is a very high degree of scatter in the data. Throughout this Chapter and Chapter 5, correlation coefficients, r, and R^2 values are reported. All the reported relationships are significant at the 99% level, individual confidence levels have not been included in the tables.

In the small water supply areas of Yorkshire and the district meter areas of Wales, rainfall appears to explain a relatively low percentage of variance in domestic water consumption (typically 3%, but ranging between 0% and 7%) (Table 4.3). A higher percentage of variance in domestic water consumption appears to be explained by sunshine amounts. In the small water supply areas of Yorkshire, sunshine amounts typically explain 14% of the variance in domestic water consumption, ranging from 10% in Conistone to 23% in Malham. In the district meter areas of Wales, sunshine amounts typically explain 11% of the variance in domestic water consumption. The percentage range of explained variance in the district meter areas is larger than that of the small water supply areas, with sunshine amounts explaining between 1% (Meliden Church, Prestatyn) and 36% (College Street, Ammanford) of the variation in domestic water consumption. However, water consumption data in Meliden Church, Prestatyn, is suspect. As the time-series plot indicates (see Appendix 4C for details) water consumption in this area appears to increase continually over the study period.

As Table 4.3 and Appendix 4G indicate, the largest variation in the relationship between domestic water consumption and sunshine amounts was found in the district meter areas of Ammanford. The percentage of explained variance ranges from 5% in Margaret Street to 36% in College Street. The dependency of domestic water consumption to variation in sunshine amounts also varies in the district meter areas of Conwy (ranging from 15% in Lower St Asaph to 29% in Glan Conwy) and Deeside (ranging from 5% in Chambers Lane to 28% in Clay Lane). In the district meter areas of Cardiff and Prestatyn, little of the variation in domestic water consumption is dependent on variation in sunshine amounts. The maximum explained variance of 8% in these two areas was observed in Courtney Road and Glyn Rhosyn, Cardiff.

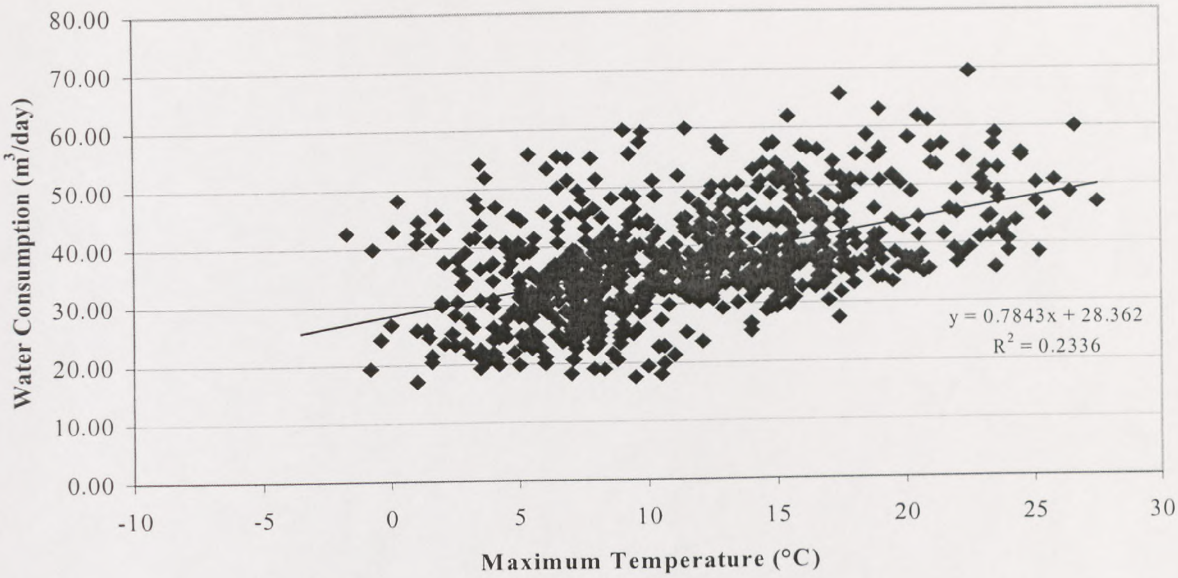


Figure 4.12: Relationship between domestic water consumption and temperature in Buckden

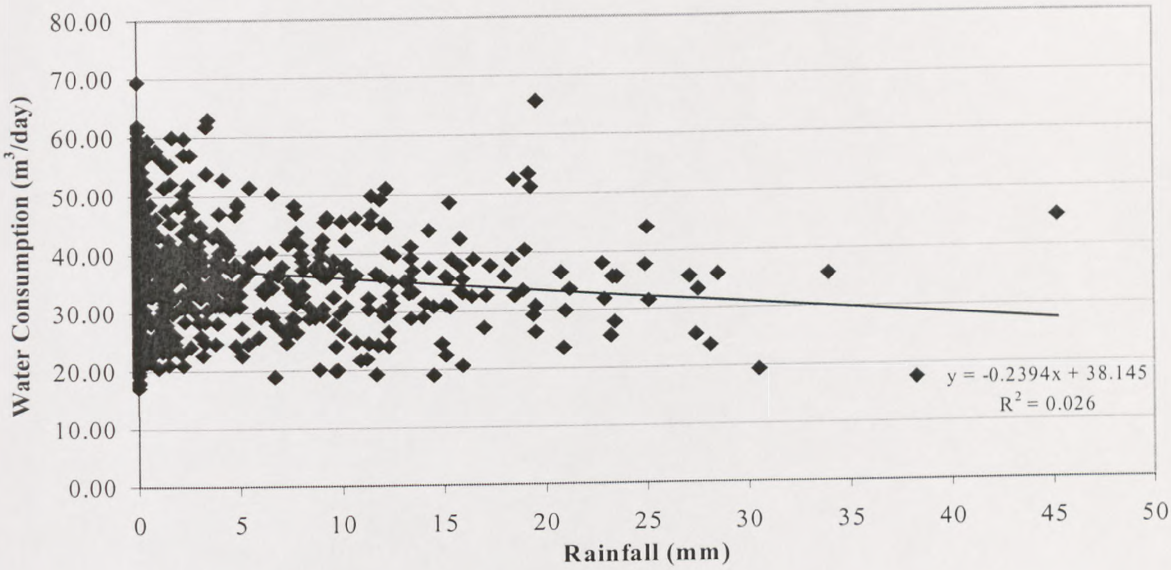


Figure 4.13: Relationship between domestic water consumption and rainfall in Buckden

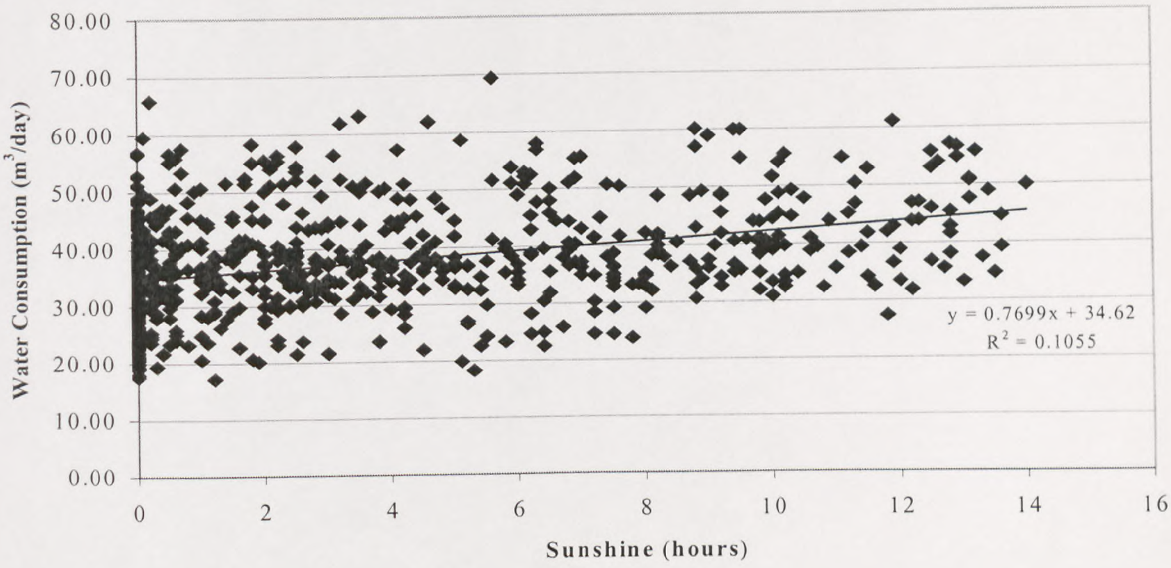


Figure 4.14: Relationship between domestic water consumption and sunshine in Buckden

In the small water supply areas of Yorkshire, temperature appears to explain the greatest percentage of variance in domestic water consumption, ranging from 20% in Conistone to 27% in Malham (Table 4.3 and Appendix 4H). In Wales, temperature explains the greatest percentage of variance in 54% of the district meter areas. The percentage of explained variance ranges from 0% in Cheriton Drive, Cardiff, and Chambers Lane, Deeside, to 35% in High Street, Prestatyn. Variation in domestic water consumption may appear to display a stronger dependency to variation in temperature due to relatively high sunshine amounts during winter periods that result in no increase in outdoor water use, such as garden watering, because of low temperatures. Linear regression was therefore used to analyse the relationship between environmental variables and domestic water consumption in each season.

When linear regression is used to analyse the influence of environmental variables on domestic water consumption in each season, the percentage of explained variance remains relatively low. In some cases, environmental variables explain a greater percentage of variance in domestic water consumption when the data are analysed for the entire monitoring period. This suggests that a sufficient range of weather data may be required to determine accurately the influence of environmental variables on domestic water demands. However, in the majority of cases, environmental variables appear to exert the greatest influence on domestic water consumption during the spring, summer and autumn seasons (Table 4.4 and Appendix 4I). During the winter season, environmental variables appear to exert little or no influence on domestic water consumption. It is highly probable that at this time of year, domestic water consumption is represented only by in-house use although values may be complicated by leakage uncorrected in the figure. Leakage might be better expected to show a relationship with temperature. However, this may only be exhibited on temperature rise.

Table 4.3: The influence of environmental factors on domestic water demands in the district meter and small water supply areas (linear regression analysis – R^2).

Area			*Linear Regression Analysis (R^2)*		
			Rainfall	*Temperature*	*Sunshine*
Small Water Supply Areas		Buckden	0.03-	0.23+	0.11+
		Conistone	0.01-	0.20+	0.09+
		Kettlewell	0.01-	0.21+	0.10+
		Malham	0.05-	0.27+	0.23+
		Starbotton	0.04-	0.23+	0.16+
District Meter Areas	Ammanford	College Street	0.05-	0.22+	0.36+
		Margaret Street	0.00	0.02+	0.05+
		Myddnfych	0.06-	0.10+	0.28+
		Wind Street	0.02-	0.08+	0.13+
	Cardiff	Brynfedw West	0.00	0.02+	0.01+
		Chapelwood	0.00	0.02+	0.06+
		Cheriton Drive	0.01-	0.00	0.02+
		Courtney Road	0.04-	0.04+	0.08+
		Excalibur Drive	0.03-	0.01+	0.02+
		Glyn Rhosyn	0.03-	0.05+	0.08+
		Lower Craig	0.00	0.19+	0.05+
		Oakwood	0.03-	0.07+	0.05+
		Pearl Street	0.02-	0.01+	0.05+
		Penylan Hill	0.01-	0.09+	0.03+
		The Farthings	0.03-	0.11+	0.07+
	Conwy	Cathedral	0.04-	0.04+	0.17+
		Glan Conwy	0.04-	0.24+	0.29+
		Llanfair Road	0.05-	0.20+	0.22+
		Lower St Asaph	0.03-	0.17+	0.15+
		Uppergate	0.03-	0.27+	0.22+
	Deeside	Chambers Lane	0.00	0.00	0.05+
		Clay Lane	0.04-	0.16+	0.28+
		Gronant	0.07-	0.08+	0.20+
		St Philomenia	0.05-	0.15+	0.15+
	Newport	Church Street	0.01-	0.00	
		Oakfield Road	0.01-	0.00	
		The Woodlands	0.06-	0.04+	
	Prestatyn	High Street	0.04-	0.35+	0.02+
		Jolly Sailor	0.03-	0.28+	0.03+
		Kingsway	0.02-	0.05+	0.02+
		Meliden Church	0.01-	0.01+	0.01+

Key: ***+ results in an increase in domestic water demands***
- results in a reduction in domestic water demands

Table 4.4: The influence of environmental variables on domestic water consumption in each season in Conistone (linear regression – R^2)

Weather	*Seasons*			
	Summer	*Autumn*	*Winter*	*Spring*
Rainfall (mm)	0.04-	0.02-	0.00	0.01-
Sunshine (hrs)	0.07+	0.03+	0.00	0.03+
Temperature (°C)	0.13+	0.09+	0.07+	0.11+

Key: ***+ results in an increase in domestic water demands***
- results in a reduction in domestic water demands

4.6.2 Multiple linear regression analysis

In an attempt to explain better how variations in environmental variables influence variations in domestic water consumption, multiple linear regression analysis was performed using rainfall, temperature and sunshine amounts as independent variables. In all of the small water supply areas and in 79% of the district meter areas, multiple linear regression analysis improved slightly the percentage of explained variance (see Appendix 4J for details). However, it is likely that some interdependency exists between the independent variables, which raises doubts about the actual percentage of explained variance.

Results from the linear and multiple linear regression analysis appear to suggest that the influence of environmental variables on domestic water consumption is related to property type. In areas with a high proportion of detached and semi-detached properties (e.g. the small water supply areas of Yorkshire, College Street in Ammanford, Llanfair Road and Uppergate in Conwy, and Clay Lane in Deeside), environmental variables explain a relatively high percentage of variance in domestic water consumption. In comparison, in areas with a high proportion of terraced properties and flats (e.g. Brynfedw West and Penylan Hill in Cardiff, and Church Street and Oakfield Road in Newport), environmental variables appear to explain little of the variance in domestic water consumption. As can be recalled from section 4.6, this is expected as detached and semi-detached properties typically have larger gardens than terraced properties or flats and hence are likely to have a higher outdoor water usage. However, there appears to be some anomalies in the relationship between environmental variables, domestic water consumption and property type. In some of the district meter areas of Wales, such as Chambers Lane in Deeside and High Street in Prestatyn, environmental variables appear to exert little influence on domestic water consumption, even though the areas are dominated by detached and semi-detached properties. Further investigations revealed that in these areas, a large proportion of the water consumption data were missing during the spring and summer seasons when outdoor water use, particularly for garden watering, is anticipated to be at its highest (see Appendix 4C for details). Missing consumption data is therefore a possible explanation why environmental variables appear to exert little influence on domestic water consumption in these district meter areas.

4.7 Environmental variables and short-term domestic water demands

As short-term domestic water demands were hypothesized to be influenced by the antecedent and/or prevailing day's weather conditions, the effects of weather variables from 24 hours to 7 days prior were investigated. Two methodologies, the lag and cumulative lag, were adopted to investigate this 'lag effect' (see section 3.14.1 for details).

Analysis of the relationship between short-term domestic water demands and weather variables demonstrated consistently that the strongest correlation coefficients were produced for the cumulative lag. Results also indicated that in all cases, rainfall produced negative correlation coefficients while sunshine amounts, maximum temperature, minimum temperature and average temperature, produced positive correlation coefficients. However, maximum temperature produced significant, repeatedly stronger relationships with short-term domestic water demands compared to the other methods of recording temperature. In further analysis, therefore, only the cumulative lags would be used to investigate the relationship between short-term domestic water demands and weather and only maximum temperature would be used to determine the relationship between short-term domestic water demands and temperature.

4.8 Environmental variables and short-term domestic water demands over the entire monitoring period

The influence of environmental variables on short-term domestic water demands in the district meter and small water supply areas was first analysed over the entire monitoring period (see section 3.14.1 for details). This analysis generally produced relatively weak correlation coefficients (typically $r = \pm 0.45$) (see Appendix 4K and 4L for details). However, in some of the district meter areas in Wales, relationships between short-term domestic water demands and the antecedent and prevailing day's weather conditions proved insignificant. In some cases, these relationships undoubtedly proved insignificant due to the lack of domestic water consumption data and/or weather data. This, however, does not disguise the fact that in some district meter areas, weather appears not to exert any significant influence on short-term domestic water demands.

In the majority of cases where significant relationships were observed between short-term domestic water demands and environmental variables, a similar emerging trend was found. The strength of the correlation coefficients increased steadily to about two or three cumulative days previous before remaining constant or declining (Figure 4.15 and Appendix 4K and 4L). This emerging trend indicates that the prevailing day's and the two days antecedent weather conditions exert the greatest influence on short-term domestic water demands.

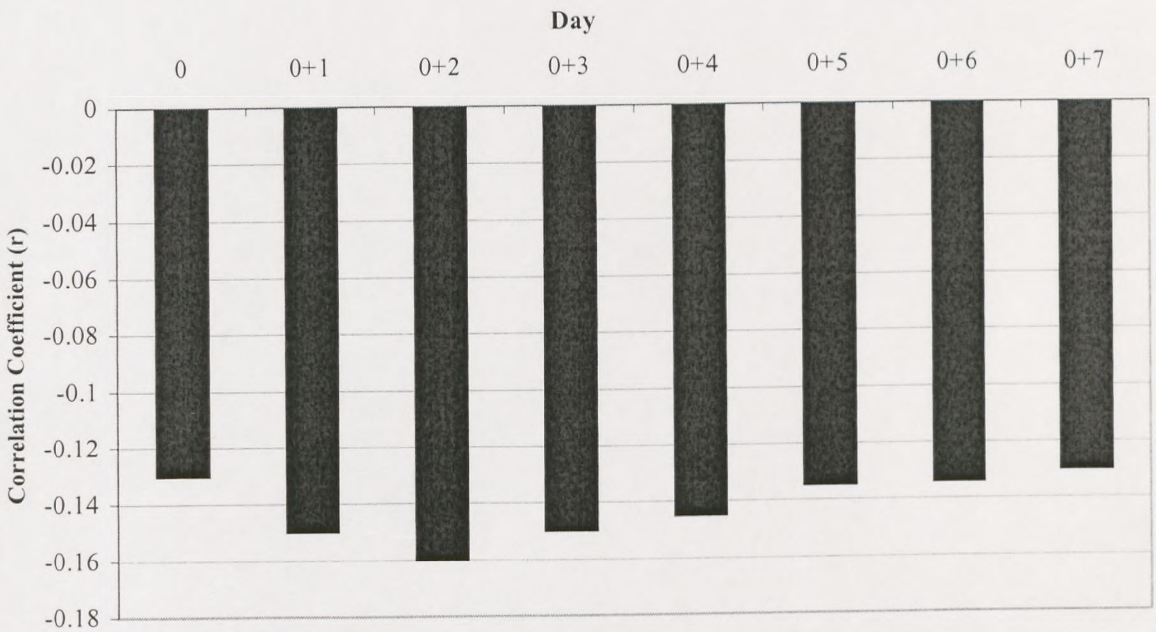


Figure 4.15: Trend between domestic water consumption and the antecedent and prevailing day's rainfall amounts in Kettlewell

4.9 Environmental variables and short-term domestic water demands over the seasons

As expected, the strongest relationships between short-term domestic water demands and the antecedent and prevailing day's weather conditions were produced during the summer season in all five small water supply areas and in approximately two-thirds of the district meter areas (Table 4.5 and Appendix 4K and 4L). This is expected as this season coincides with maximum temperatures and sunshine amounts and hence maximum outdoor water use. However, in the district meter and small water supply areas, relationships between short-term domestic water demands and the antecedent and prevailing day's weather conditions over the aggregated summer seasons are seldom strong, with no one weather variable producing significantly stronger or weaker relationships with demand than another.

Table 4.5: The relationship between environmental variables and short-term domestic water demands in each season in Malham (correlation coefficient – r)

Weather	*Seasons*			
	Summer	*Autumn*	*Winter*	*Spring*
Rainfall (mm)	0.57-	0.37-	0.00	-0.45
Sunshine (hrs)	0.53+	0.20+	0.00	0.41+
Temperature (°C)	0.73+	0.11+	0.00	0.28+

Key: ***+ indicates a positive relationship with demand***
- indicates a negative relationship with demand

The strongest relationships between aggregated summer short-term domestic water demands and maximum temperature, sunshine amounts and rainfall in the district meter and small water supply areas were recorded in Malham with correlation coefficients of 0.73, 0.53 and –0.57, respectively. One possible explanation why stronger relationships were observed between aggregated summer short-term domestic water demands and weather in Malham is that the area is a control site. Malham, therefore, has no water saving devices limiting the amount of water used, particularly during outdoor water consuming activities associated with hot/dry weather, such as garden watering. Yet if this explanation were true, short-term domestic water demands in the district meter areas and Conistone would also be expected to experience similar relationships with weather. However, this is not the case. Out of all five small water supply areas in Yorkshire, short-term domestic water demands in Conistone display the weakest relationships with weather. The second theory hypothesizes that stronger relationships between short-term domestic water demands and weather were found in Malham because water consumption data were only available for the summer months of 1997 and 1998. This period therefore excludes the severe drought and hose-pipe ban of 1995 and 1996. Consequently, no restrictions were made on the amount of water people consume during this monitoring period. However, relationships between aggregated summer short-term domestic water demands and weather in the district meter areas of Wales (which also excludes the severe drought and hose-pipe ban of 1995 and 1996) did not prove as strong as in Malham. The third theory hypothesizes that stronger relationships between aggregated summer short-term domestic water demands and weather in Malham result from the high proportion of detached properties. However, relationships between the aggregated summer short-term domestic water demands and weather in other areas with a high proportion of detached properties are not as strong. As can be recalled from section 4.6, the characteristics of the population base in Malham (a high proportion of affluent retired residents with ample opportunity for water consuming activities such as garden watering) may also result in a stronger relationship between aggregated summer short-term domestic water demands and weather.

When the summer seasons in individual years were examined, numerous relationships in both the small water supply areas of Yorkshire and the district meter areas of Wales proved insignificant (see Appendix 4K and 4L for details). In many cases, the correlation coefficients between short-term domestic water demands and weather were insignificant because of data paucity. In the summer of 1997 in Starbotton, for example, only seven days consumption data were available for analysis. There are, however, many areas where sufficient data for a single summer season exists, that fail to exhibit a significant relationship between weather and water demand. This suggests two explanations: (i) that it requires several years of summer data to develop a sufficient range of weather values to show a significant relationship and (ii) that multiple criteria must be satisfied before the demand is explained and can be observed (e.g. (a) no hose-pipe ban (b) no water saving devices (c) a sufficient range of weather variation and (d) an adequate proportion of houses/households with water using requirements).

Relationships between short-term domestic water demands and the antecedent and prevailing day's weather conditions over the aggregated spring and autumn seasons and the individual years displayed similar characteristics to those observed during the summer seasons (see Appendix 4K and 4L for details). However, in the majority of cases, the correlation coefficients were slightly weaker. Many relationships between short-term domestic water demands and weather also proved insignificant when the spring and autumn seasons in individual years were examined. In Malham, for example, water consumption data were only available for autumn 1997, of which October 1997 was missing. This again suggests that it requires several years of autumn and spring data to develop a sufficient range of weather values to show a significant relationship and that multiple criteria must be satisfied before the demand is explained and can be observed.

As expected, relationships between short-term domestic water demands and environmental variables for the aggregated and individual winter seasons proved insignificant. It is highly probable that at this time of year, domestic water consumption is represented only by in-house use although values may be complicated by leakage uncorrected in the figure (see section 4.7.1 for details).

4.10 Summary of environmental variables and short-term domestic water demands

In the district meter and small water supply areas, many significant relationships between short-term domestic water demands and environmental variables were identified. The two days antecedent and prevailing day's weather conditions appear to exert the greatest influence on short-term domestic water demands. The strength of the relationships between short-term domestic water demands and environmental variables appear to be influenced by the proportion of detached properties in an area and the number of affluent, retired residents. However, the relationships between short-term domestic water demands and environmental variables are seldom strong, with environmental variables explaining only a small amount of observed variance. It appears that several factors may have influenced the relationships between short-term domestic water demands and environmental variables, including:

(i) Data paucity.
(ii) Public holidays and bank-holidays.
(iii) School holidays and industrial 'shutdown' weeks.
(iv) 'Day of the week' consumption patterns.
(v) The hose-pipe ban enforced by Yorkshire Water in 1995 and 1996.
(vi) The influx of tourists as all five small water supply areas are popular tourist destinations within the Yorkshire Dales, as are some of the district meter areas in Wales.
(vii) The rise and fall of people migrating to and from second home residences as many of the areas studied appear to be popular second home destinations.
(viii) Unidentified leakage.
(ix) Incorrect calculation of non-household water use.
(x) Failure to adequately calibrate and maintain water meters and loggers.
(xi) The implementation of demand management measures.

In an attempt to explain better variations in short-term domestic water demands, further investigations were, therefore, undertaken.

4.11 Day of the week and short-term domestic water demands

To investigate the influence of 'day of the week' on short-term domestic water demands, data in the district meter and small water supply areas were subdivided into weekends and weekdays (see section 3.14.3.1 for details). Weekend water consumption in the small water supply areas and the district meter areas, with the exception of four, College Street, Margaret Street and Wind Street, Ammanford, and Church Street, Newport, displayed significantly higher means, medians, modes and quartiles in comparison to weekday water consumption (see Appendix 4M for details). In the district meter areas, the average percentage increase in domestic water consumption from weekdays to weekends is 10.36%, ranging from 3.48% in The Woodlands, Newport, to 22.06% in Excalibur Drive, Cardiff. In the small water supply areas, the average percentage increase is 8.81%, ranging from 6.80% in Buckden to 12.42% in Kettlewell.

It appears that domestic water consumption may not be significantly higher during weekends in College Street, Margaret Street and Wind Street, Ammanford, and Church Street, Newport, due to the large proportion of economically inactive persons. Out of all district meter and small water supply areas, College Street and Margaret Street, Ammanford, display the highest percentage of economically inactive persons (see Appendix 4B for details). In College Street and Wind Street, Ammanford, and Church Street, Newport, a large proportion of the population are pensioners. In Margaret Street, Ammanford, only a small proportion of the population are pensioners (less than 5%). However, approximately 58% of the population is comprised of struggling, multi-ethnic areas and council tenants with high unemployment. In The Woodlands, Newport, the area displaying the lowest percentage increase in weekend water consumption, a relatively high proportion of the population (39%) is also economically inactive pensioners. In comparison, in Excalibur Drive, Cardiff, the area displaying the highest percentage increase in weekend consumption, only 16% of the population are economically inactive. The majority of this area is comprised of students, young blue-collar families and educated white-collar residents. It appears that the percentage difference between weekend and weekday water consumption is related directly to the proportion of the population who are economically active. The larger the proportion of population who are economically active, the larger the difference in weekend and weekday water consumption. This is obviously because less time is spent at home during weekdays, and hence less water is consumed.

In the small water supply areas of Yorkshire, the maximum instantaneous water use was recorded during weekends and bank-holidays in the summer season in all areas except Conistone. Maximum instantaneous water use is expected in the summer, as this season coincides with maximum temperatures and sunshine amounts and hence maximum outdoor water use. In Conistone, the maximum instantaneous water use was surprisingly recorded on Friday the 27th of March, 1998 with a value of 51.87 m^3/day. Further analysis revealed that this value appears anomalous, particularly when consumption on the 26th and 28th of March, 1998 was 16.46 m^3/day and 26.63 m^3/day, respectively. However, when the value of 51.87 m^3/day was removed, the maximum instantaneous water use of 50.47 m^3/day occurred on Saturday the 29th of July, 1998 in Conistone, a more realistic outcome. In the district meter areas of Wales, the biggest number of maxima (40%) occur in summer, as expected. However, there are still significant spring numbers (30%) and some in autumn (13%) and winter (17%). These cannot be identified without component use monitoring but bursts and leakage in winter may have an effect as will replenishment of parks, ponds and gardens in spring.

Minimum instantaneous water use was recorded outside the summer months in all of the small water supply and district meter areas, with the exception of Brynfedw West, Cardiff. All areas, except Starbotton, also witnessed their lowest instantaneous water use on a weekday. During winter, minimum instantaneous water use was recorded in 70% of the district meter and small water supply areas. These figures appear realistic, as it is highly probable that at this time of year water consumption is represented only by in-house use. Just under two-thirds of the minimum instantaneous water use values recorded during the winter months occurred on the 25th of December. This is undoubtedly because on Christmas day, the majority of the population will not use water-consuming appliances such as washing machines.

To investigate whether short-term domestic water demands are influenced by particular days of the week, data in the small water supply and district meter areas were subdivided into individual days of the week (see section 3.14.3.1 for details). As Table 4.6 and Appendix 4N indicate, there was no obvious pattern in day of the week water consumption; for example, one particular day of the week did not produce consistently the highest or lowest water consumption.

Table 4.6: Day of the week domestic water consumption in the small water supply areas of Yorkshire (m^3/day)

Day of the Week	*Small Water Supply Area*				
	Buckden	*Conistone*	*Kettlewell*	*Malham*	*Starbotton*
Monday	37.00	20.08	50.08	138.46	19.81
Tuesday	35.90	19.38	47.92	135.69	18.65
Wednesday	35.77	19.38	48.46	132.92	17.88
Thursday	35.61	18.69	48.25	130.15	18.73
Friday	35.23	20.31	51.69	139.02	19.23
Saturday	40.77	24.00	62.46	158.40	21.46
Sunday	40.38	23.31	60.85	157.85	21.73

4.12 Environmental variables and weekend and weekday water consumption

It was hypothesized that the influence of environmental variables on weekend and weekday water consumption would differ. If, for example, the last two weekdays prior to the weekend were hot and dry, it was anticipated that the increase in weekend water consumption would be proportionately greater than the corresponding increase in weekday water consumption, if the first two days of the week were hot and dry. A possible reason for this is that with a greater number of people at home during the weekend, there is greater opportunity for outdoor water consumption. The effects of environmental variables on weekend and weekday water consumption were therefore investigated (see Appendix 4O for details). Many of the relationships between weekend and weekday water consumption and environmental variables proved insignificant, undoubtedly due to data shortage. Where significant relationships between weekend and weekday water consumption and environmental variables were observed, similar patterns to those for the entire data set were found (see section 4.8 for details). Rainfall produced negative correlation coefficients with weekend and weekday water consumption while sunshine amounts and maximum temperatures produced positive correlation coefficients. The strength of the correlation coefficients increased steadily to about two or three cumulative days previous before remaining constant or declining (Figure 4.15). However, although statistically significant, the relationships are weak with weather appearing not to exert a particular relation to either weekend or weekday consumption data (Table 4.7).

Table 4.7: Examples of the relationship between environmental variables and weekend and weekday water consumption (correlation coefficient – r)

Weather	*Small Water Supply Areas*							
	Buckden		*Conistone*		*Malham*		*Starbotton*	
	Weekday	*Weekend*	*Weekday*	*Weekend*	*Weekday*	*Weekend*	*Weekday*	*Weekend*
Rainfall (mm)	0.29-	0.29-	0.14-	0.17-	0.35-	0.35-	0.28-	0.25-
Sunshine (hrs)	0.48+	0.50+	0.42+	0.43+	0.55+	0.69+	0.53	0.53+
Temperature (°C)	0.54+	0.43+	0.49+	0.52+	0.64+	0.57+	0.52	0.60+

Key: ***+ indicates a positive relationship with demand***
- indicates a negative relationship with demand

4.13 Summary of 'day of the week' and short-term domestic water demands

Short-term domestic water demands in the district meter and small water supply areas are influenced by 'day of the week'. Increases in short-term domestic water demands are typically associated with weekends. This is expected as significantly more people remain at home during weekends, and are, therefore, likely to consume more water. However, the percentage increase in short-term domestic water demands associated with weekends appears to be related directly to the proportion of the population who are economically active. The larger the proportion of population who are economically active, the larger the difference in weekend and weekday water consumption. Results from the analysis of weekend and weekday water consumption and weather suggest that weather does not exert a particular relation to either weekend or weekday consumption. Both weekend and weekday water consumption would, therefore, experience a similar increase in demand if the two days antecedent and the prevailing day's weather conditions were hot and dry. Similarly, if the two days antecedent and prevailing day's weather conditions were cold and wet, both weekend and weekday water consumption would experience a similar reduction in demand.

4.14 School holidays and short-term domestic water demands

The influence of school holidays on short-term domestic water demands was investigated using school holiday data provided by some Local Education Authorities (see section 3.14.3.2 for details). In the small water supply areas of Yorkshire, a relationship was found between domestic water consumption and school holidays. Although there was no obvious variation in weather during some school holidays, domestic water consumption in the small water supply areas increased on average by 26%. During the October 1995 half-term school holiday in Kettlewell, for example, a 44% increase in domestic water consumption was recorded (Table 4.8).

Table 4.8: Domestic water consumption before, during, and after the October 1995 half-term in Kettlewell. The water consumption is the average of the Monday to Friday values.

Date	*Average Water Consumption (m^3/day)*	*Maximum Temperature (°C)*	*Sunshine (hours)*	*Rainfall (mm)*
Prior half-term	43.31	12.16	3.62	2.84
During half-term	62.24	12.04	3.08	3.18
After half-term	40.90	10.26	3.24	0.28

In some district meter areas of Wales, school holidays appeared to cause an increase in domestic water demands. However, there appeared to be no obvious difference between those district meter areas where school holidays caused an increase in domestic water demands, and those district meter areas where school holidays appeared to have no influence. Those district meter areas where school holidays were found to influence domestic water demands, for example, did not display a higher proportion of children to adults. It is, therefore, unclear why a positive relationship between domestic water consumption and school holidays occurs in all of the small water supply areas but in only some of the district meter areas. One possible explanation is that the small water supply areas are small, relatively isolated communities with only one school. The majority of children from the community attend the 'local' school. Therefore, when there is a school holiday, there is an immediate increase in domestic water demands as the children and perhaps some adults remain at home and hence consume water. In comparison, the district meter areas cover the whole of Wales, including major urban areas. The district meter areas may cut across school catchment areas where the dates of school holidays differ. There may also be increased opportunity for children to attend public or state schools. As can be recalled from section 3.14.1.2, holidays for public and state schools may differ. These differences may result in a diminution of the clarity of the signal in the domestic water demand data. However, a second possible explanation why school holidays did not appear to influence domestic water consumption in some district meter areas is due to Welsh Water's methodological approach to calculating domestic water consumption (see section 3.7.1.1 and 3.7.1.2 for details). Increases in domestic water consumption associated with school holidays may be assigned to non-household water use or leakage.

4.15 Demand management techniques and short-term domestic water demands

Yorkshire Water's small water supply area data provided the opportunity to evaluate the influence of demand management techniques on short-term domestic water demands. During the 1995 drought, several areas of Upper Wharfedale in the Yorkshire Dale's National Park, including Kettlewell, Starbotton and Buckden (see section 3.7.2 for details), had to have their water supplied by tankers as their own supplies had diminished (these areas are fed by springs and are not connected to the main distribution network). At that time, Yorkshire Water introduced several demand management techniques (leakage control, domestic metering, water saving technology e.g. pressure reduction valve and cistern displacement devices and education/awareness of residents) in an attempt to reduce domestic water consumption in these areas.

As this conservation project was based on adaptations made in response to a supply problem, no monitoring period was established before demand management techniques were introduced. Moreover, the exact timing of the actions is unknown and was spread over several months. The most viable solution to the problem of a lack of a benchmarking period is to use similar areas (where no demand management techniques have been enforced) as controls. Two control areas, Malham and Conistone, were selected. These are also villages in the Yorkshire Dales National Park close to the demand management villages (Figure 3.3).

Research has identified that several underlying factors influence water demand on the medium- to long-term (e.g. Thackray *et al.*, 1978; Water Research Council, 1997). Household size was found to exert the greatest influence on per capita domestic water demand, with a reduction in per capita consumption with greater household size (Morgan, 1973; Turton and Smith, 1976; Danielson, 1979; Power *et al.*, 1981; Agthe *et al.*, 1988; Edwards and Martin, 1995) (see section 2.5.4 for details). It is important therefore that household sizes in control and study sites should be similar. The student t-test indicated that there was no significant difference between the mean household size in all areas at the 99% significance level. Nevertheless, the control areas will always be 'questionable' as comparison sites.

Throughout this analysis, no significant differences have been observed in the relationship between domestic water consumption and geodemographic variables, environmental variables and other factors external to environmental variables, in the demand management areas and the controls. This suggests that the factors influencing short-term domestic water demands are similar in the demand management areas and the controls. The only difference may be that overall consumption for water in the demand management areas has been suppressed. Thus a different approach is needed to assess the effectiveness of the demand management measures. An analysis technique was required which could identify a slow change in water consumption rate between the test and control sites against a background of strong diurnal and seasonal periodicity within a record containing substantial random gaps and residual anomalies. Single mass curves, a well-established hydrological analysis tool (Chow, 1964), matched most of these requirements.

Single mass curves were applied to domestic water consumption in each of the five areas. Domestic water consumption was cumulated and where data gaps existed, the gaps were closed.

Cumulative domestic water consumption for each area was then plotted against the number of data points, producing a single mass curve (Figures 4.16-4.20). A straight line was then inserted from the first to the last water consumption value. This straight line represents the constant long-term demand for water in the community. When the slope of the single mass curve is steeper than that of the straight line, water consumption is above the constant and when shallower than the slope of the straight line, water consumption is below the constant.

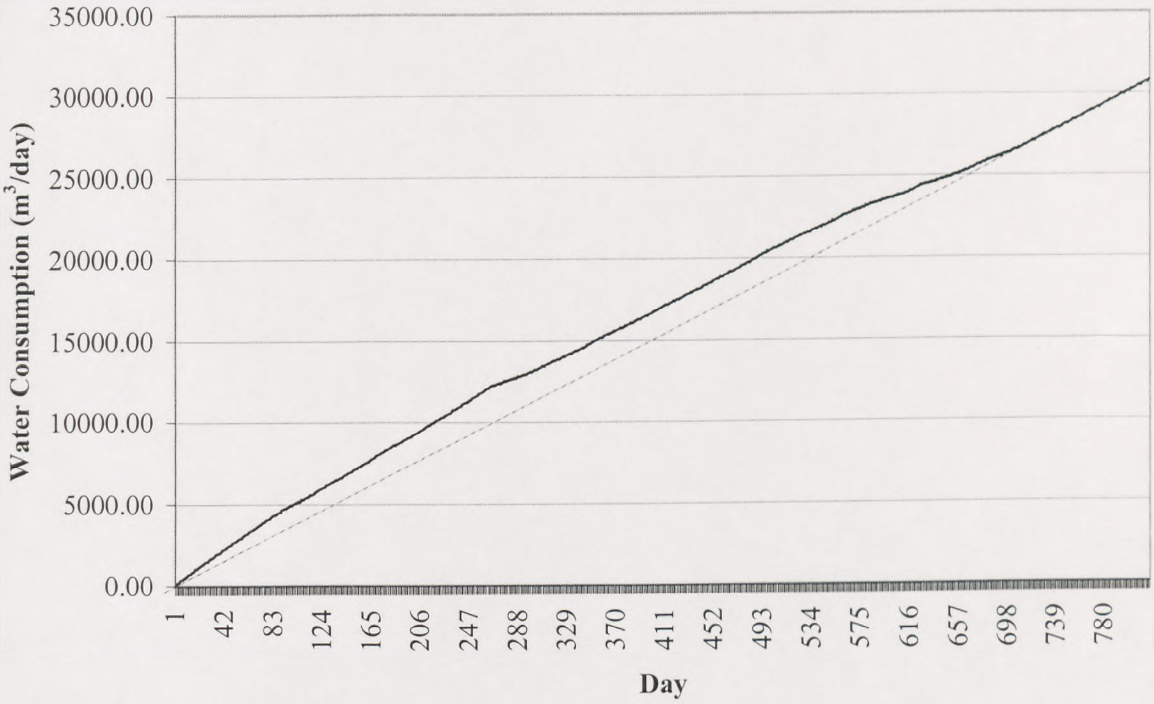


Figure 4.16: Single mass curve for domestic water consumption in Buckden (demand management area)

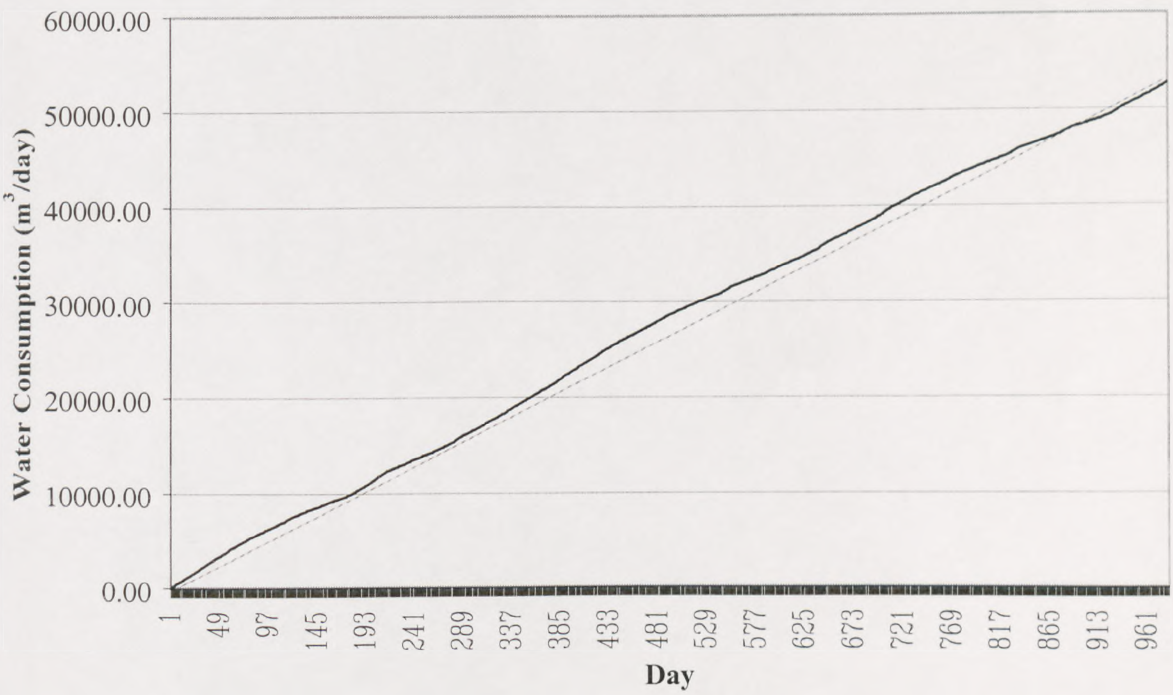


Figure 4.17: Single mass curve for domestic water consumption in Kettlewell (demand management area)

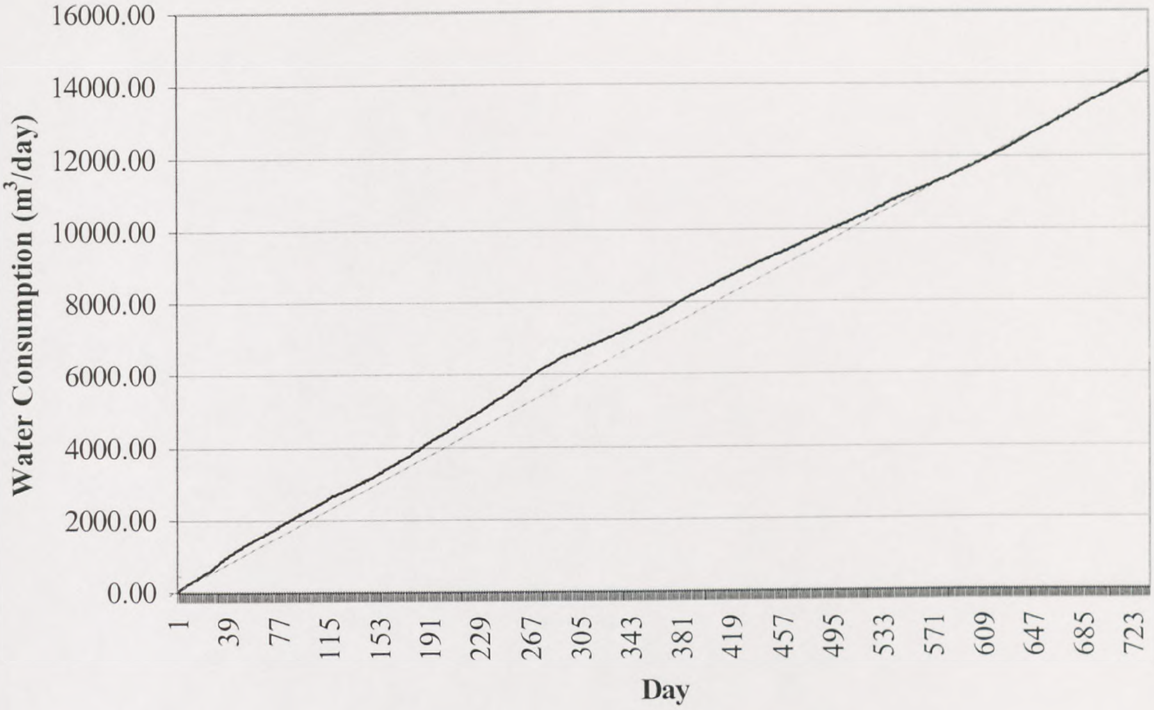


Figure 4.18: Single mass curve for domestic water consumption in Starbotton (demand management area)

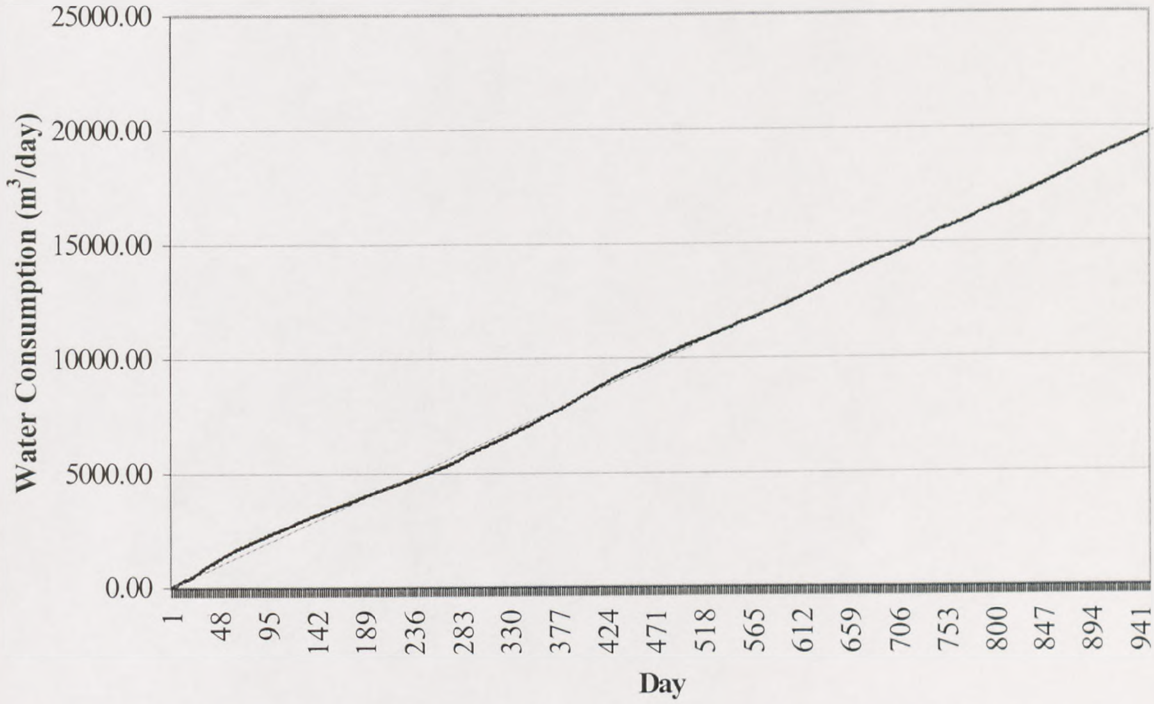


Figure 4.19: Single mass curve for domestic water consumption in Conistone (control area)

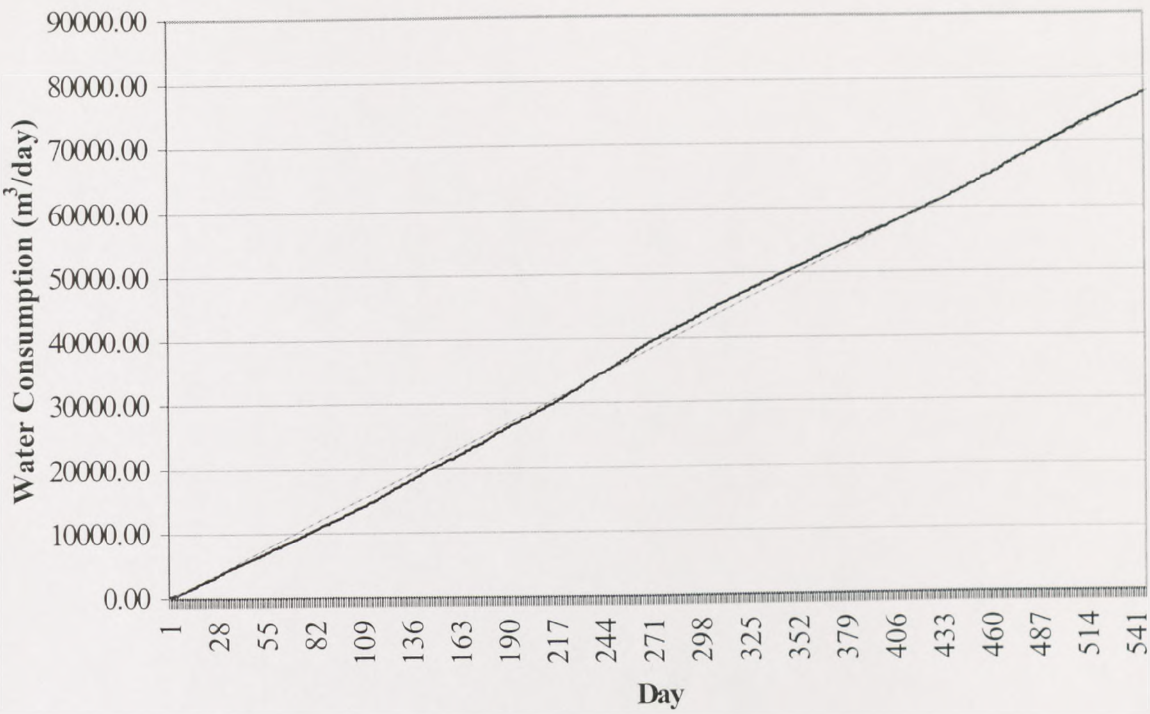


Figure 4.20: Single mass curve for domestic water consumption in Malham (control area)

4.16 Findings from the single mass curves

The single mass curves indicate that the variation in long-term domestic water demands in the two control areas is substantially less than areas where demand management techniques had been implemented. In the latter areas, domestic water consumption is initially above the long-term water demand for the study period. Progressively, water consumption begins to decline and in the final phase of the analysis period is below the 'long-term' demand. However, placing a numerical value on the level of the demand reduction is problematic. A superficial analysis of the demand levels based on the slope of the trend line at the beginning and end of the project might suggest a value of about 26%. However, this would be inaccurate because the slope of the line depends upon the length of the slope over which the trend (straight line) is developed. Anything less than a year will be in error because of the already demonstrated seasonal fluctuations (see section 4.4.4 for details). The superficial analysis described above incorporates both seasonal effects and demand control effects.

A more accurate estimate is derived from the differences in the slopes of the trend lines over the period of a year from the outset of the record period and at the end of the record period (Figure 4.21-4.23). The estimated aggregate decline in water demand is outlined in Table 4.9.

Table 4.9: The Estimated Aggregate Demand for Water in Kettlewell, Starbotton and Buckden

Site	*Initial Demand (m^3d^{-1})*	*Final Demand (m^3d^{-1})*	*Change (%)*
Kettlewell	56.52	48.04	15.00
Starbotton	21.71	17.76	18.19
Buckden	45.77	33.09	27.70
Average			20.00

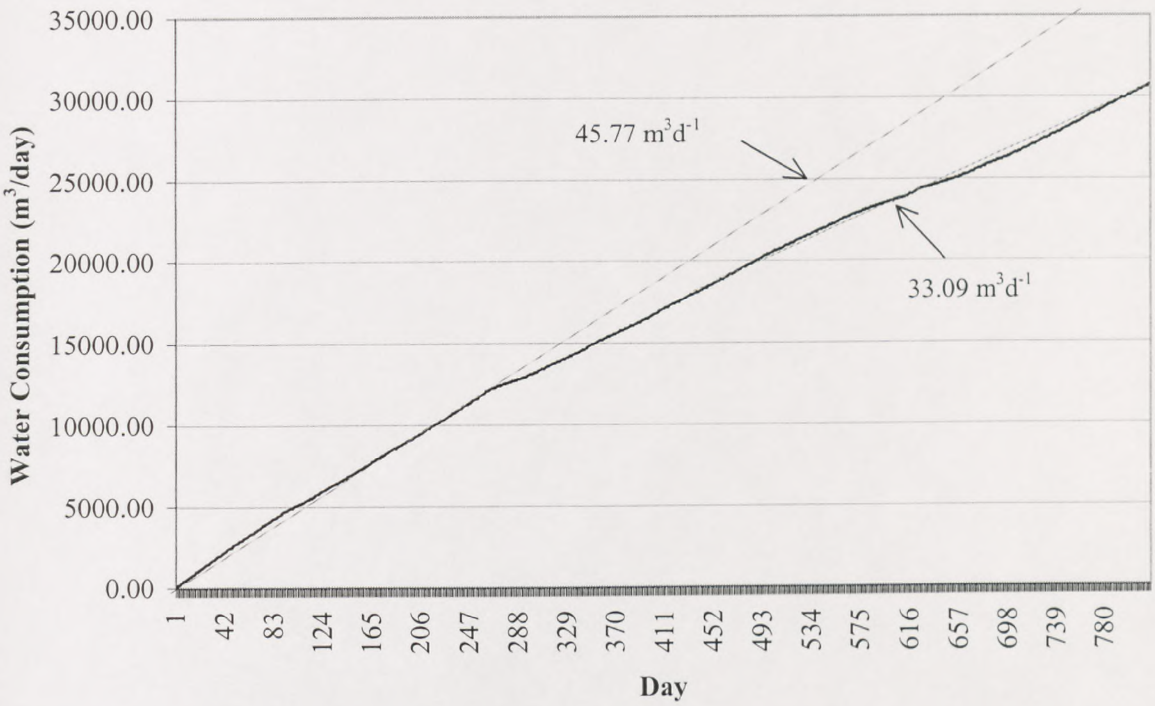


Figure 4.21: Trend lines over a period of a year in Buckden

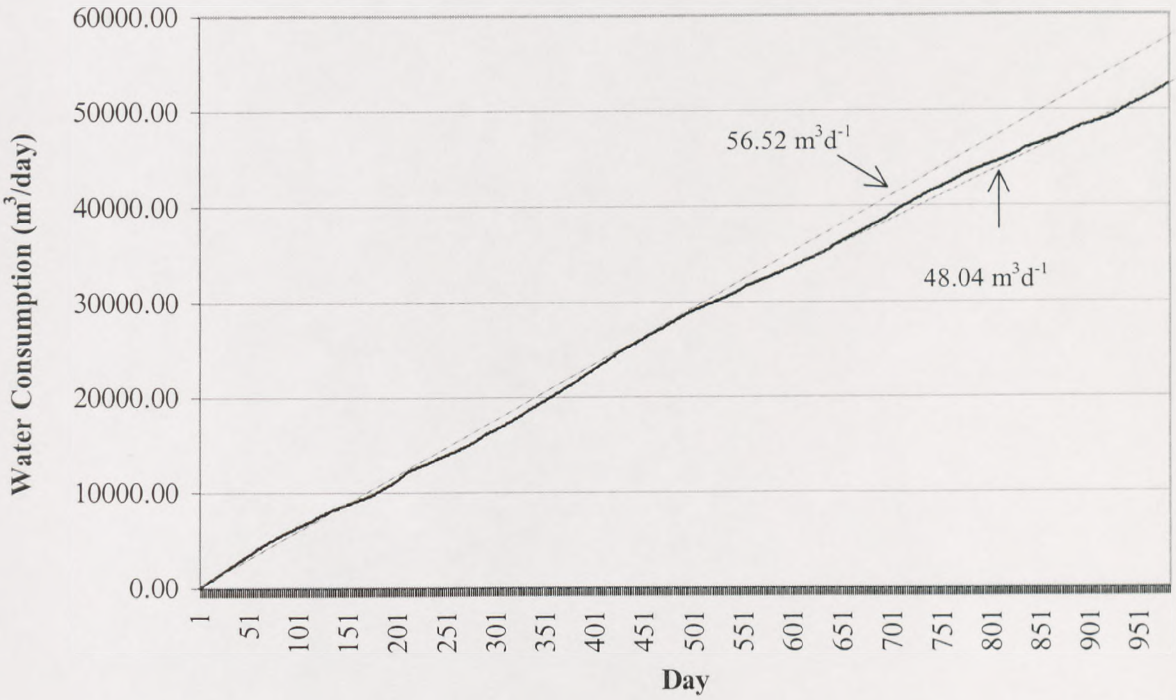


Figure 4.22: Trend lines over a period of a year in Kettlewell

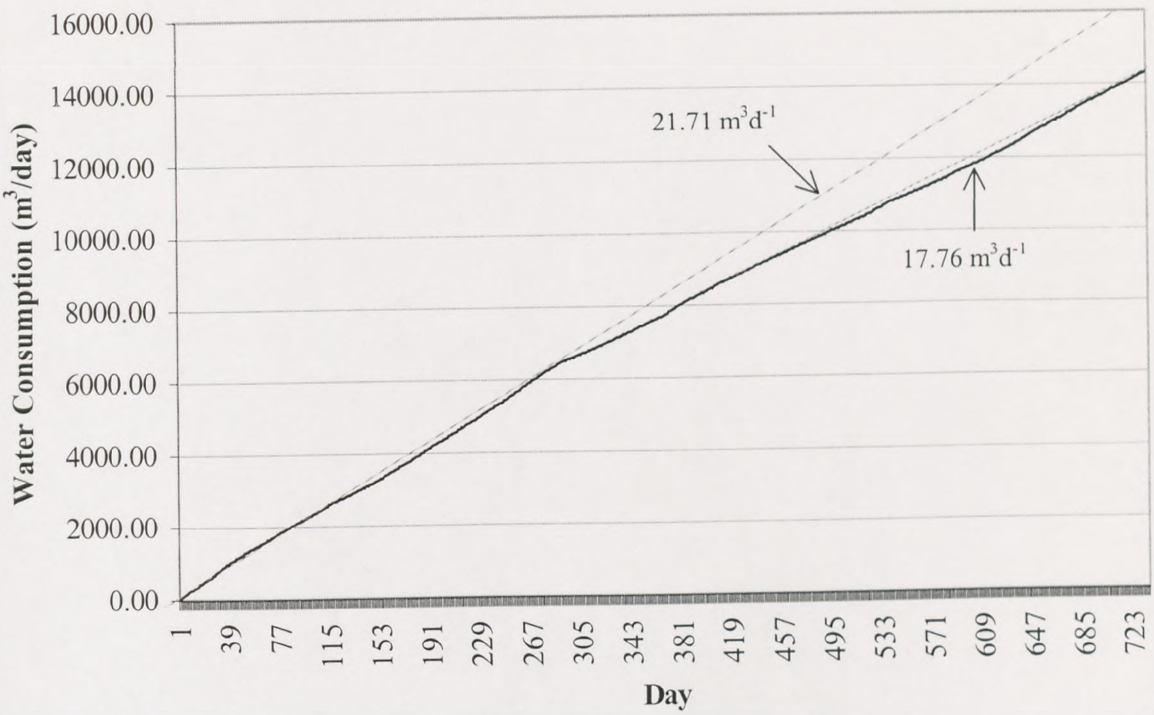


Figure 4.23: Trend lines over a period of a year in Starbotton

The introduction of demand management measures may be a possible explanation for this apparent decline in water use. However, it is impossible to say absolutely because the exact dates when the demand management measures were implemented are not known. For a more accurate analysis of the influence of demand management measures on domestic water demands, it is vital to know exactly when the demand management measures were introduced and what the uptake rate was in each of the areas. It may be that some form of lag exists between the implementation of demand management measures and the reduction in domestic water consumption. Further, a longer period of monitoring covering a range of climate and related water controlling conditions is required to clarify the analysis.

4.17 Summary

This chapter suggests that many factors influence domestic water demands in both the short- and the medium- to long-term. In the medium- to long-term, domestic water demands appear to be influenced by property type, economic activity of the population, levels of affluence and the implementation of demand management measures. In the short-term, domestic water demands appear to be influenced by the two days antecedent and prevailing day's weather, day of the week, calendar effects and school holidays. This chapter has also highlighted the need for good quality water consumption data (i.e. continual maintenance of water meters and loggers) to improve confidence in the results. In the Welsh Water study, confidence in the results would be improved significantly if Welsh Water had detailed their methodological approach to calculating leakage and non-household water use.

The next chapter uses individual household water consumption data to determine whether factors that influence domestic water demands in both the short- and the medium- to long-term in Wales and the small water supply areas of Yorkshire are similar to the whole of Yorkshire and the South East of England.

5. Factors Affecting Short-Term Domestic Water Demand in the Individual Household Studies

5.1 Introduction

This chapter uses data from two areas, the South East of England and Yorkshire. The data for these two areas, provided by Essex and Suffolk Water, Thames Water and Yorkshire Water, is a measure of consumption in individual households. As in Chapter 4, this chapter is concerned with factors that influence the demand for water in the short-term. As can be recalled from section 4.1, there are a number of underlying factors that influence both short- and medium- to long-term demand. Data from Essex and Suffolk Water, Thames Water and Yorkshire Water have been used to explore underlying factors but, due to the low frequency of meter readings, Essex and Suffolk Water data are not employed in the short-term water demand studies.

5.2 Characteristics of the individual household studies

When Essex and Suffolk Water, Thames Water and Yorkshire Water commissioned their individual household water use studies, questionnaires were issued to all participating households. Although the contents of the questionnaires were similar, slight variation in the content exists. Table 5.1 summarizes the characteristics of the three questionnaire data sets (see section 3.11.1 for details).

Table 5.1: Characteristics of the questionnaires from the individual household studies

Questionnaire contents	*Essex and Suffolk Water*	*Thames Water*	*Yorkshire Water*
Household size	✓	✓	✓
Age of population	✓	✓	✓
Property type	✓	✓	✓
ACORN classification		✓	✓
Water use classification	✓		
Rateable value	✓	✓	
Garden size	✓	✓	
Individual appliance ownership	✓	✓	✓

5.2.1 Household size

The households included in the three individual consumption studies display similar distributions in size (Figures 5.1-5.3). Two-person households are the most common, accounting for 20.12% of the households in the Essex and Suffolk Water study compared to 41.20% in the Yorkshire Water study. One-person households are the second most common, ranging from 11.51% in the Essex and Suffolk Water study to 24.84% in the Yorkshire Water study. A broadly similar distribution of three and four-person households was found. Finally, there were less five, six, seven and eight or more person households. In fact, seven or more person households are extremely atypical, with no representation in the Essex and Suffolk Water study.

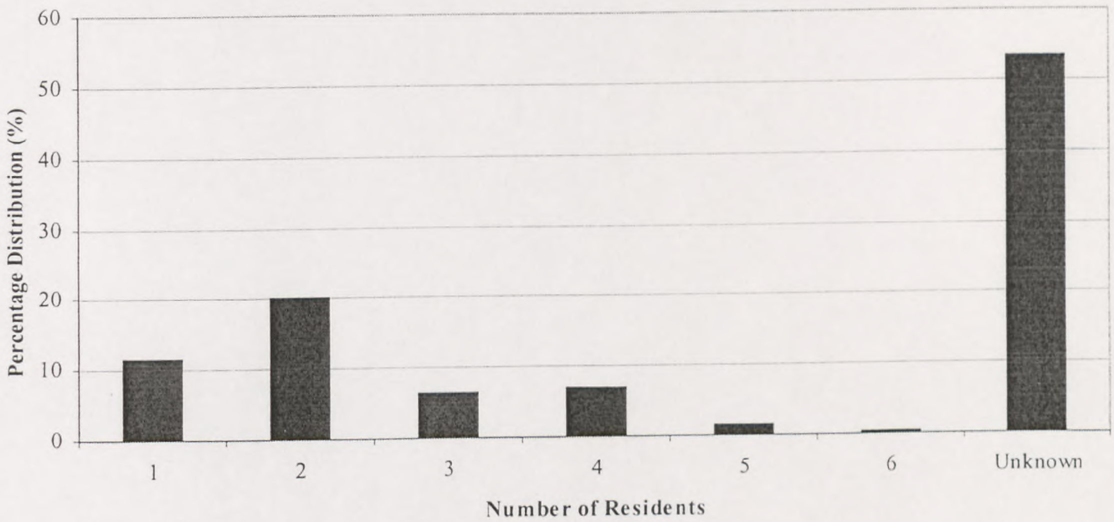


Figure 5.1: Distribution of household size in the Essex and Suffolk Water study

Figure 5.2: Distribution of household size in the Thames Water study

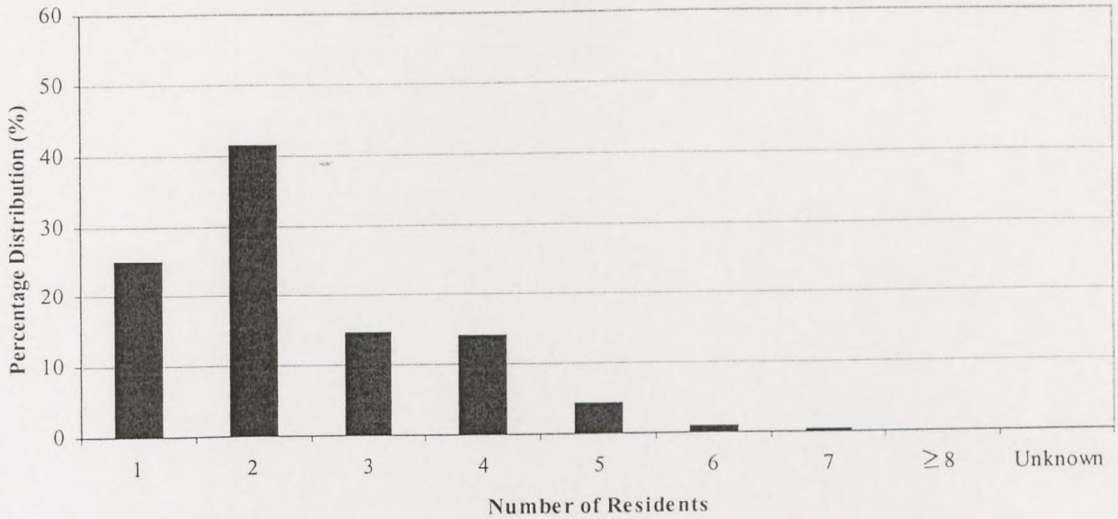


Figure 5.3: Distribution of household size in the Yorkshire Water study

5.2.2 Property type

The definition of property type used by Essex and Suffolk Water and Thames Water differs to that used by Yorkshire Water. Essex and Suffolk Water and Thames Water used the definitions detached, semi-detached, terraced or flats to classify property type. Yorkshire Water has further subdivided detached, semi-detached and terraced properties into houses or bungalows (Figures 5.4-5.6), even though the category terraced bungalows seems somewhat rare. Houses represent 75.04% of the properties included in the Yorkshire Water study while bungalows represent 19.28%.

As the definition of property type differs, a distinction must be made, for example, between semi-detached properties that incorporate both houses and bungalows, and semi-detached houses that do not include bungalows. Semi-detached properties are the most common type of property in the Essex and Suffolk Water and Thames Water studies (32.62% and 33.43%, respectively). In the Yorkshire Water study, semi-detached houses represent the largest proportion, accounting for 32.70%. In all cases, terraced properties represent over one-quarter of the properties in each study. The percentage of flats in the individual household studies is significantly higher in the Thames Water study (20.96%) compared to the Essex and Suffolk Water and Yorkshire Water studies (5.11% and 4.58%, respectively).

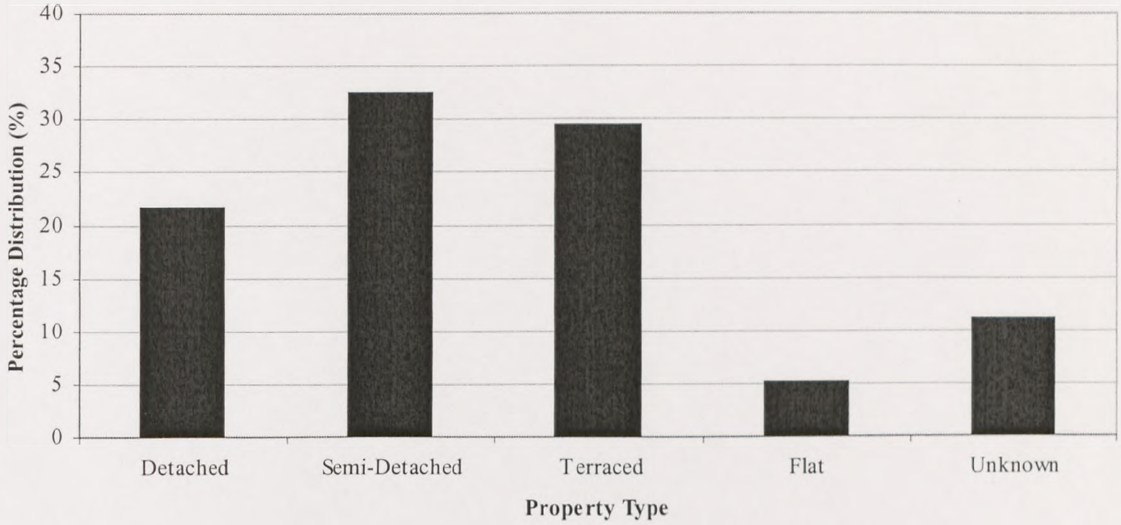


Figure 5.4: Distribution of property type in the Essex and Suffolk Water study

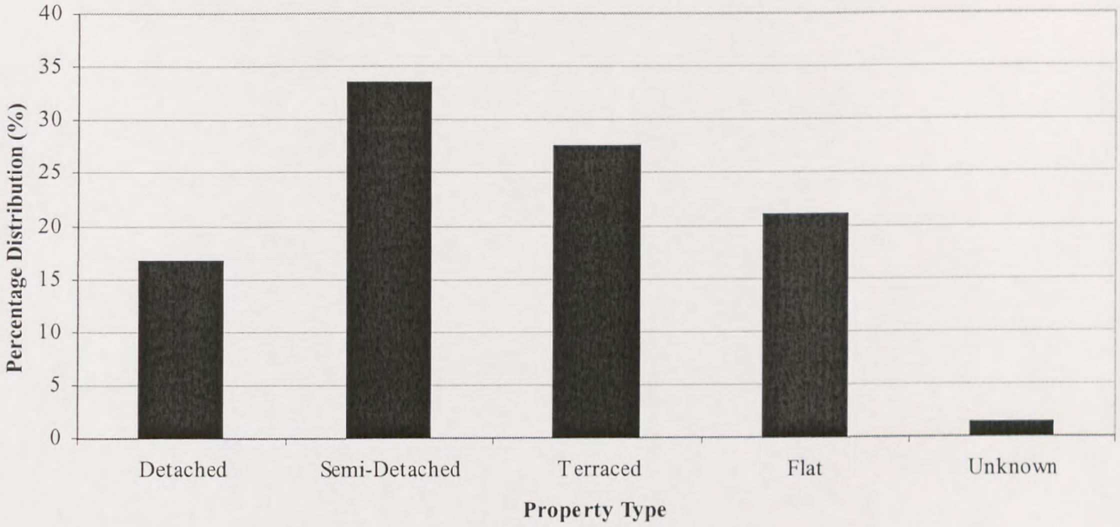


Figure 5.5: Distribution of property type in the Thames Water study

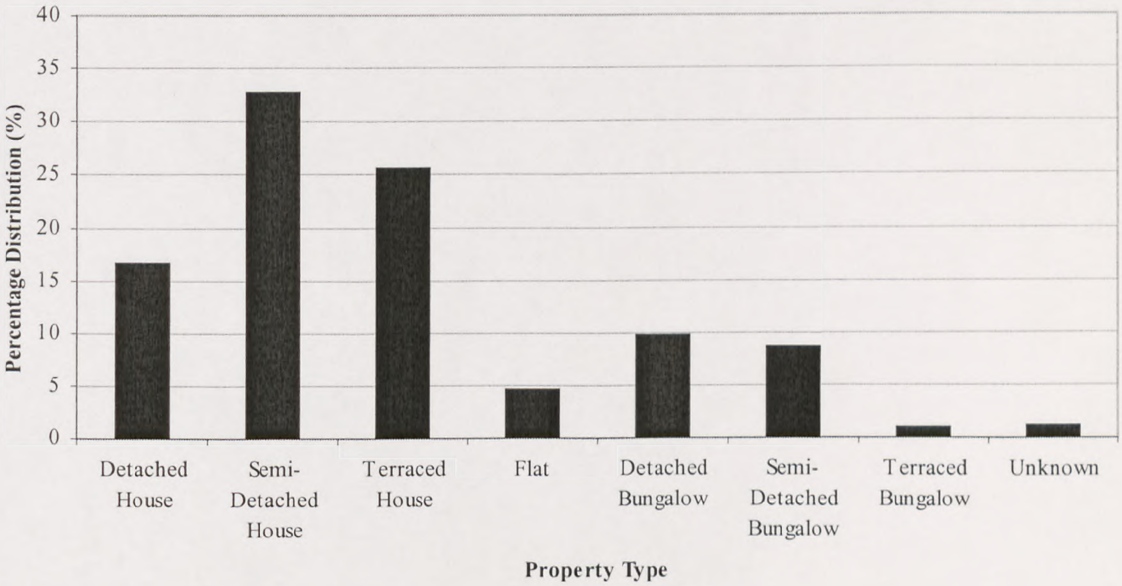


Figure 5.6: Distribution of property type in the Yorkshire Water study

5.2.3 Rateable value

Essex and Suffolk Water and Thames Water provided the rateable values of properties in their water use studies. The rateable value distribution in both studies is similar although there is a slightly larger percentage of properties in the lower rateable value bands in the Essex and Suffolk Water study (Figures 5.7 and 5.8).

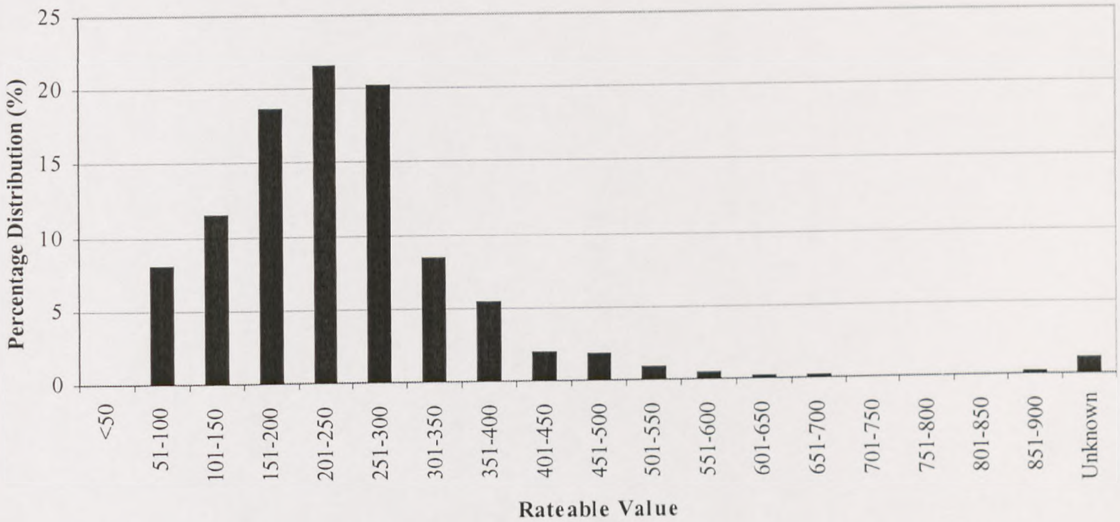


Figure 5.7: Distribution of rateable values in the Essex and Suffolk Water study

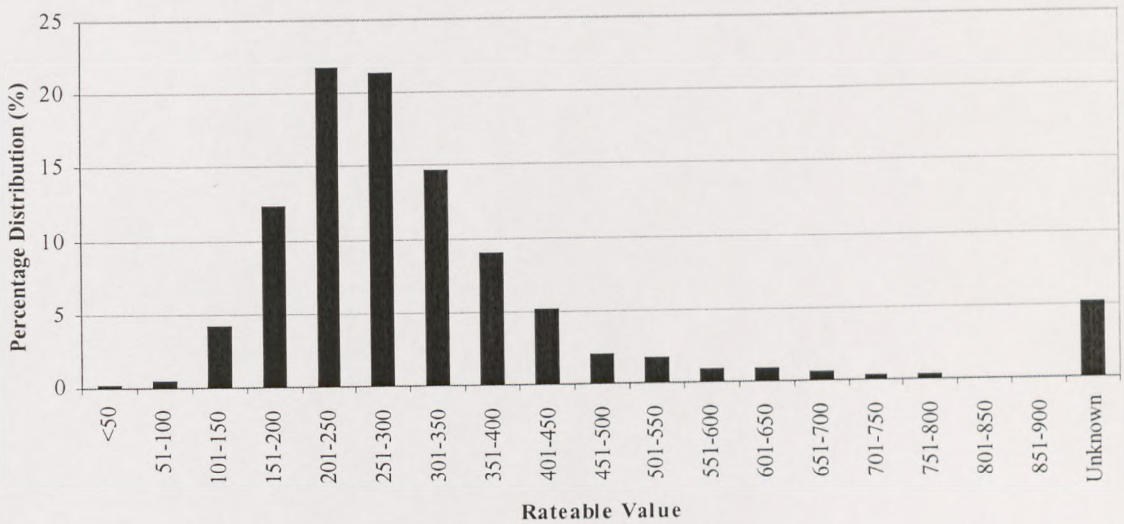


Figure 5.8: Distribution of rateable values in the Thames Water study

5.2.4 ACORN categories and water use classifications

Two approaches have been used to classify households in the domestic water use studies. Thames Water and Yorkshire Water used ACORN categories to classify households (Table 5.2). Essex and Suffolk Water used water use categories, based on a re-grouping of ACORN, to classify households into high, average and low water users (Table 5.3).

Table 5.2: Classification of households using ACORN categories

ACORN Category	*Description*
A	Thriving
B	Expanding
C	Rising
D	Settling
E	Aspiring
F	Striving

Table 5.3: Re-grouping of ACORN into estimated water use classes (Source: Ridgewell, 1999, pers. comm.)

Estimated Water Use Class	*ACORN* Category	*ACORN* Group	*ACORN* Type	*Description*
1 (High)	A	1	1	Wealthy suburbs, large detached houses
	A	1	2	Villages with wealthy commuters
	A	2	7	Holiday retreats, older people, home based workers
	F	17	54	Multi-ethnic, high unemployment overcrowding
2	C	7	20	Gentrified multi-ethnic areas
	D	9	27	Rural areas, mixed occupations
	F	14	44	Multi-occupied terraces, multi-ethnic areas
	F	17	52	Multi-ethnic, large families, overcrowding
3	A	1	3	Mature affluent home owning areas
	A	1	4	Affluent suburbs, older families
	A	1	5	Mature, well-off suburbs
	A	2	6	Agricultural villages, home based workers
	B	4	10	Affluent working families with mortgages
	B	4	11	Affluent working couples with mortgages, new homes
	B	5	14	Home owning family areas, older children
	B	5	15	Families with mortgages, younger children
	C	6	16	Well-off town and city areas
	D	9	26	Mature established home owning areas
	D	9	30	Established home owning areas, skilled workers
	E	11	35	Low rise estates, older workers, new home owners
	F	14	41	Better-off council areas, new home owners
	F	14	43	Council areas, young families, many lone parents
	F	15	49	Council flats, very high unemployment, singles
	F	16	50	Council areas, unemployment, lone parents
4	A	3	9	Private flats, elderly people
	B	4	12	Transient workforces, living at their place of work
	B	5	13	Home owning family areas
	C	6	18	Furnished flats and bedsits, younger single people
	C	7	21	Prosperous enclaves, highly qualified executives
	D	9	28	Established home owning areas
	D	9	29	Home owning areas, council tenants, retired people
	D	10	32	Home owning areas with skilled workers
	E	12	36	Home owning multi-ethnic areas, young families
	F	13	39	Home owners, small council flats, single pensioners
	F	14	42	Council areas, young families, some new home owners
	F	14	46	Council areas, residents with health problems
5	A	3	8	Home owning areas, well-off older residents
	C	6	17	Flats and mortgages, single and young working couples
	C	6	19	Apartments, young professional singles and couples
	C	7	22	Academic centres, students and young professionals
	C	8	25	Converted flats and bedsits, single people
	D	10	31	Home owners in older properties, younger workers
	E	11	33	Council areas, some new home owners
	E	11	34	Mature home owning areas, skilled workers
	E	12	38	Multi-ethnic areas, white collar workers
	F	13	40	Council areas, older people health problems
	F	14	45	Low rise council housing, less well-off families
	F	15	47	Estates with high unemployment
	F	16	51	Council flats, greatest hardship, many lone parents
6 (Low)	C	8	23	Affluent city centre areas, tenements and flats
	C	8	24	Partially gentrified multi-ethnic areas
	E	12	37	Multi-occupied town centres, mixed occupations
	F	15	48	Council flats, elderly people, health problems
	F	17	53	Multi-ethnic, severe unemployment, lone parents

In the Thames Water and Yorkshire Water studies, the distribution of ACORN categories differ (Figures 5.9 and 5.10). Rising households (ACORN category C) account for the largest proportion in the Thames Water study (26.46%) and the smallest proportion in the Yorkshire Water study (3.00%). Almost one-third of all households are classified as settling (ACORN category D) in the Yorkshire Water study while they account for less than one-fifth of all households in the Thames Water study.

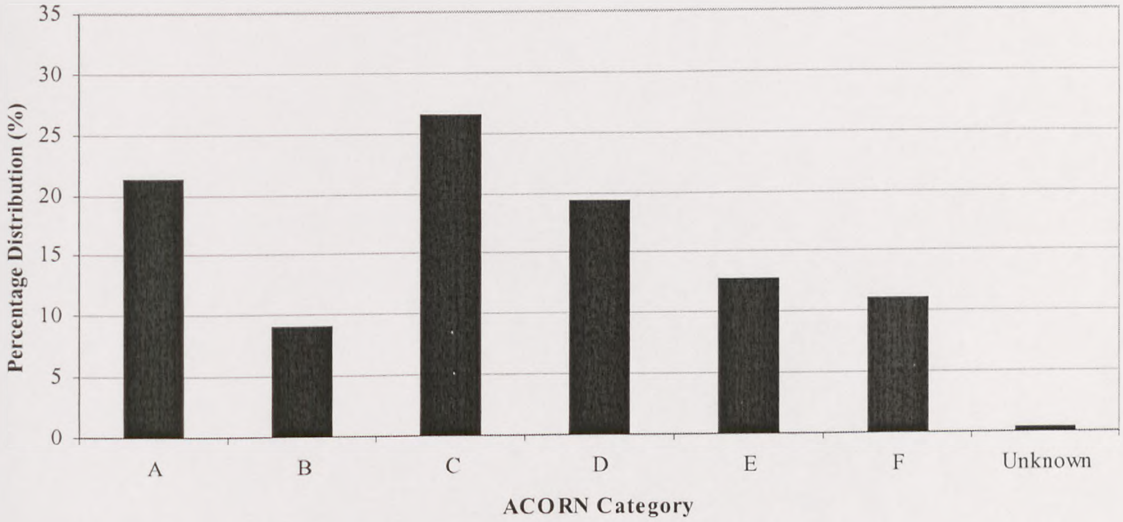


Figure 5.9: Distribution of ACORN categories in the Thames Water study

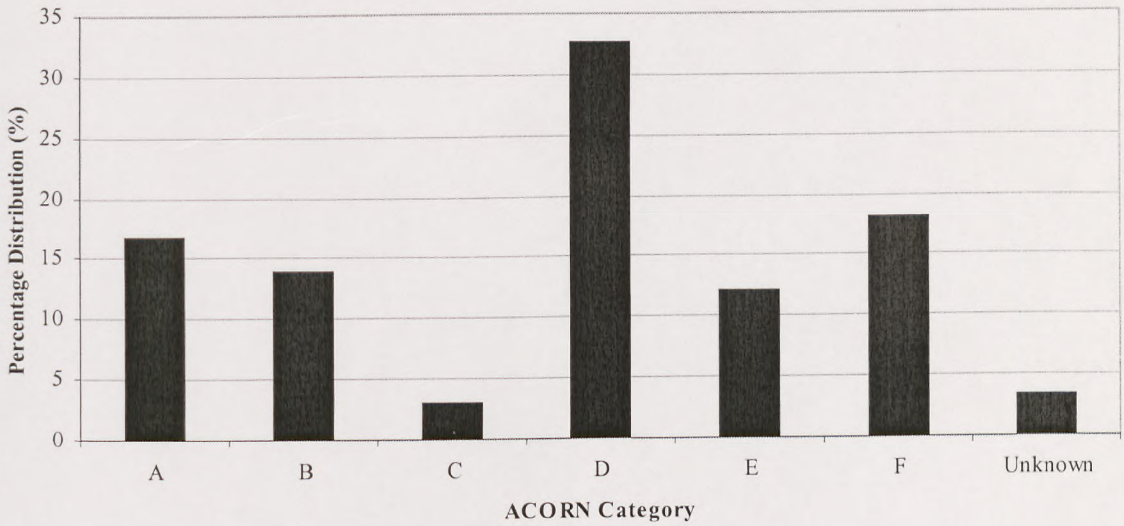


Figure 5.10: Distribution of ACORN categories in the Yorkshire Water study

In the Essex and Suffolk Water study (Figure 5.11), the majority of households are classified as average or just below average water users (84.14%). The representation of high and low water users is relatively small (2.97% and 7.39%, respectively).

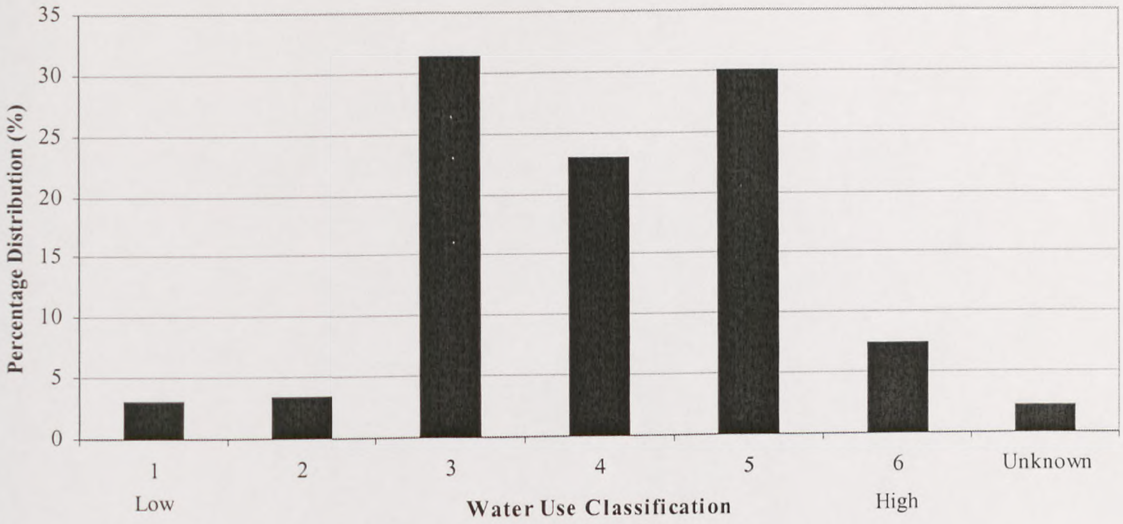


Figure 5.11: Distribution of estimated water use classes in the Essex and Suffolk Water study

5.2.5 Garden size

Essex and Suffolk Water and Thames Water provided the garden size of properties in their water use studies. Essex and Suffolk Water based garden size on a qualitative scale of one to four (small, medium, large and extra large). The majority of gardens (Figure 5.12) were, unsurprisingly, classed as medium size (45.85%) with only a small number of households with no gardens or extra large gardens in the study (0.06% and 1.43%, respectively).

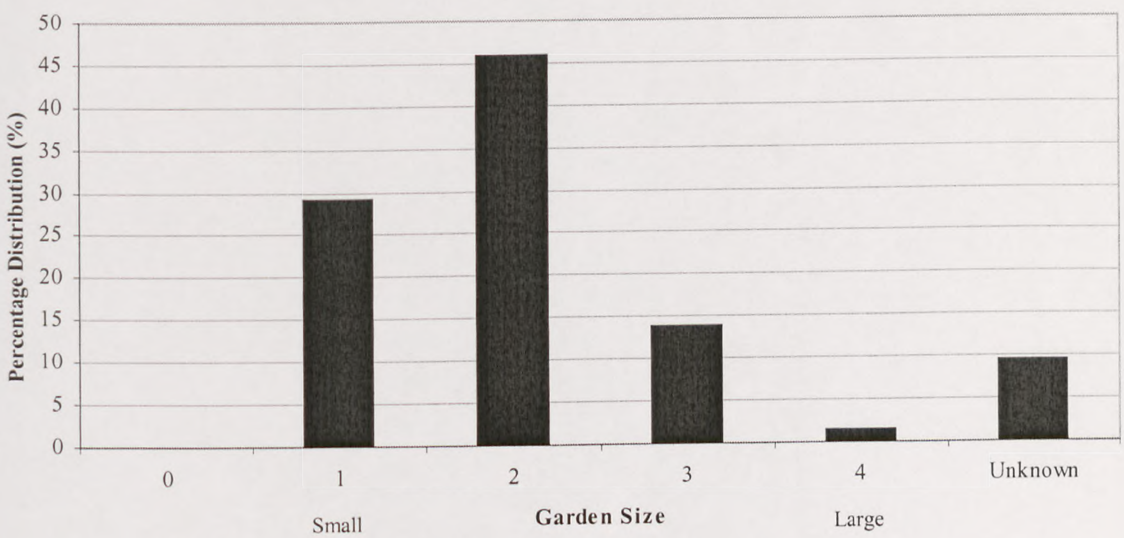


Figure 5.12: Distribution of garden size in the Essex and Suffolk Water study

A more quantitative approach, based on measurements, was used by Thames Water to determine garden size. Gardens between 1 and 100 m^2 were the most common size in the study, representing 33.08% of the total (Figure 5.13). However, a relatively large variation in garden size is evident in the Thames Water study, ranging from 11.76% of households with no garden to 2.51% with gardens over 1000 m^2.

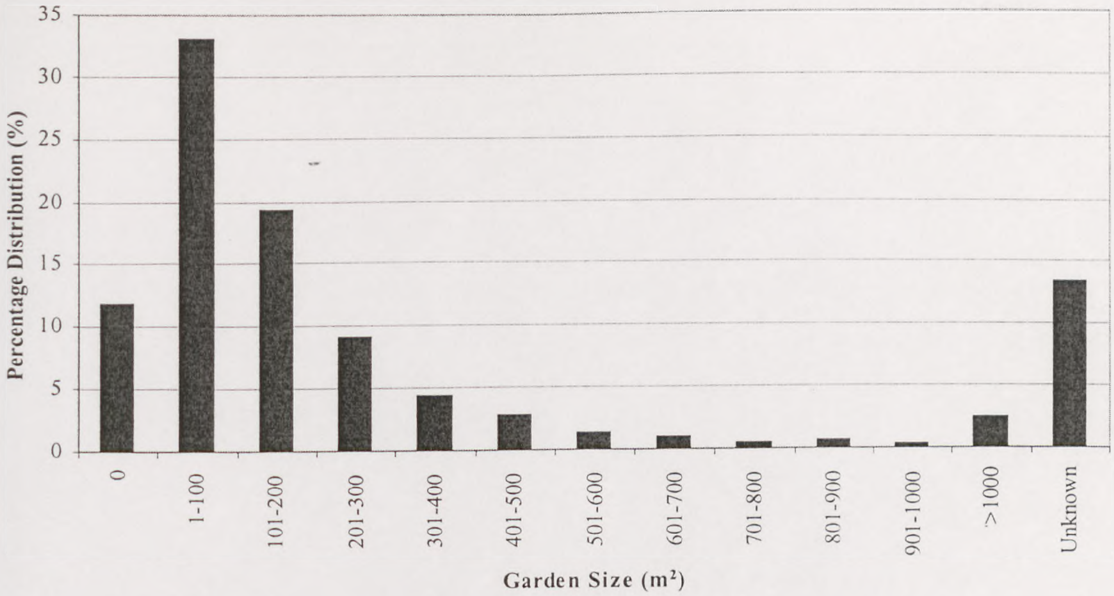


Figure 5.13: Distribution of garden size in the Thames Water study

5.2.6 Age of population

In each of the three individual household studies, the age of the population was classified differently. In the Essex and Suffolk Water study, the population was classified into adults, children and preschool children. In the Thames Water study, the population was subdivided into adults and children. In the Yorkshire Water study, the population was classified into residents under the age of ten years, residents aged between ten and fifty-four years, and residents over fifty-four years. Figures 5.14-5.16 show the distribution of population in each particular age group in the water use studies. As the age of population was classified differently, a comparison of population age in each of the water use studies was not possible.

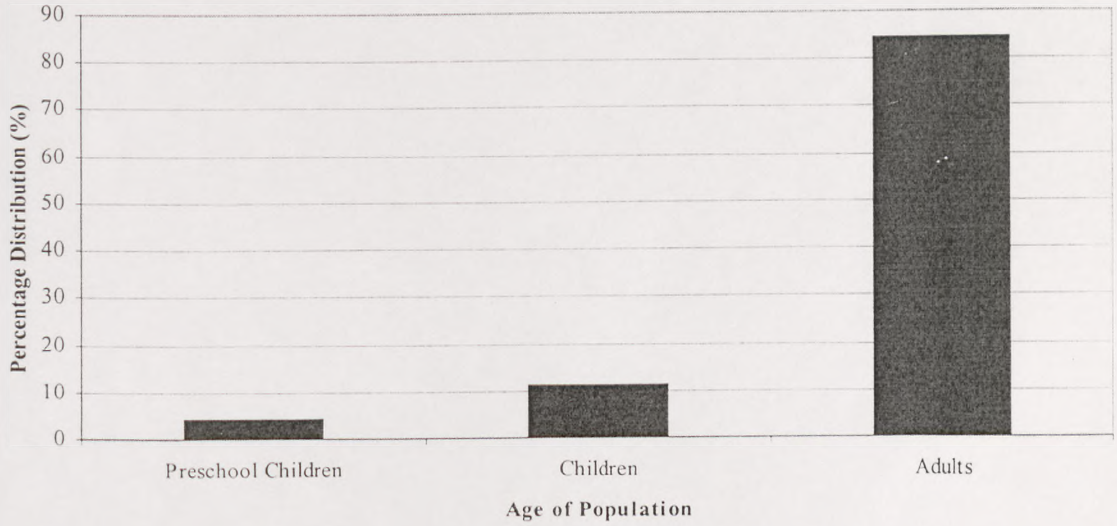


Figure 5.14: Distribution of population age in the Essex and Suffolk Water study

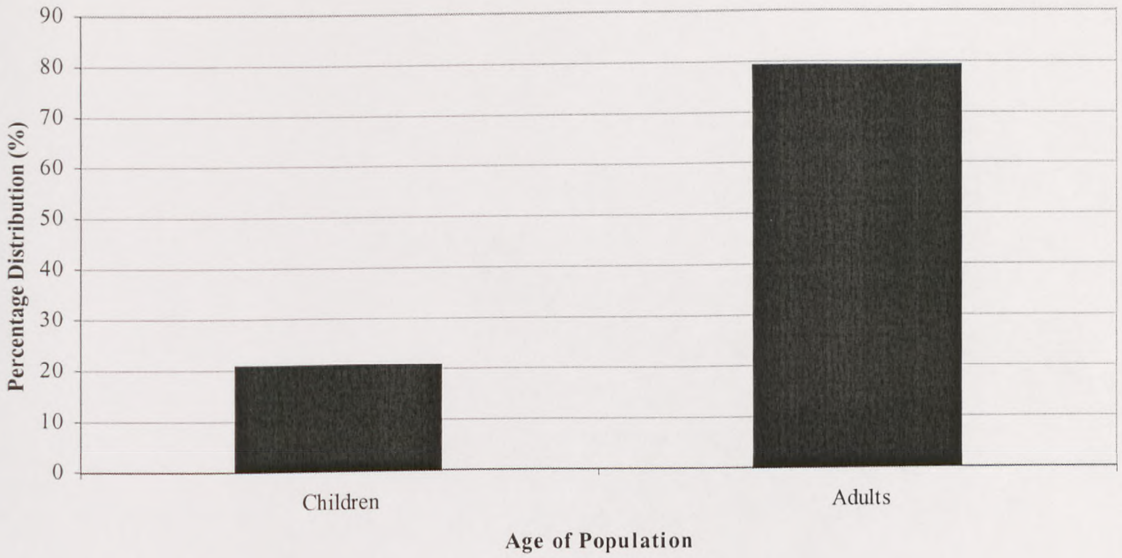


Figure 5.15: Distribution of population age in the Thames Water study

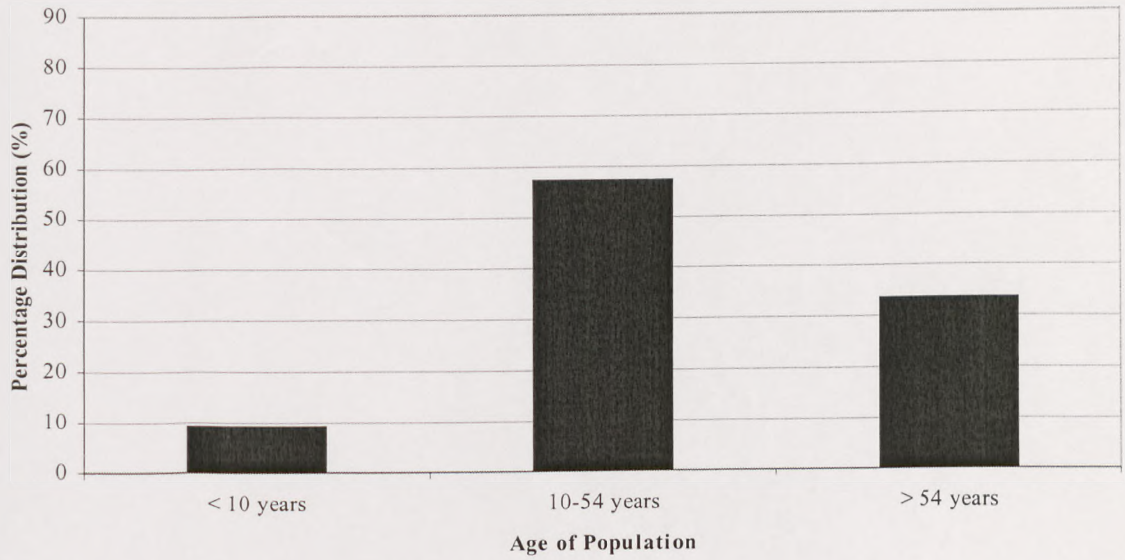


Figure 5.16: Distribution of population age in the Yorkshire Water study

5.2.7 Appliance ownership

Essex and Suffolk Water, Thames Water and Yorkshire Water collected information about the ownership of water using appliances within each household. Such appliances included the number of toilets, showers, power showers, baths, washing machines, dishwashers, twin tubs, hose-pipes, garden sprinklers, paddling pools, outside taps, etc. Although information about the ownership of water using appliances was collected, no information was collected on the frequency of appliance usage, appliance efficiency and appliance age. These factors could all influence household water use significantly.

5.3 Validation of the individual household studies

As Table 5.4 indicates, only a small fraction of the population and households from each of the water companies' supply areas are included in the water use studies. As can be recalled from section 4.3, this obviously raises questions concerning the application of the results to the wider population. Although the size of the sample used in these studies is questionable, the student t-test revealed no significant difference (at the 99% significance level) between the distribution of household composition and type in the individual household studies and the wards, districts, and counties in which they are situated.

Table 5.4: Percentage of the water companies' population and households included in the water use studies

Water Use Studies	*% of Population in the Water Use Studies*	*% of Households in the Water Use Studies*
Essex and Suffolk Water	0.28	0.24
Thames Water	0.17	0.07
Yorkshire Water	0.14	0.08

5.4 Characteristics of the data in the individual household studies

5.4.1 Missing water consumption data

In all three individual household studies, some water consumption data were missing. As mentioned in section 4.4.1, missing water consumption data almost certainly result from meter or logger failure. The study undertaken by Essex and Suffolk Water displayed the highest percentage of missing water consumption data. However, as Table 5.5 indicates, the percentage of missing data has been reduced over the study period. Missing water consumption data in the Thames Water and Yorkshire Water studies was denoted by a zero, a practice that complicates analysis. The percentage of zeros in the Thames Water and Yorkshire Water studies was 18.57% and 1.74%, respectively. It is accepted that some of these zeros may be genuine values for particular households as residents go on holiday. However, their removal is justified as this research is focusing on the behavioural and not the holiday response. In the majority of cases, zeros present in the water consumption data occurred continuously for months at a time. Empty properties, meter failure or logger failure may account for continuous zero meter readings.

Table 5.5: The percentage of missing water consumption data in the Essex and Suffolk Water study

Date	*Missing Data (%)*
July 1996	53.66
October 1996	40.63
January 1997	36.28
March 1997	35.98
July 1997	34.68
October 1997	20.12
January 1998	15.09
March 1998	11.36

5.4.2 Missing questionnaire data

Some questionnaire data were also missing in the individual household studies. The largest percentage of missing questionnaire data was observed in the Essex and Suffolk Water study, which incorporated a particularly ambitious questionnaire. In the Essex and Suffolk Water study, for example, the percentage of households with an unknown size is 53.35%. However, in the Thames Water and Yorkshire Water studies, the percentage of households with an unknown size is 1.03% and 0.00%, respectively. Similarly, the Essex and Suffolk Water study has the highest percentage of unknown property types (11.13%, compared to 1.36% in the Thames Water study and 1.11% in the Yorkshire Water study). In all three individual household study questionnaires, there was also very limited appliance ownership data available (69.40% of the appliance ownership data were missing from the Essex and Suffolk Water study, 45.20% from the Thames Water study and 39.93% from the Yorkshire Water study). The complicated nature of the questionnaires is one possible reason why so little appliance ownership data were available. It is also estimated that some 10% of the questionnaire data will change each year due to births, deaths and relocation (see section 3.3.4 for details). Since each of the studies began, questionnaires have not been updated. This will undoubtedly introduce a degree of error into the questionnaire data.

5.4.3 Data cleaning

As mentioned in section 4.4.2, erroneous data will be present. Unlike the erroneous data in the zonal meter areas, which was identified by visual inspection of the time-series plots, a value beyond which demand is deemed in error was investigated in the individual household study data. This was tackled in four ways:

(i) By identifying an extreme value beyond reasonable household demand – say a value likely to be caused by meter calibration failure or leakage.

(ii) By identifying long runs of zero values indicating meter or logger failure or an unoccupied home.

(iii) By identifying excessively low consumption values caused by meter calibration failure, an unoccupied home or questionnaire error.

(iv) By identifying long runs of constant consumption values caused by meter or logger failure.

Anomalously high consumption values were evident in both the Thames Water and Yorkshire Water studies. Some of the water consumption data (Table 5.6) were over 100,000 litres per day higher than the average per capita consumption of 154 litres/person/day in England and Wales (Turton, 1998). Removal of these excessively high consumption values was, therefore, justified. The percentage of anomalously high consumption values in the Thames Water and

Yorkshire Water studies was 0.59% and 0.79%, respectively. In the Essex and Suffolk Water study, no anomalously high values were evident during analysis. Essex and Suffolk Water had removed anomalously high consumption values caused by leakage or meter and/or logger failure prior to calculating quarterly averages (Ridgewell, 1999, pers. comm.).

Table 5.6: An example of excessively high water consumption values from the Yorkshire Water study

Property ID	*Date*	*Number of Residents*	*Water Consumption (l/property/day)*
125	27-Jan-97	4	94339.99
125	28-Jan-97	4	31964.00
125	29-Jan-97	4	34736.01
125	30-Jan-97	4	74832.00
125	31-Jan-97	4	99311.01

In the Thames Water study, 3.91% of the water consumption data displayed constant consumption values, often for months at a time (Table 5.7). These consumption values were also removed from the analysis.

Table 5.7: An example of constant water consumption values

Property ID	*Date*	*Number of Residents*	*Water Consumption (l/property/day)*
LNW2001	19-Nov-96	4	940
LNW2001	20-Nov-96	4	940
	▼		
LNW2001	07-Mar-97	4	940
LNW2001	08-Mar-97	4	940

In the Thames Water and Yorkshire Water studies, 7.91% and 10.30% fell below the designated threshold of 50 litres/person/day (see section 3.10 for details). An example of excessively low consumption values is displayed in Table 5.8.

Table 5.8: An example of excessively low water consumption values from the Yorkshire Water study

Property ID	*Date*	*Number of Residents*	*Water Consumption (l/property/day)*
PHP2012	07-Sep-96	2	8.00
PHP2012	08-Sep-96	2	9.00
PHP2012	09-Sep-96	2	10.00
PHP2012	10-Sep-96	2	8.00
PHP2012	11-Sep-96	2	9.00

5.4.4 Data interpolation

As in the zonal meter studies, data interpolation was investigated to reduce the amount of missing water consumption data (see section 4.4.3 for details). Again, it was considered unrealistic to interpolate data: (i) due to the large variation in daily water consumption and (ii) because the factors that influence short-term domestic water demand are unknown.

5.5 Analysis of the time-series data – medium- to long-term domestic water demand

The time-series data for the individual household studies undertaken by Thames Water and Yorkshire Water display a similar pattern to those in the small water supply areas (Figure 5.17 and 5.18). Some seasonal trend in domestic water consumption is evident, with peaks during summer and troughs during winter. However, the Yorkshire Water consumption data shows much less seasonal variation than expected. Undoubtedly, there would have been more seasonal variation if Yorkshire Water had taken a simpler approach to monitoring domestic water consumption, that is, if a smaller area had been studied or if the area studied displayed similar characteristics.

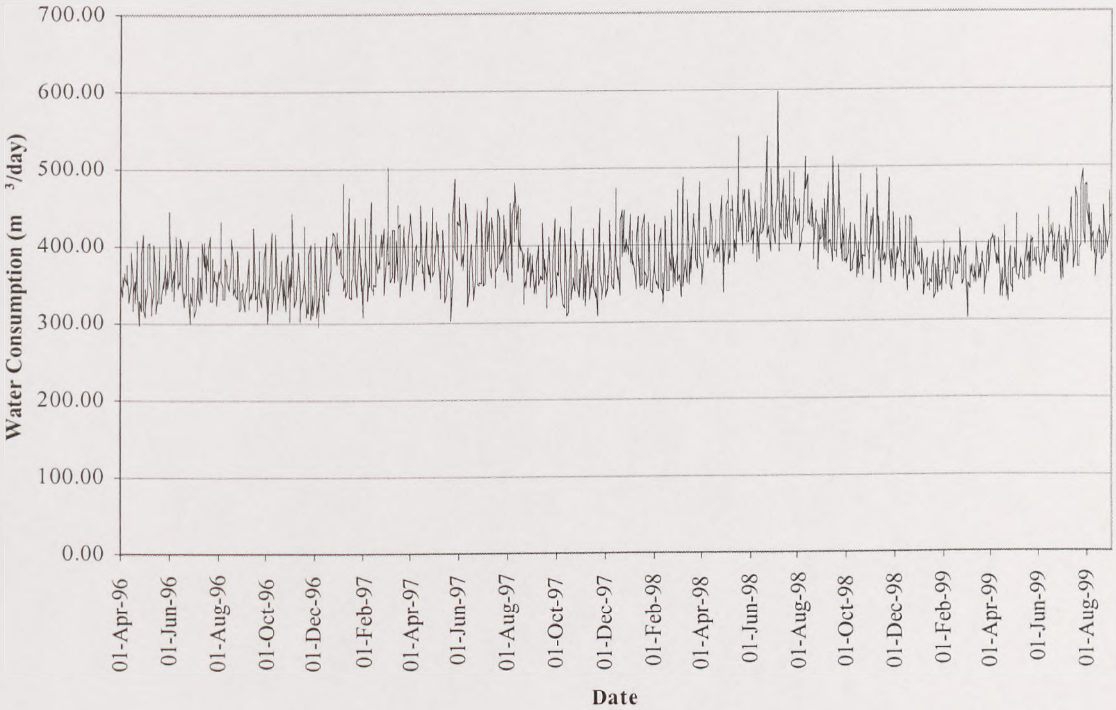


Figure 5.17: Time-series plot of water consumption in the Yorkshire Water study

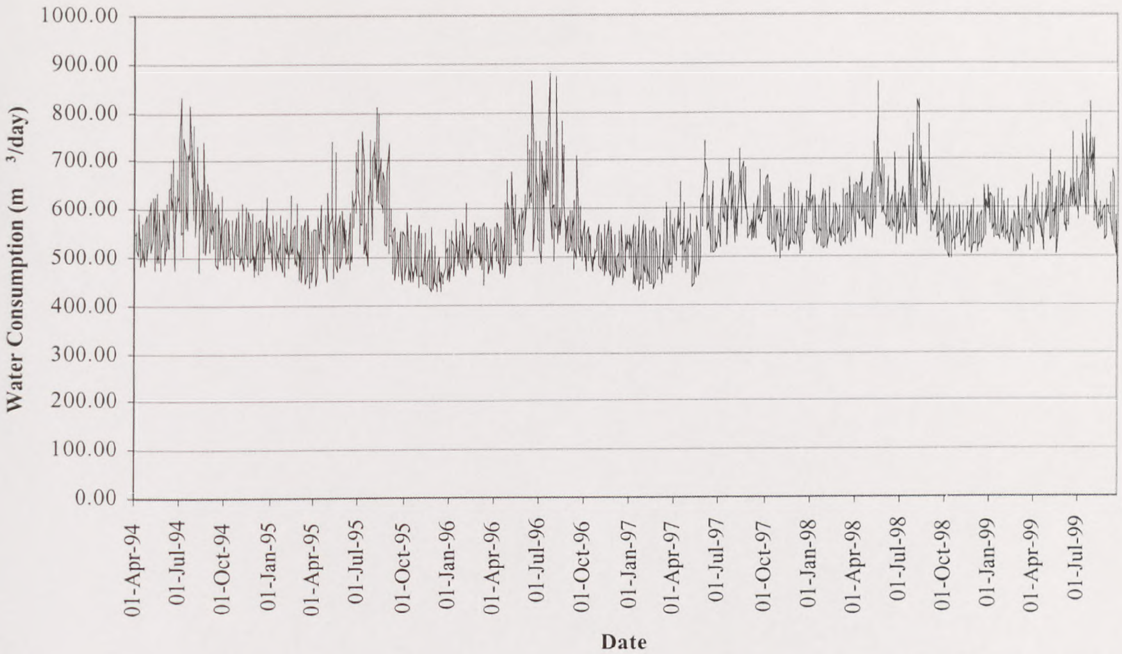


Figure 5.18: Time-series plot of water consumption in the Thames Water study

The Yorkshire Water study covers a large area geographically, extending from the Yorkshire and Humberside coast, to the upland areas of the Pennines. Yorkshire experiences greater variation in climatic conditions compared to the South East of England. In Yorkshire, for example, it could be anticipated to be hot and dry at the coast, yet cold and wet in the Pennines, or perhaps vice versa with sea fog. Therefore, anticipated variation in domestic water consumption due to weather related effects might counterbalance each other to produce little variation in domestic water consumption. The Yorkshire Water study also includes a variety of socio-economic conditions, covering affluent communities in North Yorkshire, such as Ripon and Harrogate, to poor rundown communities in the coal field areas of Yorkshire. It includes those people whom, when it is hot and sunny, have the potential to irrigate their large gardens, yet it also covers those people who have no garden. It covers densely populated urban areas, for example in Leeds and Sheffield, as well as much more rural areas in the Yorkshire Dales and North Yorkshire moors. The time-series plot in Figure 5.17 is an aggregation of all of this information. Similarly the time-series plot in Figure 5.18 aggregates all of the information from the Thames Water study, but the socio-economic and climatic variations in this study are significantly less. The South East experiences a much more continental climate with relatively hot dry summers producing peaks in domestic water demands. The South East is also much more affluent, with very few poor areas.

As the time-series plots indicate, average household water consumption in the Thames Water study appears significantly higher than that observed in the Yorkshire Water study. Data from the Thames Water and Yorkshire Water studies can, therefore, not be integrated due to higher levels of demand in the Thames Water study. However, as both time-series suggest, a slight upward shift in domestic water consumption is evident. This upward shift may result from water use restrictions imposed throughout the UK in 1995 and 1996. Further investigations are, therefore, necessary to determine whether: (i) the underlying factors influencing domestic water demand in the South East differ to those in Yorkshire and (ii) the upward shift in household water demand results from water use restrictions.

5.6 Underlying factors influencing medium- to long-term domestic water demand

5.6.1 Household size

As expected, household water consumption in each of the individual household studies increased with greater household size (Figures 5.19-5.21). Per property consumption in the Essex and Suffolk Water study and the Yorkshire Water study was remarkably similar. However, per property consumption in the Thames Water study was, on average, 21% higher. The greatest variation was observed in one-person households, where per property consumption was 54% higher than that in the Essex and Suffolk Water and Yorkshire Water studies. The nature of one-person households in the Thames Water study may account for differences in domestic water consumption. London dominates the Thames Water study. It is, therefore, likely that one-person households in the Thames Water study are comprised of young, upwardly mobile, middle-class citizens. On the other hand, it is more likely that one-person households in the Essex and Suffolk Water and Yorkshire Water studies have a higher proportion of single pensioners. The lifestyle of many pensioners means that they have physical and financial constraints (i.e., gas and electricity used for heating the water) that limit water consuming activities. However, it is likely that a young, upwardly mobile, middle-class citizen will have fewer financial constraints that limit water consuming activities for garden watering, personal hygiene and the number of appliances such as dishwashers, washing machines, etc.

It was hypothesized that a one-person household would use considerably more water per person than a six-person household. This is because the number of people in the household do not govern some water consuming activities such as garden watering. As Figures 5.22-5.24 show, the hypothesis that per capita consumption reduces as household size increases can be accepted.

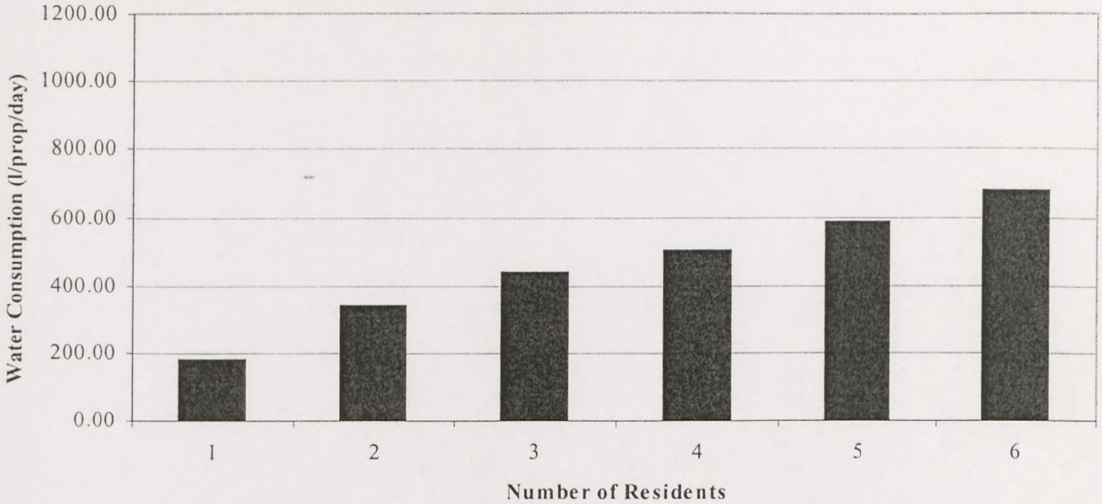


Figure 5.19: Average per property consumption according to household size in the Essex and Suffolk Water study

Figure 5.20: Average per property consumption according to household size in the Thames Water study

Figure 5.21: Average per property consumption according to household size in the Yorkshire Water study

Figure 5.22: Average per capita consumption according to household size in the Essex and Suffolk Water study

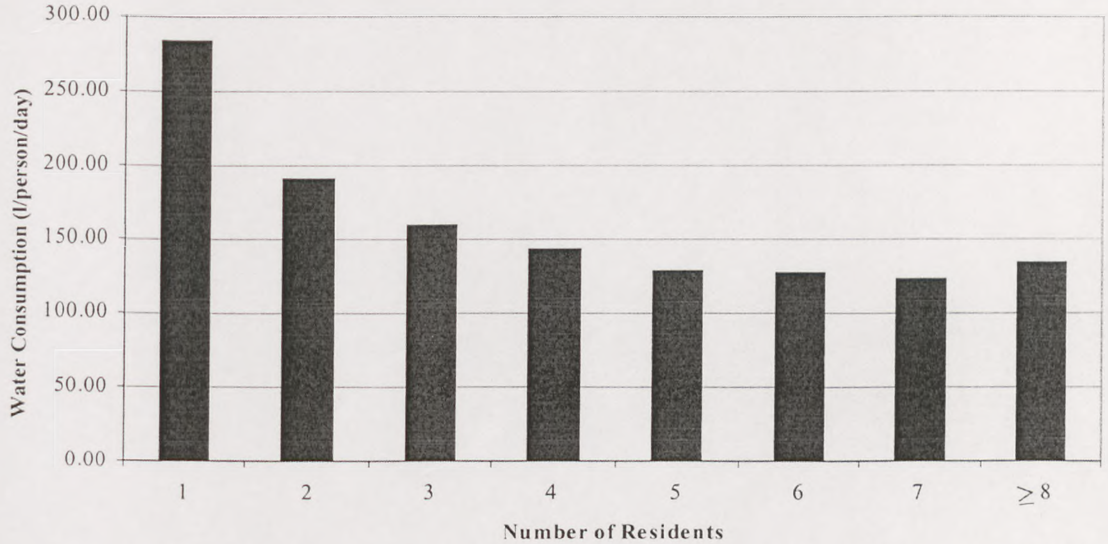


Figure 5.23: Average per capita consumption according to household size in the Thames Water study

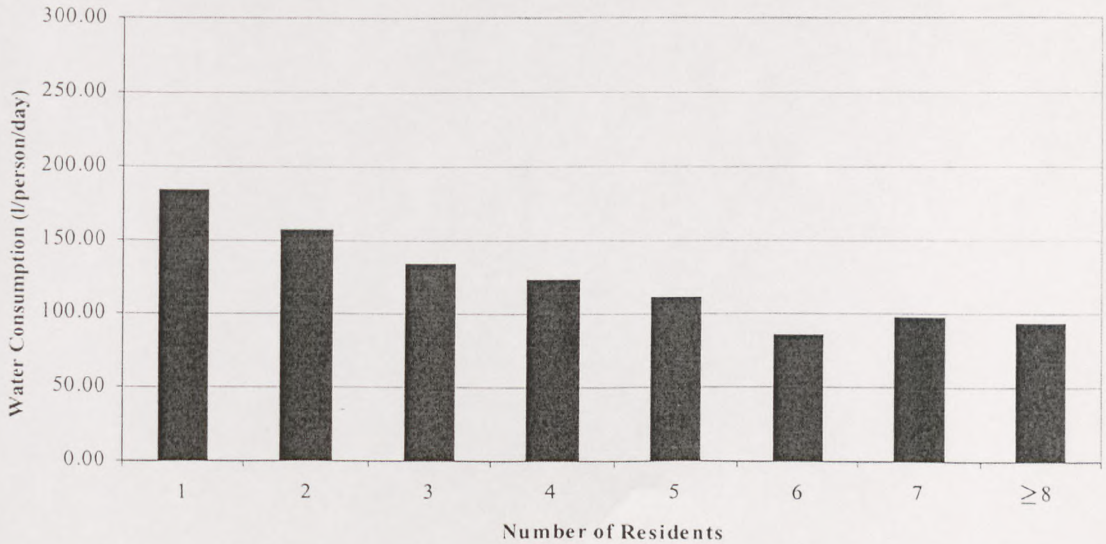


Figure 5.24: Average per capita consumption according to household size in the Yorkshire Water study

5.6.2 Property type

As a relationship was observed between number of residents and per property and per capita consumption, it was necessary to subdivide the data according to the number of residents before any further analysis was undertaken. Otherwise, if there were a disproportionate number of one-person terraced properties, for example, terraced properties may produce high per capita consumption values, influenced by the number of residents and not by the property type.

In all three studies, detached properties (Essex and Suffolk Water and Thames Water) and detached houses (Yorkshire Water) displayed the highest per property and per capita consumption values (Figures 5.25-5.27) (see Appendix 5A for details). As expected, the highest per capita consumers were one-person detached properties and houses. Flats displayed the lowest per capita consumption, particularly when the number of residents was high. For all household sizes and property types, there was a considerable range in consumption, even if the households shared common characteristics (see Appendix 5C for details). However, per capita and per property consumption was significantly higher in the Thames Water study compared to the Essex and Suffolk Water study and the Yorkshire Water study where per capita and per property consumption was quite similar.

Figure 5.25: Average per property water consumption for one-person households in the Essex and Suffolk Water study

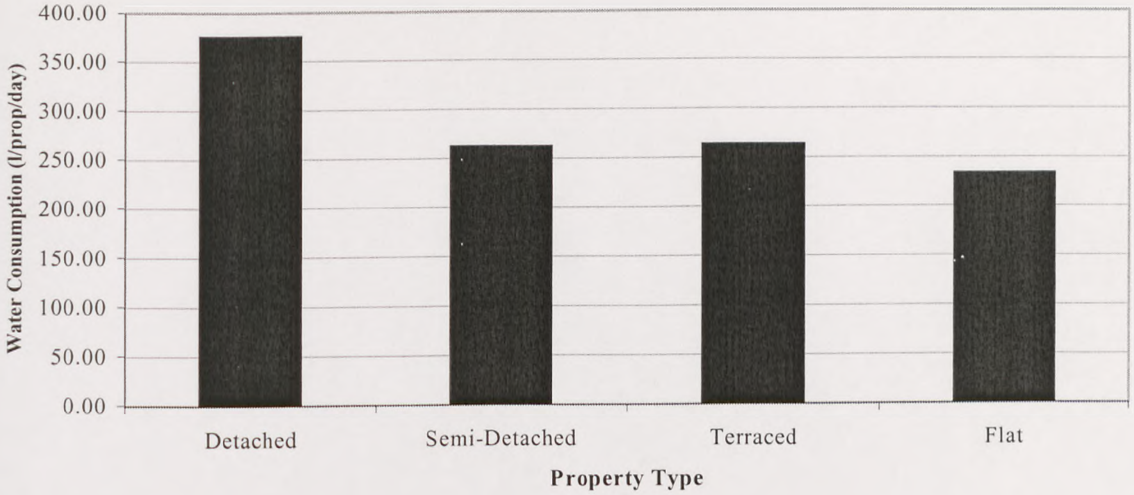


Figure 5.26: Average per property water consumption for one-person households in the Thames Water study

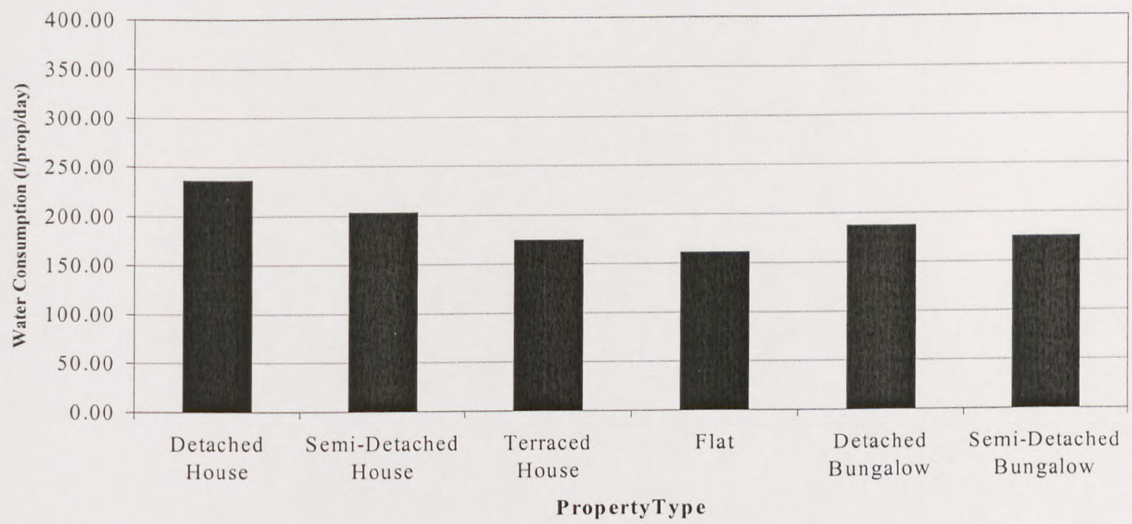


Figure 5.27: Average per property water consumption for one-person households in the Yorkshire Water study

5.6.3 ACORN and water use classifications

As household size and property types appear to exert an underlying influence on domestic water consumption, data were subdivided into household size and property type prior to further analysis. The data were then subdivided into ACORN categories in the Thames Water and Yorkshire Water studies and into estimated water use classes in the Essex and Suffolk Water study. No obvious relationship was found between domestic water consumption and ACORN categories in the Thames Water and Yorkshire Water studies (see Appendix 5B for details). As Figure 5.28 indicates, no one ACORN category consistently demonstrated the highest or lowest household water consumption. However, water consumption in the Thames Water study was consistently higher than that in the Yorkshire Water study for all ACORN categories. The categorization of ACORN data is, of course, potentially very misleading. The A-E 'categorization' and 1-19 'typing' implies an ordinal or interval data characteristic, which is not present. Both levels of subdivision are no more than ordinal.

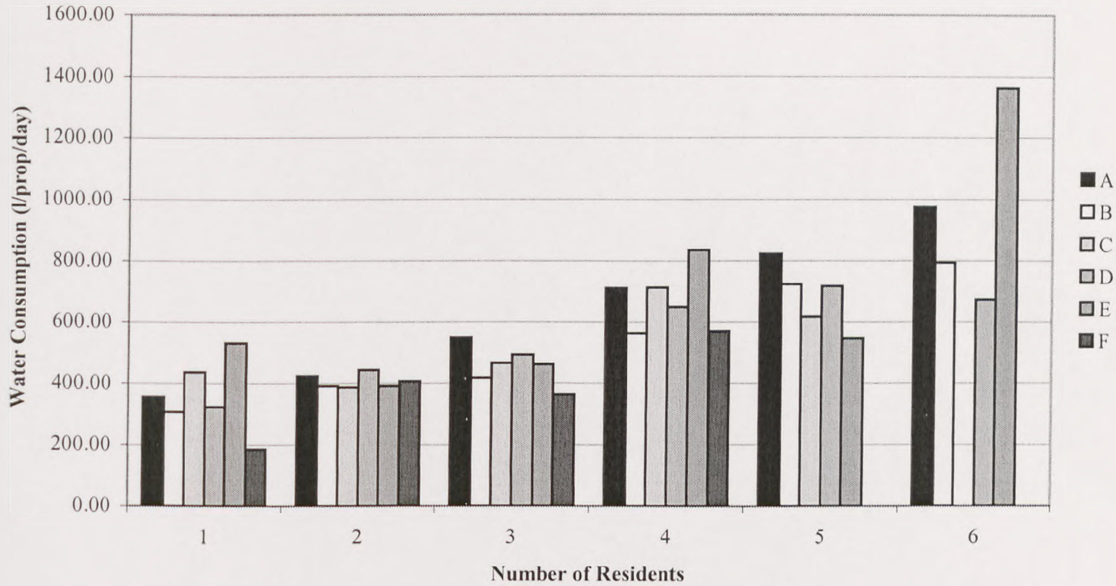


Figure 5.28: Relationship between household water consumption and ACORN categories for one to six-person detached properties in the Thames Water study

In the Essex and Suffolk Water study there was a severe lack of data in many of the water use classes. It was, therefore, impossible to determine whether or not a relationship existed between water use classification and domestic water consumption.

5.6.4 Garden size

It was hypothesized that garden size influences outdoor domestic water consumption. The data were, therefore, subdivided into number of residents, property type and garden size. In the Essex and Suffolk Water study there was a severe shortage of garden size data. This did not allow judgement to be made as to whether properties with large gardens consume more water than properties with small gardens. The definition of garden size is also very subjective. The householder, not Essex and Suffolk Water, determined garden size. However, no quantitative measures were provided to the householder identifying what constitutes a small, medium, large or extra large garden. This may be the reason why the original questionnaire undertaken by Essex and Suffolk Water did not generate much information about garden size.

Linear regression was used to analyse the relationship between domestic water consumption and garden size in the Thames Water study, as significantly more quantitative information was available. As Figures 5.29, 5.30 and Appendix 5D indicate, no relationship between domestic water consumption and garden size was evident. However, it was hypothesized that garden size would only influence domestic water consumption during the summer months when external water use is anticipated to be at its highest. The data were, therefore, subdivided into seasons. Unexpectedly, no relationship was evident between domestic water consumption and garden size during the summer season (Figure 5.31 and 5.32). However, McDonald (1996) suggests that garden size does exert an influence on household water use. McDonald (1996) reported that under drought conditions, water use for households in 'gardenless' *inner city* areas appear to respond to a hose-pipe ban, but to a somewhat lesser extent than households in *leafy suburbs* with large gardens. These findings suggest that the water use response to a hose-pipe ban is more in *leafy suburbs* as households in these areas are no longer able to water their large gardens. In the Thames Water study, however, garden size may appear to exert little influence on household water use because: (i) individuals may interpret the definition of garden size differently; some for example, may include patios and paths in their definition. Instead, it is recommended that the definition of garden size represents the area of land vegetated, and (ii) outdoor water consumption is undoubtedly influenced by the individual's behavioural water use pattern and is, therefore, independent of garden size.

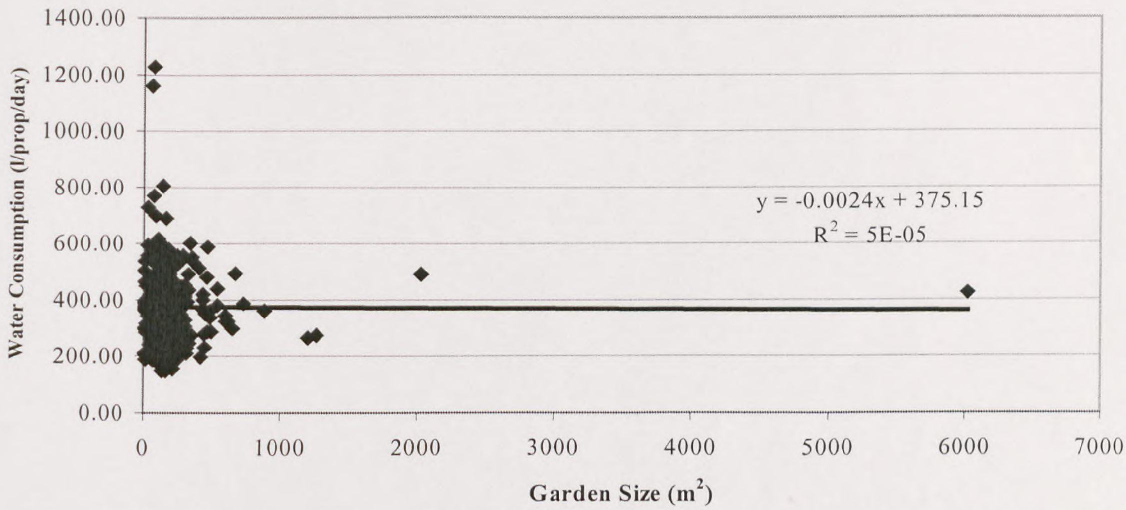


Figure 5.29: Relationship between water consumption and garden size for one-person detached properties in the Thames Water study

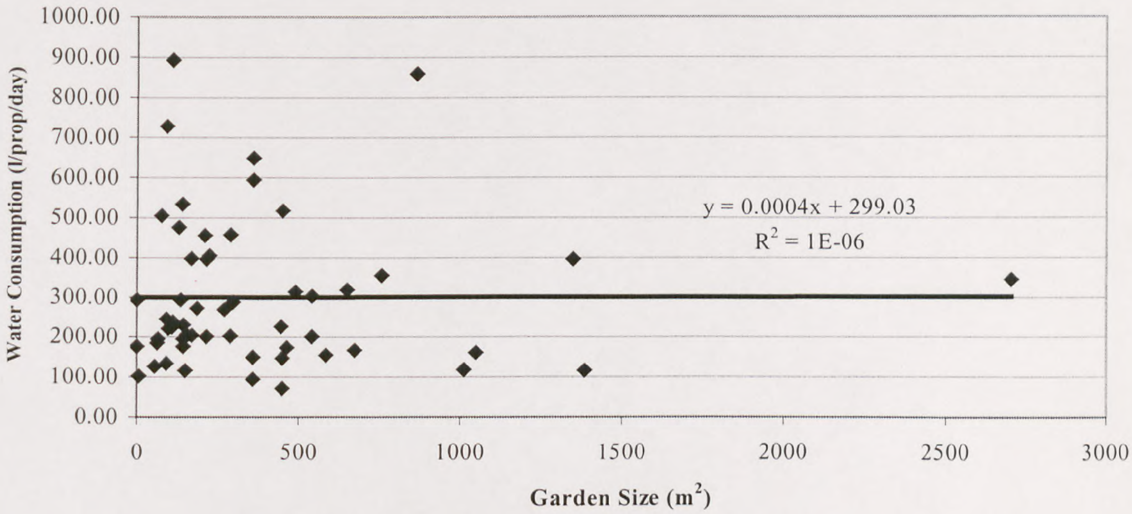


Figure 5.30: Relationship between water consumption and garden size for two-person semi-detached properties in the Thames Water study

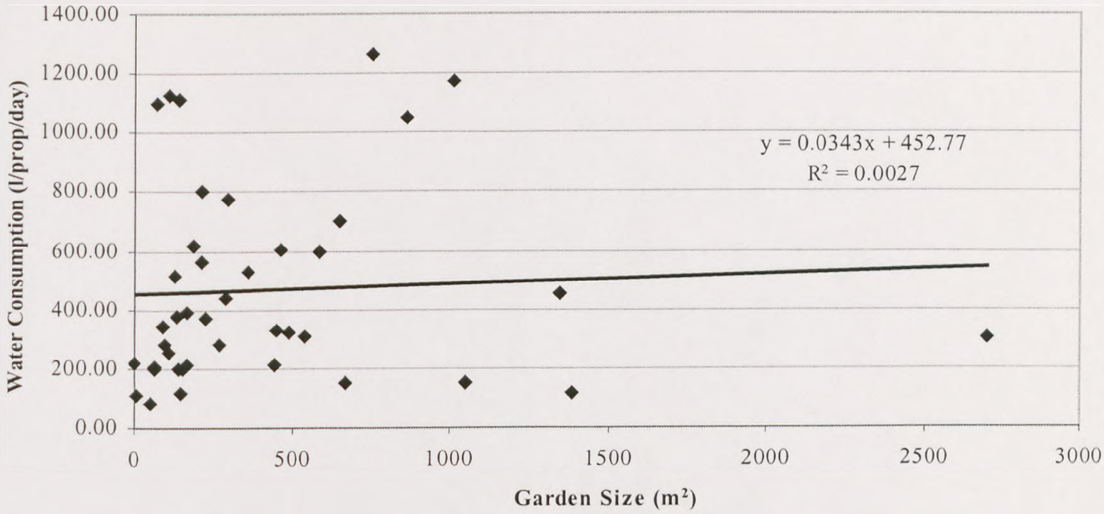


Figure 5.31: Relationship between water consumption and garden size during the summer seasons for one-person detached properties in the Thames Water study

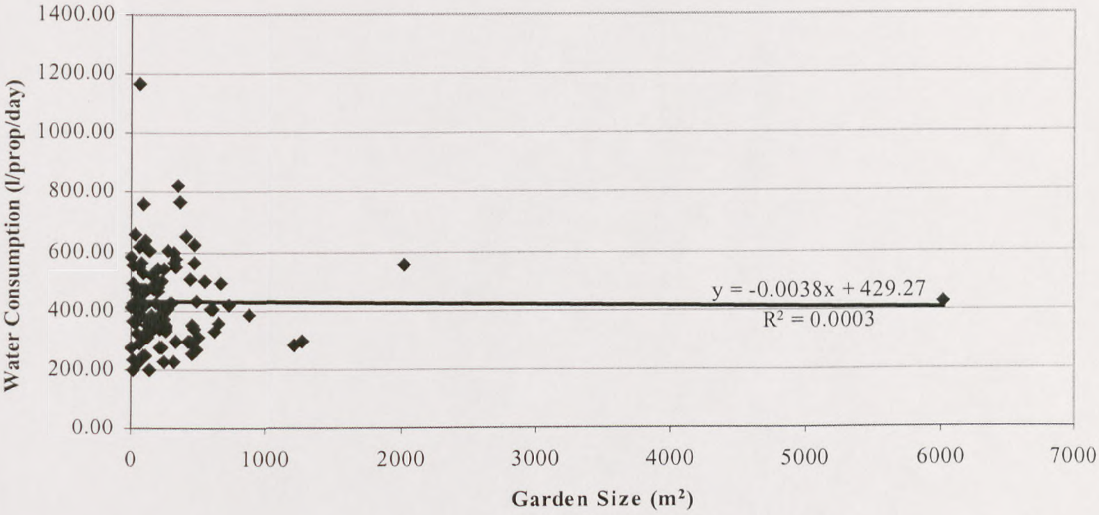


Figure 5.32: Relationship between water consumption and garden size during the summer seasons for two-person semi-detached properties in the Thames Water study

5.6.5 Rateable values

Linear regression was used to analyse the relationship between domestic water consumption and rateable values for different household sizes and property types in the Essex and Suffolk Water and Thames Water studies. As Figures 5.31, 5.32 and Appendix 4E indicate, the trends are in the intuitively expected direction, that is, as rateable value increases, domestic water consumption increases. However, there is a large degree of scatter in the data and the percentage of explained variance is low.

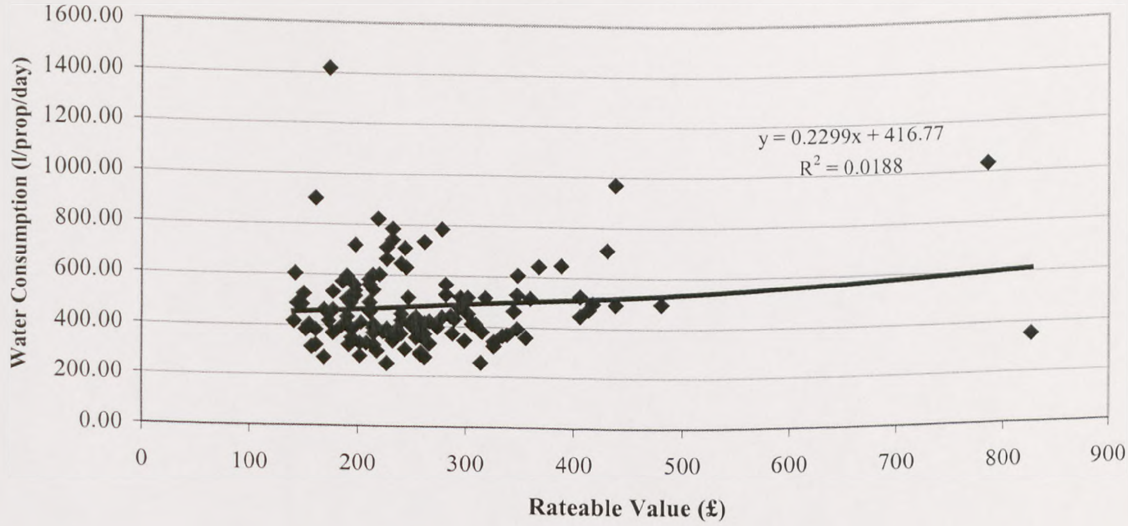


Figure 5.33: Relationship between water consumption and rateable values for three-person terraced properties in the Thames Water study

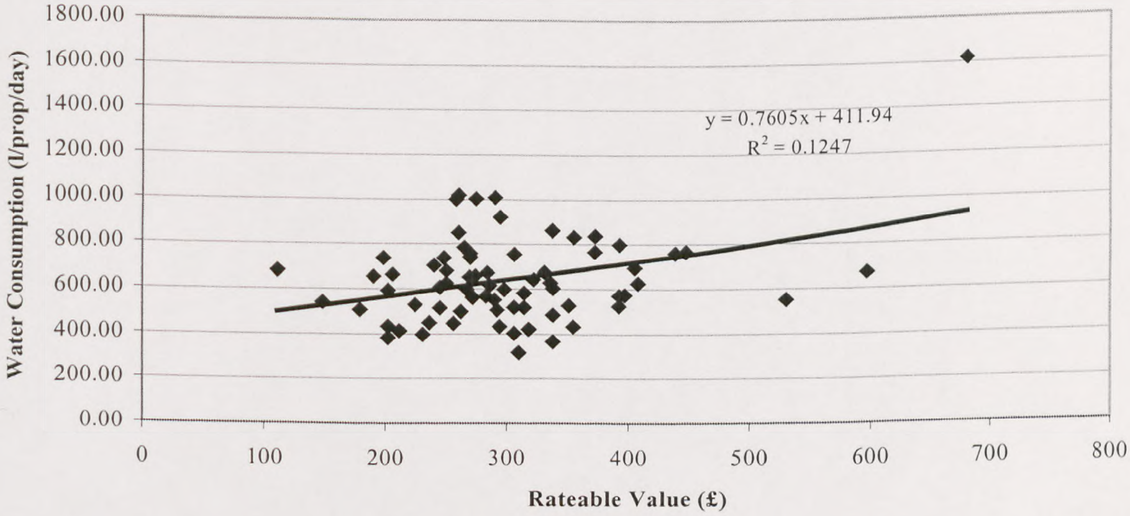


Figure 5.34: Relationship between water consumption and rateable values for five-person semi-detached properties in the Thames Water study

5.6.6 Age of population

No systematic change in household water consumption is observed as children increase in representation in the four-person households (Table 5.9 and Appendix 5F). When children are weakly represented in the household, i.e. one or no children, there appears to be a somewhat higher household consumption in comparison to those households well represented with two or three children.

Table 5.9: Average water consumption for different numbers of children and adults in four-person households in the Yorkshire Water study

Age of Population		*Property Type*			
Adults	*Children*	*Detached*	*Semi-Detached*	*Terraced*	*Flat*
1	3		585.87	550.48	386.64
2	2	624.47	523.74	540.33	489.51
3	1	572.01	600.33	592.38	479.67
4	0	737.45	598.53	605.16	580.88

5.6.7 Appliance ownership

It was hypothesized that levels of appliance ownership influence domestic water consumption. However, it was impossible to determine the relationship between domestic water consumption and appliance ownership because:

(i) There was very limited appliance ownership data available (see section 5.2.7 for details).

(ii) Subdivision of the data by household size, property type and appliance ownership significantly reduced the amount of data available for analysis and hence, increased the risk of sample bias (see section 3.3 for details). Even if appliance ownership was categorized, for example, into (i) one-person detached properties with less than three appliances and (ii) one-person detached properties with more than three appliances, there was not enough data available to accurately compare household water consumption.

(iii) As most households generally own a variety of water using appliances, it was impossible to identify, for example, that one-person detached properties who own a washing machine consume more water than one-person detached properties that do not own a washing machine, due to the influence of other water using appliances.

(iv) On its own, appliance ownership is not a satisfactory indicator of household water use. Information about the frequency of appliance usage, appliance age and appliance efficiency is also required.

5.7 Temporal shifts in domestic water consumption

To investigate the temporal upward shift in domestic water consumption, data were subdivided into household size and property type, as these factors appear to exert the greatest underlying influence on domestic water consumption. Time-series plots for each household size and property type revealed significant changes in demand (see Appendix 5G and 5H for details). In some cases, an obvious upward trend in domestic water consumption was evident (Figure 5.35). In other cases there appeared to be a downward trend (Figure 5.36). The downward shift in demand negates the possibility that restrictions imposed by the water plc's have influenced demand. Without a longer time-series of data it is impossible to determine the extent to which these shifts in demand result from individual behavioural water use patterns or errors. However, this upward or downward shift in demand will undoubtedly influence the results of this analysis.

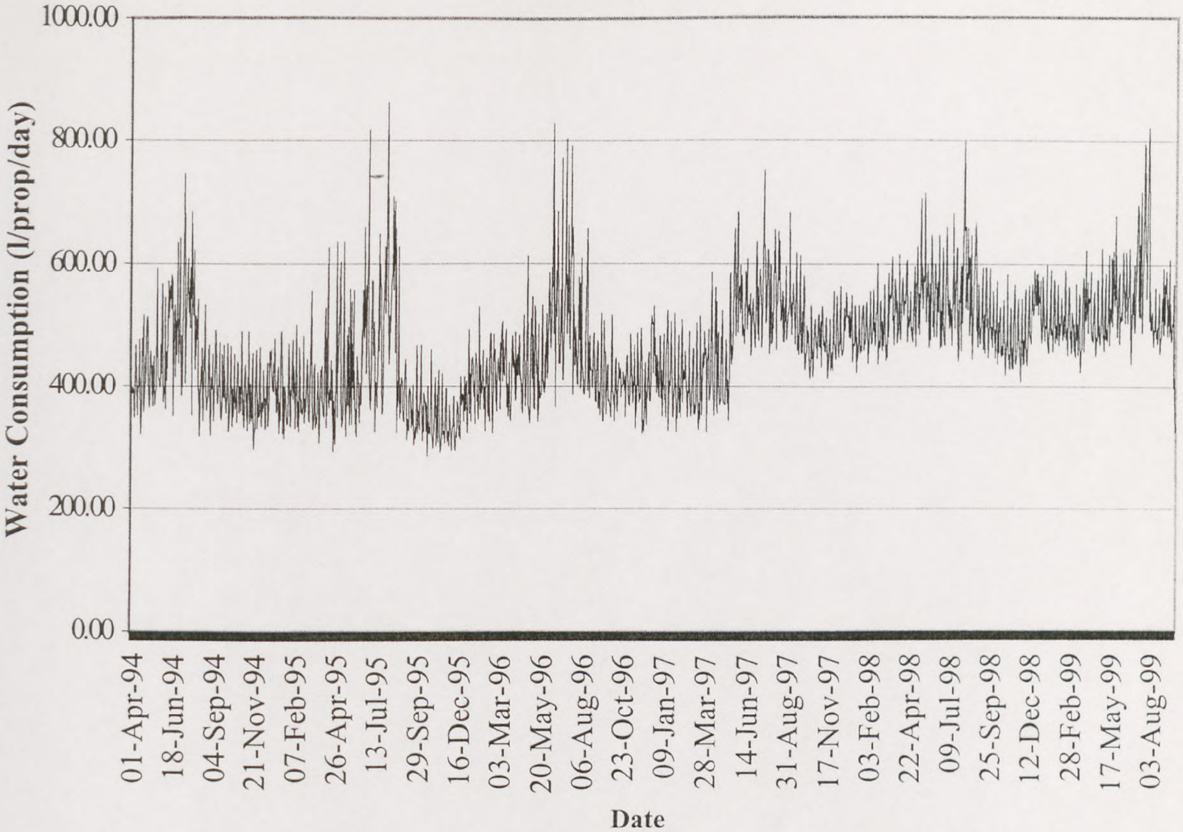


Figure 5.35: An example of an upward temporal shift in domestic water consumption in three-person semi-detached properties in the Thames Water study

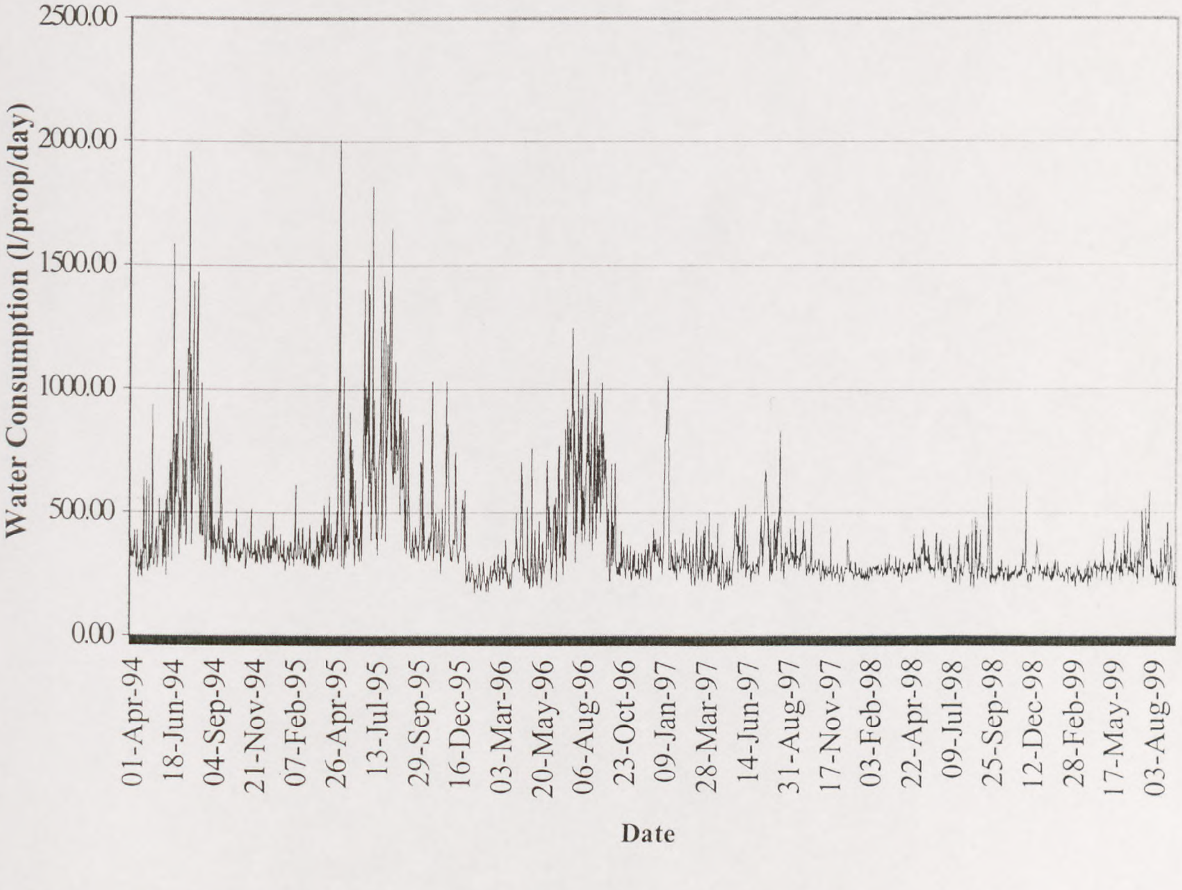


Figure 5.36: An example of a downward temporal shift in domestic water consumption in one-person detached properties in the Thames Water study

5.8 Summary of underlying factors influencing medium- to long-term domestic water demand

Household size and property types appear to exert the greatest underlying influence on domestic water consumption, even though a significant range in consumption was found for households of similar sizes and property types. Data will, therefore, be subdivided into household size and property type prior to further analysis. Other underlying factors such as levels of affluence (ACORN categories), garden size, the property's rateable value and age of population appear to exert little, if no influence, on domestic water consumption. However, some of these findings may be misleading. If, for example, a different approach to measuring garden size was adopted, i.e. by measuring the amount of area vegetated, 'true' garden size may exert an underlying influence on domestic water consumption. Also, if a simpler approach to monitoring domestic water consumption had been undertaken, that is, if a smaller area had been studied, or if the area studied displayed similar characteristics, it is likely that 'true' garden size would exert an underlying influence on domestic water consumption (see section 5.6.4 for details). At present, the data aggregates households who may or may not have the potential to irrigate their gardens. These effects may counterbalance each other to produce little variation in domestic water consumption. This suggests that both affluence and 'true' garden size may exert an underlying influence on domestic water consumption. However, further investigations, i.e. by subdividing the household size and property type data by levels of affluence and 'true' garden size was not possible (i) because 'true' garden size data were not available and (ii) further subdivisions significantly reduce the amount of data available for analysis and hence increase the risk of sample bias (see section 3.3 for details).

5.9 The influence of environmental factors on domestic water demand

As can be recalled from section 4.7, observed seasonal variation in domestic water demands (Figures 5.17, 5.18 and Appendix 5G and 5H) suggest that demands are influenced by environmental factors. To investigate the influence of environmental factors on domestic water demands, linear and multiple linear regression analysis were performed using temperature, sunshine amounts and rainfall as independent variables (see section 3.14 for details).

5.9.1 Linear regression analysis

As Figures 5.37-5.39 and Appendix 5I indicate, linear regression analysis in the Thames Water study displayed similar trends to the small water supply areas of Yorkshire and the district meter areas of Wales in that the trends are in the intuitively expected direction (i.e. when it is hotter/sunnier, more water is used and when it is colder/wetter, less water is used) (see section 4.7.1 for details).

The percentage of explained variance is highest for detached and semi-detached properties and lowest for flats (Table 5.10). 'True' garden size may account for these findings. It is highly likely that 'true' garden size is larger in detached and semi-detached properties, resulting in higher outdoor water use.

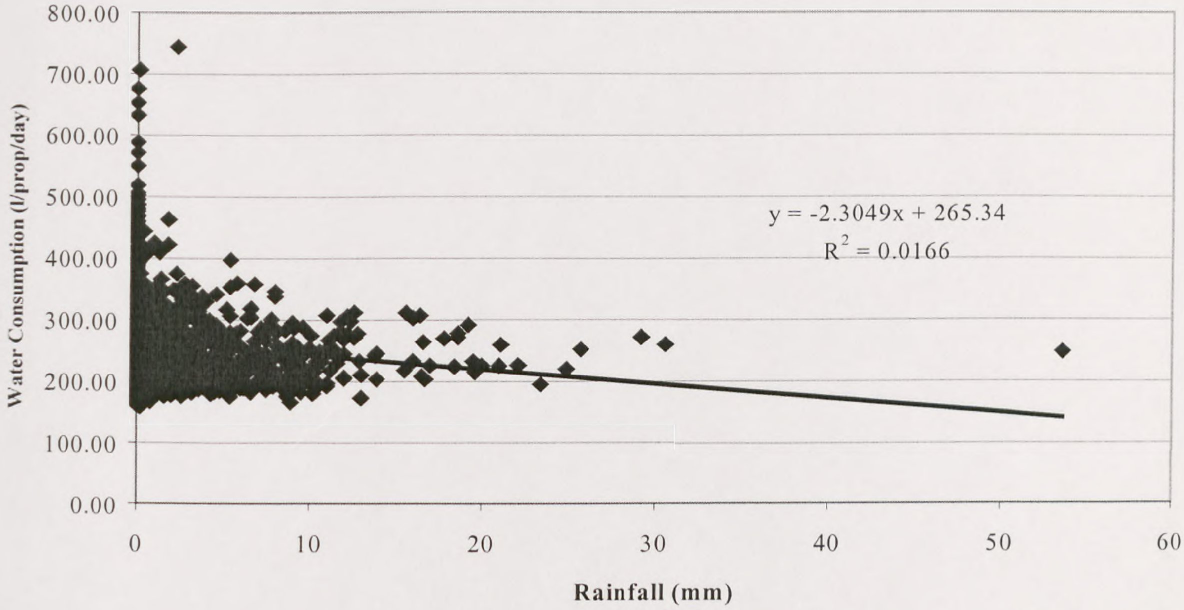


Figure 5.37: Relationship between water consumption and rainfall for one-person semi-detached properties in the Thames Water study

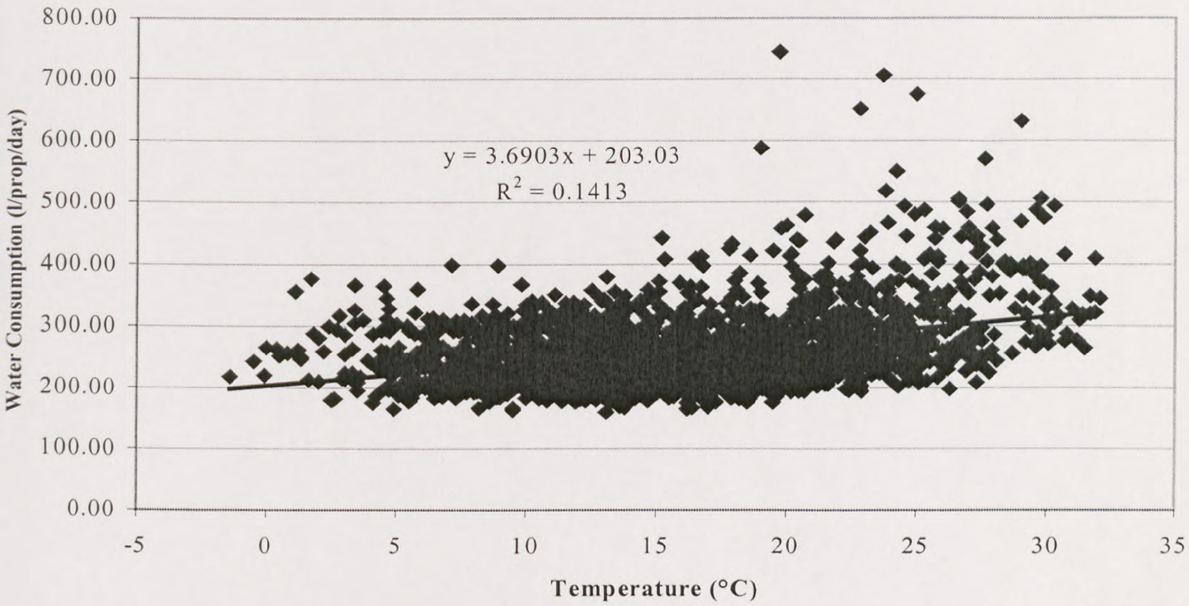


Figure 5.38: Relationship between water consumption and temperature for one-person semi-detached properties in the Thames Water study

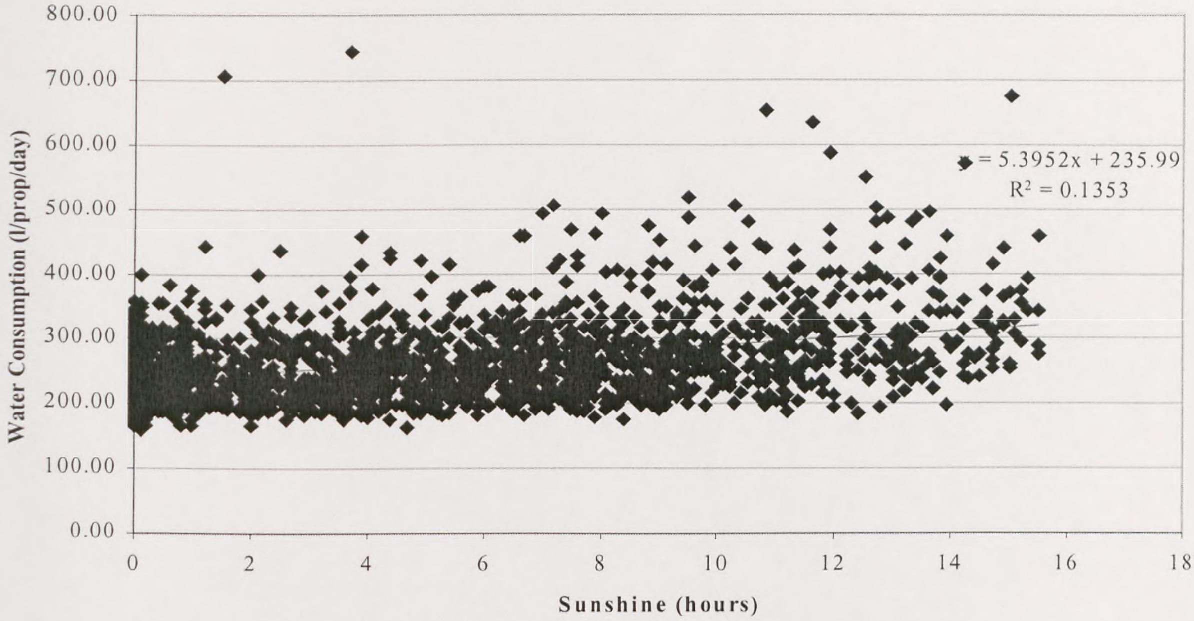


Figure 5.39: Relationship between water consumption and sunshine amounts for one-person semi-detached properties in the Thames Water study

Table 5.10: Relationship between water consumption and weather for different types of one-person households in the Thames Water study (R^2)

Weather	*PropertyType*			
	Detached	*Flat*	*Semi-Detached*	*Terraced*
Rainfall (mm)	0.016	0.002	0.017	0.009
Sunshine (hrs)	0.104	0.035	0.135	0.096
Temperature (°C)	0.160	0.013	0.141	0.104

Environmental variables had little influence on domestic water consumption in the Yorkshire Water study (Figures 5.40-5.42 and Appendix 5J). However, it was hypothesized that environmental variables only influence domestic water consumption during the spring and summer season when outdoor water use is anticipated to be at its highest. Linear regression was used to analyse the relationship between environmental variables and domestic water consumption in each season for individual household sizes and property types in the Thames Water and Yorkshire Water studies. As Tables 5.11, 5.12 and Appendix 5K show, environmental variables exert the greatest influence on domestic water consumption during the summer season. However, the percentage of explained variance, particularly in the Yorkshire Water study, is extremely low.

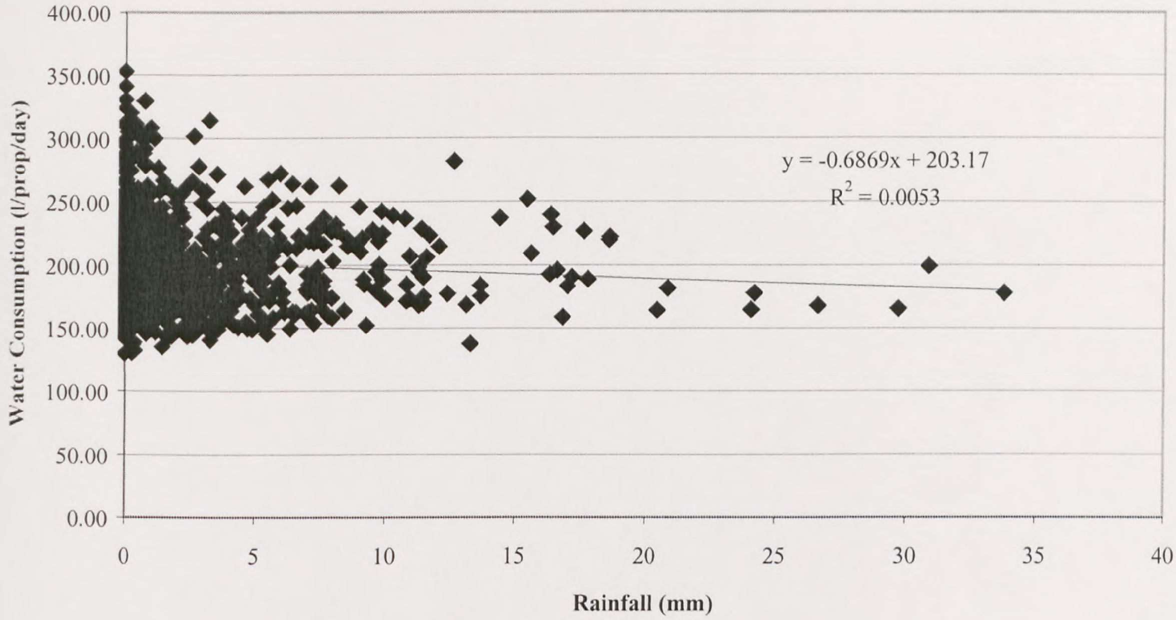


Figure 5.40: Relationship between water consumption and rainfall for one-person semi-detached properties in the Yorkshire Water study

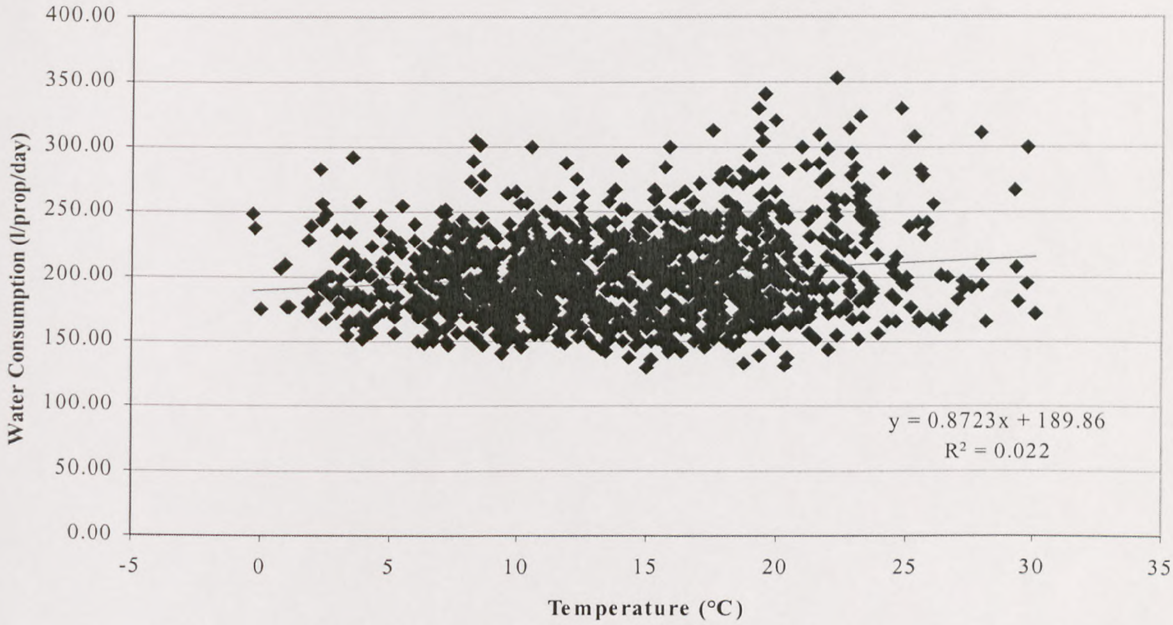


Figure 5.41: Relationship between water consumption and temperature for one-person semi-detached properties in the Yorkshire Water study

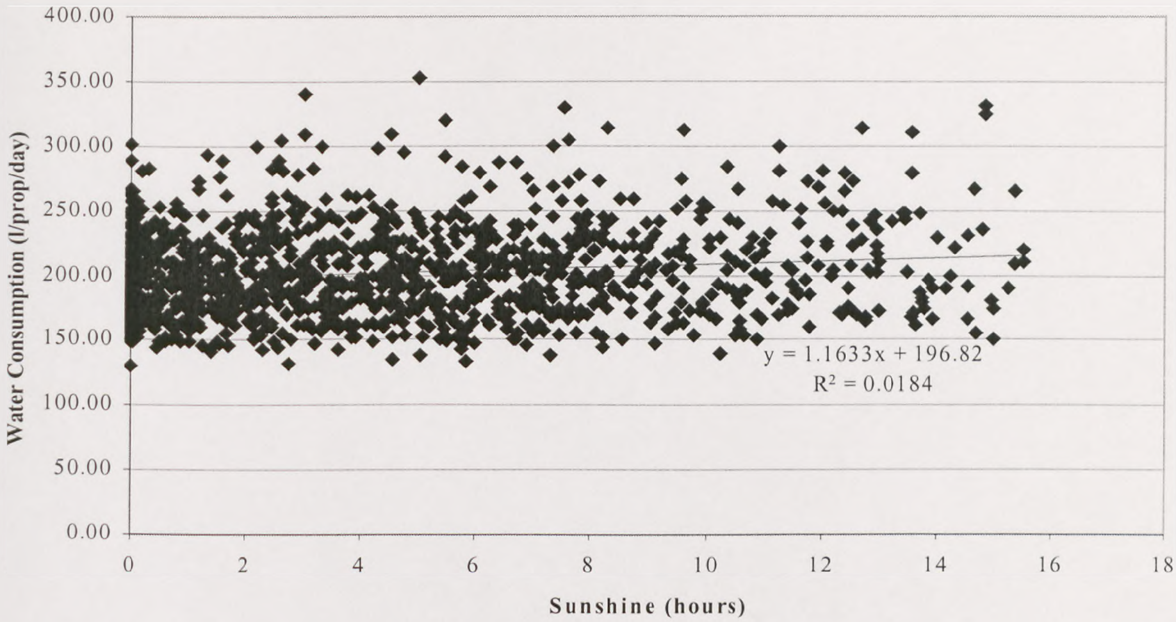


Figure 5.42: Relationship between water consumption and sunshine for one-person semi-detached properties in the Yorkshire Water study

Table 5.11: The influence of environmental variables on domestic water consumption in each season in one-person detached properties in the Thames Water study (linear regression – R^2)

Weather	*Seasons*			
	Summer	*Autumn*	*Winter*	*Spring*
Rainfall (mm)	0.03-	0.02-	0.00	0.01-
Sunshine (hrs)	0.09+	0.06+	0.00	0.00
Temperature (°C)	0.12+	0.05+	0.00	0.06+

Key: ***+ results in an increase in domestic water demands***
- results in a reduction in domestic water demands

Table 5.12: The influence of environmental variables on domestic water consumption in each season in two-person semi-detached properties in the Yorkshire Water study (linear regression – R^2)

Weather	*Seasons*			
	Summer	*Autumn*	*Winter*	*Spring*
Rainfall (mm)	0.01-	0.00	0.00	0.00
Sunshine (hrs)	0.01+	0.00	0.00	0.00
Temperature (°C)	0.01+	0.00	0.00	0.00

Key: ***+ results in an increase in domestic water demands***
- results in a reduction in domestic water demands

Several factors may explain why environmental variables appear to have little influence on domestic water consumption in the Yorkshire Water study:

(i) As mentioned in section 5.5, the aggregation of socio-economic and climatic conditions in the Yorkshire Water study may counterbalance each other to produce little variation in domestic water consumption.

(ii) The sample households may be biased towards low water users; hence households that consume large amounts of water for activities such as garden watering may have opted not to be included in the domestic water use study (see section 3.3.1 for details).

(iii) Climatic conditions in Yorkshire may be another possible explanation as to why environmental variables appear to have little influence on domestic water consumption. The South East experiences 5.68% more dry days per year than Yorkshire. The South East also experiences average daily temperatures 2°C higher than Yorkshire and an average of 0.52 hours of extra sunshine per day. The South East also experiences longer spells of dry weather. Domestic water consumption may, therefore, be further influenced by a lag effect. If the weather in the last three days for example, has been hot and dry, people may be more inclined to water their gardens than if the weather has been hot and dry for only one day previous. If this explanation were correct, environmental variables would not be expected to influence domestic water consumption in the small water supply areas of Yorkshire. However, in the small water supply areas of Yorkshire, there are a disproportionate number of affluent retired residents living in detached properties with large gardens. These residents have the potential to irrigate their large gardens when it is hot and sunny. These residents also have ample opportunity for water consuming activities such as garden watering. Such differences in the population base may account for differences in the relationship between domestic water consumption and environmental variables.

5.9.2 Multiple linear regression analysis

As mentioned in section 5.7.2, in an attempt to explain better how variations in environmental variables influence variations in domestic water consumption, multiple linear regression analysis was performed using rainfall, temperature and sunshine amounts as independent variables (Appendix 5L). In the Thames Water study, multiple linear regression analysis slightly improved the percentage of explained variance for all household sizes and property types (Table 5.13). However, flats were the exception. Both the linear and multiple linear regression analysis suggest that environmental variables have little influence on domestic water consumption in flats. This is expected as flats typically have no gardens and hence are likely to have very low or no outdoor water use.

Table 5.13: Relationship between water consumption and weather for one-person detached properties in the Thames Water study

Regression Technique	*Weather*	*Property Type*			
		Detached	*Flat*	*Semi-Detached*	*Terraced*
Linear Regression	Rainfall (mm)	0.016	0.002	0.017	0.009
	Sunshine (hrs)	0.104	0.035	0.135	0.096
	Temperature (°C)	0.160	0.013	0.141	0.104
Multiple Linear Regression	Rainfall (mm) Sunshine (hrs) Temperature (°C)	0.193	0.033	0.189	0.134

In the Yorkshire Water study, the percentage of variance in domestic water consumption explained by environmental variables in the multiple linear regression analysis remained low (typically $R^2 = 0.004$). This confirms the findings from the linear regression analysis, which suggests that environmental variables in the Yorkshire Water study have little influence on domestic water consumption.

5.10 Environmental variables and short-term domestic water demands

As can be recalled from section 4.8, short-term domestic water demands were hypothesized to be influenced by the antecedent and/or prevailing day's weather conditions. The effects of weather variables from 24 hours to 7 days prior were, therefore, investigated using two methodologies, the lag and cumulative lag (see section 3.14.1 for details). As mentioned in section 5.1, only household size and property type data from the Thames Water and Yorkshire Water studies were used in this analysis due to the low frequency of meter readings adopted by Essex and Suffolk Water (see section 3.8.3 for details).

The influence of environmental variables on short-term domestic water demands in the Thames Water and Yorkshire Water studies were similar to those in the zonal meter areas (see section 4.8 for details). The cumulative lag consistently produced the strongest relationships between environmental variables and short-term domestic water demands, with rainfall producing negative correlation coefficients and sunshine amounts, maximum temperature, minimum temperature and average temperature, producing positive correlation coefficients. Again, maximum temperature repeatedly produced stronger relationships with short-term domestic water demands compared to the other methods of recording temperature. Therefore, in further analysis, only the cumulative lags would be used to investigate the relationship between short-term domestic water demands and the antecedent and prevailing day's weather conditions, and only maximum temperature would be used to determine the relationship between short-term domestic water demands and temperature.

5.11 Environmental variables and short-term domestic water demands over the entire monitoring period

The influence of environmental variables on short-term domestic water demands was first analysed over the entire monitoring period (see section 3.14.1 for details). In the Thames Water and Yorkshire Water studies, analysis of the relationship between short-term domestic water demands and the antecedent and prevailing day's weather conditions over the entire monitoring period generally produced relatively weak correlation coefficients (see Appendix 5M for details). In the Thames Water study, the correlations coefficients were typically $r = \pm 0.45$. In the Yorkshire Water study, the correlation coefficients were typically $r = \pm 0.29$. Weaker relationships between short-term domestic water demands and environmental variables were expected in the Yorkshire Water study due to limited seasonal variation in the time-series data and the findings from the linear and multiple linear regression analysis (see section 5.9.1 and 5.9.2 for details). In the majority of cases, short-term domestic water demands in detached and semi-detached properties produced stronger relationships with environmental variables than any other property type (Table 5.14). In all cases, water consumption in flats produced the weakest relationships with environmental variables, with many correlation coefficients proving insignificant. As mentioned in section 5.9.1, this is expected as most flats have no garden, and thus are not influenced by weather for outdoor water use.

Table 5.14: Relationship between water consumption and the antecedent and prevailing day's weather conditions for two-person households in the Thames Water study

Weather	*Property Type*			
	Detached	*Semi-Detached*	*Terraced*	*Flat*
Rainfall (mm)	-0.260	-0.153	-0.062	0.000
Sunshine (hrs)	0.448	0.378	0.259	0.127
Temperature (°C)	0.486	0.440	0.323	0.244

In the majority of cases where significant relationships were observed between short-term domestic water demands and environmental variables, a similar emerging trend to that observed in the zonal meter areas was evident (see section 4.8 for details). The strength of the correlation coefficients increased steadily to about two or three cumulative days previous before remaining constant or declining (Figure 5.43 and Appendix 5M).

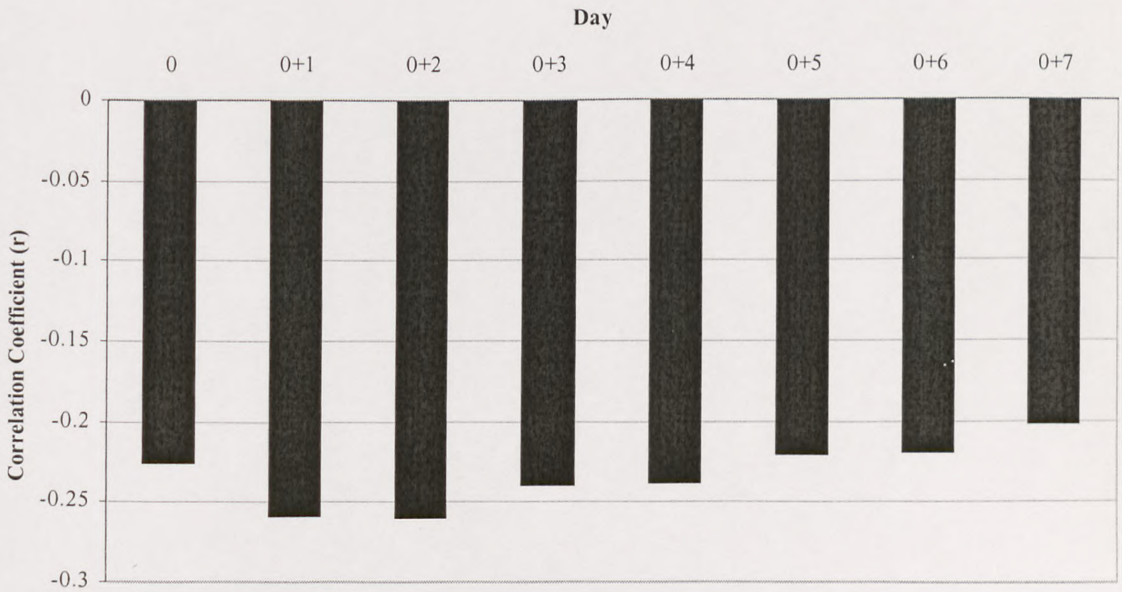


Figure 5.43: Trend between water consumption and the antecedent and the prevailing day's rainfall conditions in three-person semi-detached properties in the Thames Water study

5.12 Environmental variables and short-term domestic water demands over the seasons

As expected, the strongest relationships between short-term domestic water demands and the antecedent and prevailing day's weather conditions were produced during the summer season (Table 5.15 and Appendix 5M). As mentioned in section 4.10, this is expected as this season coincides with maximum temperatures and sunshine amounts and hence maximum outdoor water use. Short-term domestic water demands in detached and semi-detached properties produced the strongest relationships with environmental variables, while short-term domestic water demands in flats produced the weakest relationships. However, no one environmental variable produced significantly stronger or weaker relationships with short-term domestic water demands than another.

Table 5.15: Relationship between water consumption and weather for one-person detached properties in the Thames Water study (correlation coefficient – r)

Weather	*Seasons*			
	Summer	*Autumn*	*Winter*	*Spring*
Rainfall (mm)	-0.537	-0.189	0.000	-0.155
Sunshine (hrs)	0.601	0.197	0.000	0.346
Temperature (°C)	0.540	0.271	0.000	0.404

When the summer seasons were analysed for individual years, some relationships proved insignificant. As in the zonal meter studies, some of the relationships proved insignificant because of data paucity (see section 4.10 for details). However, there are many cases where sufficient data for a single summer season exist that fail to exhibit a significant relationship between weather and water demand. As can be recalled from section 4.10, this suggests that: (i) it requires several years of summer data to develop a sufficient range of weather values to show a significant relationship and (ii) that multiple criteria must be satisfied before the demand is explained and can be observed. However, for those relationships proving significant: (i) detached and semi-detached properties in the Thames Water study demonstrated the strongest relationships with weather (ii) the two days antecedent and prevailing day's weather conditions appeared to exert the greatest influence on demand and (iii) no major differences were observed in the strength of relationships from one summer season to the next. Typically, the variation in the strength of the correlation coefficients from one summer season to the next was seldom more than 0.1.

The relationships between short-term domestic water demands and the antecedent and prevailing day's weather conditions over the entire spring and autumn seasons and the individual years were similar to the relationships in the zonal meter studies (see section 4.10 for details) in that they displayed similar characteristics to those observed during the summer season. However, in the majority of cases, the correlation coefficients were slightly weaker with many relationships again proving insignificant. As expected, relationships between short-term domestic water demands and environmental variables for the aggregated and individual winter seasons proved insignificant. It is highly probable that at this time of year, domestic water consumption is represented only by in-house use.

5.13 Summary of environmental variables and short-term domestic water demands

In the individual household studies many significant relationships between short-term domestic water demands and environmental variables were identified. The two days antecedent and prevailing day's weather conditions appear to exert the greatest influence on short-term domestic water demands. The strongest relationships between short-term domestic water demands and environmental variables were observed for detached and semi-detached properties, and the weakest were for flats. These relationships appear to be independent of household size. However, the relationships between short-term domestic water demands and environmental variables are seldom strong, with environmental variables explaining only a small amount of observed variance. As in the zonal meter studies (see section 4.11 for details), findings from this analysis suggest that factors, external to environmental variables, may also influence short-term domestic water demands. Further investigations were, therefore, undertaken to determine the influence of external factors, such as day of the week, calendar effects and school holidays, on short-term domestic water demands.

5.14 Day of the week and short-term domestic water demands

To investigate the influence of 'day of the week' on short-term domestic water demands, individual household size and property type data in the Thames Water and Yorkshire Water studies were subdivided into weekends and weekdays (see section 3.14.3.1 for details). Weekend water consumption in both the zonal meter studies (see section 4.12 for details) and the individual household studies displayed significantly higher means, medians, modes and quartiles in comparison to weekday water consumption (see Appendix 5N for details). However, no one household size or property type consistently demonstrated significantly higher or lower percentage increases in domestic water consumption from weekdays to weekends. In the Thames Water study the average increase between weekday and weekend water consumption was 10.56%. In the Yorkshire Water study the average increase was 9.28%.

In both the Thames Water and Yorkshire Water studies, the minimum instantaneous water use for households of different sizes and property types was recorded frequently on weekdays during the winter season. In comparison, the maximum instantaneous water use was recorded frequently during the spring or summer season. Those instantaneous maxima recorded during the spring season occurred typically on the May Day bank-holiday weekend. Other calendar effects (bank-holidays and public holidays) also resulted in increases in short-term domestic water demands. Increases in domestic water demands associated with bank-holidays and public holidays were similar to increases in domestic water demands associated with weekends. However, no one public or bank-holiday consistently produced the highest or lowest increase in short-term domestic water demands.

To investigate whether short-term domestic water demands are influenced by particular days of the week, household size and property type data in the Thames Water and Yorkshire Water studies were subdivided into individual days of the week (see section 3.14.3.1 for details). As in the zonal meter studies, there was no obvious pattern in weekday water consumption (see section 4.13, Table 5.16 and Appendix 5O for details). However, in 77.78% of the data, water consumption was 3.61% higher on a Sunday in comparison to a Saturday. This is probably because relatively high proportions of the population work on a Saturday.

Table 5.16: Day of the week water consumption for four-person households in the Yorkshire Water study (litres/property/day)

Day of the Week	*Property Type*				
	Detached House	*Semi-Detached House*	*Terraced House*	*Detached Bungalow*	*Semi-Detached Bungalow*
Monday	709.30	480.48	463.63	452.24	488.45
Tuesday	663.36	474.48	442.89	451.67	464.28
Wednesday	685.02	473.58	450.19	466.08	472.60
Thursday	663.14	470.95	472.18	472.91	468.15
Friday	691.00	484.71	463.33	461.70	483.03
Saturday	759.98	560.21	516.76	491.58	508.34
Sunday	773.35	543.86	516.48	550.58	533.46

5.15 Environmental variables and weekend and weekday water consumption

As can be recalled from section 4.13, it was hypothesized that the influence of environmental variables on weekend and weekday water consumption would differ. The effects of environmental variables on weekend and weekday water consumption were, therefore, investigated (see Appendix 5P for details). Many of the relationships between weekend and weekday water consumption and environmental variables proved insignificant, undoubtedly due to data shortage. Where significant relationships between weekend and weekday water consumption and environmental variables were observed, similar patterns to those for the entire data set were found (see section 5.10 for details). Rainfall produced negative correlation coefficients with weekend and weekday water consumption while sunshine amounts and maximum temperatures produced positive correlation coefficients. The strength of the correlation coefficients increased steadily to about two or three cumulative days previous before remaining constant or declining (Figure 5.43). Weekend and weekday water consumption in detached and semi-detached properties frequently produced stronger relationships with environmental variables than terraced properties and flats. However, as in the zonal meter studies (see section 4.13 for details), weather appeared not to exert a particular relation to either weekend or weekday consumption data (Table 5.17 and Appendix 5P).

Table 5.17: The relationship between environmental variables and weekend and weekday water consumption in two-person households in the Thames Water study (correlation coefficient – r)

Weather	*Property Type*							
	Detached		*Semi-Detached*		*Terraced*		*Flat*	
	Weekday	*Weekend*	*Weekday*	*Weekend*	*Weekday*	*Weekend*	*Weekday*	*Weekend*
Rainfall (mm)	0.11-	0.10-	0.09-	0.10-	0.08-	0.08-	0.00	0.00
Sunshine (hrs)	0.07+	0.09+	0.06+	0.07+	0.05+	0.05+	0.00	0.00
Temperature (°C)	0.14+	0.09+	0.11+	0.12+	0.08+	0.08+	0.00	0.00

Key: ***+ indicates a positive relationship with demand***
- indicates a negative relationship with demand

5.16 Summary of 'day of the week' and short-term domestic water demands

Short-term domestic water demands in the zonal meter studies (see section 4.12 for details) and the individual household studies are influenced by 'day of the week' with increases in short-term domestic water demands associated with weekends. This is expected as significantly more people remain at home during weekends, and are, therefore, likely to consume more water. However, no one household size or property type consistently demonstrated significantly higher or lower percentage increases in domestic water consumption from weekdays to weekends. Results from the analysis of weekend and weekday water consumption and weather were also similar to the zonal meters as weather does not appear to exert a particular influence on either weekend or weekday consumption (see section 4.13 for details).

5.17 School holidays and short-term domestic water demands

The influence of school holidays on short-term domestic water demands was analysed using school holiday data provided by some Local Education Authorities (see section 3.14.3.2 for details). School holidays were found to significantly influence short-term domestic water demand in some households with three or more persons. These households displayed an average 8% increase in short-term domestic water demand, despite no obvious variation in weather (Table 5.18). The specific process of how school holidays influence short-term domestic water demands is unknown. However, it is undoubtedly related to both children and adults staying at home. School holidays are not expected to influence short-term domestic water demands in one or two-person households, obviously because the majority of householders are adults. However, in some households with three or more persons, school holidays appeared to exert little or no influence on short-term domestic water demand. As can be recalled from section 4.15, the relationship between short-term domestic water demands and school holidays may be influenced by: (i) differences in public and state school holidays and (ii) school catchment areas where the dates of school holidays differ. These differences may result in a diminution of the clarity of the signal in the domestic water demand data and hence the absolute impact of school holidays on short-term domestic water demands is impossible to quantify.

Table 5.18: Domestic water consumption before, during and after the February half-term school holiday for six-person semi-detached houses in Leeds. The water consumption is the average of the Monday to Friday values.

Date	*Average Water Consumption (l/property/day)*	*Rainfall (mm)*	*Sunshine (hours)*	*Maximum Temperature (℃)*
Prior half-term	601.03	0.78	3.90	4.96
During half-term	642.33	0.92	2.68	9.96
After half-term	610.38	0.10	4.10	8.80

5.18 Summary

This and the preceding chapter have proved that many factors influence domestic water demands in both the short- and the medium- to long-term. Household size and property types appear to exert the greatest underlying influence on domestic water demands in the medium- to long-term. In the short-term, domestic water demands appear to be influenced by the two days antecedent and prevailing day's weather, day of the week, calendar effects and school holidays. Environmental variables exert the strongest influence on short-term domestic water demands in detached and semi-detached properties, regardless of household size. Short-term domestic water demands in all household sizes and property types are influenced by day of the week and calendar effects. However, school holidays only influence short-term domestic water demands in households with three or more persons.

Some of the time-series data for individual household sizes and property types display an unexplained upward or downward temporal shift in domestic water consumption. It is impossible to determine the extent to which these shifts in demand result from individual behavioural patterns or errors. The only possible way of explaining these changes in demand is to use a longer time-series of good quality data (i.e., questionnaires updated, continual maintenance of water meters and loggers, etc.).

The next chapter is an exploration of modelling strategies to forecast short-term domestic water demand using the findings from Chapters 4 and 5. In Chapter 6, data from the Thames Water and Yorkshire Water studies are treated separately due to the higher levels of consumption in the Thames Water study. Data also continues to be subdivided by household size and property type due to the strong underlying influence that they exert on demand.

6. Exploration of Modelling Strategies to Forecast Short-Term Domestic Water Demands

6.1 Introduction

Pragmatic and advanced approaches were explored to forecast short-term domestic water demands. The pragmatic approach is based on a form of accounting using a series of 'lookup tables'. Advanced approaches include stepwise regression, both with and without k-means cluster analysis, and univariate and multivariate ARMA time-series modelling. The exploration of modelling strategies focused on the individual household study data: (i) due to lack of confidence in the Welsh Water data resulting from the weak specification of data processing and (ii) due to relatively large amounts of missing data in Yorkshire Water's small water supply areas. As significantly more households with less than four persons were included in both the Thames Water and Yorkshire Water studies, more confidence was placed on this data. More confidence was also placed on the data from the Thames Water study, as a longer time-series of data was available. The exploration of modelling strategies, therefore, concentrated on households with less than four persons in the Thames Water study. Models were developed for each individual household size and property type because these factors appear to exert the greatest underlying influence on medium- to long-term domestic water demands (see section 5.6 for details). To forecast short-term domestic water demands in a given area, the demand forecast for each household size and property type would simply be multiplied by the number of households in that given area.

In all approaches, the variables explored to forecast short-term domestic water demands were based on the results of Chapters 4 and 5. Variables explored included the two days antecedent and the prevailing day's rainfall, temperature and sunshine amounts, days of the week and calendar effects. School holidays were omitted from this investigation, as the absolute impact of school holidays on short-term domestic water demands was impossible to quantify (see section 4.17 and 5.17 for details). To ensure consistency between the results from the different modelling strategies, the first sixty-percent of the data was used in the calibration/training of the models, and the remaining forty-percent was used to validate the models. To inform the assessment of the different modelling approaches, the mean average error, the root mean squared error and the R^2 were used to determine the accuracy with which short-term domestic water demands could be forecast.

This chapter:

(i) Examines each modelling strategy individually from the more simple pragmatic approach through to the more complex advanced approaches.

(ii) Evaluates the accuracy with which short-term domestic water demands can be forecast using the different modelling approaches.

(iii) Provides recommendations for the forecasting of short-term domestic water demands.

6.2 Pragmatic approach: lookup tables

The pragmatic approach was probably the least complex technique applied to the forecasting of short-term domestic water demands. The pragmatic approach is based on a form of accounting using a series of 'lookup tables'. A typical 'lookup table' for one-person semi-detached properties in the Thames Water study is shown in Table 6.1. Average weekday water consumption for each month of the year was calculated, using the time-series of past data, to establish a baseline for monthly domestic water demand. As several years of data were used to calculate the baseline for monthly domestic water demand, it was assumed that the figures represent the general background seasonal variation in domestic water consumption. Modifications to the baseline water demand could then be made by means of percentage change according to day of the week, calendar effects and the two days antecedent and the prevailing day's weather conditions.

To account for day to day changes in weather, the two days antecedent and the prevailing day's daily rainfall totals and daily maximum temperatures were averaged. To avoid complexity, sunshine amounts were not included in this approach. Instead, rainfall was assumed to act as a surrogate for sunshine amounts. For each month of the year, measures of dispersion in the two days antecedent and the prevailing day's average rainfall totals and maximum temperatures were calculated using quartiles. If the two days antecedent and the prevailing day's average maximum temperatures and average rainfall totals were dispersed in the inter-quartile range, weather conditions were assumed typical. No change would be made to the monthly baseline water demand as this figure already accounts for 'typical' weather conditions. However, if either or both of the two days antecedent and the prevailing day's average rainfall totals and maximum temperatures were dispersed in the upper or lower quartiles, weather conditions were assumed atypical. A change in the monthly baseline water demand was therefore necessary. The first sixty-percent of the data was used to determine changes in the monthly baseline water demand. For each month of the year, the average percentage change in water demand was calculated depending on whether the two days antecedent and the prevailing day's average rainfall totals and average maximum temperatures were dispersed in the inter-quartile range or in the upper or lower quartiles.

Overall, prediction results from this approach appear very promising. Where seasonal variation was evident in the water demand data, the lookup tables were able to follow the general seasonal pattern, with peaks in demand during summer and troughs in demand during winter (Figures 6.1 and 6.2). However, even where no obvious seasonal variation was evident in the water demand data, the predicted data from the lookup tables appear to follow the overall trend in demand (Figure 6.3 and Appendix 6A).

Table 6.1: A typical example of a lookup table for one-person semi-detached households in the Thames Water study

Month	*Baseline water demand*	*Percentage change for weekends*	*Percentage change for bank-holidays and public holidays*	*Percentage change for school holidays*	*Two days antecedent and prevailing average maximum temperatures (°C)*	*Two days antecedent and prevailing average rainfall totals (mm)*	*Percentage change for the two days antecedent and prevailing day's average maximum temperatures and rainfall totals*
January	230	14	12	N/A	N/A	N/A	N/A
February	226	16	N/A	N/A	N/A	N/A	N/A
March	230	13	9	N/A	4.80 - 8.60	<1.43	-2
						>1.43	-2
					8.61 - 13.07	<1.43	0
						>1.43	0
					13.08 - 16.60	<1.43	+2
						>1.43	No Data
April	237	8	13	N/A	8.07 - 11.32	<1.20	-5
						>1.20	-5
					11.33 - 16.40	<1.20	0
						>1.20	-6
					16.41 - 21.20	<1.20	+0.7
						>1.20	No Data
May	243	12	23	N/A	8.93 - 13.98	<2.22	-5
						>2.22	-14
					13.99 - 19.15	<2.22	0
						>2.22	-10
					19.16 - 26.67	<2.22	+8
						>2.22	-2
June	282	4	N/A	N/A	13.83 - 17.88	<2.00	-13
						>2.00	-23
					17.89 – 23.00	<2.00	0
						>2.00	-23
					23.01 - 29.37	<2.00	+2
						>2.00	-19

Month	*Baseline water demand*	*Percentage change for weekends*	*Percentage change for bank holidays and public holidays*	*Percentage change for school holidays*	*Two days antecedent and prevailing average maximum temperatures (°C)*	*Two days antecedent and prevailing average rainfall totals (mm)*	*Percentage change for the two days antecedent and prevailing day's average maximum temperatures and rainfall totals*
July	301	15	N/A	N/A	17.40 - 22.75	<1.08	-18
						>1.08	-15
					22.76 - 26.18	<1.08	0
						>1.08	-9
					26.19 - 30.43	<1.08	+19
						>1.08	+5
August	286	22	1	N/A	17.93 - 21.02	<1.75	-18
						>1.75	-24
					21.03 - 26.90	<1.75	0
						>1.75	-26
					26.91 - 31.13	<1.75	+12
						>1.75	-9
September	245	16	N/A	N/A	13.63 - 17.68	<2.37	-0.7
						>2.37	-4
					17.69 - 19.93	<2.37	0
						>2.37	-2
					19.94 – 23.00	<2.37	-1
						>2.37	No Data
October	242	14	N/A	N/A	11.27 - 14.87	<1.94	-4
						>1.94	-6
					14.88 - 18.12	<1.94	0
						>1.94	-3
					18.13 - 23.33	<1.94	+0.7
						>1.94	No Data
November	244	12	N/A	N/A	7.20 – 10.97	<2.99	-0.6
						>2.99	-2
					10.98 - 14.41	<2.99	0
						>2.99	-3
					14.42 - 17.33	<2.99	+2
						>2.99	+1
December	247	10	21	N/A	N/A	N/A	N/A

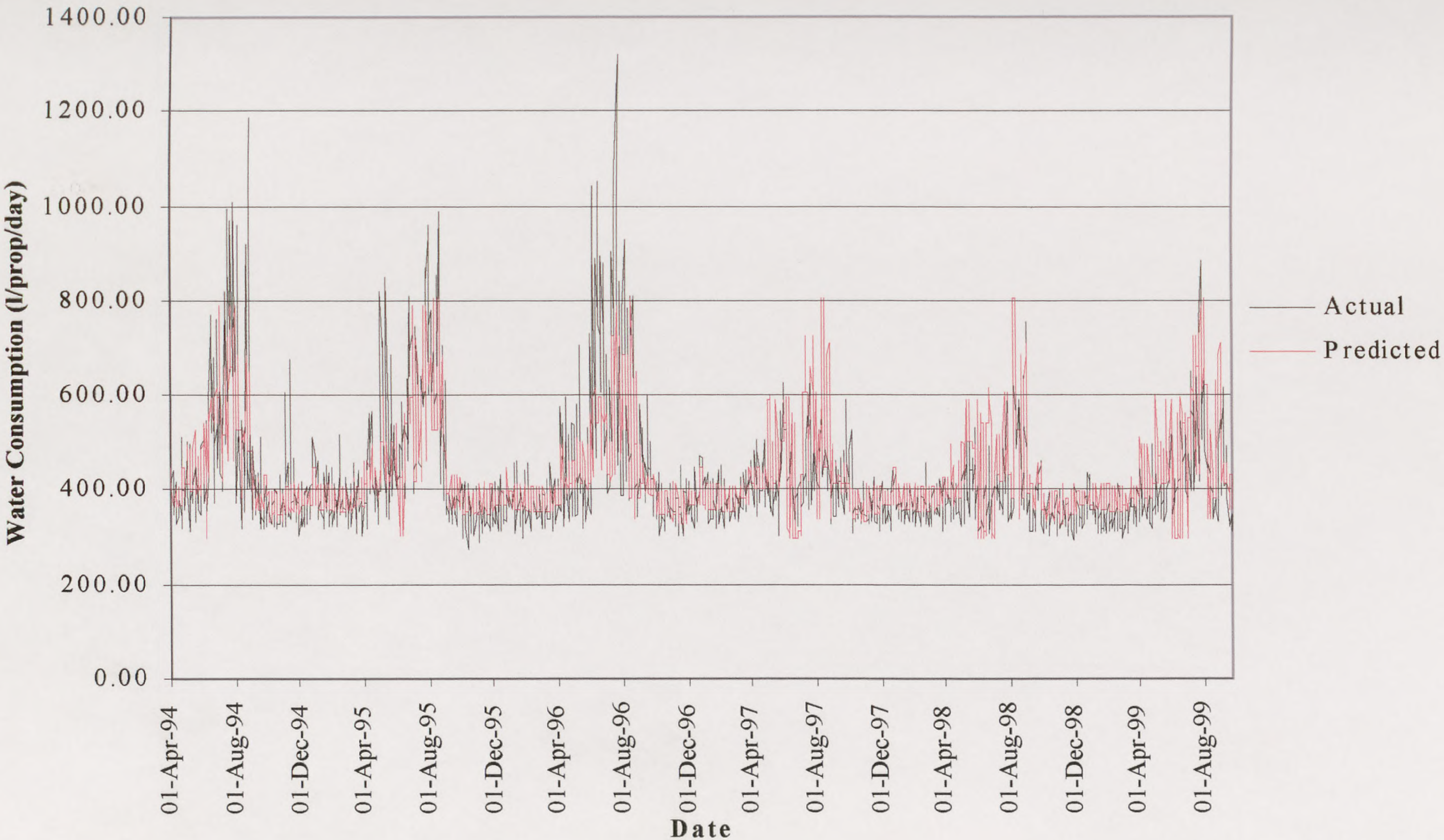


Figure 6.1: Actual and predicted water demands for two-person detached properties in the Thames Water study using the 'lookup table' approach

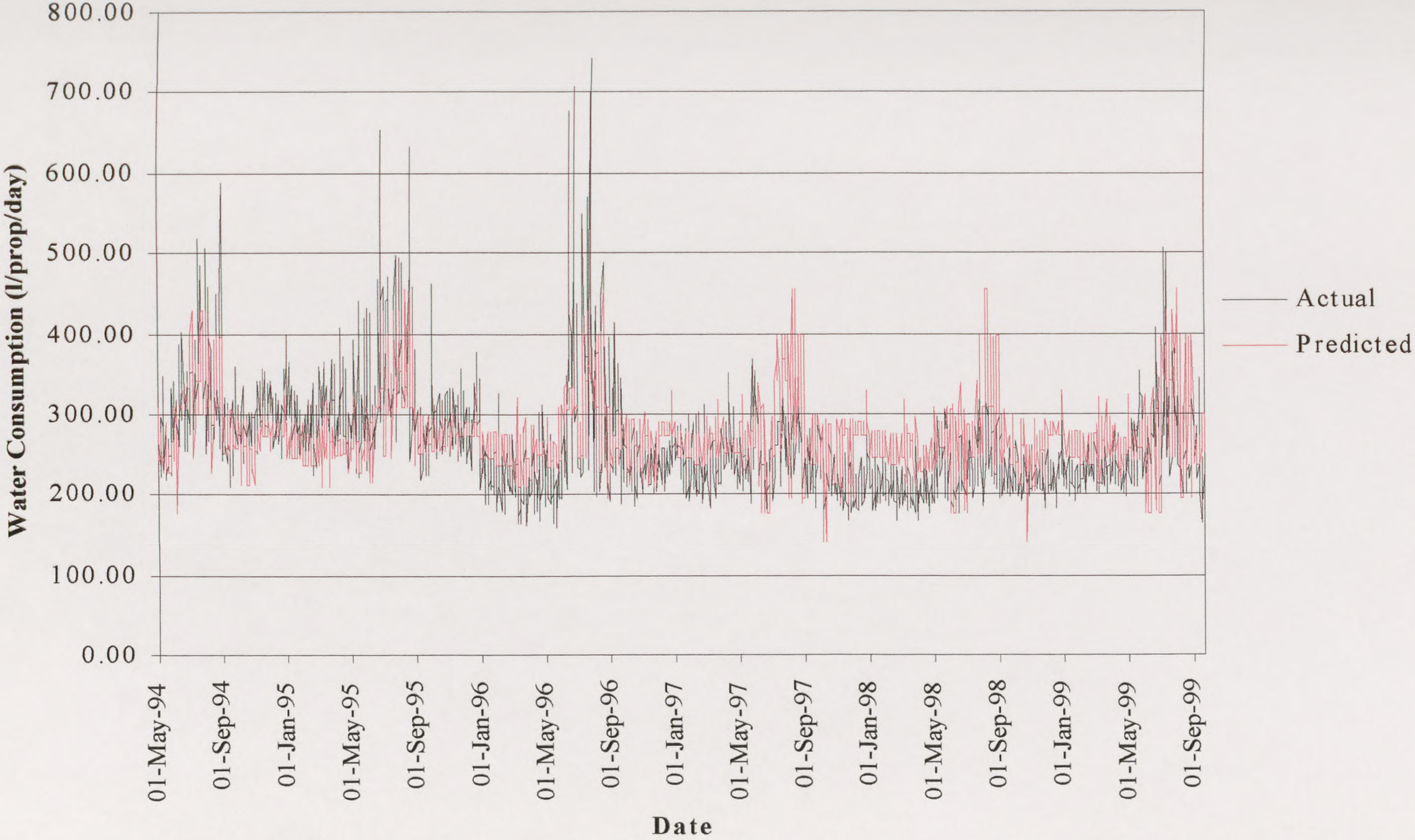


Figure 6.2: Actual and predicted water demands for one-person semi-detached properties in the Thames Water study using the 'lookup table' approach

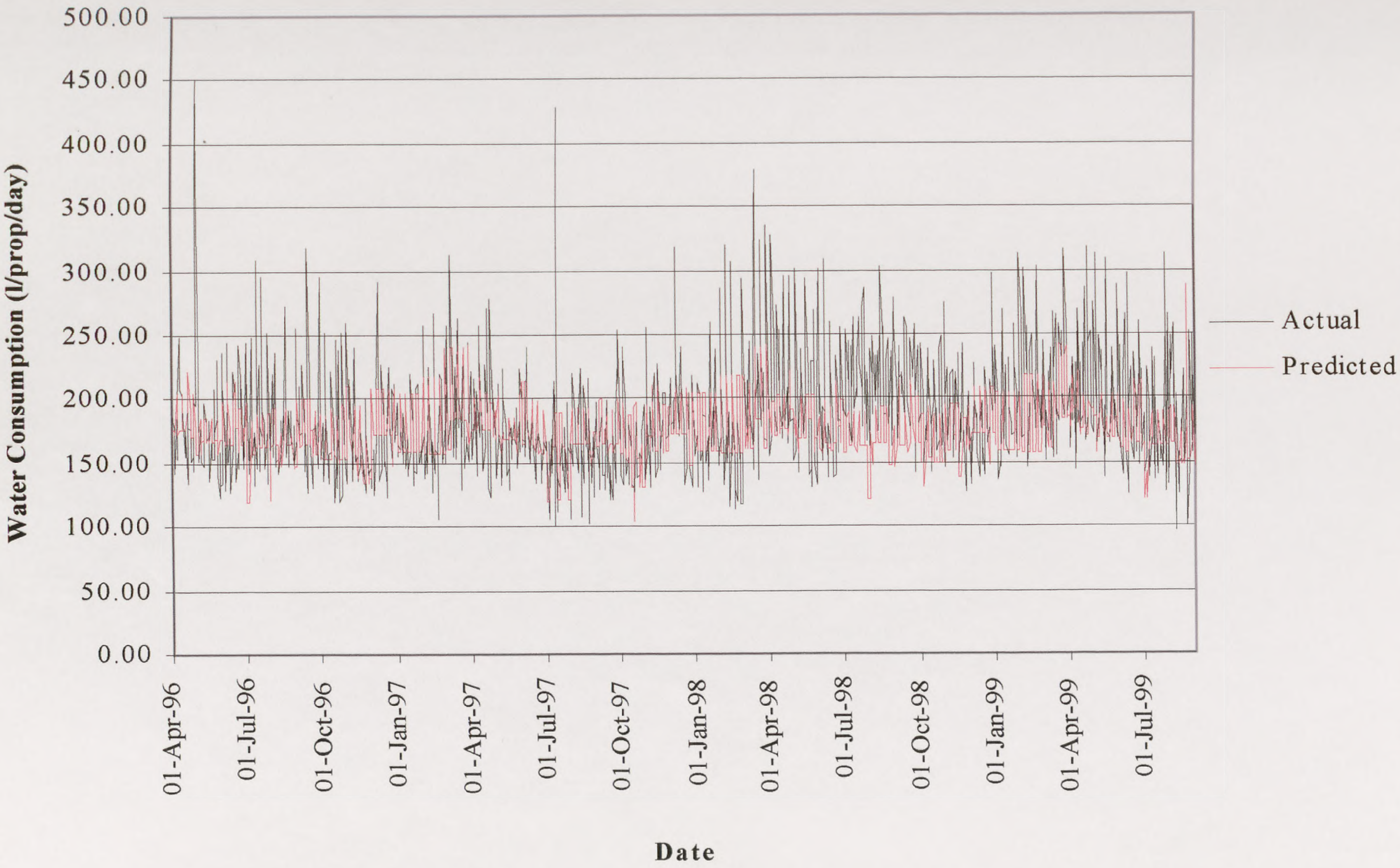


Figure 6.3: Actual and predicted water demands for one-person detached bungalows in the Yorkshire Water study using the 'lookup table' approach

The lookup tables were able to forecast day to day weather induced changes in water demand in both the training and validation periods (Figures 6.4 and 6.5). As can be recalled from section 4.9 and 5.11, increases in water demand were associated with a rise in the two days antecedent and the prevailing day's temperature, and decreases in demand were associated with an increase in the two days antecedent and the prevailing day's rainfall. In both the training and validation periods, the lookup tables were also successful in predicting variations in water demand associated with weekends and weekdays (Figures 6.6 and 6.7). Similarly, the lookup tables were also successful at predicting changes in water demand associated with bank-holidays and public holidays (Figures 6.8 and 6.9).

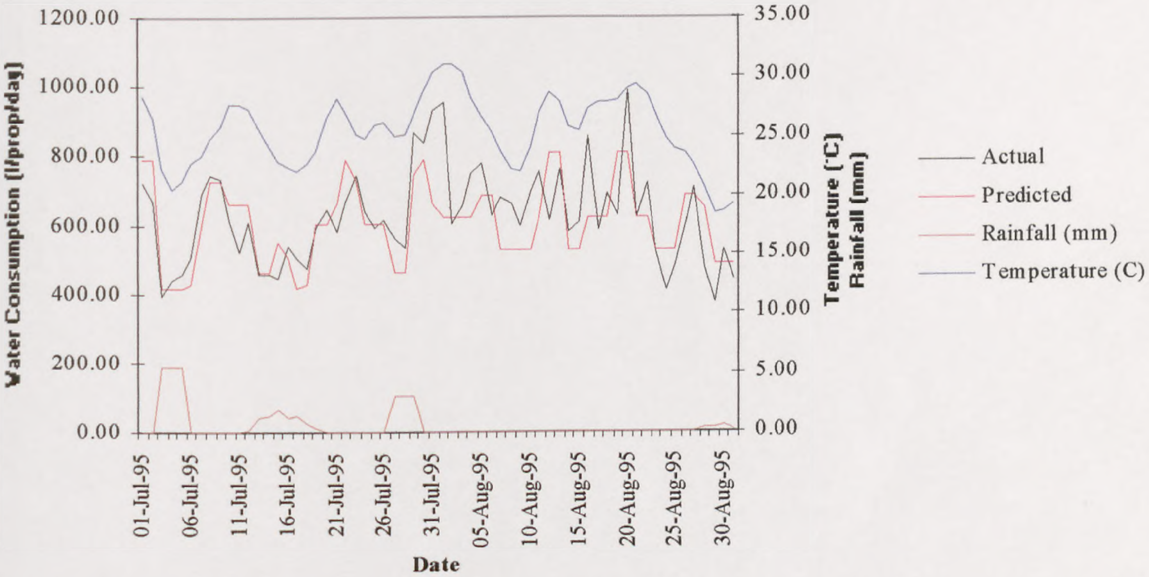


Figure 6.4: Actual and predicted water demands in the training period for two-person detached properties in the Thames Water study using the 'lookup table' approach

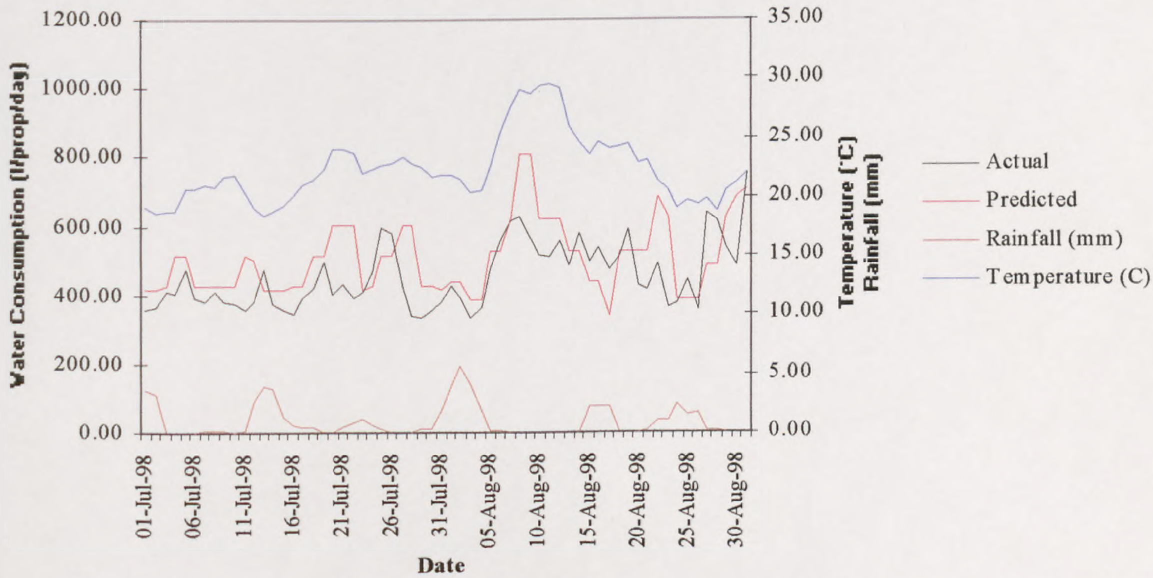


Figure 6.5: Actual and predicted water demands in the validation period for two-person detached properties in the Thames Water study using the 'lookup table' approach

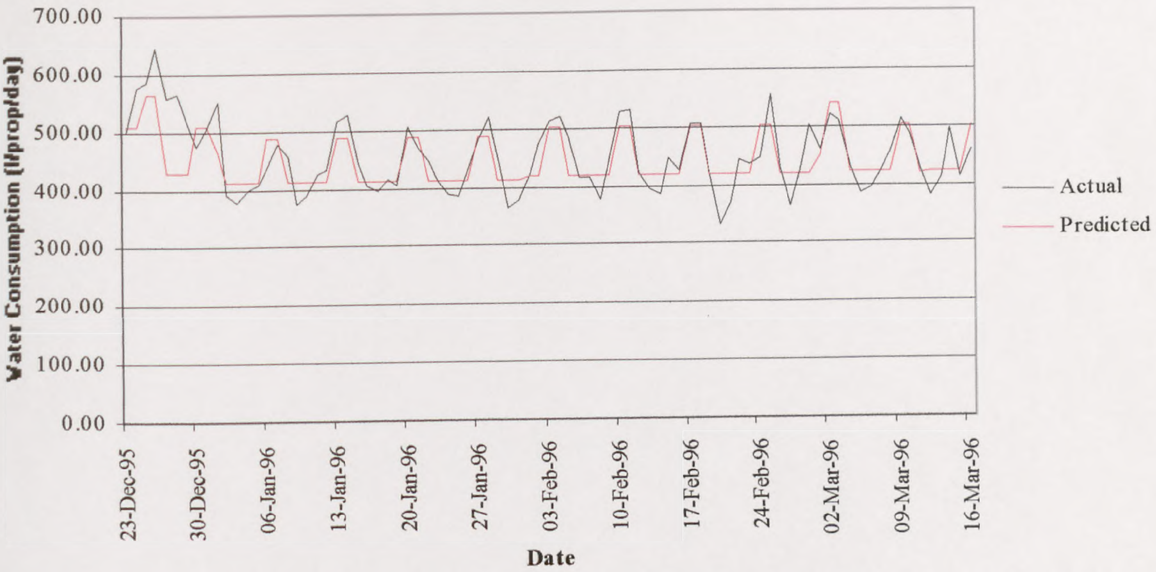


Figure 6.6: Actual and predicted water demands in the training period for three-person detached properties in the Thames Water study using the 'lookup table' approach

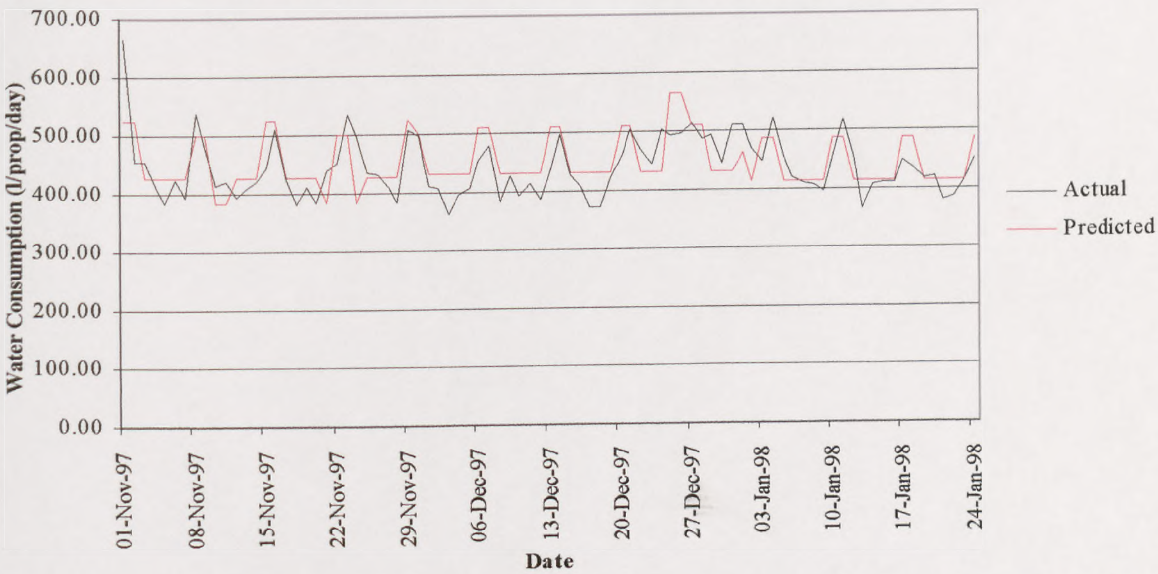


Figure 6.7: Actual and predicted water demands in the validation period for three-person detached properties in the Thames Water study using the 'lookup table' approach

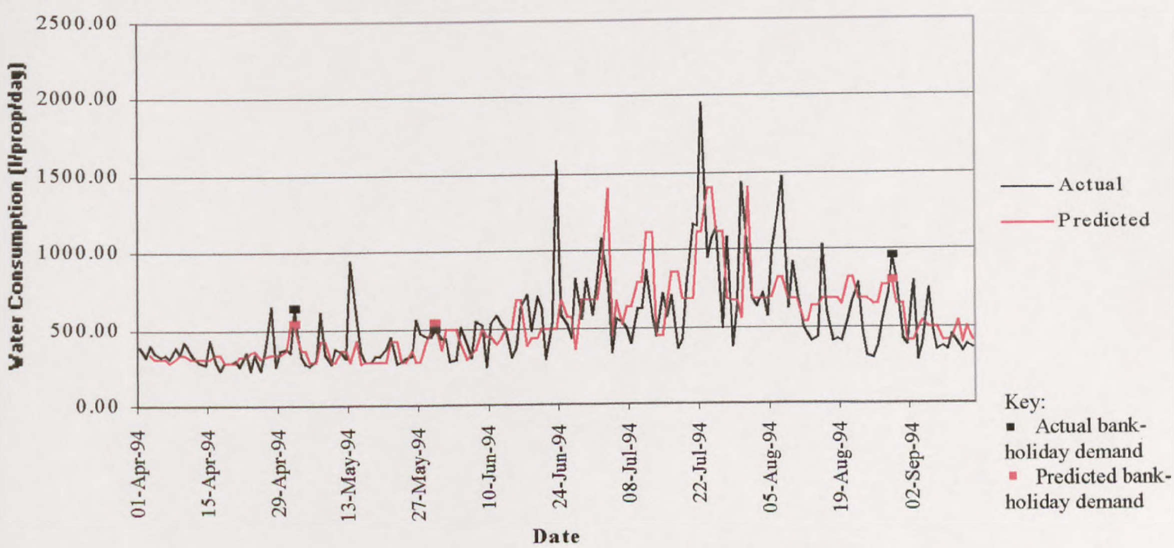


Figure 6.8: Actual and predicted water demands in the training period for one-person detached properties in the Thames Water study using the 'lookup table' approach

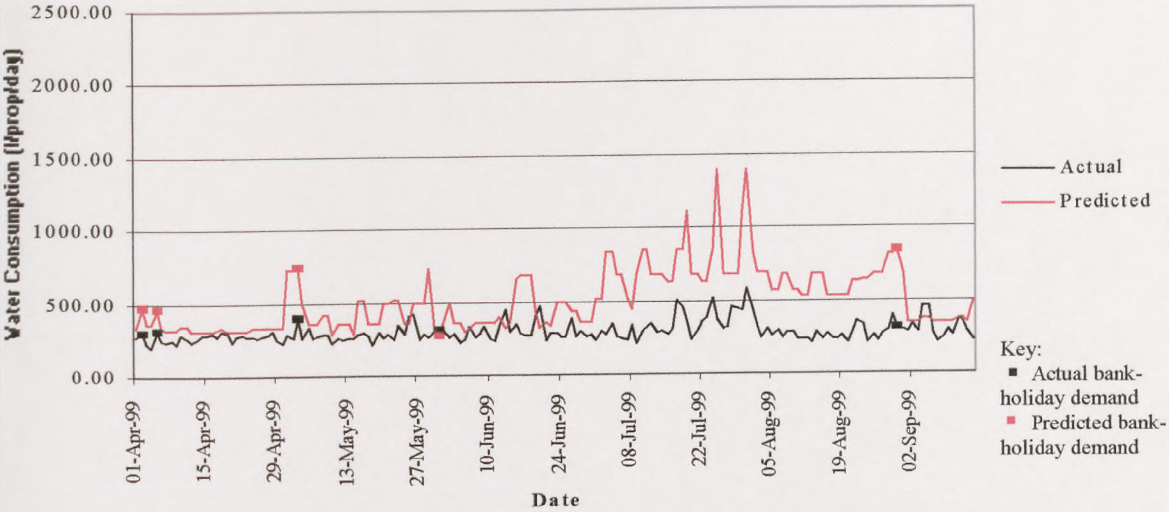


Figure 6.9: Actual and predicted water demands in the validation period for one-person detached properties in the Thames Water study using the 'lookup table' approach

The lookup tables were able to predict changes in domestic water demands in both the medium- to long-term and in the short-term. In the medium- to long-term, the lookup tables were able to follow the general seasonal variation in domestic water demands. In the short-term, the lookup tables were able to predict changes in demand associated with the antecedent and prevailing weather conditions, day of the week and calendar effects. Although the lookup tables were successful in predicting changes in short- and medium- to long-term domestic water demands, problems were encountered when predicting actual demands. Several reasons may explain why the lookup tables were not able to predict actual water demands:

(i) As noted in section 5.7, some of the individual household demand data in both the Thames Water and Yorkshire Water studies experienced an unexplained upward or downward temporal shift in domestic water consumption. An upward trend in domestic water consumption resulted in under predictions of demand while a downward trend resulted in over predictions. It is impossible to determine the extent to which these shifts in demand result from individual behavioural water use patterns or errors. The only real way of determining the source of these shifts and hence, overcoming problems of over or under predictions, is to use a longer time-series of good quality data (see section 5.7 for details).

(ii) A further reason why the lookup tables may over or under predict domestic water demand is due to the way in which weather is incorporated into the lookup tables. It should be recalled that for each month of the year, measures of dispersion in the two days antecedent and the prevailing day's average rainfall totals and maximum temperatures were calculated using quartiles. If the two days antecedent and the prevailing day's average maximum temperatures and average rainfall totals were dispersed in the inter-quartile range, weather conditions were assumed typical, resulting in no change to the monthly baseline water demand. However, if either or both of the two days antecedent and the prevailing day's average rainfall totals and maximum temperatures were dispersed in the upper or lower quartiles, weather conditions were assumed atypical, requiring a change to the monthly baseline water demand. This method only permits six ways in which weather can be incorporated into the lookup table (Table 6.1). It is probable that if these arbitrary bands were subdivided further, accuracy in water demand predictions would increase. However, if more bands were created using the Thames Water and Yorkshire Water data, some bands had very few or no consumption values. This suggests that a longer time-series of data is necessary to gain a more accurate picture of how weather influences water demand in different scenarios.

6.3 Advanced approaches

6.3.1 Stepwise regression

Stepwise regression was the simplest advanced approach investigated to forecast short-term domestic water demands. Stepwise regression is a form of multiple regression (Mendenhall, 1996) in which variables are added to the equation individually, dependent upon a number of criteria that can be modified by the analyst. An important and typical criterion is the highest explained variance of the variable not yet added to the equation. In this case, criteria were the two days antecedent and the prevailing day's maximum temperatures, sunshine amounts and rainfall totals, day of the week and calendar effects, and the variable explained was the demand for domestic water in the short-term. These criteria were based on the results of factors found to influence short-term domestic water demand in Chapters 4 and 5. To incorporate day of the week and calendar effects into the stepwise regression equation, binary numbers were used. Zero represented a weekday and one represented a weekend. Similarly, one represented a bank-holiday or public holiday.

When stepwise regression was performed on the first sixty-percent of the data for each household size and property type, the two days antecedent and the prevailing day's temperature provided the greatest explanation of variations in short-term domestic water demands (see Appendix 6B for details). Day of the week, the two days antecedent and the prevailing day's rainfall and sunshine amounts were also found to be significant explanatory variables with day of the week and the two days antecedent and the prevailing day's sunshine amounts interchanging frequently between the second and third most important explanatory variable. In most cases, bank-holidays were also found to add explanation to the variation in short-term domestic water demands. In all cases, all significant explanatory variables, except rainfall, caused an increase in short-term domestic water demands. The typical percentage of explained variance in short-term domestic water demands was 39% in the Thames Water study and 16%

in the Yorkshire Water study. The percentage of explained variance ranged from 13% for two-person detached houses in Yorkshire, to 48% for two-person detached properties in the Thames Water study.

Stepwise regression proved relatively successful in predicting changes in domestic water demands in both the medium- to long-term and in the short-term. In the medium- to long-term, the stepwise regression models were able to follow seasonal variation in domestic water demands (Figures 6.10, 6.11 and Appendix 6C). In the short-term, predicted water demand data were similar to the actual demand data in that both closely followed trends in temperature and rainfall (Figures 6.12 and 6.13). The stepwise regression models were also able to forecast changes in demand associated with weekdays and weekends (Figures 6.14 and 6.15). In those stepwise regression models where calendar effects provided some significant explanation of variations in short-term domestic water demands, the stepwise regression models were relatively successful in predicting changes in demand due to calendar effects (Figures 6.16 and 6.17). As expected, in the stepwise regression models where calendar effects provided no significant explanation of variations in short-term domestic water demands, the stepwise regression models were unable to predict any changes in demand associated with calendar effects (Figure 6.18).

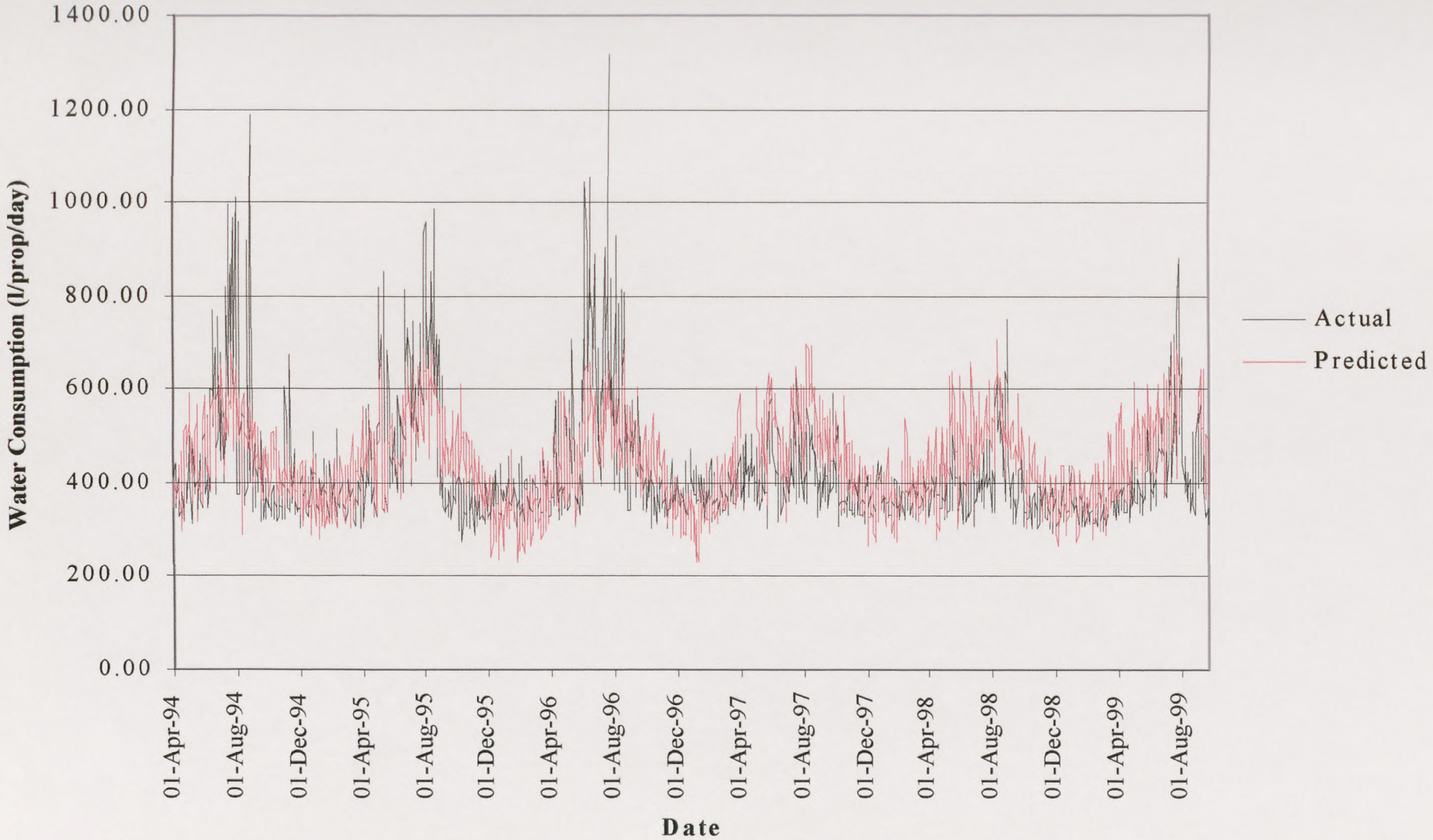


Figure 6.10: Actual and predicted water demands for one-person semi-detached properties in the Thames Water study using stepwise regression

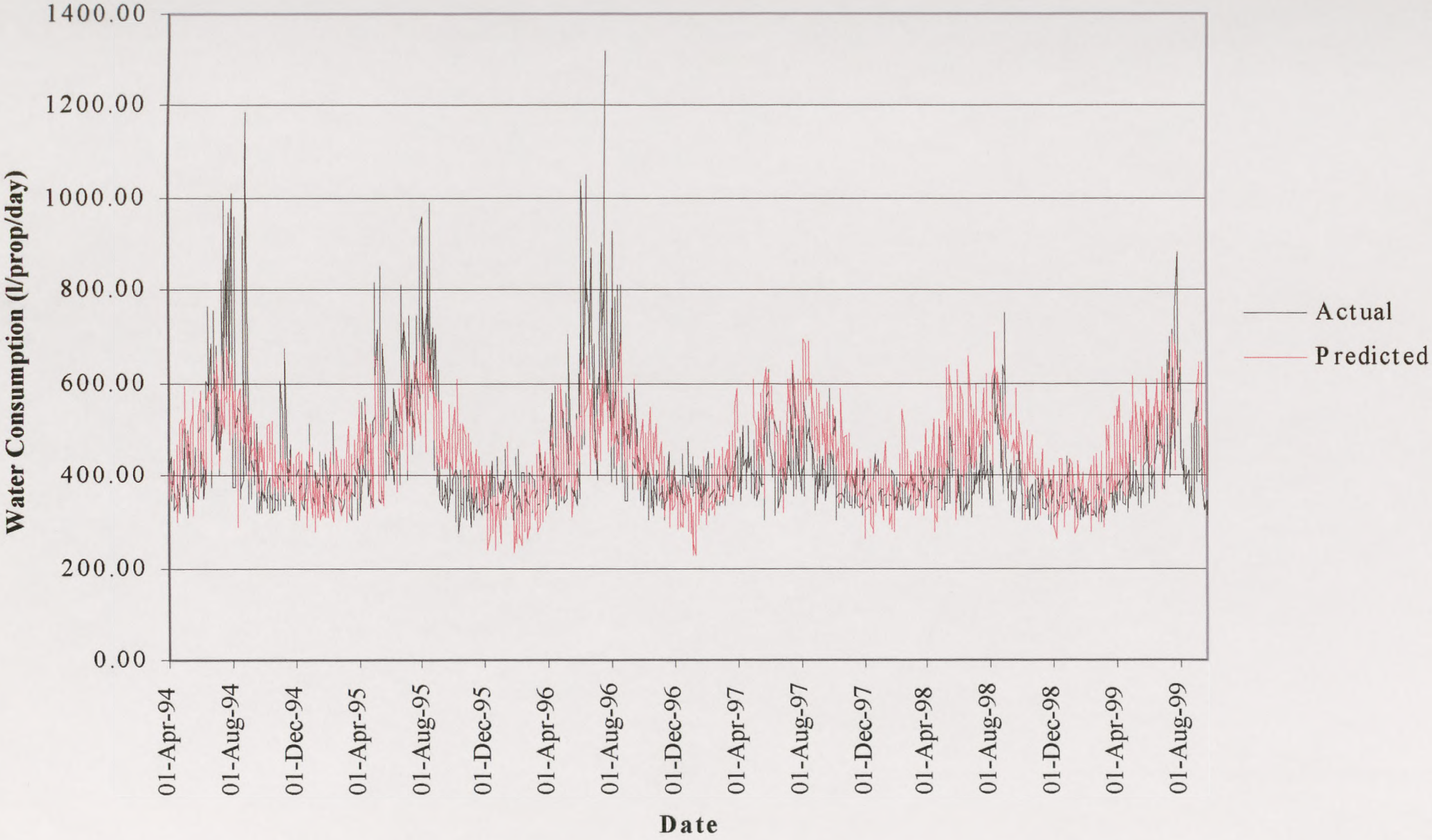


Figure 6.11: Actual and predicted water demands for two-person detached properties in the Thames Water study using stepwise regression

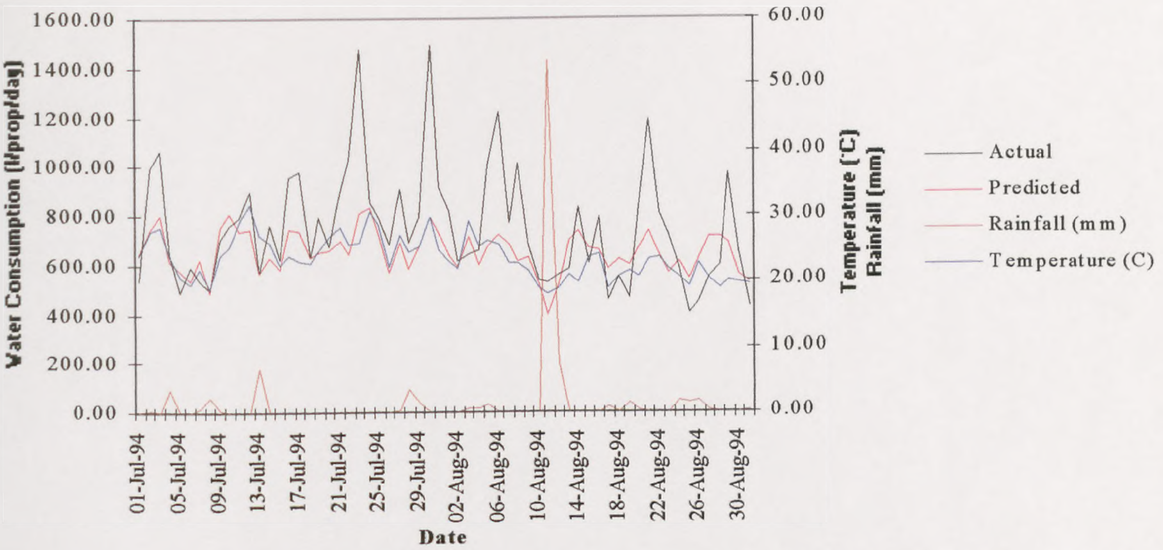


Figure 6.12: Actual and predicted water demands in the training period for three-person detached properties in the Thames Water study using stepwise regression

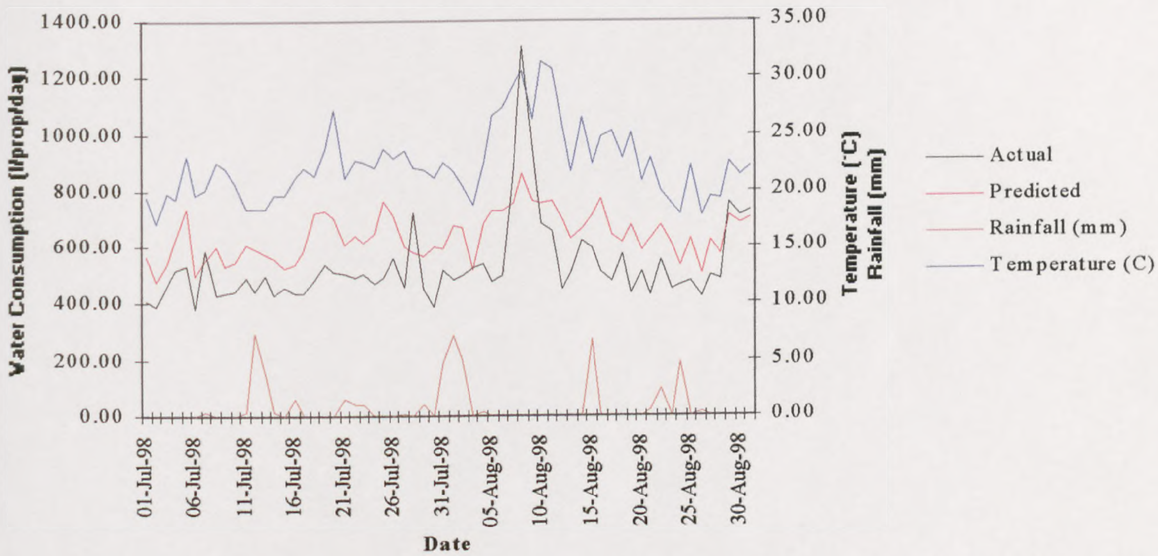


Figure 6.13: Actual and predicted water demands in the validation period for three-person detached properties in the Thames Water study using stepwise regression

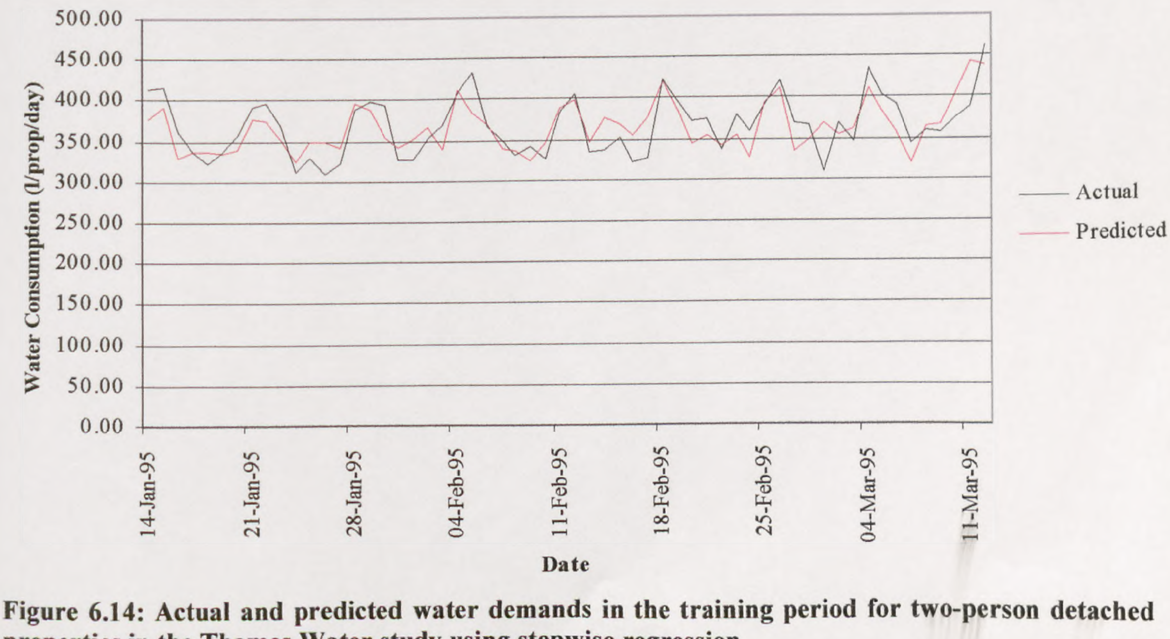


Figure 6.14: Actual and predicted water demands in the training period for two-person detached properties in the Thames Water study using stepwise regression

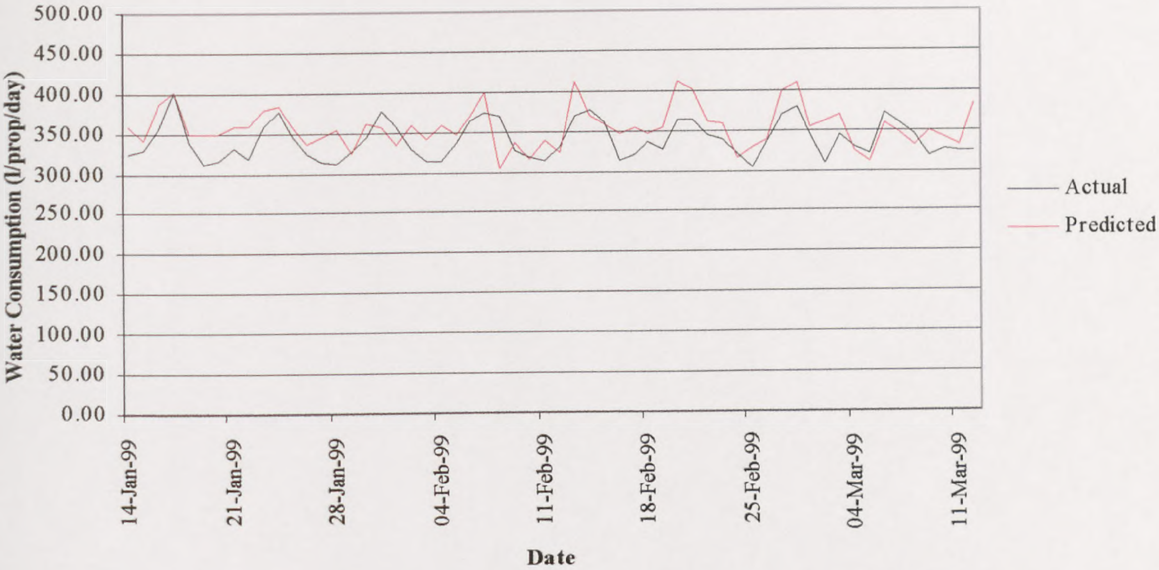


Figure 6.15: Actual and predicted water demands in the validation period for two-person detached properties in the Thames Water study using stepwise regression

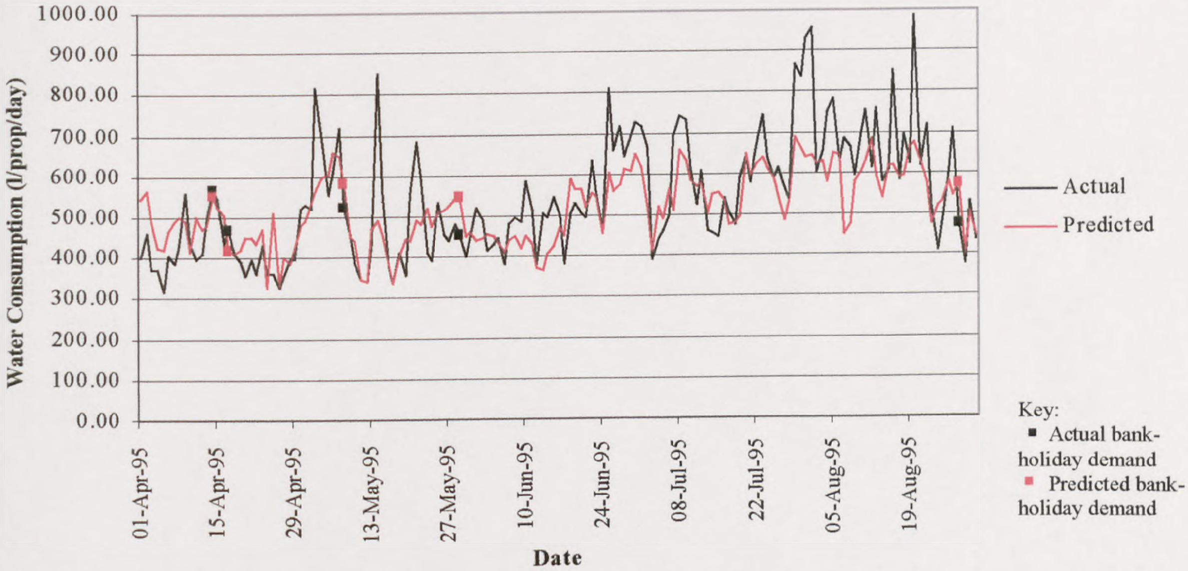


Figure 6.16: Actual and predicted water demands in the training period for two-person detached properties in the Thames Water study using stepwise regression

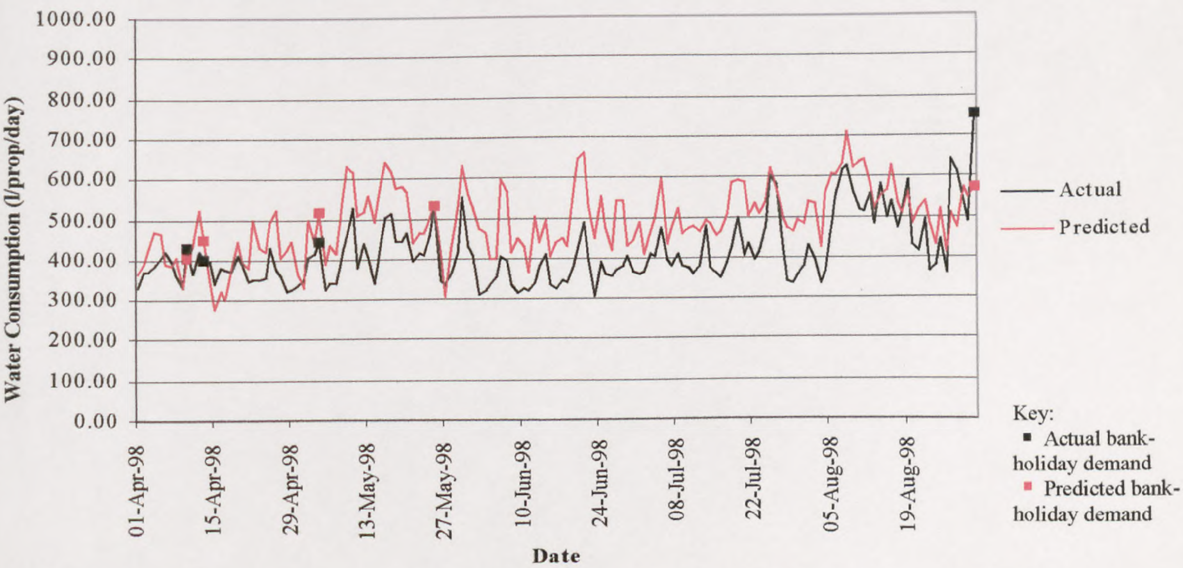


Figure 6.17: Actual and predicted water demands in the validation period for two-person detached properties in the Thames Water study using stepwise regression

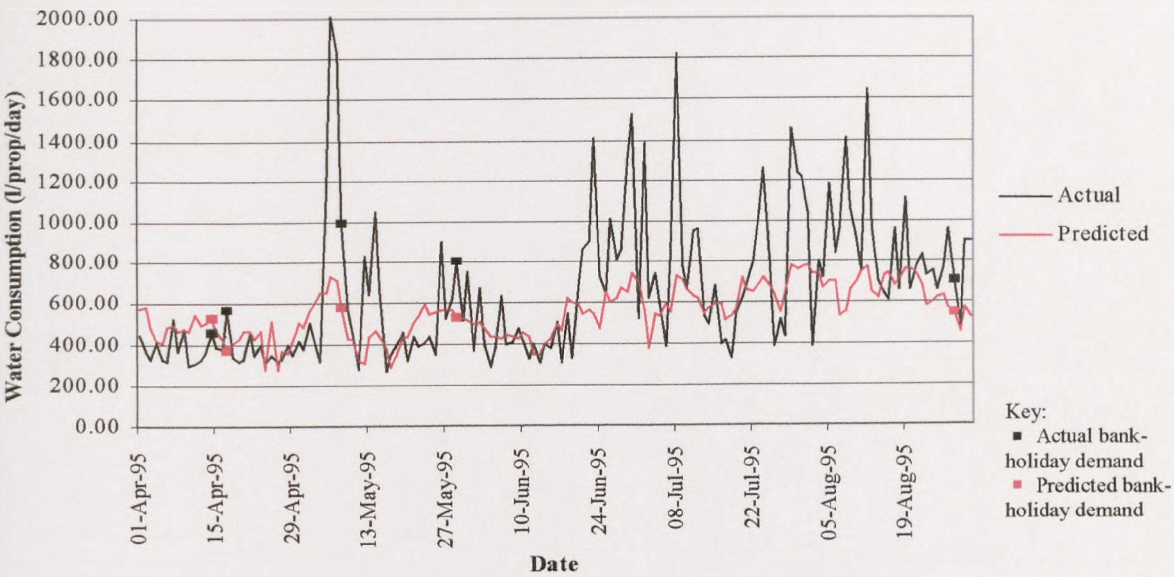


Figure 6.18: Actual and predicted water demands in the training period for one-person detached properties in the Thames Water study using stepwise regression

The stepwise regression models were similar to the lookup tables because both were: (i) able to forecast changes in demand in the medium- to long-term and in the short-term and (ii) unable to predict the magnitude of these changes. However, these findings were influenced by the unexplained upward or downward temporal shift in domestic water consumption. The stepwise regression models and the lookup tables were unable to adapt to these changes in domestic water consumption, particularly because these changes occurred after the training period. Instead, the predicted water demand data appeared to follow virtually the same medium- to long-term pattern throughout the training and validation periods. As mentioned in section 6.2.1, the only real way of improving prediction accuracy is to determine the extent to which these temporal changes in demand result from individual behavioural water use patterns or errors. This can only be achieved using a longer time-series of good quality data.

6.3.2 Stepwise regression with k-means cluster analysis

The second advanced approach investigated to forecast short-term domestic water demands was stepwise regression with k-means cluster analysis. It was hypothesized that prediction accuracy of short-term domestic water demands might be improved: (i) by classifying the data into clusters that display similar characteristics and (ii) by performing stepwise regression analysis on each individual cluster. K-means cluster analysis was the procedure selected to classify the data into individual clusters. K-means cluster analysis attempts to identify relatively homogenous groups of cases based on selected characteristics, using an algorithm that can handle large numbers of cases (Robinson, 1998). Selected characteristics were the two days antecedent and the prevailing day's average rainfall, temperature and sunshine amounts, day of the week and calendar effects. The algorithm in the k-means cluster analysis also requires the number of cases to be specified. The number of cases specified for each household size and property type was five. If more than five cases were specified, the amount of data in some clusters was too small for further analysis. If less than five cases were specified, levels of accuracy were sacrificed as the groups became larger. Nevertheless, in both the Thames Water and Yorkshire Water studies two of the five clusters had to be combined to ensure enough data for further analysis (clusters two and four in the Thames Water study and clusters one and three in the Yorkshire Water study). As Tables 6.2 and 6.3 indicate, significant differences were observed in each cluster, ranging from clusters with high rainfall, low temperatures and low sunshine amounts, to clusters with low rainfall, high temperatures and high sunshine amounts. For each individual cluster, stepwise regression was performed to identify those independent variables (weather, day of the week and calendar effects) adding the most explanation to the variation in short-term domestic water demands (see section 6.3.1 for details).

Table 6.2: Cluster centres for households in the Thames Water study

Selected characteristics	*Cluster*				
	1	*2*	*3*	*4*	*5*
Rainfall	0.84	11.08	0.94	53.60	0.31
Temperature	17.37	14.19	9.34	18.20	23.84
Sunshine	3.98	2.95	2.40	0.00	10.24
Day of the week	0.27	0.33	0.28	0.00	0.30
Bank-holidays and public holidays	0.03	0.02	0.04	0.00	0.02
Number of cases in each cluster	394	70	424	1	250

Table 6.3: Cluster centres for households in the Yorkshire Water study

Selected characteristics	*Cluster*				
	1	*2*	*3*	*4*	*5*
Rainfall	19.80	0.95	7.82	1.24	0.53
Temperature	11.68	8.01	11.95	16.38	20.84
Sunshine	1.02	2.65	1.61	3.62	10.14
Day of the week	0.09	0.29	0.30	0.26	0.33
Bank-holidays and public holidays	0.04	0.04	0.05	0.03	0.02
Number of cases in each cluster	23	433	114	430	248

The independent variables adding the most explanation to variations in short-term domestic water demands in the stepwise regression analysis performed on each individual cluster differed in the Thames Water and Yorkshire Water studies (see Appendix 6D for details). In the Yorkshire Water study, clustered stepwise regression for each individual household size and property type revealed only one or two significant variables that provided some explanation of variations in demand. In all cases, day of the week added the most explanation to variations in short-term domestic water demands. In the Thames Water study, significantly more variables added to the explanation of variations in demand in each cluster. In clusters one and five (Table 6.2), which were centred on relatively high temperatures, sunshine amounts and low rainfall (hence the summer months), temperature and day of the week frequently interchanged between the first and second most significant explanatory variable. Sunshine, rainfall and calendar effects were also found to provide some explanation of variations in short-term domestic water demands. When clusters two and four were combined, day of the week and sunshine amounts were the most significant explanatory variables for each household size and property type. Clusters two and four predominantly encompassed the months of spring and autumn. The most significant explanatory variables for each household size and type in cluster three were day of the week and calendar effects. Cluster three, dominated by low temperatures and sunshine amounts, was centred on the winter months. These findings conform to those from the regression analysis (see section 4.7.1 and 5.9.1 for details) and the correlation coefficient analysis (see section 4.10 and 5.1.2 for details), where weather was found to have the greatest influence on demand during the summer months, a lesser influence during spring and autumn, and no influence during winter. It is unclear why the stepwise regression analysis revealed significantly more explanatory variables for each cluster in the Thames Water study. Lack of seasonal variation in the Yorkshire Water data may be one possible explanation. However, it is likely that significantly more explanatory variables were observed in the Thames Water study due to the longer time-series of data. More data in each cluster may mean that there are a sufficient range of weather values to show a significant relationship.

Results from the clustered stepwise regression analysis were similar to that from the stepwise regression analysis detailed in section 6.3.1, in that all variables, except rainfall, had a positive influence on short-term domestic water demands. The percentage of explained variance for the clustered stepwise regression was less than that for the stepwise regression performed on the entire data set, with no one cluster consistently producing stronger or weaker percentages of explained variance. In the Thames Water and Yorkshire Water studies, the R^2 was typically 0.25 and 0.15, respectively.

To predict short-term domestic water demands, the validation data had to be assigned to an individual cluster. To determine which cluster each day should be assigned to, the following procedure was undertaken using the cluster centres for households in the Thames Water study (Table 6.2) as an example:

(i) The difference between the predicted rainfall value on any given day and the rainfall value in cluster 1 was calculated and squared. This procedure was repeated for each selected characteristic.

(ii) The six squared differences for cluster 1 were summed.

(iii) The square root of the summed value was then taken. This value represents the distance between the predicted value on any given day and cluster 1.

(iv) This procedure was then repeated for clusters two, three, four and five. The distances between all five clusters and the predicted value on any given day were compared. The cluster displaying the shortest distance is the cluster to which that given day is assigned.

(v) The appropriate stepwise regression equation is applied to predict short-term domestic water demands.

The clustered stepwise regression predictions of short-term domestic water demands were similar to the predictions from the stepwise regression models developed using the entire data set and the lookup tables. In the medium- to long-term, the clustered stepwise regression models were able to follow the overall seasonal trend in domestic water consumption, with peaks in demand during summer and troughs in demand during winter (Figures 6.19, 6.20 and Appendix 6E). In the short-term, the clustered stepwise regression models were able to forecast changes in demand associated with weather (Figure 6.21 and 6.22), day of the week (Figures 6.23 and 6.24) and calendar effects (Figures 6.25 and 6.26). However, no vast improvements were made in the accuracy with which short-term domestic water demands could be forecast using stepwise regression with k-means cluster analysis. As with the previous modelling approaches explored, stepwise regression with k-means cluster analysis were not able to cope with the unexplained upward or downward temporal shift in domestic water consumption.

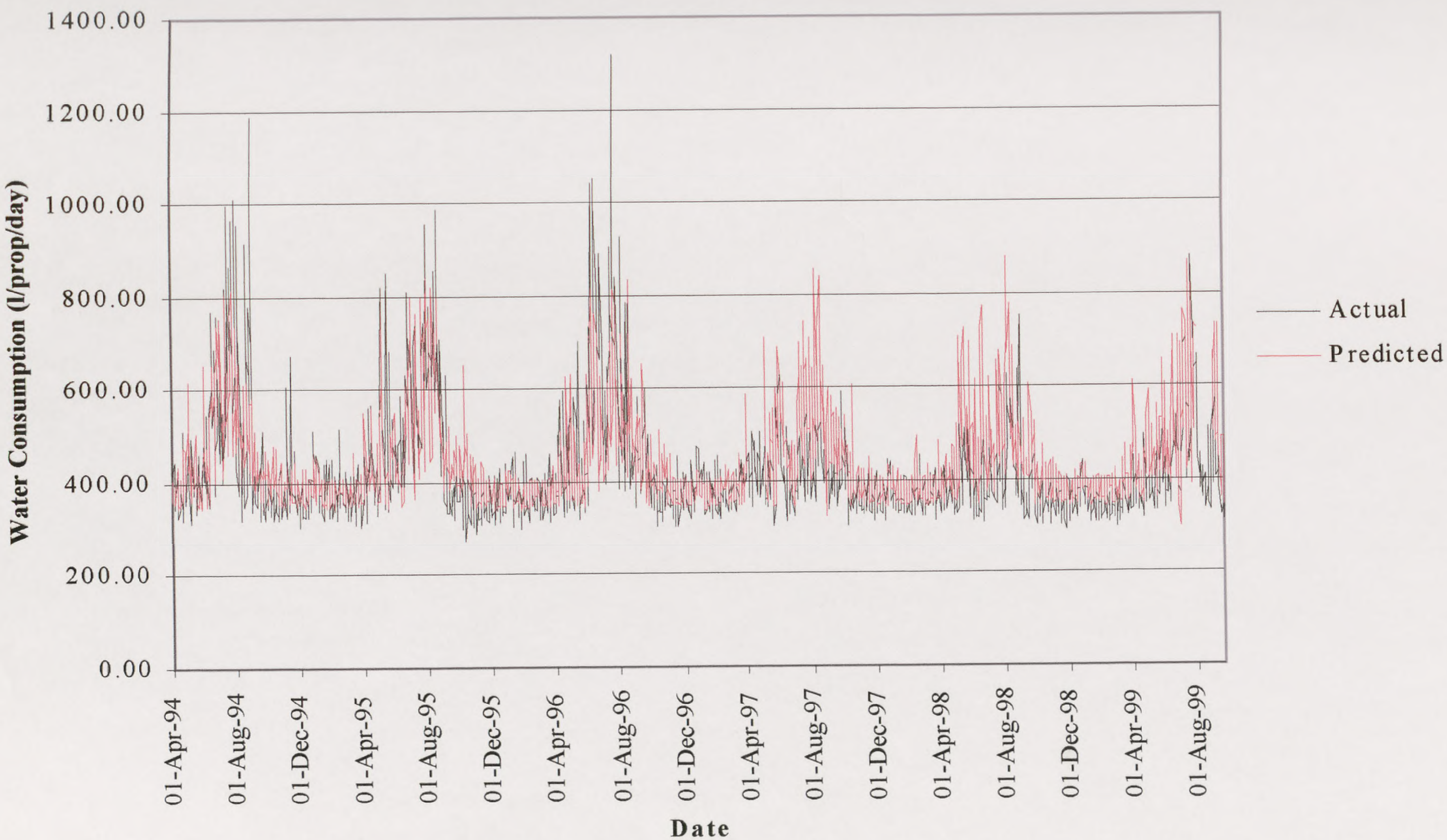


Figure 6.19: Actual and predicted water demands for two-person detached properties in the Thames Water study using clustered stepwise regression

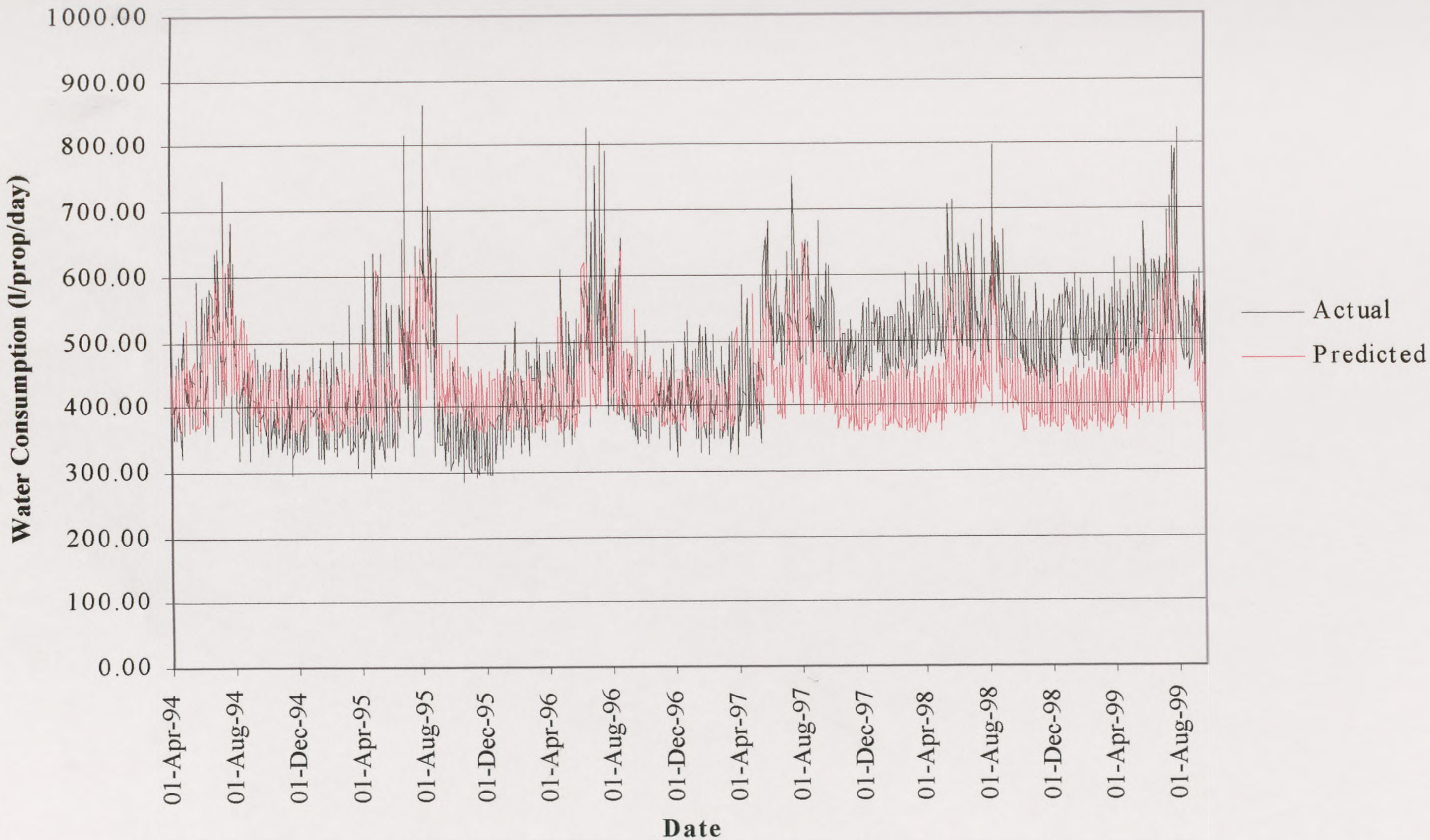


Figure 6.20: Actual and predicted water demands for three-person semi-detached properties in the Thames Water study using clustered stepwise regression

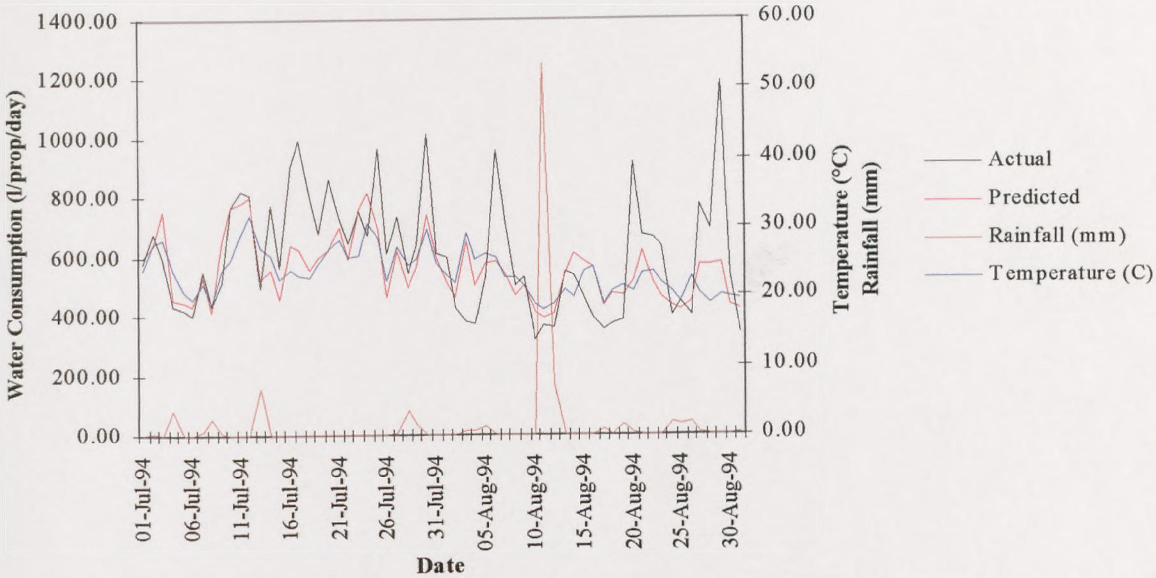


Figure 6.21: Actual and predicted water demands in the training period for two-person detached properties in the Thames Water study using clustered stepwise regression

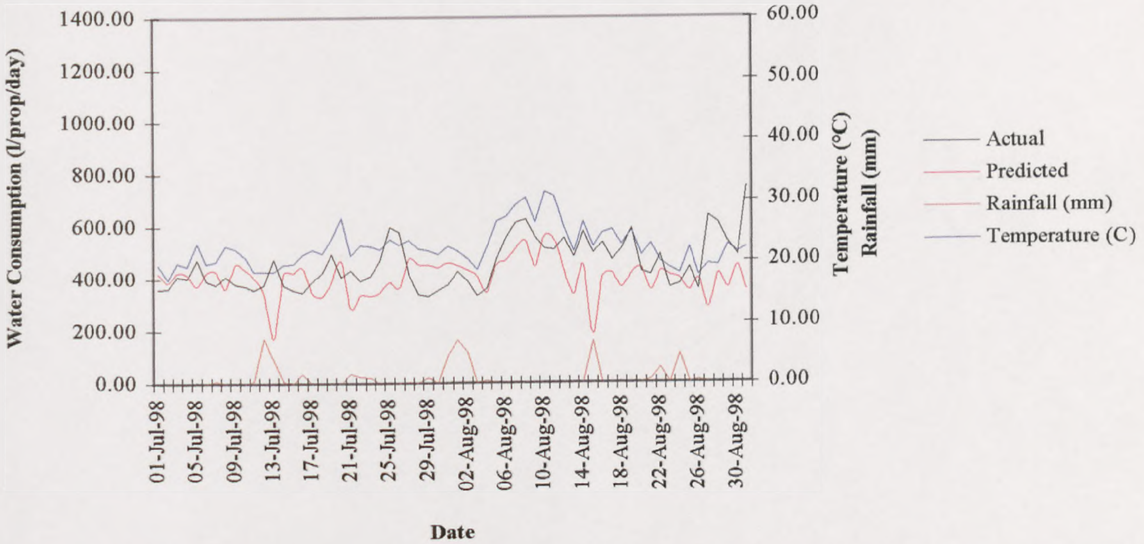


Figure 6.22: Actual and predicted water demands in the validation period for two-person detached properties in the Thames Water study using clustered stepwise regression

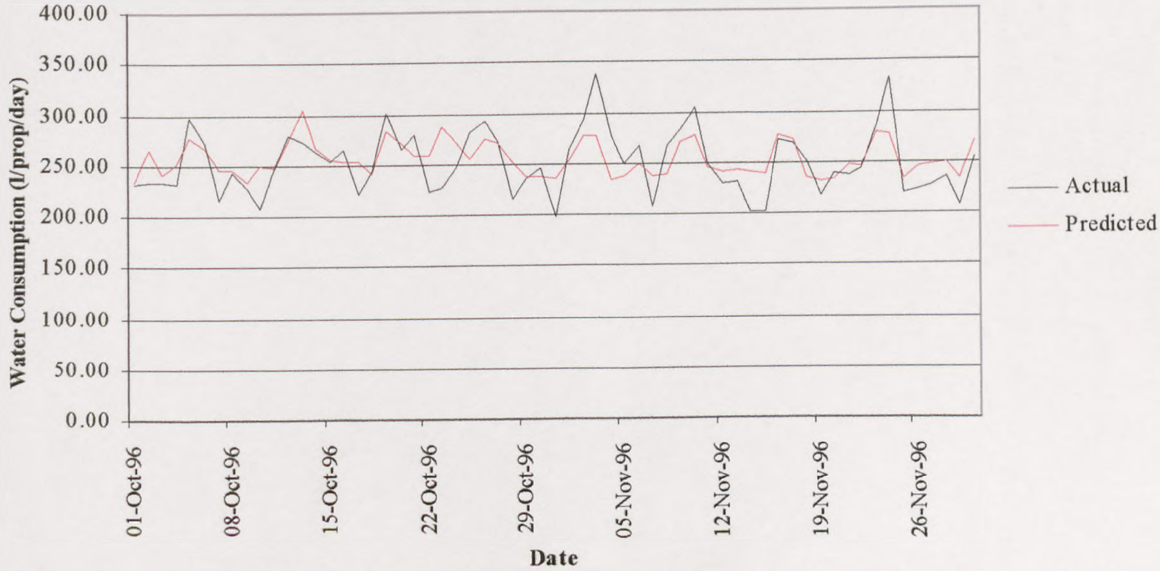


Figure 6.23: Actual and predicted water demands in the training period for one-person terraced properties in the Thames Water study using clustered stepwise regression

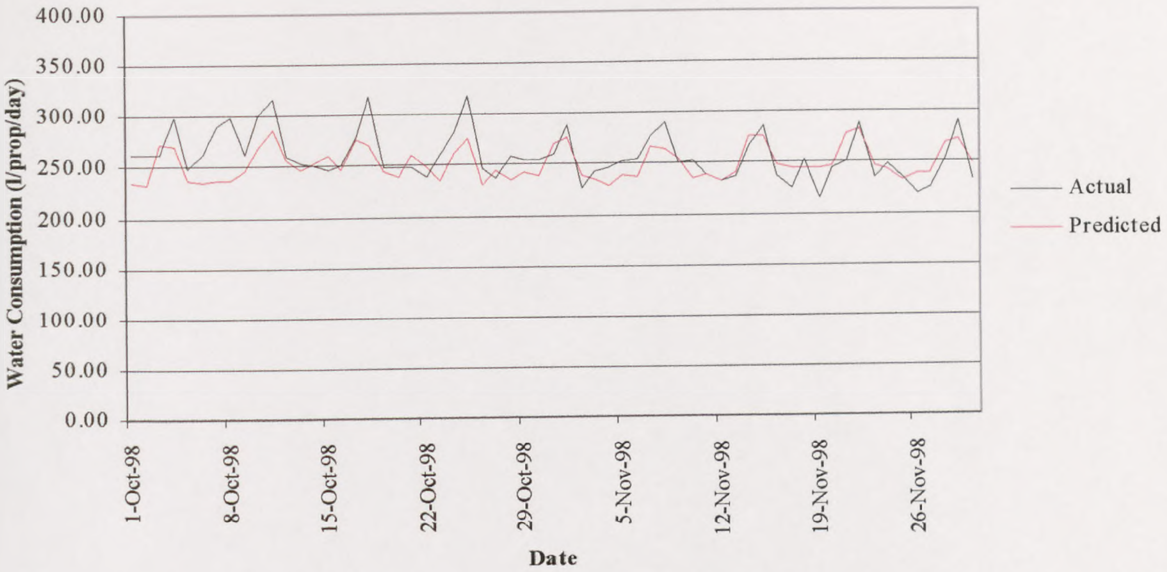


Figure 6.24: Actual and predicted water demands in the validation period for one-person terraced properties in the Thames Water study using clustered stepwise regression

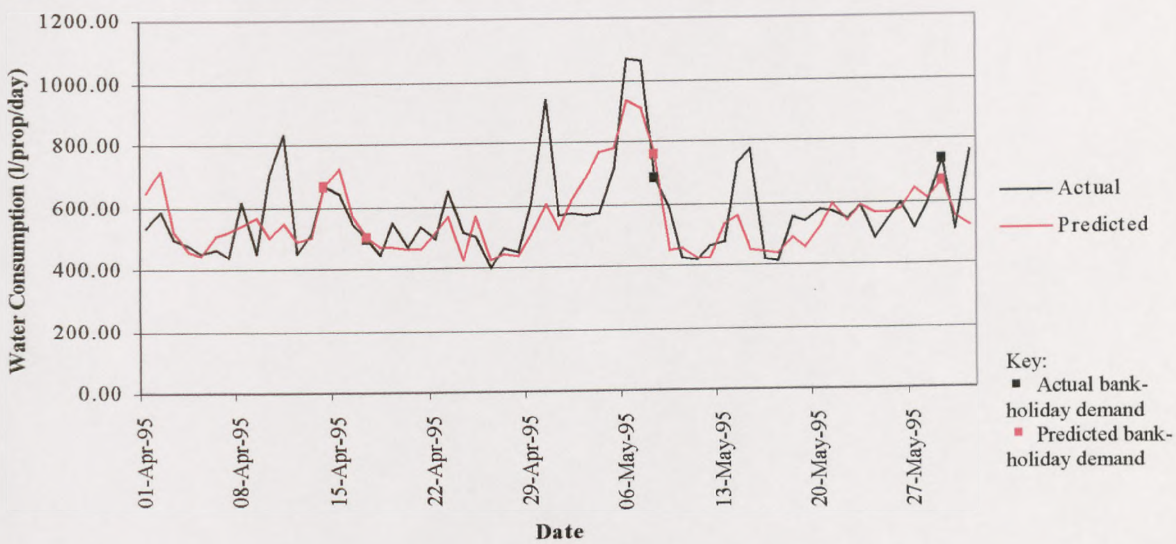


Figure 6.25: Actual and predicted water demands in the training period for three-person detached properties in the Thames Water study using clustered stepwise regression

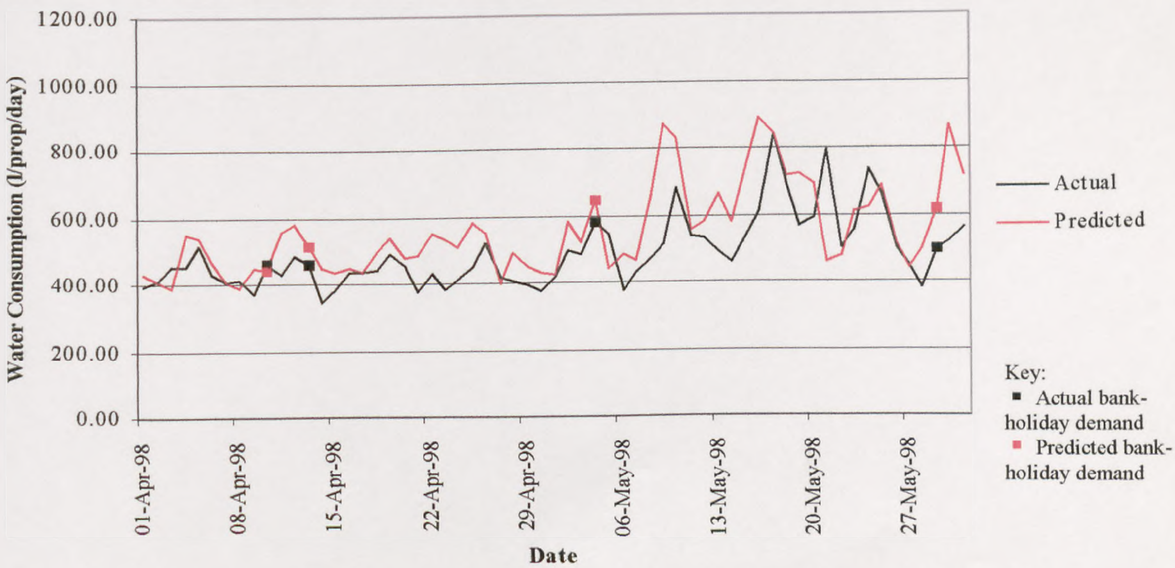


Figure 6.26: Actual and predicted water demands in the validation period for three-person detached properties in the Thames Water study using clustered stepwise regression

6.3.3 Auto regressive moving average (ARMA) time-series models

Univariate and multivariate Auto Regressive Moving Average (ARMA) time-series models were investigated to forecast short-term domestic water demands for each household size and property type using the NPREDICT program developed by Masters (1995). These models are based on the original method of time-series prediction pioneered by Box and Jenkins (1976). Stationarity is one attribute that is vital to the correct use of ARMA models. A time-series is said to be strictly stationary if its statistical distribution does not change across time (Masters, 1995). There are three methods of assessing the stationarity of a data series:

(i) Statistical distribution – changes in level or slope indicates that the series is nonstationary (Figure 6.27).

(ii) Autocorrelation – the autocorrelation of a stationary series usually drops to zero quite rapidly (Figure 6.28) while that of a nonstationary series remains high for relatively large lags (Masters, 1995).

(iii) The power spectrum - a nonstationary series will virtually always have most of its spectral energy concentrated in the lower frequencies (Masters, 1995).

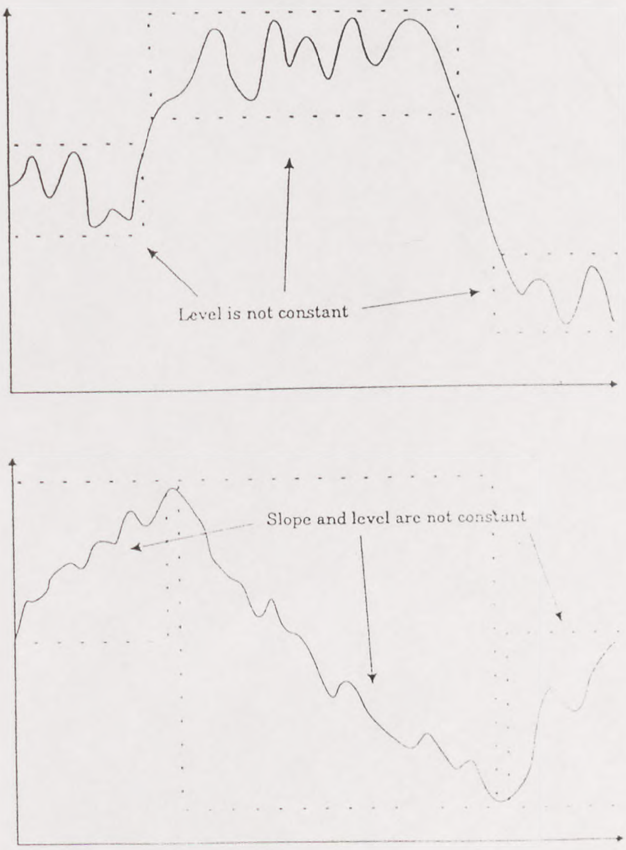


Figure 6.27: A typical example of nonstationarity (Masters, 1995)

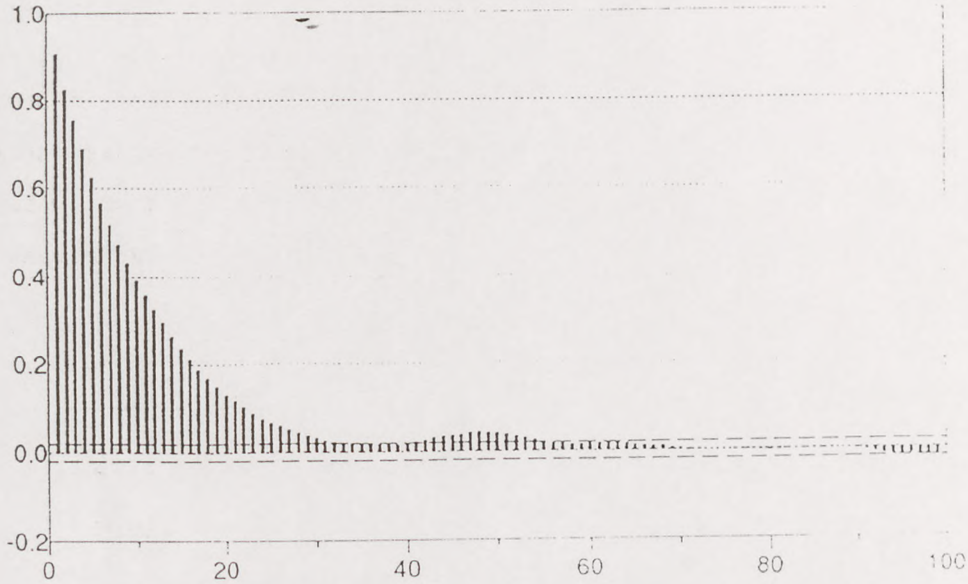


Figure 6.28: **Autocorrelation of a nearly nonstationary series (Masters, 1995)**

The most straightforward method for dealing with a nonstationary series is to compute adjacent differences. In practice, most types of nonstationarity can be rendered stationary by a single differencing operation (Masters, 1995). Sometimes a series requires two stages of differencing but that is not common. Series which requires more than two differencing operations are almost unknown. The need for seasonal differencing must also be considered. Seasonal behaviour can be detected in two ways: (i) autocorrelation - a seasonal component will create a string of large correlations at integer multiples of the season's length and (ii) the power spectrum - in most practical situations, a seasonal component will generate a spike in the power spectrum corresponding to the frequency of the repetition. Additional spikes at integer multiples (harmonics) of the frequency are also common. However, it sometimes happens that the current value of a time-series is somewhat influenced by the value of the series at a relatively distant lag. This is not the same thing as true seasonality. This situation may sometimes be handled by seasonal differencing. However, it is more likely that an Autoregressive (AR) or Moving Average (MA) component at that lag is the best approach (Masters, 1995).

Visual inspection of the time-series for each household size and property type demonstrated changes in level, suggesting nonstationarity in the series. Autocorrelation plots of the demand data also detected nonstationary behaviour, as demand remained high for relatively large lags (Figure 6.29). Nonstationary behaviour was also evident in the power spectrum as all of the series had most of their spectral energy concentrated in the lower frequencies (Figure 6.30). Adjacent-point differencing was applied to the demand data in an attempt to render the data stationary. The adjacent-point differenced series is shown in Figure 6.31. The single differencing has apparently rendered the series moderately stationary, so a second adjacent-point differencing need not be considered. This conclusion was supported by the power spectrum (Figure 6.32), which now has its spectral energy concentrated at higher frequencies, and the autocorrelation plot (Figure 6.33). The autocorrelation plot (Figure 6.33) does bear the unmistakable signature of a seasonal component with a period of seven samples. The DFT spectrum (Figure 6.32) barely shows the spectral energy at multiples of 0.07. However, the ME spectrum, at an order of 20, exposes peaks at a lag of seven (Figure 6.34).

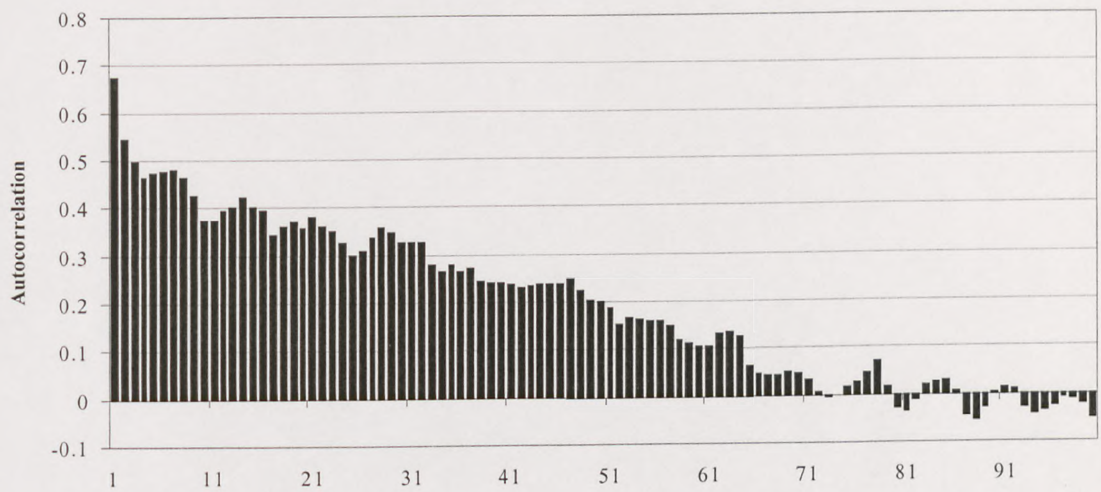


Figure 6.29: Autocorrelation plot of water demand in one-person detached properties in the Thames Water study

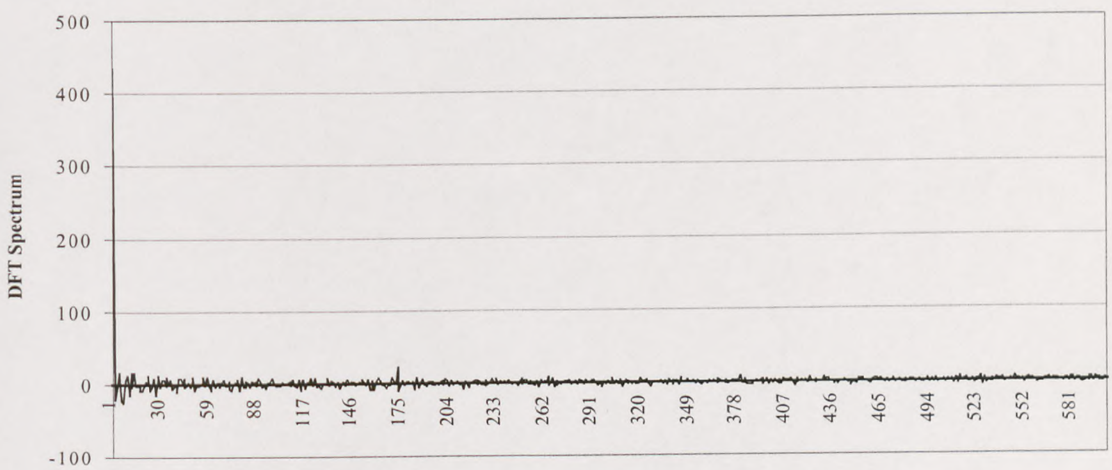


Figure 6.30: DFT spectrum of water demand in one-person detached properties in the Thames Water study

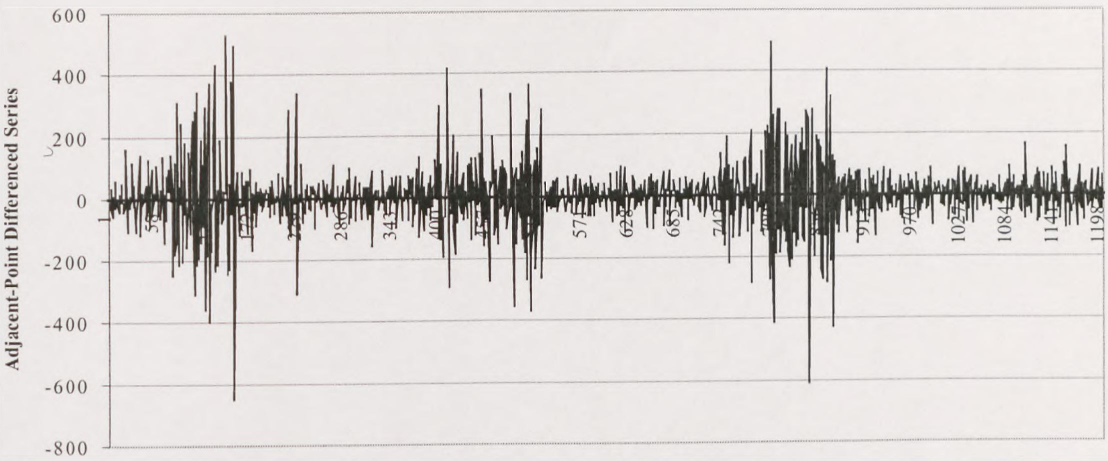


Figure 6.31: An adjacent-point differenced series for two-person detached properties in the Thames Water study

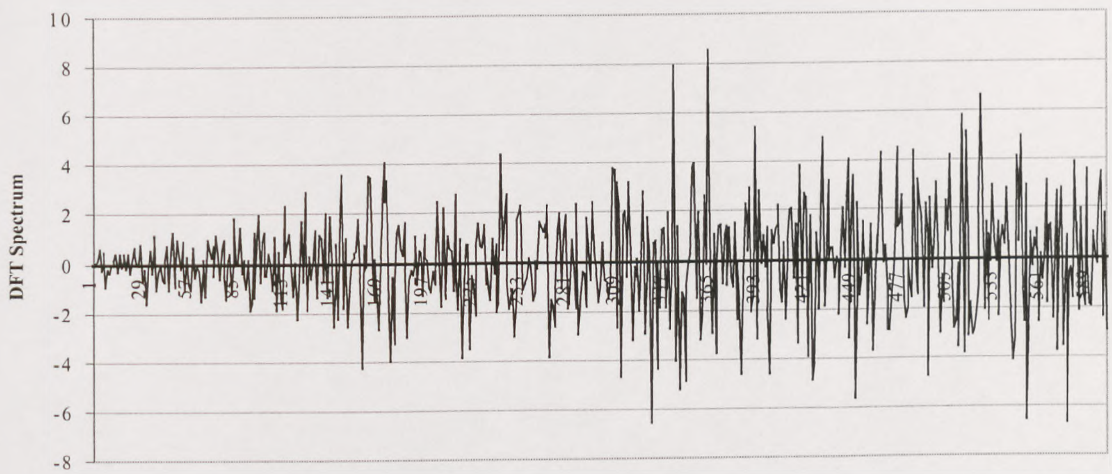


Figure 6.32: DFT spectrum of adjacent-point differenced water demand for two-person detached properties in the Thames Water study

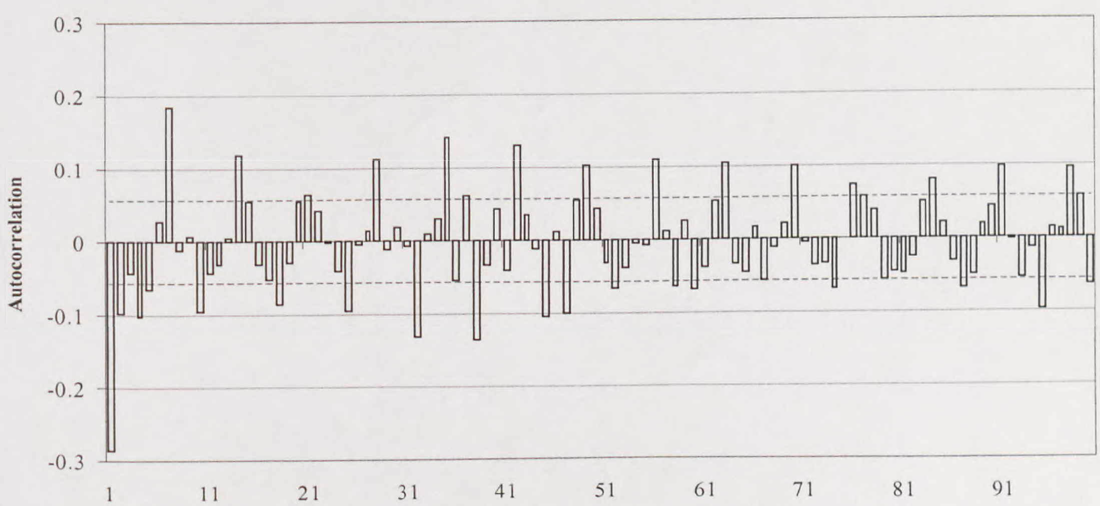


Figure 6.33: Autocorrelation plot of adjacent-point differenced water demand in two-person detached properties in the Thames Water study

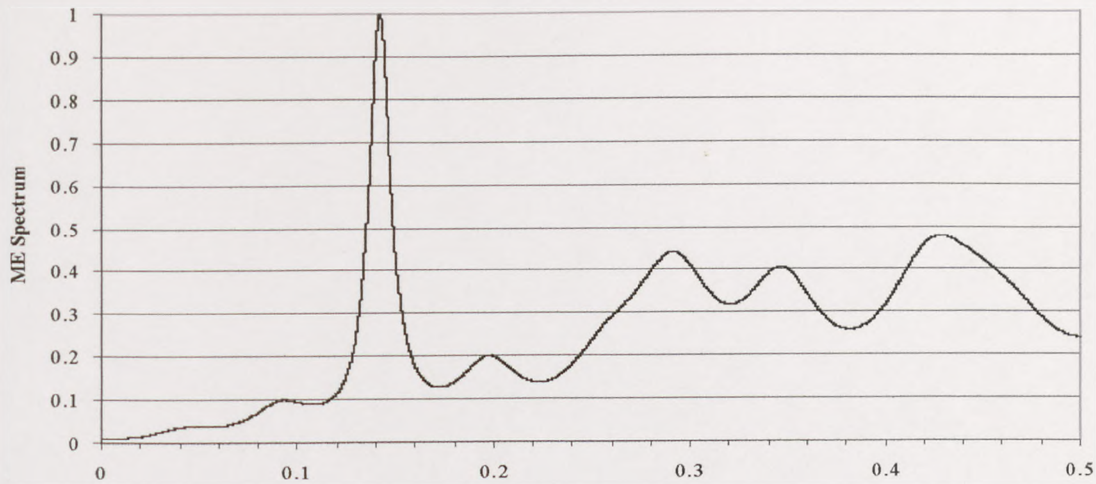


Figure 6.34: ME spectrum of water demand in two-person detached properties in the Thames Water study

Seasonal differencing at a lag of seven was performed on the adjacent-point differenced series. After several trial models were studied, it was evident that seasonally differencing the data was not the best approach. Figure 6.35 is an example of a univariate ARMA time-series model using an adjacent-point and seasonally differenced lag seven series. There are clear lags in the water demand forecasts creating large errors in prediction accuracy. Quevedo and Cembrano (1988) observed a similar problem. Quevedo and Cembrano (1988) also noted a clear seven day seasonal pattern in the water demand data for Barcelona. This non-decreasing pattern of the autocorrelation function corresponding to 7, 14, 21 and so on, was initially dealt with by means of a stationary inducing seasonal operator ($1-B^7$). However, further investigations revealed that seasonally differencing the water demand data for Barcelona was not the best approach. Instead, an ARMA (7,7) model was developed.

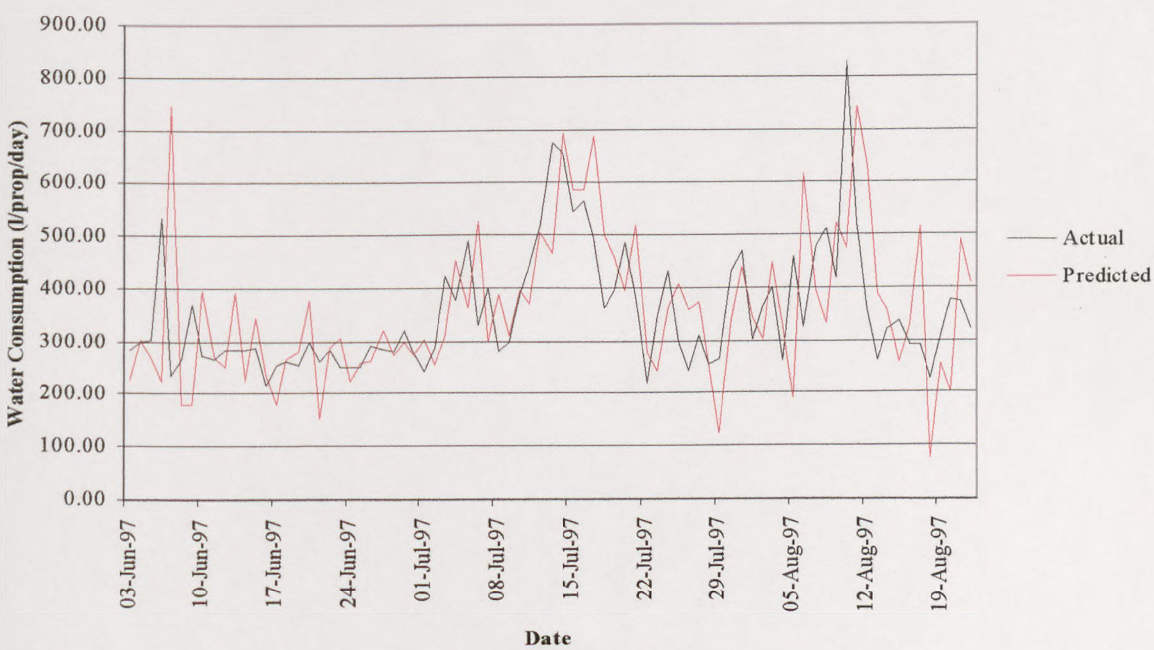


Figure 6.35: A univariate ARMA time-series model for one-person detached properties in the Thames Water study using an adjacent-point and seasonally differenced lag seven series

6.3.3.1 Univariate ARMA time-series modelling

Univariate ARMA time-series models were explored to forecast short-term domestic water demands for each household size and property type in the Thames Water and Yorkshire Water studies using the NPREDICT program developed by Masters (1995). In the univariate ARMA time-series model, the number of AR terms, traditionally called p, and the number of MA terms, traditionally called q, were identified for each household size and property type. Determination of the values p and q are crucial to good performance of the model and their determinations require intelligent guesswork and trial and error (Masters, 1995). A useful tool in determining values for p and q is by calculating the relationship between current values of the series and lagged values. These were exposed using the autocorrelation of the stationary time-series. When the autocorrelation function of the stationary time-series is plotted, a pair of lines two standard deviations either side of zero provide rough guidance about the significance of the correlations.

The Power Spectrum of a series can also reveal important information about the values of p and q. The Maximum Entropy Power Spectrum (ME Spectrum) is able to zoom in on extremely narrow features. Simultaneously, the ME Spectrum can smooth areas of low spectral energy. The vast plains of low spectral power lie low and flat, while the important spikes jut out prominently (Masters, 1995). The spikes often have such sharp peaks that their precise location can be found to a resolution far higher than that obtained by the discrete fourier transform (DFT). However, Masters (1995) recommends that the ME method should never be used alone. The DFT spectrum, which serves as a reality check on the ME spectrum, should always be calculated and displayed. The purpose of the ME spectrum is to show the existence of subtle spikes and to locate their position precisely. The purpose of the DFT spectrum is to confirm that there is at least a good possibility of a mass of spectral energy at the indicated location. The ME spectrum and the DFT spectrum were calculated using the NPREDICT program. To calculate the ME spectrum, the order of the spectral estimator had to be stated. For many routine applications in which there is no reason to expect a large number of peaks, a good order is about 20 (Masters, 1995).

The univariate ARMA time-series model was trained on the first sixty-percent of the water demand data for each household size and property type using different combinations of seven in the AR and MA terms, to incorporate the observed lag. As in the study undertaken by Quevedo and Cembrano (1988), the ARMA (7,7) model appeared to produce the most satisfactory results. Initially, results from this model appeared good (Figure 6.36). Unlike the previous pragmatic and advanced approaches, the ARMA (7,7) model was able to cope with the upward or downward temporal shift in demand. However, further inspection revealed a one-day lag in prediction accuracy (Figure 6.37). Basically, the ARMA (7,7) model proposed that tomorrow's demand will be equal to today's consumption. However, water demand is stochastic in nature and independent of demand in the preceding days; hence water demand is not a good predictor of itself. As already proved in Chapters 4 and 5, short-term domestic water demand is influenced by a number of external factors. Multivariate ARMA time-series modelling was, therefore, considered the best approach.

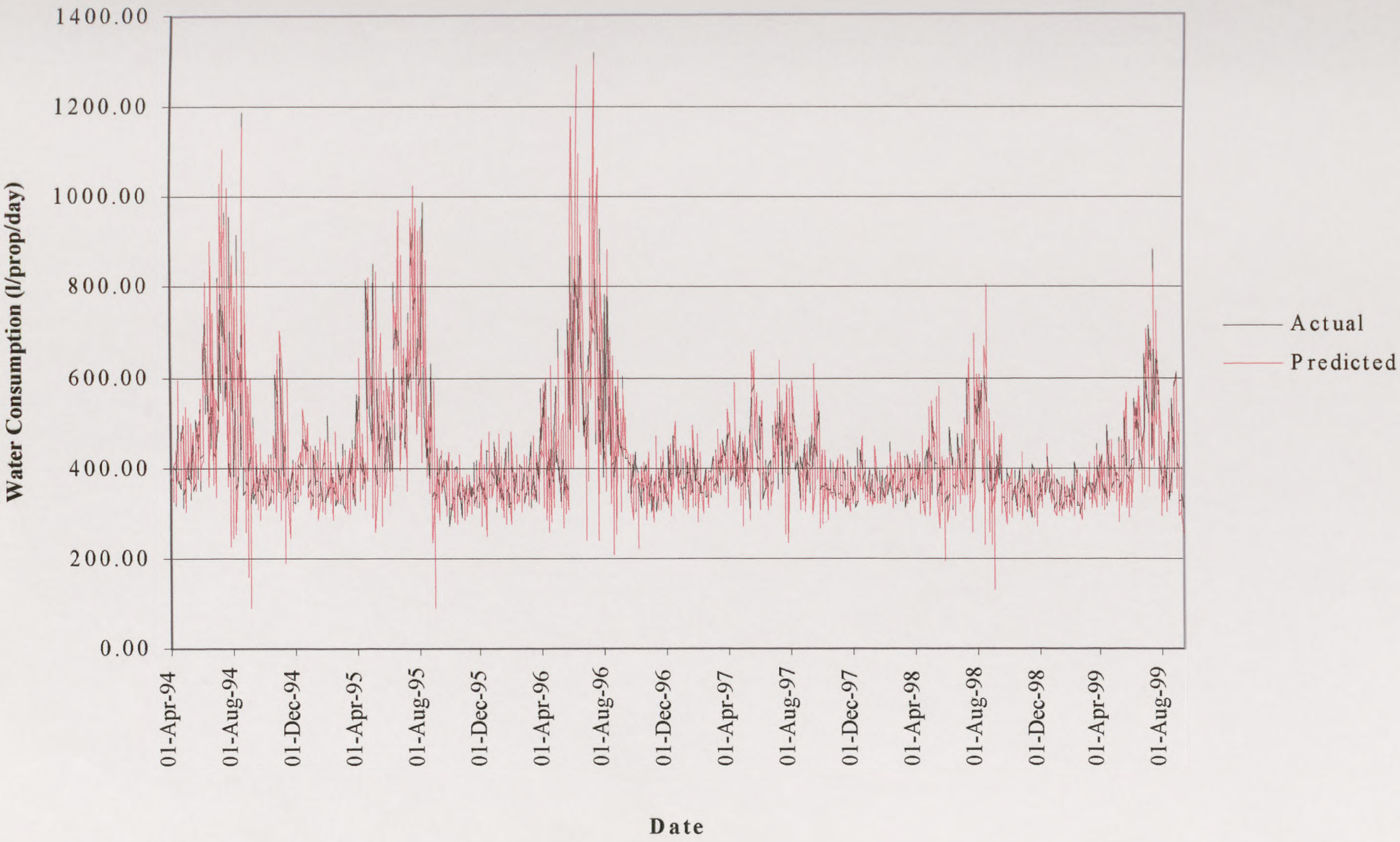


Figure 6.36: Actual and predicted water demand for two-person detached properties in the Thames Water study using an ARMA (7,7) model

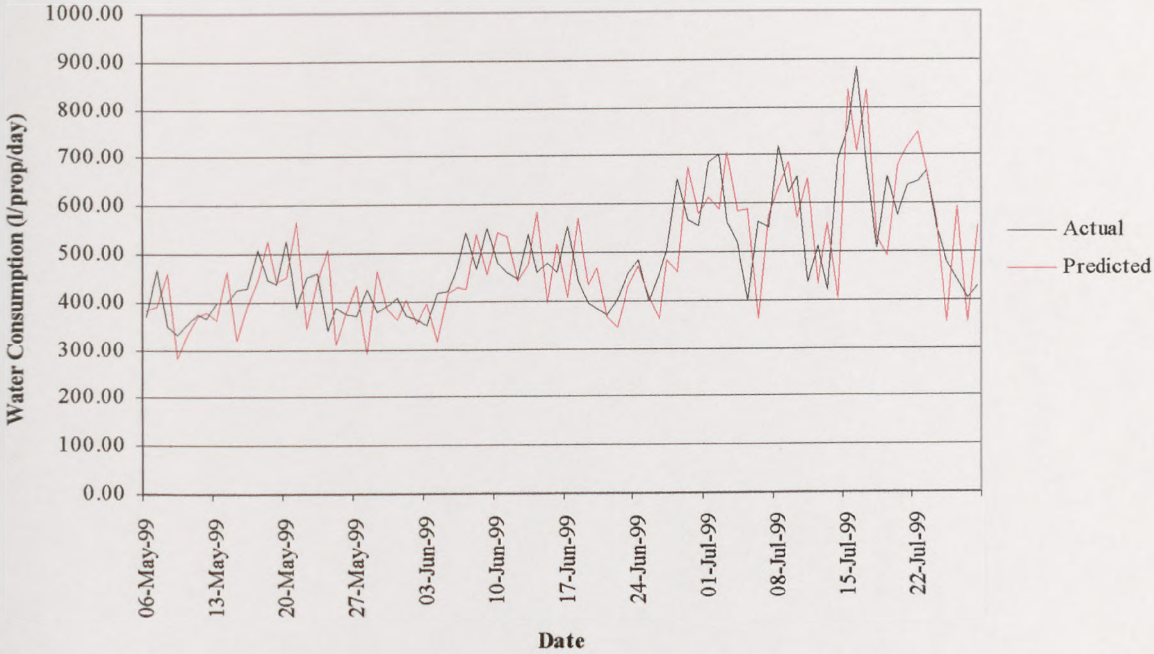


Figure 6.37: Actual and predicted water demand in the validation period for two-person detached properties in the Thames Water study using an ARMA (7,7) model

6.3.3.2 Multivariate ARMA time-series modelling

Multivariate ARMA time-series models were explored to forecast short-term domestic water demands using the adjacent-point differenced data. As these models are extremely complex, it was decided to explore the model with just two independent variables, day of the week and temperature. Selection of these two independent variables was based on the results from the stepwise regression analysis (see section 6.3.3.1 for details) and Chapters 4 and 5. Values for the input (AR) weights and the output (MA) weights were again estimated using the first sixty-percent of the data. To determine the input (AR) weights and the output (MA) weights, crosscorrelation, as opposed to autocorrelation was used. Crosscorrelation is a tool that relates two different series to each other, as opposed to relating a single series to itself. The crosscorrelations were examined to identify prominent peaks. Crosscorrelation between day of the week and demand produced a seven-day lag (Figure 6.38). Different combinations of AR and MA weights, set to seven, were investigated. No prominent lags were evident in the crosscorrelations between demand and temperature (Figure 6.39). Different combinations of the values 0 and 1 were, therefore, used in the AR and MA weights. The final step was to chck that the crosscorrelations of the residuals of every input series were reasonably small. Otherwise, another term may be needed (Masters, 1995). Figure 6.40 is a typical example of a water demand prediction using the multivariate ARMA time-series model. Results from the multivariate approach are similar to the univariate approach (Figure 6.41). The overall trend in demand exists but problems are encountered with the lags in demand prediction. Regardless of what combination of AR and MA weights was used, the model could not accurately predict demand. Instead, the multivariate ARMA model appeared to forecast demand using demand, rather than using the independent variables. Even when the crosscorrelations of the residuals were checked and improved, prediction accuracy did not increase.

Figure 6.38: Crosscorrelation between day of the week and water demand in two-person semi-detached properties in the Thames Water study

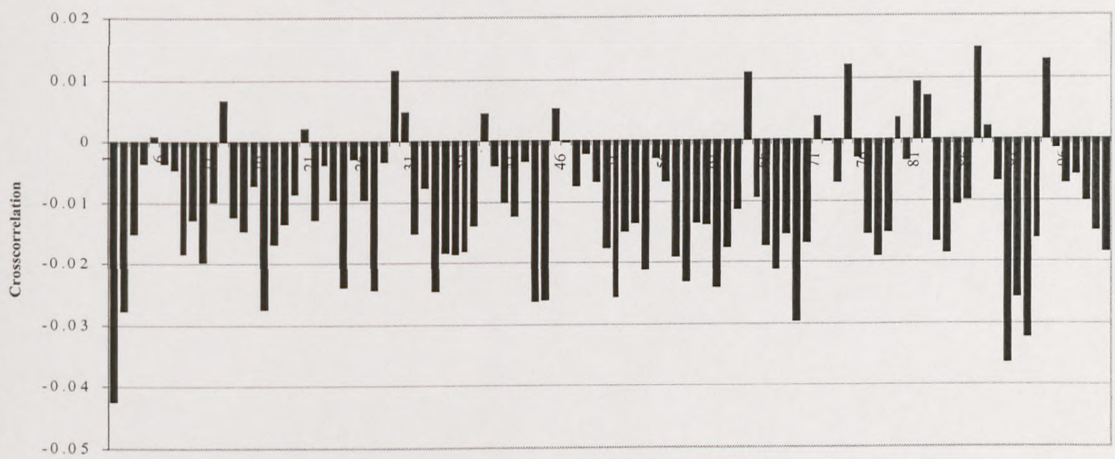


Figure 6.39: Crosscorrelation between temperature and water demand in two-person semi-detached properties in the Thames Water study

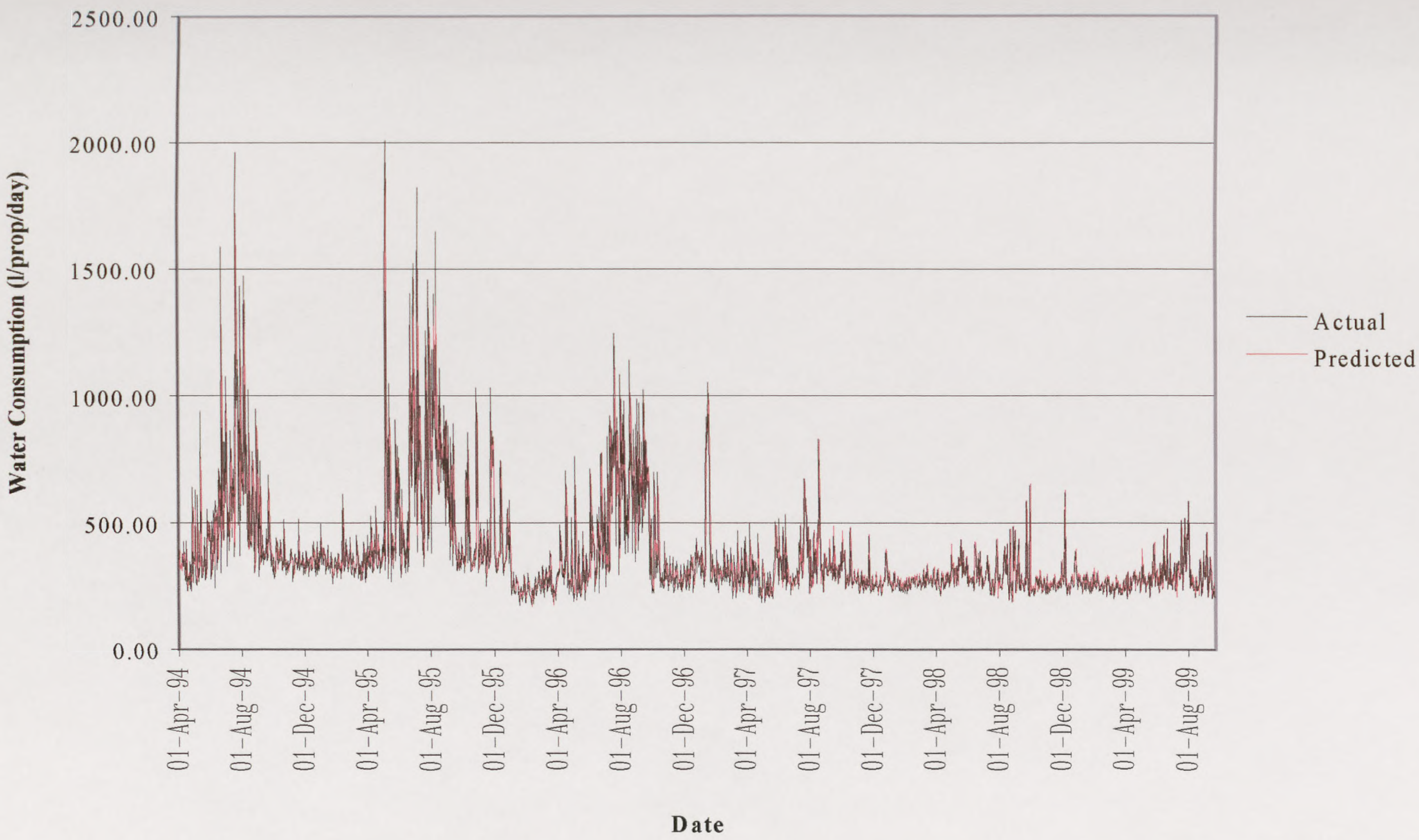


Figure 6.40: Actual and predicted water demand for two-person detached properties in the Thames Water study using a multivariate ARMA time-series model

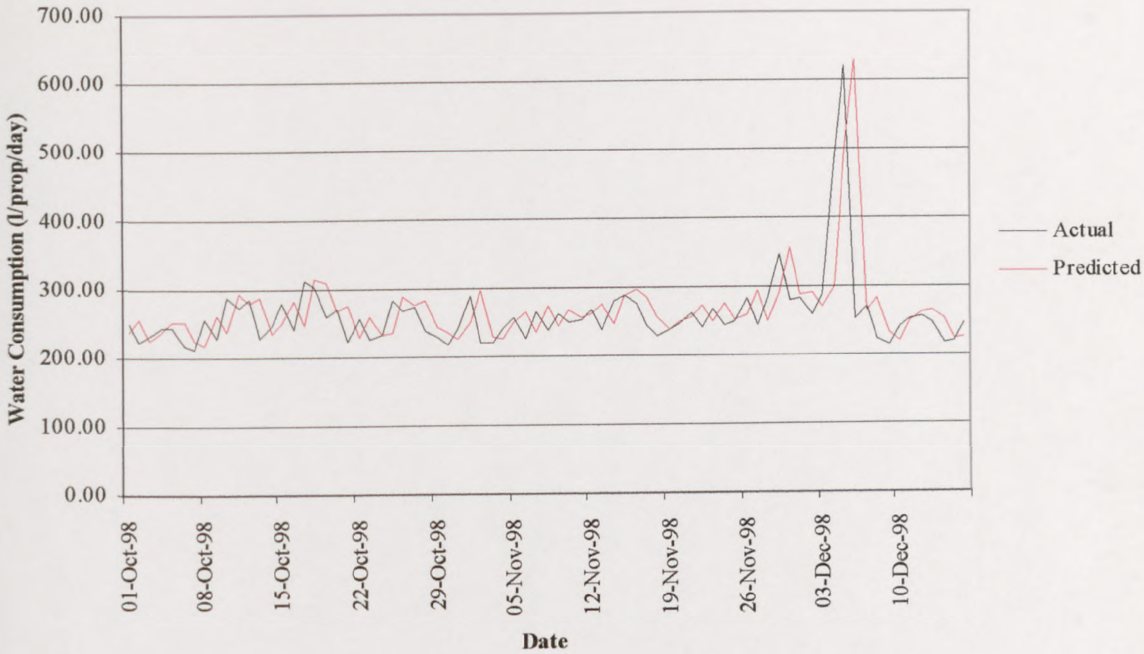


Figure 6.41: Actual and predicted water demand for two-person detached properties in validation period the Thames Water study using a multivariate ARMA time-series model

Several reasons may explain why the multivariate ARMA time-series models could cope with the upward or downward temporal shift in domestic water demand but were unable to predict variations in short-term domestic water demands associated with temperature and day of the week:

(i) The multivariate ARMA time-series model cannot find a definite relationship between day of the week and demand, and temperature and demand. The demand predictions are, therefore, based on demand, rather than the external variables.

(ii) The demand data are not truly stationary. The approach to render the data stationary was the same as that used by Quevedo and Cembrano (1988) and Saporta and Munoz (1995). However, the water demand data used in these two studies differs significantly to that used in this research:

- Both studies use water demand data for the whole of Barcelona. This, therefore, includes demand from industrial, commercial, domestic and agricultural users as well as leakage. If the demand data covers: (i) more components of demand or (ii) a larger area, then the day to day variability in water demand is expected to be relatively low. As there are so few households in the Thames Water and Yorkshire Water studies, particularly when the data are subdivided into household size and property type, a single change in the individual behavioural water use patterns, such as taking a bath, has the potential to change the series and hence, increase variability. However, if significantly more households were included in the studies, a change in the individual behavioural water use patterns would probably have little or no effect on the overall series.

- It is also likely that the weather in Barcelona reduces variability in the demand data. In the Mediterranean climate of Barcelona, it is highly likely that if one day is hot, the next day will also be hot. Weather induced influences on demand are, therefore, likely to be relatively constant. However, in the temperate climate of the UK, weather induced influences on demand are more likely to change from day to day. This will undoubtedly increase the variability in the domestic water demand data.

These reasons obviously account for the success of using ARMA time-series models to forecast short-term water demands in Barcelona. However, this research has proved that the univariate and multivariate ARMA time-series approaches are unsuccessful in predicting short-term water demands for each individual household size and property type in the Thames Water and Yorkshire Water studies. This, however, does not negate the possibility of using ARMA time-series models to forecast short-term domestic water demands in the future. If a longer time-series of data were available for analysis and the number of households in the studies increased, then: (i) variability in demand would be expected to fall (ii) the data may be rendered more stationary due to a reduction in variability and (iii) definite relationships between short-term domestic water demands and independent variables may be established as more consumption data would provide a more accurate and representative picture of household water use.

6.4 Measures of uncertainty in the forecasts of short-term domestic water demands

Determination of errors between actual and predicted water demands are extremely important, particularly for water managers, who need to place confidence limits on their forecasts. Errors between the actual and predicted water demand can be measured in a variety of ways. The simplest measure of error is the average difference between the estimate and the actual result (equation 1):

$$error_i = predicted_i - actual_i \tag{1}$$

where subscript $_i$ denotes output unit i. The commonly used error measure is the residual standard deviation, otherwise known as the root mean squared error (RMSE) (Smith, 1996). In practical terms, this error measure gives more importance to those examples for which the error is larger. The equation for this error measure is:

$$\overline{error} = \sqrt{\sum_{i=1}^{n} (predicted_i - actual_i)^2} \tag{2}$$

where $\overline{error}$ is the average error over a set of outputs. Both measures of error were applied to the actual and predicted domestic water demands from the different modelling approaches explored. The R^2 between the actual and predicted water demand was also calculated.

As the univariate and multivariate ARMA time-series models were unable to accurately predict variations in short-term domestic water demands, measures of uncertainty were only calculated for the lookup tables and the stepwise regression, both with and without k-means cluster analysis. As Table 6.4 indicates, no one modelling approach consistently produced the highest or lowest errors. As expected, short-term domestic water demand predictions in the validation periods produced the lowest R^2 and the highest mean average errors and root mean squared errors. The unexplained upward or downward temporal shift in domestic water consumption has undoubtedly increased the measures of uncertainty in the forecasts of short-term domestic water demands. It is hypothesized that if the source of these temporal shifts are determined, that is, the extent to which these temporal shifts in demand result from individual behavioural water use patterns or errors, prediction accuracy would increase and errors would be reduced.

Table 6.4: Measures of uncertainty in short-term water demand predictions for ten sample household sizes and property types in the Thames Water and Yorkshire Water studies

Modelling Approach	*Measures of Uncertainty*		*Household Size and Property Type*									
			1-Person Detached (Thames)	*1-Person Semi-Detached (Thames)*	*1-Person Terraced (Thames)*	*1-Person Detached Bungalow (Yorkshire)*	*2-Person Detached (Thames)*	*2-Person Flat (Thames)*	*2-Person Semi-Detached (Thames)*	*2-Person Detached House (Yorkshire)*	*3-Person Detached (Thames)*	*3-Person Semi-Detached (Thames)*
Lookup Tables	R^2	All	0.27	0.29	0.17	0.19	0.51	0.22	0.40	0.22	0.36	0.34
		Training	0.39	0.38	0.14	0.24	0.58	0.23	0.40	0.25	0.42	0.45
		Validation	0.16	0.27	0.34	0.14	0.46	0.28	0.49	0.18	0.29	0.42
	MAE (l/prop/day)	All	50.80	11.59	4.94	12.40	6.22	9.17	4.08	12.16	2.56	42.22
		Training	3.88	5.84	0.26	3.60	9.31	0.14	6.31	10.75	19.13	7.55
		Validation	132.71	37.67	11.95	25.55	29.45	22.68	19.62	14.27	35.03	94.12
	RMSE (l/prop/day)	All	2266.61	517.86	220.77	437.95	277.96	410.09	182.32	429.49	114.58	1888.29
		Training	134.15	201.99	9.11	98.52	322.28	4.91	218.32	293.87	662.39	261.55
		Validation	3746.68	1065.58	337.91	571.41	833.52	642.00	555.27	319.10	991.46	2663.79
Stepwise Regression	R^2	All	0.20	0.24	0.20	0.17	0.43	0.20	0.40	0.15	0.41	0.32
		Training	0.32	0.26	0.15	0.18	0.48	0.15	0.38	0.13	0.41	0.40
		Validation	0.24	0.42	0.43	0.18	0.51	0.43	0.63	0.18	0.46	0.52
	MAE (l/prop/day)	All	63.54	20.18	4.21	9.14	20.92	4.21	13.10	2.71	24.21	35.65
		Training	5.21	0.11	0.02	0.00	0.21	0.02	0.14	0.00	0.15	0.16
		Validation	160.62	50.99	10.67	22.81	53.02	10.67	33.28	6.77	60.92	91.06
	RMSE (l/prop/day)	All	2796.55	888.04	185.32	322.89	920.83	185.32	581.18	95.86	1064.87	1581.26
		Training	180.25	3.64	0.64	0.01	7.24	0.64	4.82	0.01	5.15	5.69
		Validation	4451.30	1413.90	295.33	510.14	1470.37	295.33	923.35	151.43	1686.12	2523.49
Stepwise Regression with K-Means Clustering	R^2	All	0.26	0.29	0.22	0.04	0.52	0.24	0.48	0.11	0.47	0.37
		Training	0.38	0.34	0.18	0.06	0.59	0.22	0.46	0.17	0.54	0.55
		Validation	0.28	0.44	0.39	0.05	0.57	0.37	0.68	0.04	0.46	0.49
	MAE (l/prop/day)	All	0.00	28.94	3.96	2.88	20.00	8.64	12.39	3.10	22.80	52.21
		Training	59.82	0.00	0.02	13.47	0.03	0.03	0.00	0.09	0.17	92.64
		Validation	91.07	50.96	9.96	12.95	50.40	21.83	31.26	7.60	57.76	0.02
	RMSE (l/prop/day)	All	0.14	1505.17	174.38	101.89	880.22	380.25	545.36	109.47	1003.24	2298.02
		Training	2045.38	0.06	0.81	368.40	0.90	0.90	0.08	2.52	5.98	0.56
		Validation	2523.70	1997.39	275.94	289.62	1396.79	604.99	866.19	169.86	1600.64	2567.28

6.5 Summary

This chapter has explored both pragmatic and advanced approaches to forecast short-term domestic water demands. The lookup tables and the stepwise regression models, both with and without k-means cluster analysis, were able to predict changes in short-term domestic water demands associated with environmental conditions, day of the week and calendar effects. However, these approaches were unable to adapt to the unexplained upward or downward temporal shift in domestic water consumption, producing relatively low R^2 values and relatively high mean average errors and root mean squared errors. On the other hand, the univariate and multivariate ARMA time-series models were able to adapt to the temporal shifts in domestic water consumption as these models used previous demand to predict future demands. However, the univariate and multivariate ARMA time-series models were unable to predict short-term changes in demand associated with environmental conditions, day of the week and calendar effects. However, it is hypothesized that if the source of these temporal shifts are determined, the prediction accuracy of all approaches explored, particularly the lookup tables and the stepwise regression, both with and without k-means cluster analysis, would significantly improve the results and errors would be reduced. It is, therefore, recommended that water plc's attempt to increase the number of households included in their studies and obtain a longer time-series of good quality data (see section 5.18 for details).

The next chapter uses the lookup table approach to explore how the characteristics of short-term domestic water demands might vary due to changes in the population base, climate, culture and technology. It is accepted that the lookup tables are unable to accurately predict short-term domestic water demands. However, the lookup tables are ideal for determining how the characteristics of short-term domestic water demands might change in the future.

7. Short-Term Domestic Water Demand: Future Scenarios

7.1 Introduction

Future changes in the population base, climate, culture and technology are likely to influence short-term domestic water demands. It is important to consider the possible impact of these changes, as accurate predictions of short-term domestic water demands are a vital component of a sustainable water resource strategy (see section 1.1 for details). If predictions of short-term domestic water demands are not accurate, serious detrimental impacts on freshwater ecology and riparian species may be induced. These detrimental impacts result from continued over-abstraction of rivers, surface reservoirs and groundwater, which cause low river flows. These low river flows impact directly on habitat diversity and indirectly through pollution, due to the lack of effluent dilution. Accurate predictions of short-term domestic water demands also have the potential to aid in resource needs forecasting (see section 1.2 for details). This would be an invaluable tool in determining whether new water resources, such as surface reservoirs, need to be developed.

The characteristics of short-term domestic water demands can be explored through a variety of scenarios including:

(i) Changes in the population base - a reduction in household size. Changes in the distribution of property type. An increase in the level of affluence.

(ii) Climatic conditions - global warming. Changes in temperature and rainfall, likely to result in hotter drier summers and warmer wetter winters.

(iii) Cultural differences - growth in telecommuting. Telecommuting is an umbrella term covering a host of alternatives to the traditional office routine. The most common scenario is working at home.

(iv) Technological changes - implementation of demand management measures and improvements in the efficiency of water using appliances.

This chapter will analyse how short-term domestic water demands may vary under these scenarios, based on the findings from Chapters 4 and 5. The pragmatic approach is used in this analysis (see section 6.2.1 for details). Stepwise regression, both with and without k-means cluster analysis, and the univariate and multivariate ARMA time-series models cannot be applied to short-term domestic water demand predictions under future scenarios because the techniques use current/recent demand to forecast future demand. In the stepwise regression models, coefficients are developed for the most significant explanatory variables influencing demand (see section 6.3.1 and 6.3.2 for details). If no demands are available then the most significant explanatory variables cannot be determined. Univariate and multivariate ARMA time-series models base demand predictions on previous demands (see section 6.3.3.1 and 6.3.3.2 for details). The pragmatic approach is, therefore, the most suitable method to predict short-term domestic water demands in future scenarios. It is accepted that the pragmatic approach cannot accurately forecast short-term domestic water demands. However, this chapter is not based on absolute short-term domestic water demand values, but relative values that can be compared to those experienced currently.

7.2 Population base scenarios and short-term domestic water demands

It is important to consider the possible impact of changes in the population base on short-term domestic water demands. Changes in the population base may result in changes in the current distribution of household size and property type. These changes may be induced by a reduction in family size. Family size may be reduced by an increase in divorce rates, resulting in more single parent families or single person households. An improvement in levels of education may also reduce household size as the population become more *career* orientated rather than *family* orientated. Household statistics from the Department of the Environment, Transport and Regions (2001) predict a 73% increase in the number of one-person households and a concomitant reduction in average household size between 1999 and 2021 (Table 7.1).

Table 7.1: Household statistics from the Department of the Environment, Transport and Regions (2001)

Households	*1999*	*2021*	*Change (1999-2021)*
Total no. of households	20.7m	24.0m	3.3m
One-person households	6.1m	8.5m	2.4m
Average household size (persons)	2.36	2.15	0.21

A change in the distribution of property type may result from a change in the distribution of household size. People in smaller households may prefer to live in inner city flats and apartments as opposed to large spacious detached and semi-detached suburban properties. There may also be an increase in the population's overall level of affluence, resulting in higher disposable incomes. This may result from improvements in education and/or reductions in family size.

7.2.1 Changes in household size

The characteristics of short-term domestic water demands were explored through a variety of household size scenarios. These household size scenarios were based on a hypothetical water supply area containing ninety households. As less confidence was placed on individual household size data for four or more persons due to data shortage, household size scenarios were based on one, two and three-person households. It was also necessary to subdivide the household size data by property type, as the models based on the pragmatic approach were developed for each individual household size and property type (see section 6.1 for details). Seven scenarios were explored using detached properties from the Thames Water study as an example (Table 7.2).

Table 7.2: Seven household size scenarios using detached properties from the Thames Water study

Household size and property type	*Scenarios*						
	1	*2*	*3*	*4*	*5*	*6*	*7*
1-person detached	90	0	0	45	0	45	30
2-person detached	0	90	0	45	45	0	30
3-person detached	0	0	90	0	45	45	30

As can be recalled from section 5.6.1, a significant positive relationship is evident between per property consumption and household size. As expected, results from the hypothetical water supply area containing ninety detached properties from the Thames Water study indicate that as household size increases, water consumption increases (Figure 7.1). Water consumption in three-person detached properties (scenario 3) is 23.30% higher than one-person detached properties (scenario 1), and 21.70% higher than two-person detached properties (scenario 2). This observed increase in domestic water consumption would undoubtedly continue in four or more person households for all property types in all water supply areas.

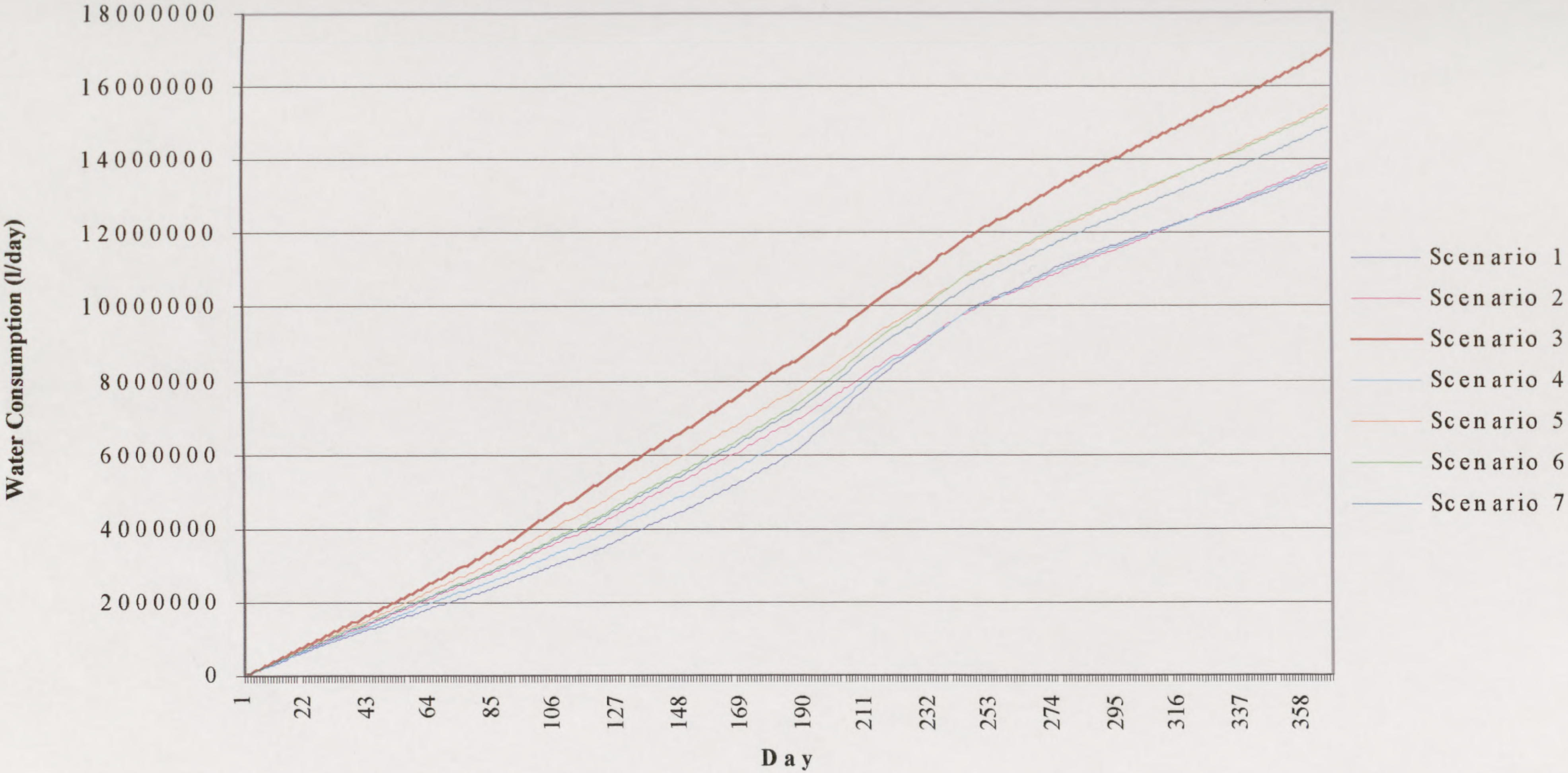


Figure 7.1: Cumulative plot of short-term domestic water demands in a hypothetical water supply area containing ninety households

When detached properties in the hypothetical water supply area are comprised equally of two and three-person households (scenario 5) water consumption is 11.60% higher than if the area is comprised equally of one and two-person households (scenario 4). However, if the hypothetical water supply area is comprised equally of one and three-person households (scenario 6), water consumption is only 0.60% higher than scenario 5. This suggests that the difference between per property consumption in two and three-person detached properties is significantly larger than the difference between one and two-person detached properties. However, as household size increases, the associated percentage increase in domestic water consumption differs for each individual household study and for each property type.

If the hypothetical water supply area consists of equal numbers of one, two and three-person detached properties (scenario 7), domestic water consumption is 3.80% lower than if two and three-person households dominate (scenario 5), and 3.20% lower than if one and three-person households dominate (scenario 6). However, domestic water consumption in scenario 7 is 7.50% higher than scenario 4. These findings suggest that a reduction in household size will result in a reduction in short-term domestic water demands per property. However, if the population in the UK remains constant but the trend changes towards smaller household sizes, the overall demand for water in the short-term will increase. This is because per capita consumption reduces with greater household size (see section 5.6.1 for details).

7.2.2 Changes in property type

Property type scenarios were explored to determine the possible impact of changes in property type on short-term domestic water demands. Property type scenarios were based on a hypothetical water supply area containing one hundred households. Eleven property type scenarios were explored using one-person detached, semi-detached and terraced properties and flats from the Thames Water study (Table 7.3).

Table 7.3: Eleven property type scenarios using one-person detached, semi-detached and terraced properties and flats from the Thames Water Study

Household size and property type	*Scenarios*										
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
1-person detached	100	0	0	0	50	0	50	50	0	0	25
1-person semi-detached	0	100	0	0	50	0	0	0	50	50	25
1-person terraced	0	0	100	0	0	50	50	0	50	0	25
1-person flat	0	0	0	100	0	50	0	50	0	50	25

As can be recalled from section 5.6.2, property types significantly influence domestic water demands. As expected, results from the one hundred households in the hypothetical water supply area indicate that detached properties consume more water than any other property type (Figure 7.2). Water consumption for one hundred one-person detached properties (scenario 1) is 53.70% higher than one-person semi-detached properties (scenario 2), 56.90% higher than one-person terraced properties (scenario 3), and 71.30% higher than one-person flats (scenario 4). The percentage differences in domestic water consumption for each property type appears to differ for each individual household study and for each household size (see section 5.6.2 for details). However, in all cases, detached properties consume the most water while flats consume the least. When there is an equal distribution of two property types in the hypothetical water supply area (scenarios 5-10), water consumption is highest for detached and semi-detached properties (scenario 5), and lowest for terraced properties and flats (scenario 6). In fact, domestic water consumption is consistently higher when detached properties are included in the scenarios. This emphasizes the fact that detached properties consume significantly more water than any other property type.

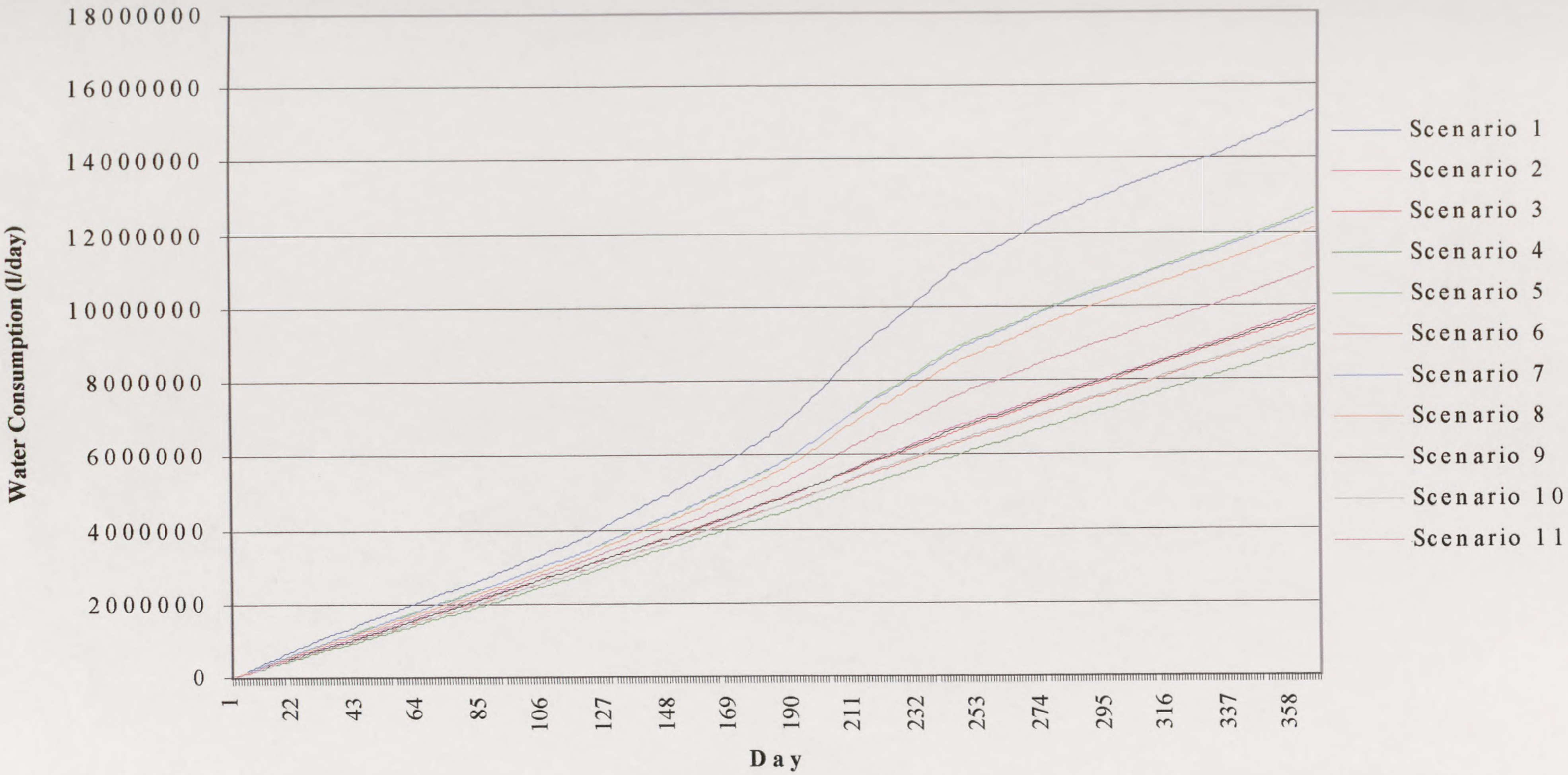


Figure 7.2: Cumulative plot of short-term domestic water demands in a hypothetical water supply area containing one hundred households

An equal number of detached, semi-detached and terraced properties and flats (scenario 11) in the hypothetical water supply area produces consumption values 15.00% lower than detached and semi-detached properties (scenario 5), and 17.60% higher than terraced properties and flats (scenario 6). These findings suggest that if there is an increase in the development of flats as opposed to other property types, domestic water consumption in the short-term will decline.

7.2.3 Changes in affluence

It is impossible to explore how the characteristics of short-term domestic water demands might change with levels of affluence. As can be recalled in section 5.6.3, no obvious relationship was found between domestic water consumption and ACORN categories, which suggests that water consumption is independent of affluence. However, once the data are subdivided by household size and property type, there may not be enough households in the studies to provide a representative sample of households for each ACORN category. This suggests that affluence may account for higher consumption figures for households in the Thames Water study and in Yorkshire Water's small water supply areas. However, other intervening factors may also explain the higher consumption figures in these areas. In the Thames Water study, climatic conditions may account for higher consumption figures. In Yorkshire Water's small water supply areas, a high percentage of detached properties, coupled with a large proportion of retired residents who have ample opportunity for water consuming activities such as garden watering, may account for higher consumption figures. It is impossible therefore to quantify, or indeed determine the effects of changing affluence on short-term domestic water demands.

7.3 Climate change scenarios and short-term domestic water demands

Climate change scenarios were based on general circulation models (GCMs) from the Climatic Research Unit at the University of East Anglia (Hulme and Jenkins, 1998). Changes in the UK's mean annual temperature (°C) and mean summer rainfall (percentage change) were established for thirty year periods centred on the 2020s, 2050s and 2080s. Four scenarios (low, medium-low, medium-high and high) were developed to span a range of future global warming rates from 0.1°C to 0.3°C per decade (Figure 7.3 and 7.4). As Hulme and Jenkins (1998) only predicted changes in mean summer rainfall, research by Warrick and Barrow (1991) in Haughton and Hunter (1994) was used to predict changes in winter rainfall. Warrick and Barrow (1991) predicted a 5% increase in winter precipitation in the UK by 2030.

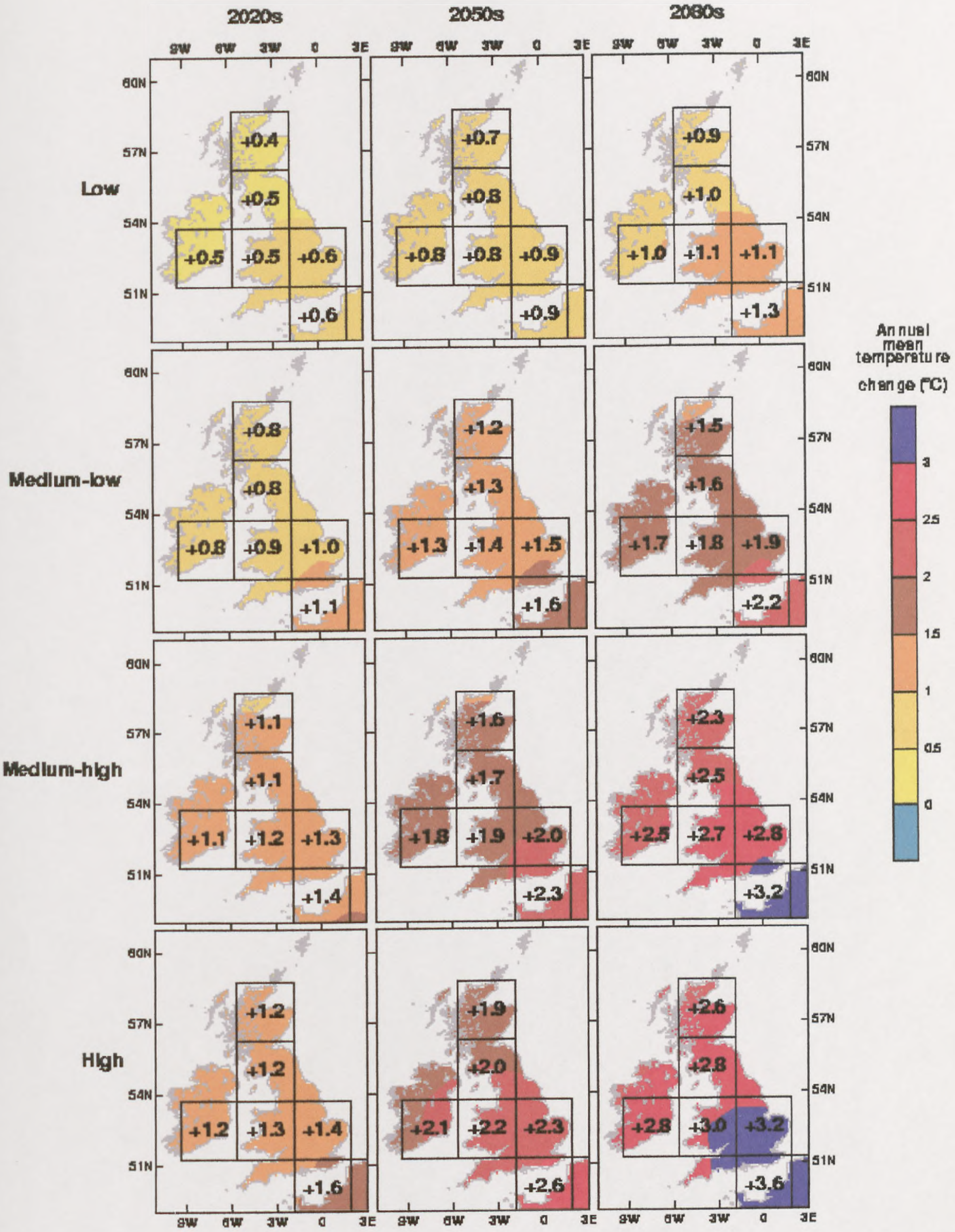


Figure 7.3: Change in mean annual temperature (°C) for thirty year periods centred on the 2020s, 2050s and 2080s (Hulme and Jenkins, 1998)

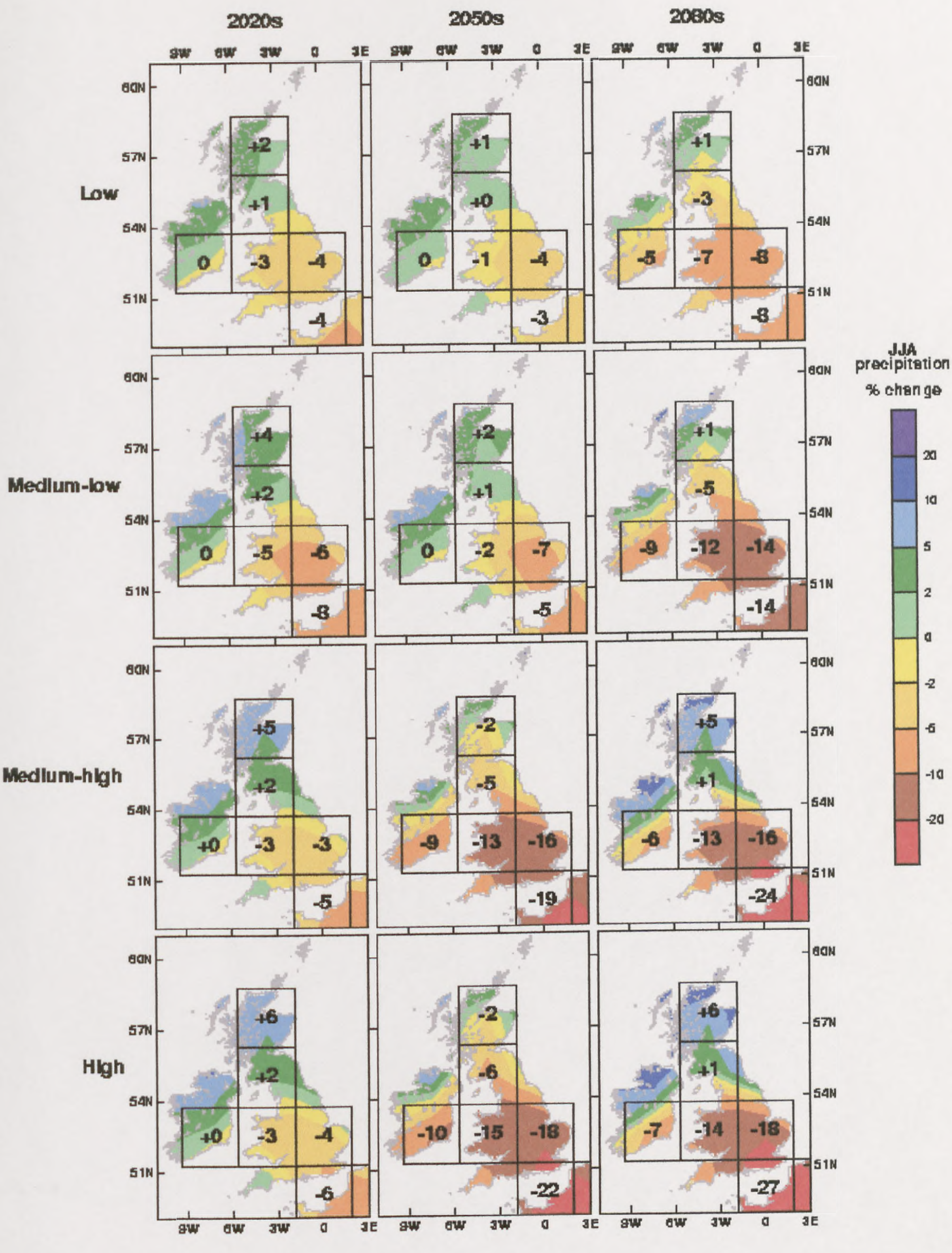


Figure 7.4: Change in mean summer rainfall (% change) for thirty year periods centred on the 2020s, 2050s and 2080s (Hulme and Jenkins, 1998)

The characteristics of short-term domestic water demands were explored for each individual household size and property type in the Thames Water and Yorkshire Water studies using the low (best case) and high (worst case) scenarios in the 2020s, 2050s and 2080s. As the forecasts of winter precipitation by Warrick and Barrow (1991) did not coincide with that undertaken by Hulme and Jenkins (1998), winter rainfall was assumed to increase by 5% in all scenarios. This prediction is considered adequate for this research as climate change scenarios for moisture-related variables are predicted with lesser confidence than temperature variables (Hulme and Jenkins, 1998). Neither Hulme and Jenkins (1998) nor Warrick and Barrow (1991) specified which months constituted summer and winter. It was decided, therefore, to designate *winter* as October to March and *summer* as April to September.

Figures 7.5 and 7.6 are cumulative plots of short-term domestic water demands for the present day (average of 1994-1999 in the Thames Water study and average of 1996-1999 in the Yorkshire Water study) and the best and worst case scenarios in 2020, 2050 and 2080. As a result of seasonality in the water demand data, cumulative plots for the Thames Water study display an upward shift in demand at approximately 188 days. In comparison, cumulative plots for the Yorkshire Water study remain relatively constant throughout the year due to the lack of seasonal variation in the water demand data (see section 5.5 for details). In the Thames Water study, both the best and worst case scenarios caused short-term domestic water demands to increase above those of the present day in all household sizes and property types. Short-term domestic water demands in all best case scenarios for 2020, 2050 and 2080 were less than the three worst case scenarios. The worst case scenario in 2080 displayed on average an 8.20% increase in short-term domestic water demand, while the best case scenario in 2020 displayed on average a 0.90% increase. For different household sizes and property types in the Yorkshire Water study, only short-term domestic water demands proved higher than that of the present day in the worst case scenario for 2080. As in the Thames Water study, short-term domestic water demands in all best case scenarios for 2020, 2050 and 2080 proved less than the three worst case scenarios. The worst case scenario in 2080 displayed a 0.50% increase in short-term domestic water demand, while the best case scenario in 2020 displayed a 2.20% reduction in demand.

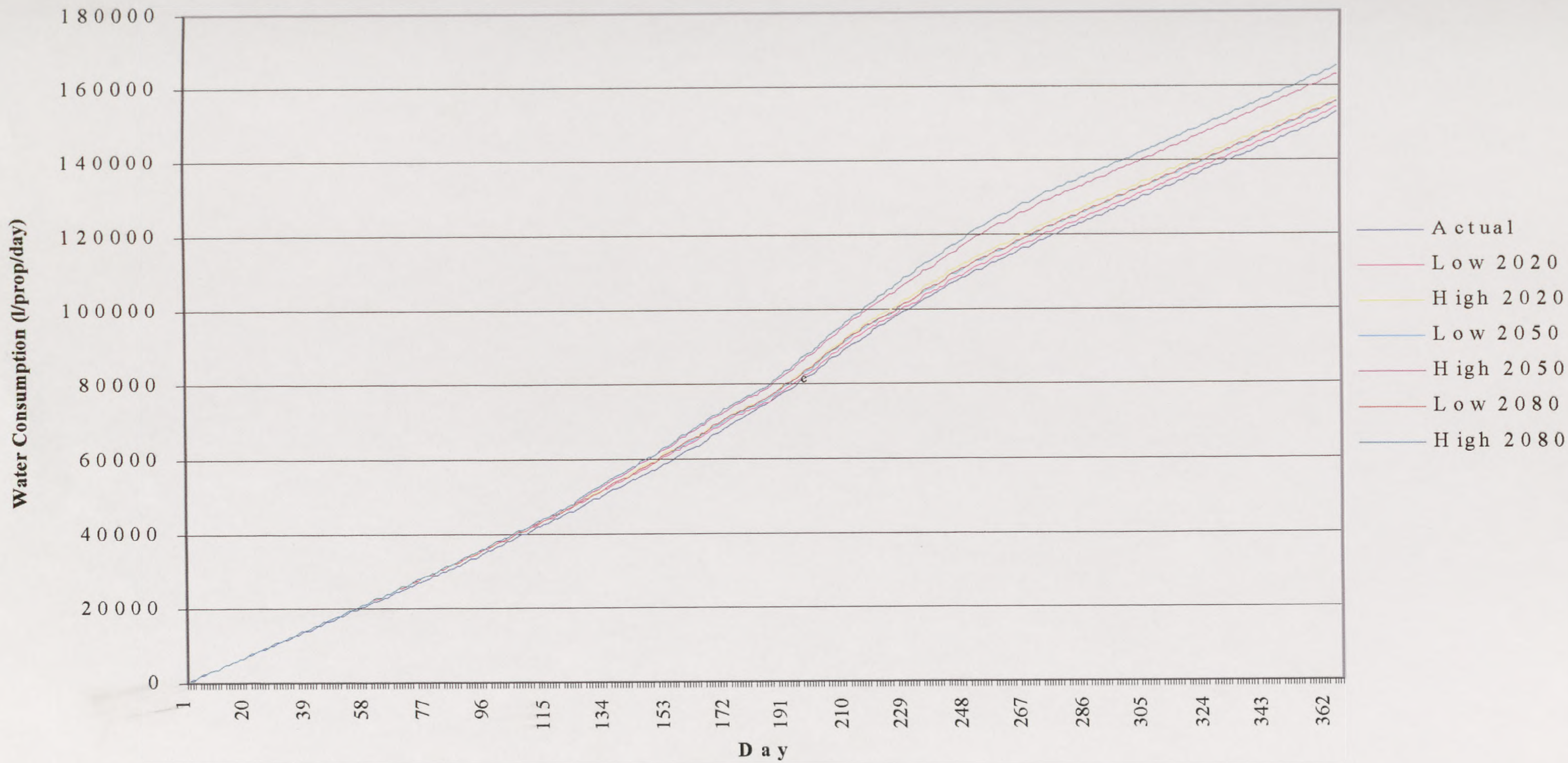


Figure 7.5: Cumulative plot of short-term domestic water demands for two-person detached properties in the Thames Water study for the present day and the best and worst case scenarios in 2020, 2050 and 2080

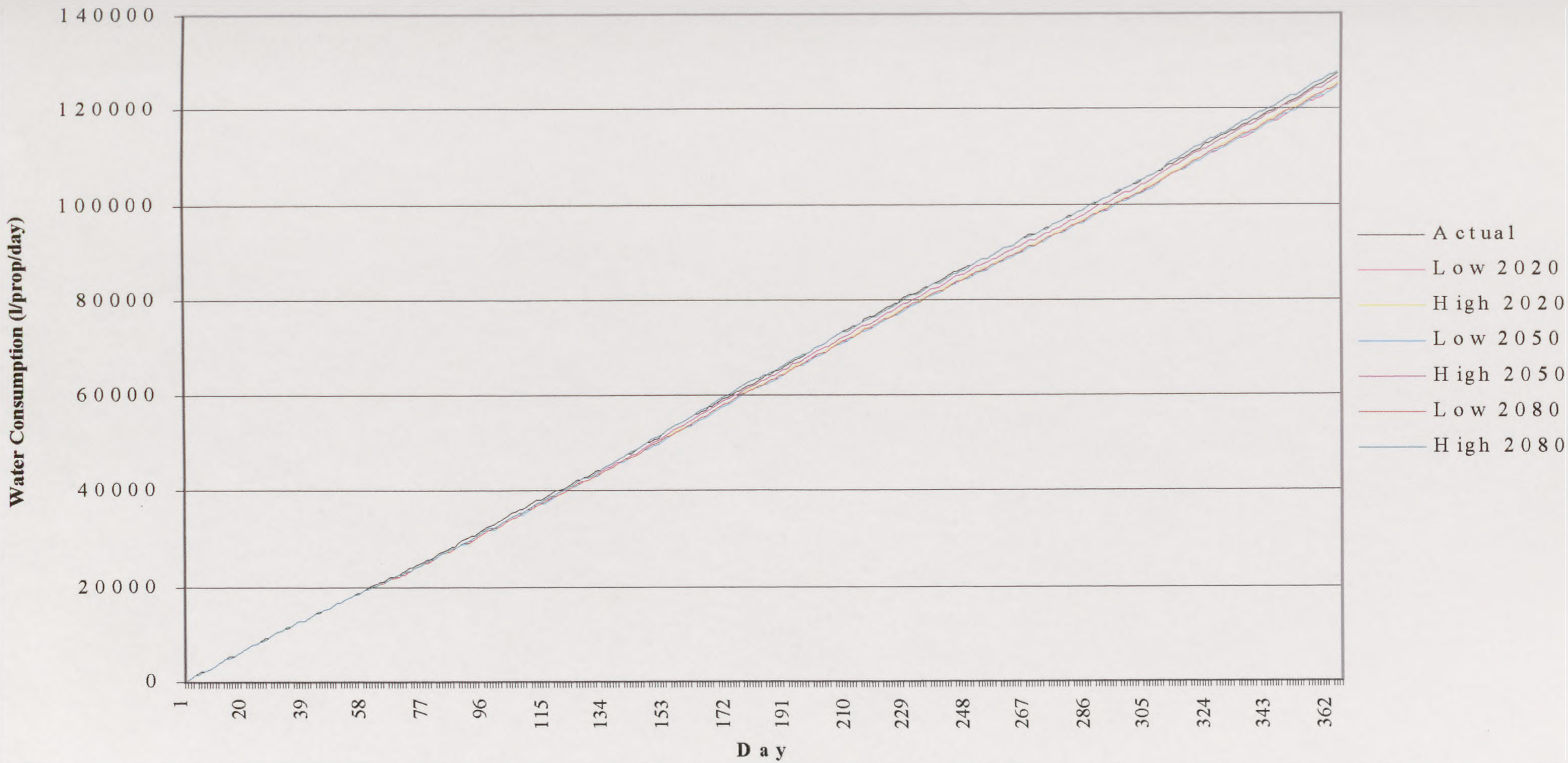


Figure 7.6: Cumulative plot of short-term domestic water demands for two-person detached houses in the Yorkshire Water study for the present day and the best and worst case scenarios in 2020, 2050 and 2080

Predicted demands may underestimate actual demands in the Yorkshire Water study because bank-holidays, public holidays and school holidays, which are proven to cause an increase in demand, are not included in the predictions. However, they are also not included in predictions of climate change scenarios in the Thames Water study. It is highly probable that predicted demands in the Yorkshire Water study are less than in the Thames Water study because of climatic differences. In Yorkshire, weather scenarios now and in the future remain significantly wetter and colder than in the South East (see section 5.9.1 for details). In the Thames Water study, rainfall in the summer months is already relatively low. The larger percentage change in mean summer rainfall in the South East then reduces the rainfall total even further. This percentage reduction in mean summer rainfall usually causes a shift in rainfall to the lower quartile (see section 6.2 for details). This, along with higher increases in temperature in the Thames Water study, produces a larger increase in demand. However, in the Yorkshire Water study, because changes in temperature and rainfall are relatively small, shifts from one quartile to another are not common. The exception is in March, October and November, when a 5% increase in rainfall is predicted. This generally causes a shift in rainfall to the upper quartile and hence causes a reduction in water demands. However, even if temperature shifts to the upper quartiles, changes in demand are relatively small as the relationship between demand and weather in the Yorkshire Water study is not as strong as that observed in the Thames Water study (see section 5.9.1 and 5.11 for details).

7.4 Cultural scenarios and short-term domestic water demands

Future cultural scenarios associated with major advances in telecommuting have the potential to significantly influence the characteristics of short-term domestic water demands. Major advances in telecommuting will inevitably result in the 'virtual workplace' at home. These changes in work patterns have the potential to change the weekly cyclic pattern in domestic water consumption. Currently, the weekly cyclic pattern in domestic water consumption experiences a two-day increase in demand associated with weekends as more people remain at home and hence are likely to consume more water (see section 4.12 and 5.14 for details). However, if a large proportion of the population are working from home one or two days per week, typical two-day increases in weekly domestic water demands associated with weekends may be extended to three or four-day increases as more people remain at home consuming water.

Telecommuting is a growing trend. In the United States, 7.6 million people were telecommuting in one form or another in 1994 and the number is growing at 15% per year (Niles, 1994). To determine the influence of telecommuting on short-term domestic water demands, six future scenarios were devised:

(i) 25% of the population telecommuting from home one day per week.

(ii) 50% of the population telecommuting from home one day per week.

(iii) 75% of the population telecommuting from home one day per week.

(iv) 25% of the population telecommuting from home two days per week.

(v) 50% of the population telecommuting from home two days per week.

(vi) 75% of the population telecommuting from home two days per week.

These six scenarios were applied to the best (low case) and worst (high case) climatic change scenarios in 2020, 2050 and 2080. More than 75% of the population telecommuting from home was considered unrealistic as occupations such as fire fighters, doctors and nurses, do not have the potential to telecommute.

Figures 7.7 to 7.10 are cumulative plots of short-term domestic water demands in the Thames Water and Yorkshire Water studies for the present day and the six telecommuting scenarios for the best case climatic scenarios in 2020 and the worst case climatic scenarios in 2080. In all cases, telecommuting increases demand predictions compared to demand predictions using only future climatic scenarios. As expected, maximum demand predictions are observed when 75% of the population are telecommuting two days per week for the worst case climatic scenario in 2080. Minimum demand predictions are observed when 25% of the population are telecommuting one day per week for the best case climatic scenario in 2020.

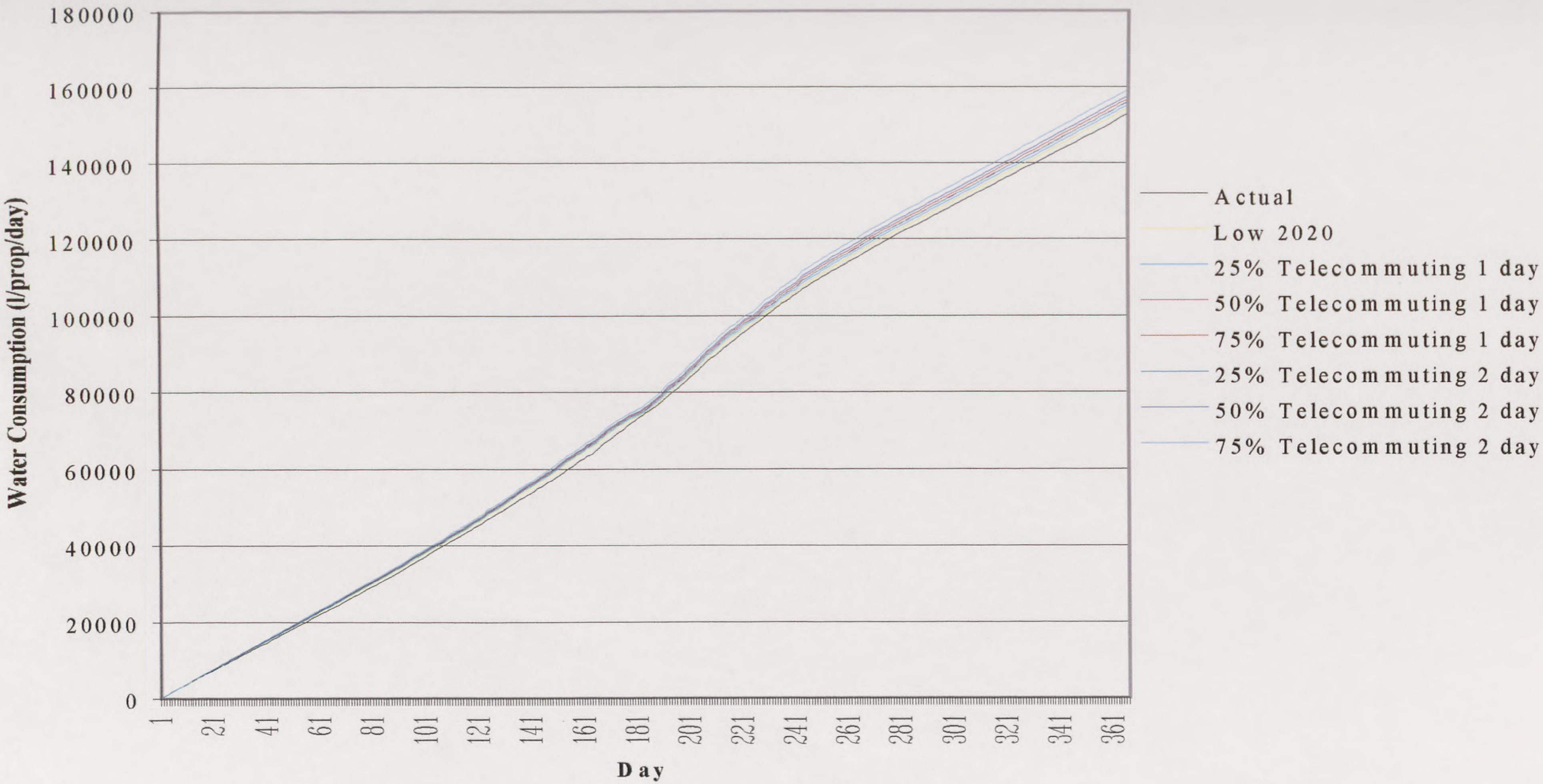


Figure 7.7: Cumulative plot of short-term domestic water demands for two-person detached properties in the Thames Water study for the present day and the six telecommuting scenarios in the best climatic case scenarios in 2020

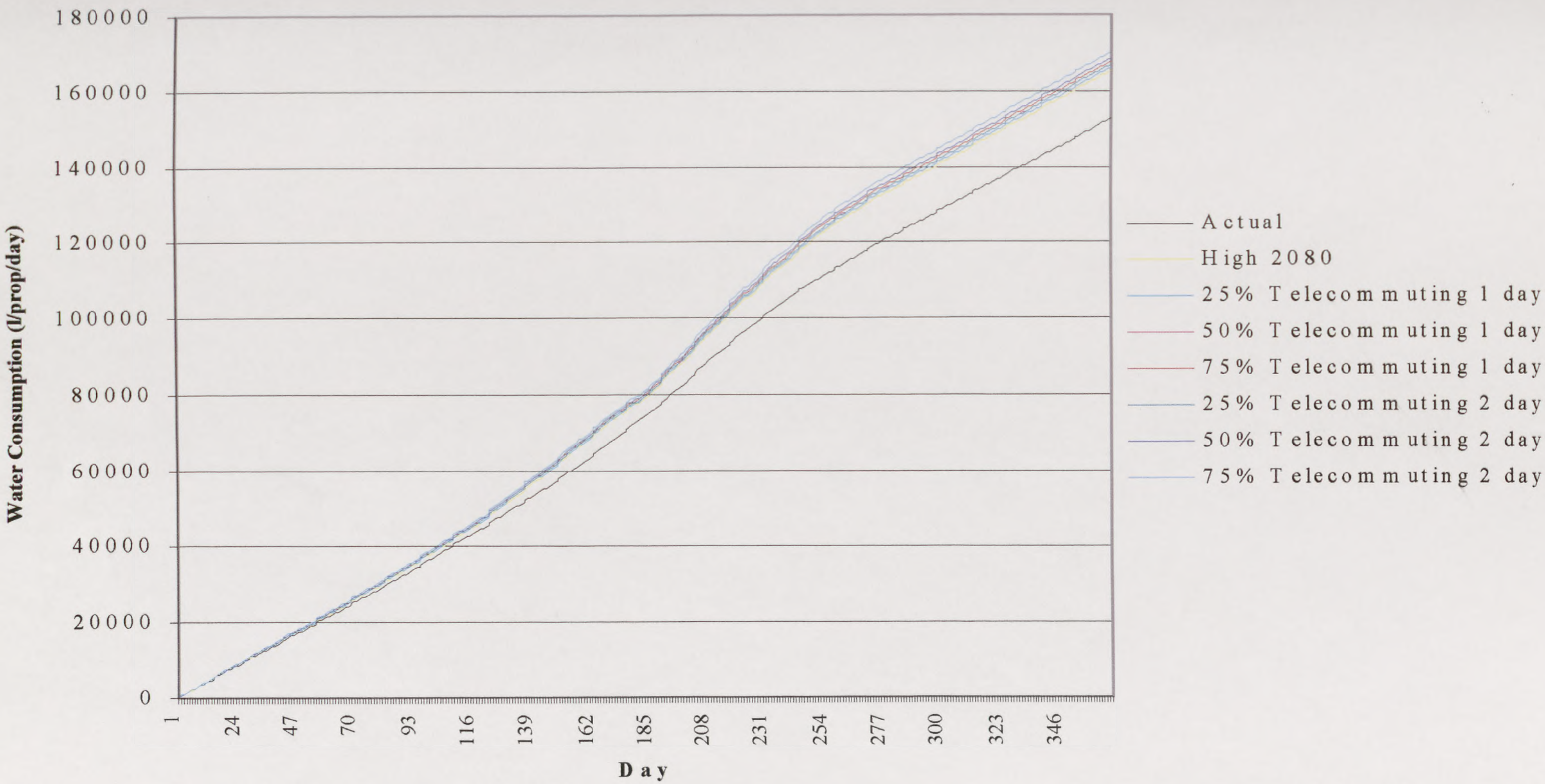


Figure 7.8: Cumulative plot of short-term domestic water demands for two-person detached properties in the Thames Water study for the present day and the six telecommuting scenarios in the worst climatic case scenarios in 2080

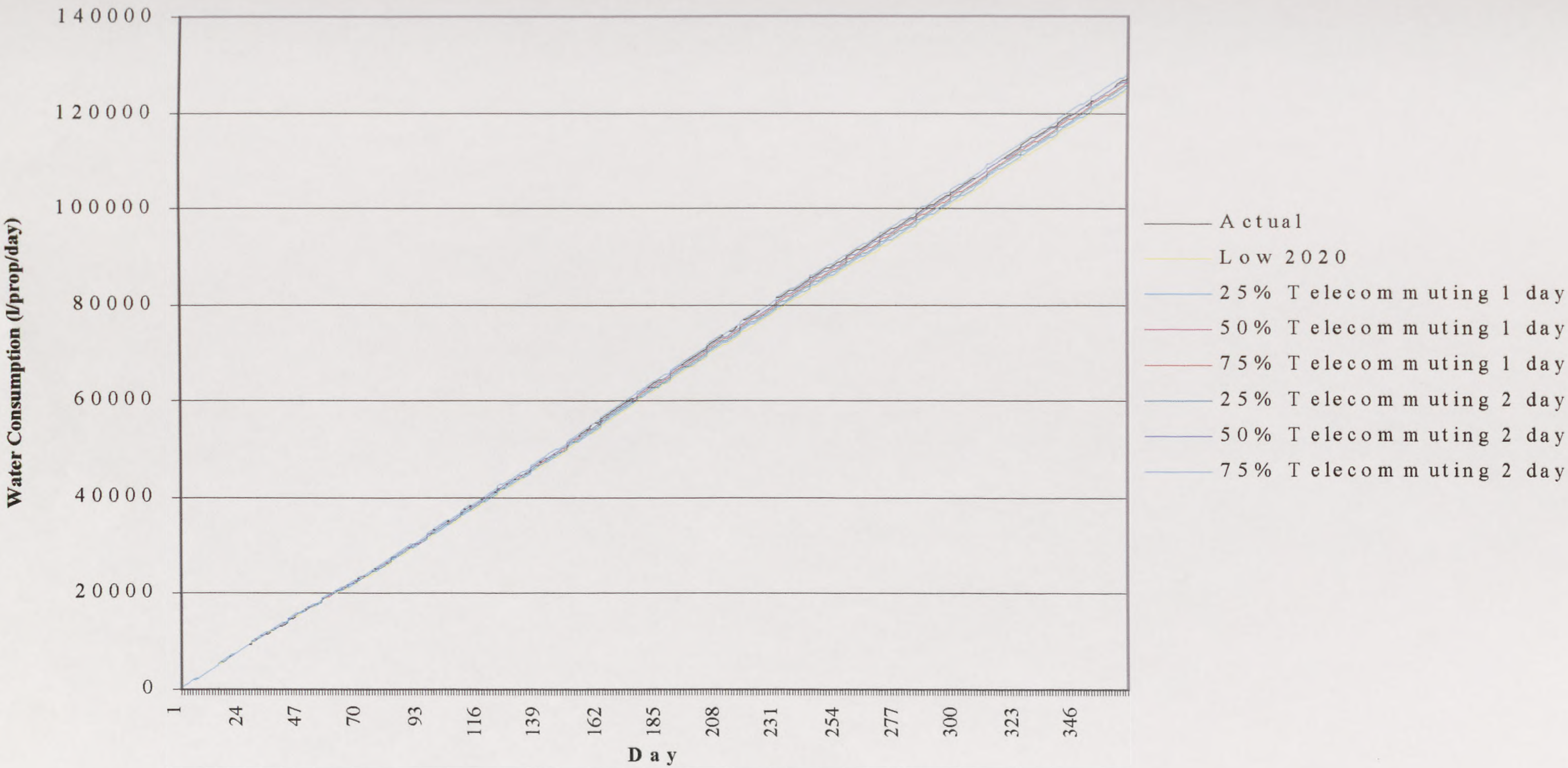


Figure 7.9: Cumulative plot of short-term domestic water demands for two-person detached houses in the Yorkshire Water study for the present day and the six telecommuting scenarios in the best climatic case scenarios in 2020

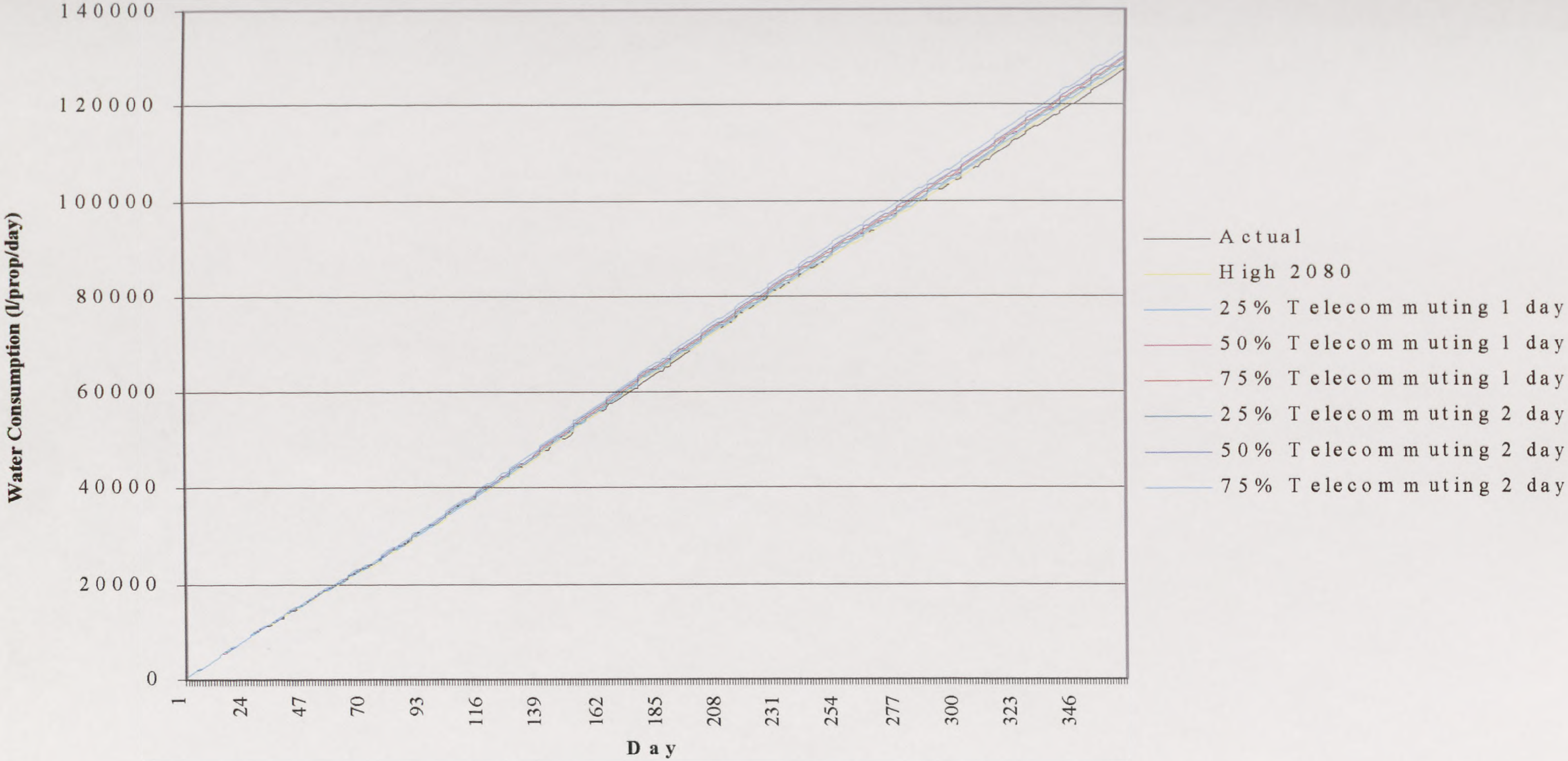


Figure 7.10: Cumulative plot of short-term domestic water demands for two-person detached houses in the Yorkshire Water study for the present day and the six telecommuting scenarios in the worst climatic case scenarios in 2080

For each individual household size and property type in the Thames Water study, actual demands are lower consistently than predicted demands for the six telecommuting scenarios. Average increases in demand range from 1.50% in the best case climatic scenario in 2020 with 25% of the population telecommuting one day per week to an 11.40% increase in demand in the worst case climatic scenario in 2080 with 75% of the population telecommuting two days per week.

Demand predictions for each individual household size and property type in the Yorkshire Water study are only higher than the present day demands when 75% of the population are telecommuting two days per week. The exception is the worst case weather scenario in 2080 when all six telecommuting scenarios produce higher demands than the present day. Predictions range from a 1.70% reduction in demand in the best case climatic scenario in 2020 when 25% of the population are telecommuting one day per week, to a 3.20% increase in demand for the worst case weather scenario in 2080 when 75% of the population are telecommuting two days per week. It is likely that demand predictions in the Yorkshire Water study remain lower than present day demands in many of the telecommuting and climatic scenarios because increased rainfall in March, October and November causes a relatively large reduction in short-term domestic water demands. Climatic scenarios influence demand more than telecommuting scenarios and hence, in many cases predicted demands remain less than present day demands.

7.5 Technology scenarios and short-term domestic water demands

In the UK, the promotion of water saving devices or water efficient appliances appear to be relatively limited in number (Environment Agency, 1998). Water saving devices and water efficient appliances, therefore, have massive potential to influence short-term domestic water demands. There is a paucity of research that reports household water savings from the implementation of demand management measures. Results from the evaluation of demand management practices in Yorkshire Water's small water supply areas (see section 4.17 for details) are therefore used to estimate the aggregate decline in domestic water use. It is accepted that the characteristics of the small water supply areas are unique. The influence of demand management measures may differ in urban households, in different household sizes and property types, in different socio-economic groupings, and in different climatic conditions. However, results from this study suffice in providing an estimate of how domestic water demands might be affected.

The estimated aggregate decline in domestic water demand in the small water supply areas of Yorkshire averaged 20%. Twenty-percent reductions were, therefore, made from predicted water demands from the different climatic and cultural scenarios in the Thames Water and Yorkshire Water studies. Figures 7.11 and 7.12 are cumulative plots of short-term domestic water demands in the Thames Water and Yorkshire Water studies for the worst case climatic scenario in 2080. For all household sizes and property types in the Thames Water and Yorkshire Water studies, demand management measures reduced short-term domestic water demands to levels lower than those today. For the worst case climatic scenario in 2080 with 75% of the population telecommuting two days per week, predicted short-term water demands fell by 12.20% in the Thames water study and 21.20% in the Yorkshire Water study in comparison to present day levels. The percentage reduction in predicted demand associated with demand management measures is less in the Thames Water study because climate change scenarios result in a significantly larger increase in short-term domestic water demands.

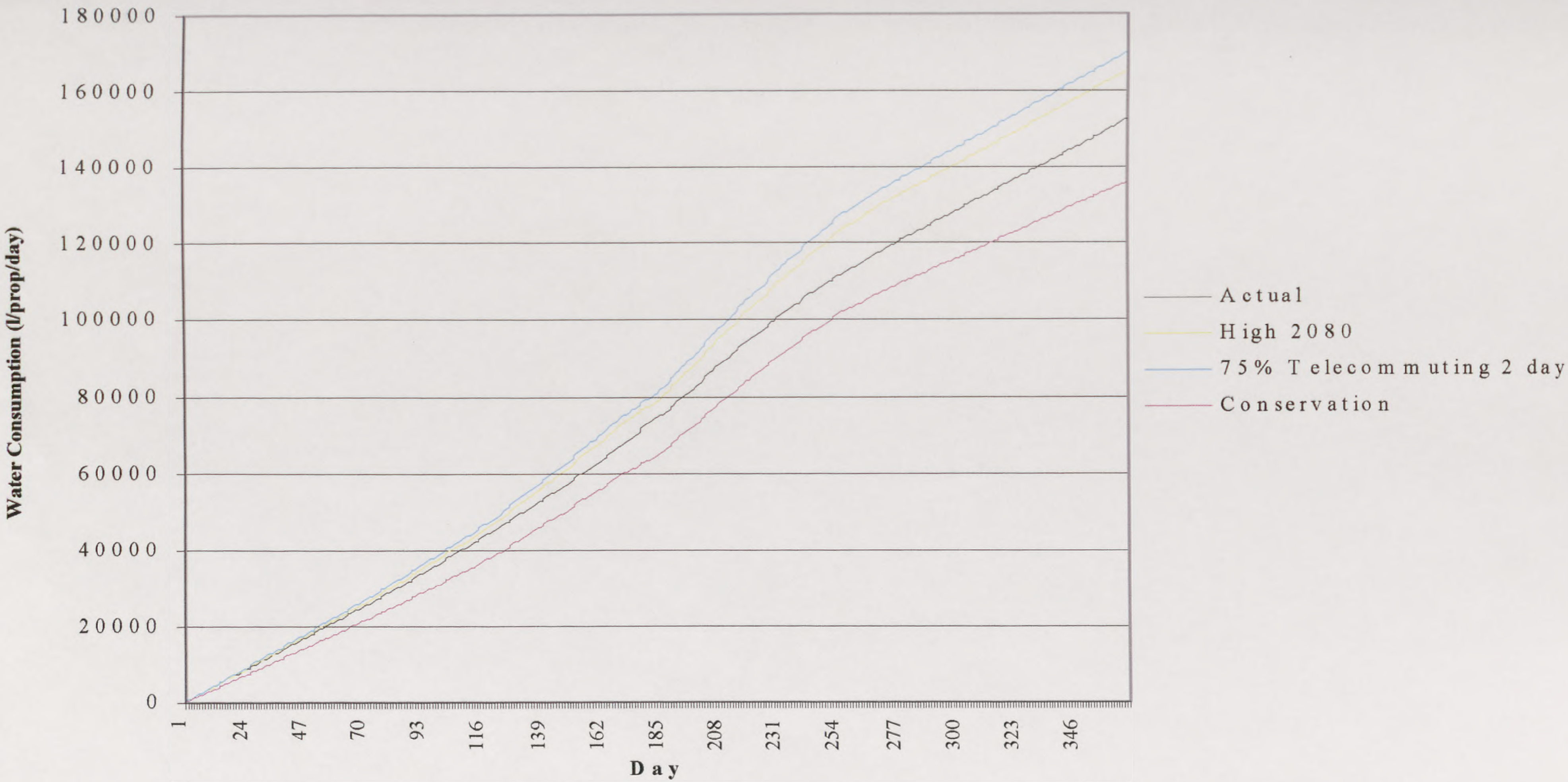


Figure 7.11: Cumulative plots of short-term domestic water demands for two-person detached properties in the Thames Water Study for the worst case climatic scenario in 2080

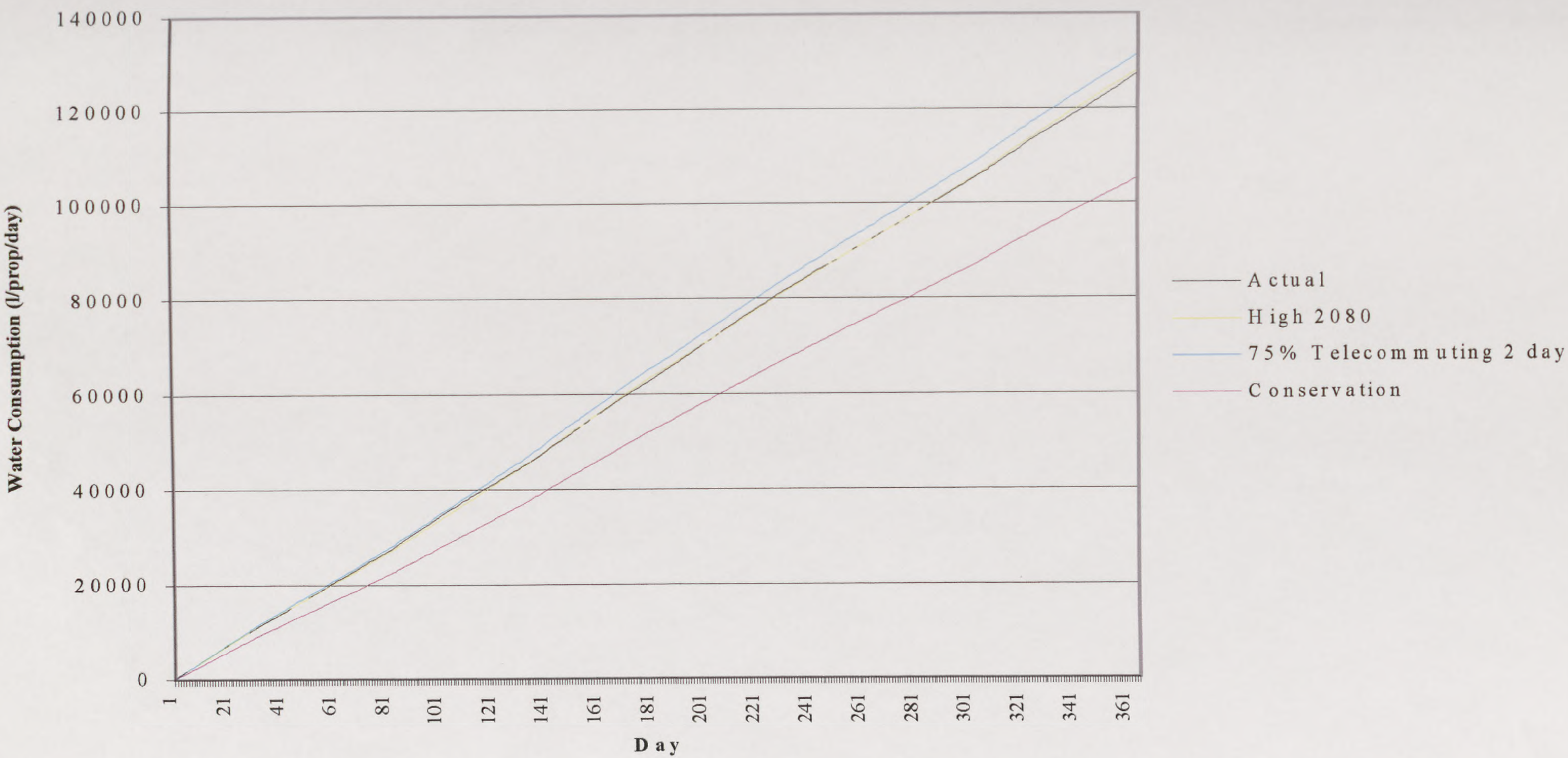


Figure 7.12: Cumulative plots of short-term domestic water demands for two-person detached houses in the Yorkshire Water Study for the worst case climatic scenario in 2080

7.6 Summary

This chapter has provided evidence that the characteristics of short-term domestic water demands are likely to be influenced by changes in the population base, climate, culture and technology. Future changes in the population base may cause short-term domestic water demands to fall in an area if the population trend changes towards smaller household sizes and the population choose to live in flats and apartments. Typically, future changes in climate and culture will result in an increase in short-term domestic water demands. However, demand management measures have the potential to suppress these increases in demand and indeed reduce demands to less than those of the present day.

The next chapter seeks to explain the findings of the research into the demand for domestic water and compares the findings to similar research reported in the literature and reviewed in Chapter 2. The potential for this research to be used as a component of a sustainable water resource strategy in the 21st Century is also discussed along with suggestions of ways to improve further our understanding of domestic water demands.

8. Discussion

8.1 Introduction

This chapter seeks to explain the research findings presented in earlier chapters. The results are compared to the findings of similar research reported in the literature and reviewed in Chapter 2. Wider implications of this research, in particular the potential it has to be used as a vital component of a sustainable water resource strategy in the 21st Century, are discussed. Finally, limitations of this research are identified along with suggestions of ways to further improve our understanding of domestic water demands.

8.2 Quality of data sources

It is impossible to determine whether zonal meter studies or individual household studies provide the best estimation of domestic water consumption (see section 3.3 for details). No previous work provides an evaluation of these techniques nor is there a fully instrumental region from which to make such an evaluation. *True* domestic water consumption in the zonal meter studies relies on accurate determinations of leakage and water consumption for non-household properties. *True* domestic water consumption is probably obtained using individual household studies. However, several forms of bias (e.g. self-selection, the Hawthorne Effect, financial advantage bias and sample decay) may have affected these consumption rates which influence the value for the true population. It was, therefore, decided to use data from both of these sources. Component metering data was not pursued in this research as component metering data in the UK do not provide a good estimation of domestic water consumption (see section 3.5 for details).

Data from the zonal meter and individual household studies used in this research represent a good cross-section of the UK population, both spatially and socio-economically (see section 3.6 for details). As the water companies believe that households included in their studies are representative of the company area as a whole (the exception is Yorkshire Water's small water supply areas which were never developed to be representative), the data represents approximately twenty million people. These studies successfully capture the domestic water using behaviour of a range of people, housing and climatic conditions. Managing to capture the water using behaviour of such a large proportion of the population is vital for determining the way in which individuals in the population consume water. A domestic water use study of this type, that is, using such a large cross-section of the population, has never been undertaken in the UK.

8.3 Underlying factors influencing medium- to long-term domestic water demand

Medium- to long-term domestic water demands in the zonal meter studies appear to be influenced by property type, economic activity of the population, levels of affluence and the implementation of demand management measures (see section 4.18 for details). However, because the zonal metering data refers to an aggregate flow and not a measure of a single household, it is difficult to accurately estimate domestic water consumption for an affluent, economically active family, for example, living in a detached property with no demand management measures. Instead, it appeared that a more accurate estimation of domestic water demand, and the underlying factors that influence it, could be made using the individual household study data.

Household size appears to exert the greatest underlying influence on medium- to long-term domestic water demand in the individual household studies (see section 5.6.1 for details). As expected, domestic water consumption increases with greater household size. However, as household size increases, per capita consumption is reduced. Similar findings have been observed in previous domestic consumption studies (e.g. Primeaux and Hollman 1974; Males, 1975; Turton and Smith, 1976; Thackray *et al.*, 1978; Danielson, 1979; Agthe *et al.*, 1988; Hall *et al.*, 1988; Russac *et al.*, 1991; Edwards and Martin, 1995). The observed reduction in per capita consumption with greater household size is likely because: (i) the number of persons in a household does not govern some water consuming activities such as garden watering and (ii) appliance ownership per person is reduced with greater household size. Such a decline in appliance ownership was reported by Russac *et al.* (1991) (Figure 8.1).

Property type also appears to influence medium- to long-term domestic water demand in the individual household studies (see section 5.6.2 for details). Detached properties consume more water than any other type. This is expected as detached properties typically have large gardens and hence are likely to have high outdoor water use. Flats displayed the lowest water use. Flats typically have no gardens and are, therefore, likely to have a very low outdoor water use. Semi-detached and terraced properties interchanged frequently between the second and third highest water consumer. Gardens in these types of properties tend to be smaller than detached properties; hence outdoor water use is higher than flats but lower than detached properties. As expected, per capita consumption was highest for detached properties containing one person and lowest for flats, particularly when the number of residents was high. Such findings conform to those reported by Russac *et al.* (1991) (Figure 8.2). Other research has collected information about the type of properties in their consumption studies (e.g. Turton and Smith, 1976;

Thackray *et al.*, 1978). However, the influence of property type on domestic water use was not reported.

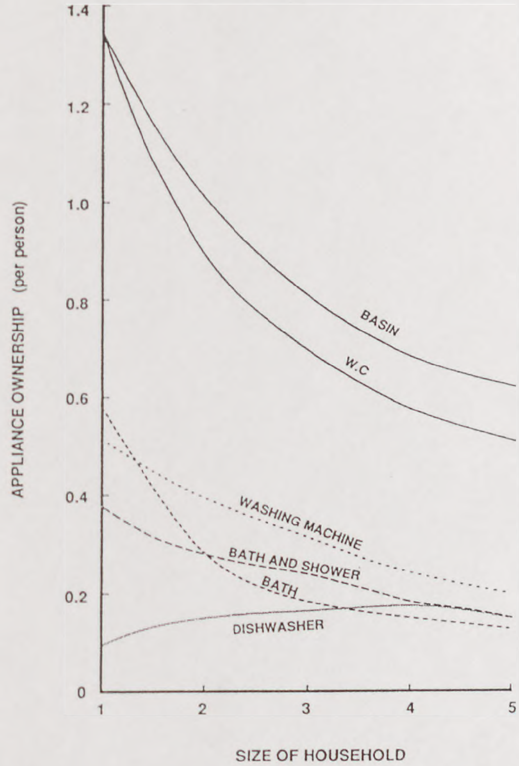


Figure 8.1: Appliance ownership per person relative to household size (Source: Russac *et al.*, 1991)

Figure 8.2: Average consumption by property type (Source: Russac *et al.*, 1991)

Russac *et al.* (1991) found that the number of appliances per person was dependent on property type (Figure 8.3). Detached and semi-detached properties generally own a greater number of appliances per person than flats. This, as well as differences in garden size, may account for higher water use in detached and semi-detached properties. However, due to the paucity of information relating to appliance ownership in the individual household studies (see section

5.6.7 for details), it was impossible to explore the relationship between the number of appliances per person and property type.

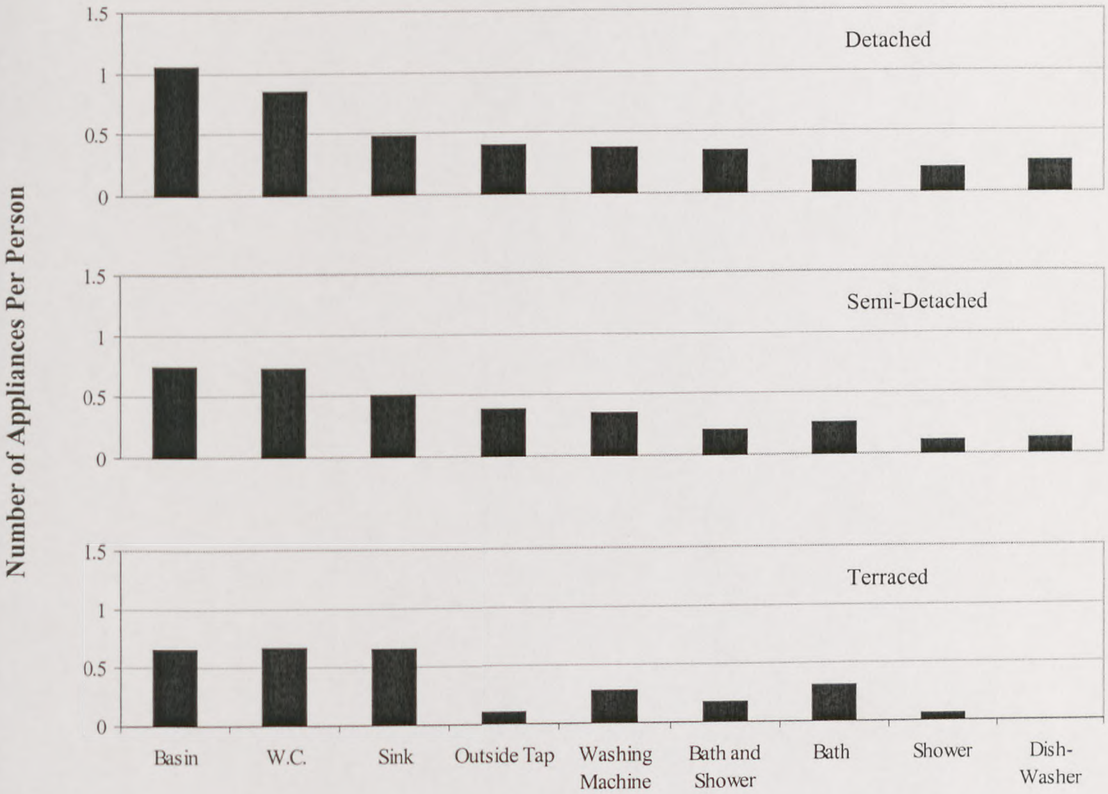
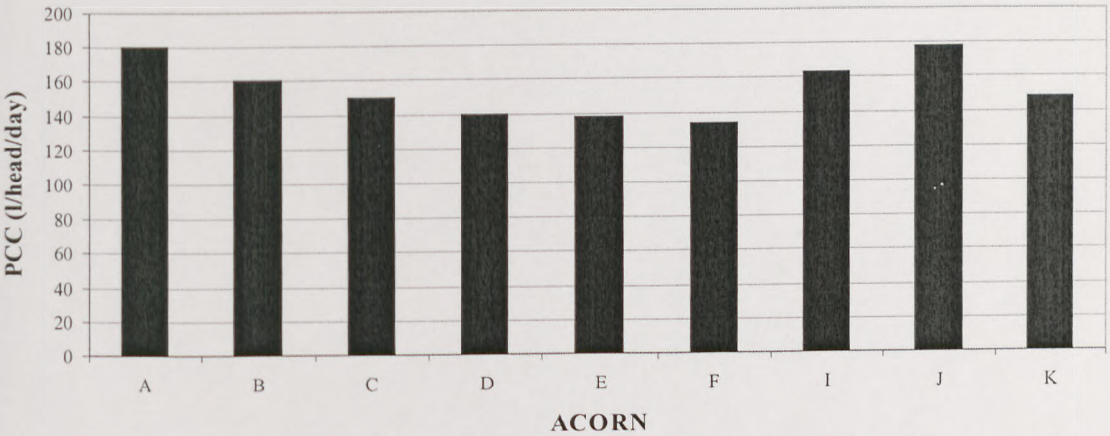


Figure 8.3: Number of appliances per person and the dependence on property type (Source: Russac *et al.*, 1991)

Previous research has identified other underlying factors that influence medium- to long-term domestic water demands (e.g. Russac *et al.*, 1991; Edwards and Martin, 1995). These factors include ACORN groups, the rateable value of properties and appliance ownership. Edwards and Martin (1995) found that per capita consumption was highest in ACORN groups A (agricultural villages) and J (affluent suburban houses), and lowest in ACORN group F (council housing) (Figure 8.4). Edwards and Martin (1995) also observed that per capita consumption was directly related to the property's rateable value (Figures 8.5). In the individual household studies, other underlying factors influencing medium- to long-term domestic water demands such as the age of population, garden size, ACORN categories, Water Use Classifications, rateable values and appliance ownership could not be established (see section 5.6.3 to 5.6.6 for details). One possible reason, particularly for garden size, is that outdoor water use is influenced by the individual's behavioural water use pattern, which may mask the influence of garden size. A second reason is that once the data are subdivided by household size and property type, there may not be enough households in the study to provide a representative sample of households for each ACORN category, for each rateable value band, etc. Russac *et al.* (1991) indicate that misleading results may be obtained if only small samples are used. This is due to a great variability in water use between individual properties, even if the properties share common characteristics (Thackray *et al.*, 1978; Hall *et al.*, 1988; Russac *et al.*, 1991). Russac *et al.* (1991) found that there are significantly different consumption figures for the same ACORN classification and also that similar consumption occurs with different ACORN groups. This variability may produce spurious results if households are not *truly* representative of a particular group.



Key:

A	Agricultural areas
B	Modern family housing, higher income
C	Older housing of intermediate status
D	Poor quality older terraced housing
E	Better-off council estates
F	Less well-off council estates
I	High status non-family areas
J	Affluent suburban housing
K	Better-off retirement areas

Figure 8.4: Mean per capita consumption by ACORN classification (Source: Edwards and Martin, 1995)

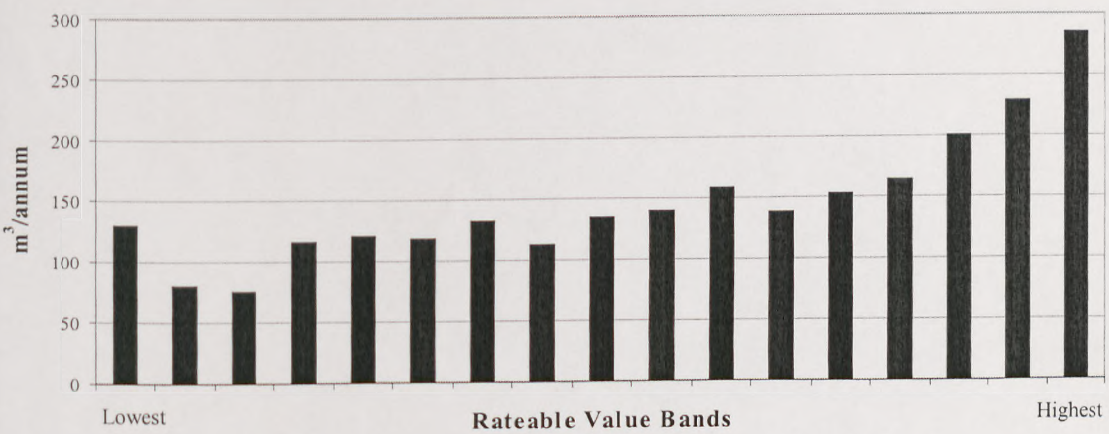


Figure 8.5: Mean annual household consumption by rateable value band (Source: Edwards and Martin, 1995)

In domestic water use studies outside the UK, the price variable and/or income were also found to be significant underlying factors that influence water demand in the medium- to long-term

(Primeaux and Hollman, 1974; Danielson, 1979; Foster and Beattie, 1979; Agthe *et al.*, 1988; Murdock *et al.*, 1991). However, the relevance of these studies to this research is negligible as so few domestic customers are metered and charged accordingly in the UK.

8.3.1. Per capita domestic water consumption

Per capita consumption appears to be highest for households in the Thames Water study and Yorkshire Water's small water supply areas (see section 4.6 and 5.6.1 for details). No obvious difference in consumption for ACORN categories in the individual household studies (see section 5.6.3 for details) suggest that these differences in per capita consumption might be related more to climatic influences than to affluence. However, due to major fluctuations in demand for households with similar characteristics and the fact that households may not be representative of the ACORN category in which they are placed (Thackray *et al.*, 1978; Hall *et al.*, 1988; Russac *et al.*, 1991), confidence in these results is limited. Instead, differences in per capita consumption may be accounted for by differences in the population base. The population in the Thames Water study and Yorkshire Water's small water supply areas are generally much more affluent than the other areas. Many of these people have the potential to irrigate their gardens when it is hot and sunny. They also have no financial constraints that may limit heating costs for water consuming activities. Domestic water consumption in Yorkshire Water's small water supply areas may also be higher than that in the other areas due to the large proportion of detached properties, which as proved have a higher water use than any other property type (see section 8.3 for details). This area is also comprised predominately of retired residents and pensioners who have ample opportunity for water consuming activities such as garden watering. This conforms to the findings of Russac *et al.* (1991) who observed that on average retired householders use almost 70% more water than adults of a working age.

Per capita consumption appears similar for individual household sizes and property types in the Essex and Suffolk Water and Yorkshire Water studies (see section 5.6.1 and 5.6.2 for details). A direct comparison with per capita consumption in the district meter areas of Wales and those observed in previous water consumption studies is not possible due to the different methodological approaches of calculating and reporting per capita consumption. This means, for example, that: (i) per capita consumption reported for a given area may be derived from different proportions of household sizes and property types or (ii) per capita consumption may be calculated using different time periods, e.g. the summer months. Both factors will significantly influence the overall per capita consumption figure. However, a considerable range in per capita consumption was observed in the zonal meter and individual household studies (see section 4.6 and 5.6.2 for details). This large range in per capita and per property consumption was also observed by Russac *et al.* (1991) and Edwards and Martin (1995) (Figure 8.6).

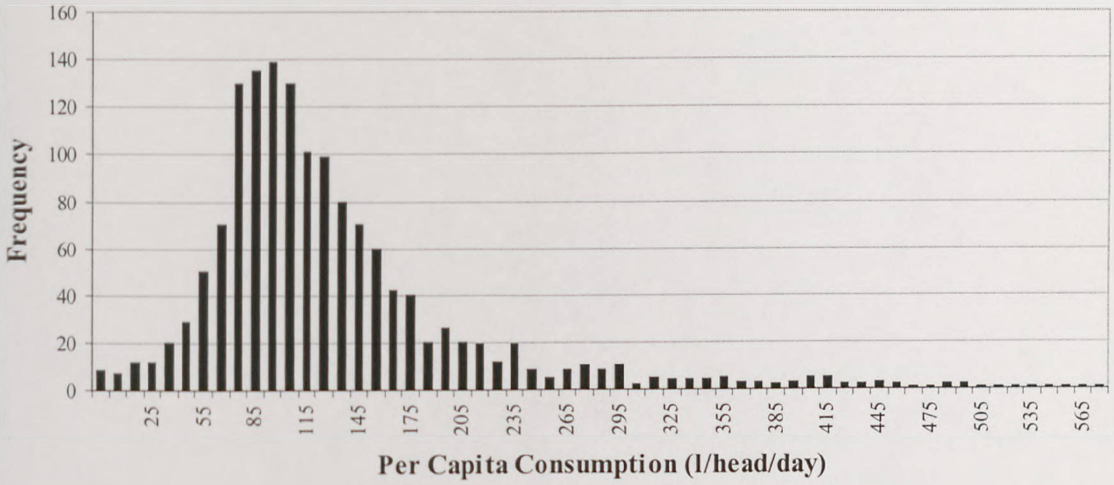


Figure 8.6: Distribution of daily per capita consumption (Source: Edwards and Martin, 1995)

8.3.2. Seasonality in domestic water consumption

Households in the Thames Water study and Yorkshire Water's small water supply areas displayed a seasonal trend in domestic water consumption with peaks during summer and troughs during winter. Hall *et al.* (1988) and Edwards and Martin (1995) also observed a distinct seasonal pattern in domestic water use (Figure 8.7). Limited seasonal variation was evident for households in Yorkshire Water's individual household study while households in the district meter areas of Wales demonstrated a relatively constant demand for water throughout the year. It was impossible to know if true seasonal variation in water consumption was evident for households in the Essex and Suffolk Water study due to the low frequency of meter readings. Households in the Thames Water study and Yorkshire Water's small water supply areas may display more seasonal variation in domestic water consumption due to a higher degree of affluence within the population. As can be recalled from section 8.3.1, many of these households will have the potential to irrigate their gardens when it is hot and sunny. Households in the Thames Water study may also show increased seasonal variation in domestic water consumption due to the more continental climate, resulting in higher outdoor water use (see section 5.9.1 for details). Climatic conditions may also account for the seasonal variation in domestic water use observed in the Anglian region (Edwards and Martin, 1995) and South West England (Hall *et al.*, 1988). Households in the small water supply areas of Yorkshire obviously do not experience this more continental climate. However, the predominance of detached properties with large gardens coupled with the high percentage of affluent, retired residents and pensioners who have ample opportunity to water their gardens will undoubtedly cause higher outdoor water use.

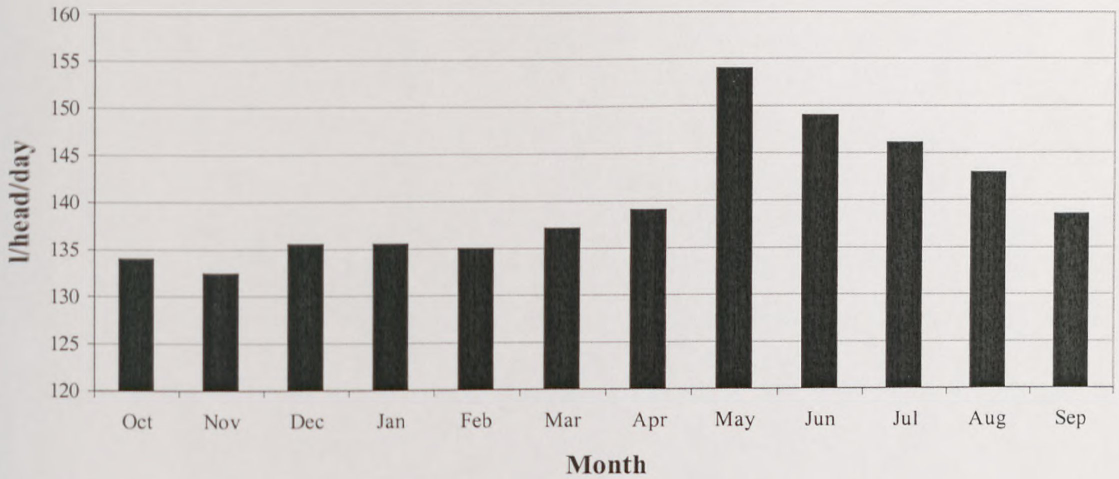


Figure 8.7: Daily per capita consumption (October 1992 to September 1993) (Source: Edwards and Martin, 1995)

Several reasons may explain the limited seasonal variation in water consumption for households in the Yorkshire Water study (see section 5.5 for details). Yorkshire experiences greater variation in climatic conditions compared to the South East of England. In Yorkshire for example, it could be anticipated to be hot and dry at the coast, yet cold and wet in the Pennines, or perhaps vice versa with sea fog. Furthermore, the study covers a variety of socio-economic conditions, covering affluent communities in North Yorkshire, such as Ripon and Harrogate, to poor rundown communities in the coal field areas of Yorkshire. It includes those people whom, when it is hot and sunny, have the potential to irrigate their large gardens, yet it also covers those people who have no garden. It covers densely populated urban areas, for example in Leeds and Sheffield, as well as much more rural areas in the Yorkshire Dales and North Yorkshire moors. Aggregation of these different socio-economic and climatic conditions might counterbalance each other to produce little seasonal variation in domestic water consumption.

Data processing may account for the relatively constant demand for water throughout the year in the Welsh Water study. It is likely that severe smoothing of the data may result from improper calculation of non-household consumption and leakage (see section 3.6.1.1 and 3.6.1.2 for details). Seasonal fluctuations in domestic water use may, therefore, be assigned wrongly to non-household water use and leakage. The weak specification of data processing in the Welsh Water study certainly raises questions about the validity of this data. No certain conclusions about this data set can, therefore, be drawn. This serves to highlight the need for good quality domestic water consumption data.

To investigate further seasonal variation in the individual household studies, the data were subdivided by household size and property type. As expected, detached and semi-detached properties generally displayed more seasonal variation in water consumption than terraced properties and flats (see section 8.3 for details). It was impossible to subdivide the data further by area to investigate whether variations in climatic conditions within Yorkshire produced changes in domestic water consumption, for example, it could be hot and dry at the coast and cold and wet at the Pennines, or perhaps vice versa with sea fog. Such subdivisions reduce the amount of data available for analysis and, therefore, questions how representative the data are to the wider population. This is accentuated by the findings that: (i) major fluctuations in demand occurs for households with similar characteristics (Thackray *et al.*, 1978; Russac *et al.*, 1991) and (ii) the estimation that probably less than 10% of all households regularly use a hose-pipe or a garden sprinkler (see section 3.3.1 for details).

8.3.3. Temporal shifts in domestic water consumption

Temporal upward and downward shifts were evident in the water consumption data for individual household sizes and property types in the Thames Water and Yorkshire Water studies (see section 5.7 for details). It was hypothesized that water use restrictions imposed by the water plc's in 1995 and 1996 may have resulted in these temporal shifts. However, the temporal downward shifts in demand negate this theory. It, therefore, appears impossible to determine the extent to which these temporal shifts in demand result from individual behavioural water use patterns or errors. The only possible way of explaining these temporal shifts in demand is to use a longer time-series of good quality data (i.e. questionnaires updated regularly, continual maintenance of water meters and loggers, etc.).

8.4 Factors influencing short-term domestic water demand

Previous research has identified several factors that influence short-term water demands in large distribution networks (Hartley and Powell, 1991; Cubero, 1991, 1992; An *et al.*, 1996,1997; Lertpalangsunti *et al.*, 1999). Factors include weather conditions, day of the week, and whether a particular day is an observed holiday. Such aggregate data includes demands from industrial, commercial, public and domestic water users as well as leakage. However, no previous research has been undertaken which identifies factors that influence only domestic water demands in the short-term.

In this research, several factors were found to influence domestic water demands in the short-term. These are detailed in the following subsections.

8.4.1. Two days antecedent and the prevailing day's weather

The two days antecedent and the prevailing day's weather conditions appear to influence short-term domestic water demands (see section 4.9 and 5.11 for details). If the two days antecedent and the prevailing day's weather are hot and dry, short-term domestic water demands increase.

Similarly, if the two days antecedent and the prevailing day's weather are cold and wet, short-term domestic water demands are reduced. The two days antecedent and the prevailing day's weather conditions appear to exert the greatest influence on short-term domestic water demands in the summer months, a lesser influence in spring and autumn, and no influence during winter (see section 4.10 and 5.12 for details). It is highly probable that during winter, domestic water consumption is represented only by in-house use. However, the extent to which variations in the two days antecedent and the prevailing day's weather conditions influence short-term domestic water demands appears to depend on property type. Water consumption in detached and semi-detached properties demonstrates the strongest relationship with weather (see section 4.10 and 5.12 for details). As can be recalled from section 8.3, this is expected due to differences in garden size and hence outdoor water use. However, household water consumption in the Thames Water study and the small water supply areas of Yorkshire demonstrate the strongest relationships with weather. This appears to suggest that affluence and the more continental climate in the Thames Water study, and affluence and levels of economic activity in the small water supply areas of Yorkshire, also influence the relationship between the antecedent and the prevailing day's weather conditions and short-term domestic water demands (see section 8.3.2 for details). However, the influence of the antecedent and the prevailing day's weather conditions is not just limited to domestic water demands in the short-term. A similar lagged weather effect was observed in the short-term water demand studies for large distribution networks (An *et al.*, 1996, 1997; Lertpalangsunti *et al.*, 1999) (Table 8.1).

Table 8.1: Weather factors found to influence short-term water demands in moderate sized cities in North America (Source: An *et al.*, 1996)

Attributes
Day of week
Today's maximum temperature
Today's minimum temperature
Today's average humidity
Today's rainfall
Today's snowfall
Today's average speed of wind
Yesterday's maximum temperature
Yesterday's minimum temperature
Yesterday's average humidity
Yesterday's rainfall
Yesterday's average speed of wind
Yesterday's bright sunshine hours
The day before yesterday's maximum temperature
The day before yesterday's average humidity
The day before yesterday's rainfall
The day before yesterday's average speed of wind
The day before yesterday's bright sunshine hours

8.4.2. Day of the week

Weekends and weekdays were found to significantly influence short-term water demands in large distribution networks (Maidment and Miaou, 1986; Hartley and Powell, 1991; Cubero, 1991, 1992; An *et al.*, 1996,1997; Lertpalangsunti *et al.*, 1999). Daily total distribution flows during weekends were found to be less than during weekdays. These findings are obviously influenced by industrial and commercial users in the distribution network (see section 8.4 for details). Weekends and weekdays also appear to significantly influence short-term domestic water demands. However, the weekly cyclic pattern in domestic water demand differs to that in a large distribution network, as increases in demands are associated with weekends (see section 4.12 and 5.14 for details). This is expected, as more people remain at home during weekends and hence are likely to consume more water. Typical 10% increases in domestic water demands were observed during the weekend. However, the percentage increase in domestic water demands during the weekend is related directly to the proportion of the population who are economically active. The larger the proportion of population who are economically active, the larger the difference in weekend and weekday water consumption (see section 4.12 for details). These cyclic patterns in weekend and weekday water consumption appear to be unrelated to household size, property type, and demand management measures. It also appears that the two days antecedent and the prevailing day's weather exert a similar influence on weekend and weekday demands. However, as can be recalled from sections 4.12 and 5.14, it appears that no obvious pattern is evident for domestic water demands on individual days of the week. This conforms to investigations of day of the week consumption patterns in large distribution networks (e.g. Maidment and Miaou, 1986; Hartley and Powell, 1991; Cubero, 1991, 1992; An *et al.*, 1996,1997; Lertpalangsunti *et al.*, 1999).

8.4.3. Calendar effects

Calendar effects such as bank-holidays and public holidays were seen to cause a change in the weekly cyclic pattern of domestic water consumption, with bank-holidays and public holidays resulting in an increase in demands. Increases in domestic water demands associated with bank-holidays and public holidays appeared similar to increases in demands associated with weekends (see section 8.4.2 for details). This is likely to result from the source of the increase, that is, more people remaining at home and hence consuming more water. Water demands on bank-holidays and public holidays were also similar to that during weekends as increases in demand are independent of household size, property type and demand management measures, and both are influenced by the two days antecedent and the prevailing day's weather conditions. In large distribution networks, bank-holidays and public holidays were also seen to cause a change in the weekly cyclic pattern of water demand (Hartley and Powell, 1991; Cubero, 1991, 1992; An *et al.*, 1996,1997; Lertpalangsunti *et al.*, 1999). However, the change in demand associated with bank-holidays and public holidays in the large distribution networks resulted in a reduction in demand. Industrial and commercial users undoubtedly influence this reduction in demand, which was similar to reductions in demand associated with weekends (see section 8.4.2 for details).

8.4.4. School holidays

School holidays appear to cause an approximate 8% increase in short-term domestic water demands (see section 4.15 and 5.17 for details). This increase was only observed in households with three or more persons which is expected due to the low representation of school children in one and two-person households. The specific process of how school holidays influence short-term domestic water demands is unknown. However, it seems likely to include both children and adults staying at home. Hartley and Powell (1991) also found that school holidays have a distorting effect on demand during very popular holiday periods such as Whitsuntide week. However, it is not stated whether this distorting effect results in an increase or decrease in short-term water demands.

8.5 Exploration of modelling strategies to forecast short-term domestic water demand

Pragmatic and advanced approaches were explored to forecast short-term domestic water demands. The exploration of modelling strategies focused on the individual household study data due to: (i) lack of confidence in the Welsh Water data resulting from the weak specification of data processing and (ii) relatively large amounts of missing data in Yorkshire Water's small water supply areas (see section 6.1 for details).

8.5.1. Pragmatic approach

The pragmatic approach used to predict short-term domestic water demands was similar to approaches used by Rahman and Bhatnagar (1988), Hartley and Powell (1991) and An *et al.* (1996, 1997) to predict short-term water demands in large distribution networks. Basically, these approaches developed a series of rules to predict short-term demands based on previous observations of water demand data. The rules were derived from factors such as the antecedent and prevailing weather conditions, days of the week and calendar effects. These rules are incorporated into the prediction of short-term water demands by simple 'if-then' procedures, which can be understood easily by users (An *et al.*, 1996). The experimental results from previous studies indicate that the proposed algorithms can generate rules for water demand prediction, providing more precise information than is available through knowledge acquisition from human experts (An *et al.*, 1996, 1997). Similar findings were also observed using the pragmatic approach to forecast short-term domestic water demands. This technique was able to predict changes in short-term domestic water demands associated with day of the week, weather conditions and calendar effects. However, the pragmatic approach was unable to cope with the unexplained upward or downward temporal shift in the domestic water demand data (see section 6.2.1 for details). This produced relatively low R^2 values between actual and predicted water demands and large prediction errors (see section 6.4 for details). Even so, the average prediction error was approximately 8% less than those recorded in large distribution networks (e.g. An *et al.*, (1997)).

8.5.2. Stepwise regression with and without k-means cluster analysis

Predictions of short-term domestic water demand using stepwise regression, both with and without k-means cluster analysis (see section 6.3.1 and 6.3.2 for details), were similar to predictions from the pragmatic approach. All three techniques were able to predict changes in short-term domestic water demands associated with day of the week, weather conditions and calendar effects. However, all three techniques were unable to cope with the unexplained upward or downward temporal shift in domestic water demands. These temporal shifts produced relatively large errors between actual and predicted water demands that were of a similar order for each modelling approach (see section 6.4 for details). However, the order of errors cannot be compared to other predictions of short-term water demands using stepwise regression, as this approach has never been applied previously.

8.5.3. Univariate and multivariate ARMA time-series models

ARMA time-series models have been applied to the forecasting of short-term water demands in large distribution networks (Quevedo and Cembrano, 1988; Canu *et al.*, 1990; Jowitt and Xu, 1992; Saporta and Munoz, 1995). Despite this progress in the development of short-term demand forecasting models, there is little published material relating to how such forecasting algorithms were established and their actual performance in practice (Jowitt and Xu, 1992). Both univariate and multivariate ARMA time-series models were applied to the forecasting of short-term domestic water demands (see section 6.3.3.1 and 6.3.3.2 for details). Unlike the pragmatic and stepwise regression approaches, the univariate and multivariate ARMA time-series models were able to cope with the unexplained upward or downward temporal shift in domestic water demand. This is because the ARMA time-series models base predictions of demand on the previous day's demand. However, because the ARMA time-series models forecast water demand by proposing that tomorrow's demand will be equal to today's consumption, they were unable to predict short-term changes in demand associated with day of the week, weather conditions and calendar effects. Similar prediction results were observed by Canu *et al.* (1990). Canu *et al.* (1990) found that the ARMA time-series model was always late in predicting consumption.

Some ARMA time-series models have proved relatively successful in predicting short-term water demands (e.g. Quevedo and Cembrano, 1988; Saporta and Munoz, 1995). It is hypothesized that the success of the time-series approach is dependent on the nature of the water demand data. Quevedo and Cembrano (1988) and Saporta and Munoz (1995) applied the ARMA time-series approach to the forecasting of short-term water demands for Barcelona. As the water demand data for Barcelona is an aggregate of industrial, commercial, domestic and agricultural users, as well as leakage, it is expected that the day to day variability in demand is significantly less than: (i) a smaller area or (ii) modelling with fewer components of demand. As there are so few households in the Thames Water and Yorkshire Water studies, particularly when the data are subdivided into household size and property type, a single change in the individual behavioural patterns of demand, such as taking a bath, has the potential to change the time-series and hence increase variability. However, if significantly more households were included in the studies, it is likely that a change in the individual behavioural water use patterns would have little or no effect on the overall time-series. It is also likely that the weather in Barcelona reduces variability in the demand data. In the Mediterranean climate of Barcelona it is highly likely that if one day is hot, the next day will also be hot. Weather induced influences on demand are therefore likely to be relatively constant. However, in the temperate climate of the UK, weather induced influences on demand are more likely to change from day to day. This will increase undoubtedly the variability in the domestic water demand data.

8.5.4. Neural networks

Artificial neural networks (also referred to as 'neural networks', 'artificial neural systems', 'parallel distributed processing systems', and 'connectionist systems' (Mehrotra *et al.*, 1997)) were also proposed to forecast short-term domestic water demands. Neural networks are a type of biologically inspired computational model based superficially on the way in which the human brain works. A neural network consists of a network of interconnected units called artificial neurons or processing nodes that resemble the neurons in a human brain (Bharath and Drosen, 1994). This interconnected layer of neurons or processing nodes perform the mapping of inputs to outputs using adaptable weights that change as the network learns the correct mapping. An activation function, such as the sigmoid, then takes the weighted sum and converts the value to a single output (Haykin, 1994).

To date, neural networks have many diverse applications including pattern recognition, classification, optimization problems and dynamic modelling, and have been used in a wide variety of disciplines such as neuroscience, physics and engineering (Landau and Taylor, 1998). Artificial neural networks have many successful applications because, like real neural networks, they share the ability to learn and adapt, can generalize to unseen data, and exhibit distributed processing, parallelism, associative memory storage, robustness and fault tolerance. Neural networks have been applied to the forecasting of short-term water demands in large distribution networks (Canu *et al.*, 1990; Cubero, 1991; Lertpalangsunti *et al.*, 1999). Results from these studies indicate that neural networks are able to deal with the non-linearities of water demand (Canu *et al.*, 1990). The neural networks are also able to learn the seasonal and special behaviour of the time-series (Cubero, 1991). Cubero (1991) found that errors from the neural network predictions of short-term water demands were on the same order as the Box-Jenkins approach used by Quevedo and Cembrano (1988). However, the neural networks do not require any previous filtering or statistical treatment of the demand data prior to forecasting.

The use of neural networks in predicting short-term domestic water demands appears promising. However, as Lertpalangsunti *et al.* (1999) recognise, the accuracy of the prediction system depends on the quality of the available data sets. It is expected that no matter how simple or sophisticated the modelling approach, predictions of short-term domestic water demands using the existing data from the Thames Water and Yorkshire Water studies will be inaccurate. This is because:

(i) There is not a long enough time-series of good quality water demand data. Canu *et al.* (1990) used a thirteen-year time-series of data to train the neural network to predict short-term water demands in the South East suburbs of Paris.

(ii) Subdivision of the data by household size and property type dramatically reduces the amount of data available for analysis. Using a small data set can produce misleading results (Russac *et al.*, 1991) due to great variability in water use between individual properties, even if the properties share common characteristics (see section 8.3 for details). A relatively large data set is, therefore, required to ensure that the samples are representative of each household size and property type. Another potential problem of using a small sample is that a single change in the individual's behavioural patterns of demand has the potential to change the time-series. If a larger sample of households were used, a change in the individual's behavioural patterns of demand would probably have little or no effect on the overall time-series (see section 8.5.3 for details).

(iii) Neural networks and the other modelling approaches may be unable to accurately predict short-term domestic water demands because households in the sample may not be representative of their allocated household size and property type. This is likely to result from questionnaire error. In the Thames Water and Yorkshire Water studies, the characteristics of the individual households that make up the domestic consumption studies were surveyed only once, at the start of the monitoring programme (1994 in the Thames Water study and 1996 in the Yorkshire Water study). Thus factors such as family growth, death, unemployment or new employment, divorce etc., will all reduce the validity of the original data (see section 3.3.4 for details). With reference to relocation, it is estimated that more than 10% of the households in the domestic consumption study might change each year based solely on relocation. Potential errors in the questionnaire data and hence the water demand data are, therefore, likely to be large.

(iv) The unexplained upward or downward temporal shift in domestic water demand is likely to cause large prediction errors in the forecasts of short-term domestic water demands using the neural network approach. Although the neural network may be able to learn and adapt to these temporal changes in demand, it is vital to determine the source of these temporal shifts. This can only be accomplished by obtaining a longer time-series of good quality data.

8.5.5. Changes in the characteristics of short-term domestic water demands: future scenarios

To date, long-term domestic water demand forecasts have been developed to avoid the under provision of supply (Mitchell, 1999). These forecasts were estimated conventionally using extrapolations of past demand data (e.g. Sharp, 1967; Water Resources Board, 1973; Central Water Planning Unit, 1977) or linear regression (e.g. Turnovsky, 1969; Grima, 1971; Herrington, 1973; Batchelor, 1975; Gallagher, 1981). More recently, microsimulation has been applied to the estimation of future domestic water demands (Clarke *et al.*, 1997). As sustainable development now requires water resource forecasters to not only avoid under provision of supply but also to minimize over supply, accurate forecasts of demand are now much more essential than ever if sustainable water resource management is to be achieved (Mitchell, 1999). This research raises questions about the accuracy of existing forecasts as they seldom acknowledge potential changes in domestic water demands associated with changes in the population base, climate, culture and technology.

Several factors appear to influence domestic water demands in both the short- and the medium- to long-term (see section 8.3 and 8.4 for details). Changes in these influential factors have the potential to change the characteristics of short-term domestic water demands. As can be recalled from section 7.2, changes in the population base may result in changes in the current distribution of household size and property type. The Department of the Environment, Transport and Regions (2001), for example, has predicted a reduction in household size. This reduction in household size is likely to cause a reduction in per property consumption. However, if the population in the UK remains constant but the trend changes towards smaller household sizes, the overall demand for domestic water will increase. A reduction in household size is also likely to change property type distributions. People in smaller households may prefer to live in inner city flats and apartments as opposed to large spacious detached and semi-detached properties. Such a change in the distribution of property types has been shown to cause a reduction in short-term domestic water demands (see section 7.2 for details).

The general consensus in the UK is that climate change will result in hotter drier summers and warmer wetter winters (see section 7.3 for details). Such changes in the climate have been shown to cause an increase in short-term domestic water demands (see section 7.3 for details). The scale of this increase appears to be dependent on the absolute change in climate. In the South East of England, increases in short-term domestic water demands range from 0.90% (best case scenario of 2020 with a 0.6°C increase in average annual temperatures and a 4 mm reduction in average summer rainfall) to 8.20% (worst case scenario in 2080 with a 3.2°C increase in average annual temperatures and a 18 mm reduction in average summer rainfall). In Yorkshire, only the worst case scenario of 2080 (a 2.8°C increase in average annual temperatures and a 4 mm reduction in average summer rainfall) resulted in an increase in short-term domestic water demands. However, this finding may be misleading. As the temporal distribution of precipitation appears to be changing, with wetter winters and drier summers, there is no guarantee that precipitation will occur at the time of year when it could be used (Mitchell, 1999).

Future cultural scenarios associated with major advances in telecommuting and hence the 'virtual workplace' at home is also likely to increase short-term domestic water demands. This increase is dependent on the percentage of the population working from home. The higher the percentage of people working from home, the higher the increase in short-term domestic water demands. These findings suggest that changes in the population base, climate and culture have the potential to increase domestic water demands in both the short- and the medium- to long-term.

8.6 Managing the changing characteristics of short-term domestic water demands

The conventional response to these suggested increases in demand associated with the population base, climate and culture would be 'supply-fix'. This approach assumes that all new demand must be met by developing new resources, either by reservoir construction or abstracting additional water from rivers and aquifers (Mitchell, 1999). However, demand management is seen increasingly as an alternative to the 'supply-fix' approach. This research suggests that demand management techniques (leakage control, domestic metering, water saving technology, e.g. pressure reduction valve and cistern displacement devices, and education/awareness of residents) have the potential to suppress increases in demand associated with changes in the population base, climate and culture and, indeed, reduce demands to less than those of the present day (see section 7.5 for details). In the UK there is significant potential for the implementation of demand management techniques to promote the sustainable use of water resources. This potential can be highlighted using domestic water metering as an example. With proposed changes in the payment structure for potable water for domestic use and the fact that in 1996, only 8.10% of domestic customers were taking metered supplies (OFWAT, 1996), significant potential exists for demand management through the promotion of domestic water meters. Domestic water use has been reported to be price elastic in research derived from studies outside the UK (e.g. Turnovsky, 1969; Primeaux and Hollman, 1974; Danielson, 1979; Foster and Beattie, 1979). Exploration of price elasticity of water demand in the UK is not available as water charging on a metered basis is still in its infancy and remains voluntary. However, Espey *et al.* (1997) concluded that price elasticity associated with water demand could be transferred from regions with similar characteristics. Hence, water demand in the UK can be controlled, to a certain degree, by price. However, domestic metering is one of many demand management techniques that have the potential to reduce water use, and hence, promote the sustainable use of water resources.

8.7 Limitations

There are several limiting factors in this research which appear to relate, in part, to quality control and quality assessment of the zonal meter and individual household studies. These factors include:

(i) The limited time-series.
(ii) Missing water consumption data.
(iii) Anomalous water consumption data.
(iv) The need for socio-economic refinement.

In each of the zonal meter and individual household studies, the length of the time-series appears adequate for establishing relationships between domestic water demands and the factors that influence it in both the short- and the medium- to long-term. However, large amounts of missing and anomalous water consumption data has significantly reduced the amount of time-series data available for analysis. This is accentuated by the questionnaire data, a large amount of which is out of date or missing. These factors reduce confidence in the water consumption and questionnaire data and question the application of the results to the wider population. However, it is hypothesized that if the water plc's actively adopt quality control and quality assessment strategies into their domestic water use studies, confidence in the data would improve significantly which in turn would further improve our understanding of domestic water demands. Such quality control and quality assessment strategies would include regular maintenance of water meters and loggers, efficient leakage detection and repair, accurate calculations of non-household water use, and regular resurveys of households in the water use studies.

8.8 Summary

This chapter has discussed the findings of the research into the demand for domestic water and compared the findings to similar research reported in the literature and reviewed in Chapter 2. The findings of the research are comparable to research conducted elsewhere. Similar underlying factors are found to influence domestic water demands in the medium- to long-term, while factors that influence domestic water demands in the short-term are similar to factors found to influence short-term water demands in large distribution networks. This chapter has also discussed potential changes in domestic water demands associated with changes in the population base, climate, culture and technology. Accurate forecasts of domestic water demands must, therefore, account for these potential changes in demand. The development of accurate forecasts of domestic water demands in both the short- and the medium- to long-term in conjunction with the implementation of demand management measures are potential components of a sustainable water resource strategy in the 21st Century. However, to improve further our understanding of domestic water demands and to develop accurate predictions of short-term domestic water demands, quality control and quality assessment strategies must be a routine part of the domestic water use studies.

Conclusions from this research are presented in the next and final chapter. The conclusions relate to the principal findings of this research and highlight the relevance of this research to water resource managers now and in the future. This chapter also suggests future research needs.

9. Conclusions and Recommendations

9.1 *Introduction*

This chapter concludes the thesis by summarizing the research findings and emphasizing the main discoveries with reference to the aims and objectives of the research stated in Chapter 1. Recommendations for future research are provided that will improve the current understanding of domestic water demands, making it possible to more accurately forecast domestic water demands in the short-term.

9.2 *Summary of the research findings*

The fundamental aim of this research was to estimate and forecast short-term domestic water demands to promote sustainable water resource management in the 21st Century. Estimations of domestic water demands were derived from zonal metering and individual household studies (see Chapter 3 for details). These estimations, in conjunction with the literature reviewed in Chapter 2, were used in the determination of factors that influence domestic water demands in both the short- and the medium- to long-term (see Chapters 4 and 5 for details). These influential factors aided in the exploration of modelling strategies to forecast short-term domestic water demands (see Chapter 6 for details). The pragmatic modelling approach was then selected to determine how future changes in the population base, climate, culture and technology might influence the characteristics of short-term domestic water demands (see Chapter 7 for details). Findings have suggested future research needs, which is the subject of the latter half of this chapter. The research findings and the primary lessons learnt from the present research are summarized below.

9.3 *Estimations of domestic water demands*

As can be recalled from section 3.2, estimations of domestic water demand can be derived from zonal metering, individual household metering, and component metering studies. Component metering studies in the UK fail to provide good estimations of domestic water demands (see section 3.5 for details). Estimations of domestic water demands were, therefore, derived from both zonal meter and individual household studies, as it is impossible to determine which of these approaches provide the best estimation of domestic water demands (see section 3.5 for details). Estimations of domestic water demands from the zonal meter and individual household studies and the literature reviewed in Chapter 2 suggest that household size and property type exert the greatest underlying influence on medium- to long-term domestic water demands (see section 4.6 and 5.6 for details). As expected, domestic water consumption increases with greater household size. However, as household size increases, per capita consumption is reduced. Detached properties consume more water than any other property type. This is expected because detached properties: (i) typically have large gardens and hence are likely to have a high outdoor water use and (ii) generally contain households with the greatest number of appliances per person (Russac *et al.*, 1991). Flats consumed the least amount of water. Again this is expected because flats: (i) typically have no garden and are therefore likely to have a very low outdoor water use and (ii) generally contain the least number of appliances per person (Russac *et al.*, 1991). Therefore, per capita consumption is highest for detached properties containing one person and lowest for flats, particularly when the number of residents is high. However, for each household size and property type, significant variations in domestic water demands exist. This variation may be explained, in part, by other underlying factors such as levels of affluence, economic activity of the population, the property's rateable value, appliance ownership and *true* garden size, some of which were found to influence domestic water demands in other consumption studies (see section 8.3 for details). However, due to: (i) data paucity and (ii) great variability in water use between individual properties, even if the properties share common characteristics (Thackray *et al.*, 1978; Hall *et al.*, 1988; Russac *et al.*, 1991), it proved impossible to assess the direct influence of any one of these variables on domestic water demands.

Day of the week, calendar effects, school holidays and the two days antecedent and the prevailing day's weather conditions appear to exert the greatest influence on short-term domestic water demands:

(i) Weekends and calendar effects are associated with an approximate 10% increase in demand (see section 4.12 and 5.14 for details). This is expected as more people remain at home during weekends and hence are likely to consume more water. However, the percentage increase appears to depend on the proportion of the population who are economically active. The larger the proportion of the population who are economically active, the larger the percentage increase in demand.

(ii) School holidays are associated with an approximate 8% increase in short-term domestic water demands which appears to result from both children and adults staying at home (see section 4.15 and 5.17 for details). However, this increase was only observed in households with three or more persons, which is expected due to the low representation of school children in one and two-person households.

(iii) The current water demand is controlled by the weather conditions that prevail on the forecast day and on the two previous days (see section 4.9 and 5.11 for details). Increases in short-term domestic water demands are associated with hot dry weather while decreases are associated with cold wet weather. The two days antecedent and prevailing day's weather conditions exert the greatest influence on short-term domestic water demands during the summer months, a lesser influence during spring and autumn, and no influence during winter. However, the extent to which variations in the two days antecedent and the prevailing day's weather conditions influence short-term domestic water demands appears to depend on property type. Water consumption in detached and semi-detached properties demonstrate the strongest relationship with weather (see section 4.10 and 5.12 for details). As can be recalled from section 8.3, this is expected due to differences in garden size and hence outdoor water use. However, household water consumption in the Thames Water study and the small water supply areas of Yorkshire demonstrate the strongest relationships with weather. This suggests that affluence and the more continental climate in the Thames Water study, and affluence and levels of economic activity in the small water supply areas of Yorkshire, also influence the relationship between the two days antecedent and the prevailing day's weather conditions and short-term domestic water demands.

The factors found to influence domestic water demands in both the medium- to long-term and in the short-term occur, regardless of whether or not demand management measures have been implemented. However, demand management measures do appear to suppress the overall demand for water by approximately 20%.

9.4 Forecasting short-term domestic water demands

Pragmatic and advanced approaches were explored to forecast short-term domestic water demands (see Chapter 6 for details). However, neither the pragmatic nor the advanced approaches could provide accurate predictions. Three of the five approaches (the lookup tables and stepwise regression both with and without k-means cluster analysis) were able to predict short-term changes in domestic water demands associated with day of the week, calendar effects and the two days antecedent and the prevailing day's weather conditions. However, these three approaches were unable to adapt to the unexplained upward or downward temporal shift in domestic water demands (see section 6.2.1, 6.3.1 and 6.3.2 for details). The remaining two approaches (univariate and multivariate ARMA time-series models) were able to adapt to the unexplained upward or downward temporal shift in domestic water demands. However, they were unable to predict short-term changes in domestic water demands associated with day of the week, calendar effects and the two days antecedent and the prevailing day's weather conditions (see section 6.3.3.1 and 6.3.3.2 for details). It is hypothesized that no matter how simple or sophisticated the modelling approach, predictions of short-term domestic water demands using the existing data from the Thames Water and Yorkshire Water studies will be inaccurate. This is due primarily to data paucity (see section 8.5.4 for details).

9.5 Changes in the characteristics of short-term domestic water demands: future scenarios

The pragmatic approach was selected to determine how changes in the population base, climate, culture and technology might influence the characteristics of short-term domestic water demands. It appears reasonable to assume that in the UK there will be: (i) a reduction in household size (see section 7.2.1 for details) (ii) a change in climate resulting in hotter drier summers and warmer wetter winters (see section 7.3 for details) (iii) growth in the number of people working from home (see section 7.4 for details) and (iv) an increase in the number of households with demand management measures (see section 7.5 for details). The first three changes will result undoubtedly in an overall increase in short-term domestic water demands (see section 7.2-7.5 for details). This increase is likely to be more in the South East of England because this is the area where the severity of climate change is at its greatest. However, the fourth change, an increase in the number of households with demand management measures, has the potential to suppress increases in short-term domestic water demands associated with changes in the population base, climate and culture, and indeed reduce demands to less than those of the present day.

Findings from this research suggest that the widespread implementation of demand management measures and the development of accurate forecasts of short-term domestic water demands will aid in the reduction of unnecessary over-abstraction of surface reservoirs, groundwater and rivers. Hence, it will promote immensely, sustainable water resource management in the 21st Century.

9.6 Recommendations

This thesis has made a significant contribution to the understanding of domestic water demands in both the short- and the medium- to long-term in the UK. However, to improve further the current understanding of domestic water demands and to develop accurate predictions of domestic water demands in the short-term, it is recommended that several quality control and quality assessment procedures are applied to the domestic water use studies. Many of these quality control and quality assessment procedures, which apply to administrators of both zonal metering and individual household studies, result from the limitations of this research addressed in section 8.7. These recommendations, outlined below, are foreseeable goals for the water plc's and complement the protocol for monitoring unmetered domestic water consumption provided by UK Water Industry Research Limited (UKWIR) (1999).

(i) Water meters and loggers must be accurate and reliable (UKWIR, 1999), and include regular maintenance.

(ii) The water plc's must adopt an efficient leakage detection and repair programme, particularly in the zonal meter studies. This must run in parallel with accurate measurements of non-household water consumption.

(iii) The administrators of domestic water use studies must regularly check the water consumption data for anomalous or zero consumption values. UKWIR (1999) recommend that this check should be made at least monthly.

(iv) The water plc's must select an adequate number of households to participate in their water use study. A recommended figure for an individual household study would be one thousand. UKWIR (1999) recommend that 20% should be added to this figure to allow for unreliable or missing consumption data.

(v) The water plc's should frequently update the questionnaire data. As it is possible that more than 10% of households in the study may change each year (see section 3.3.4 for details), it is recommended that water plc's update questionnaires at least once every year.

(vi) UKWIR (1999) suggest that different companies could share data. Data sharing would result in a significantly larger sample size, increasing confidence in the results. However, a common methodology must be used for: (i) measuring domestic water consumption and (ii) determining the socio-economic characteristics of the population.

(vii) UKWIR (1999) also recommend that water plc's measure pressure as routine part of their domestic water use studies. Pressure may influence significantly the amount of water used by individual appliances and hence is likely to influence household water use.

It is hypothesized that if administrators of domestic water use studies actively adopt the recommendations associated with quality control and quality assessment procedures, there is significant potential to: (i), further improve the current understanding of domestic water demands and (ii) more accurately predict domestic water demands in the short-term. This is because:

(i) The data from the water use studies would allow a more detailed investigation of factors that influence domestic water demands in both the short- and the medium- to long-term. In this research some factors such as ACORN categories, the age of population, garden size, the property's rateable value and appliance ownership appear to exert little or no influence on domestic water demands. It appears likely that the relatively high proportion of missing water consumption and missing and out of date questionnaire data may significantly influence some of these relationships.

(ii) A more detailed account of factors that influence domestic water demands in both the short- and the medium- to long-term may significantly improve the accuracy with which short-term domestic water demands can be forecast. The lookup tables, for example, have shown the potential to predict short-term domestic water demands. However, prediction accuracy of the lookup tables appears to be limited by: (i) the unexplained variation in domestic water demands and (ii) the impaired water consumption and questionnaire data.

(iii) As can be recalled from section 8.5.4, neural networks also appear to have the potential to accurately predict short-term domestic water demands. However, as with the lookup tables, prediction accuracy of the neural networks will undoubtedly depend on: (i) the percentage of explained variance in the domestic water demand data and (ii) the percentage of unimpaired data.

(iv) A more detailed account of factors that influence domestic water demand in both the short- and the medium- to long-term could be used to more accurately determine how future scenarios might influence the characteristics of short-term domestic water demands.

It is recognized that the quality of the water consumption and questionnaire data used in this research has been a limiting factor in the estimation and forecasting of short-term domestic water demands. Irrespective of this, the research has not only made a significant contribution to the current understanding of domestic water demands but has highlighted the importance of incorporating good quality control and quality assessment strategies into existing and proposed domestic water use studies. Improvements in the quality of the data sources will undoubtedly improve further current understandings of domestic water demands, which in turn, will aid in the promotion of a sustainable water resource strategy in the 21st Century.

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Appendix

(Investigation of domestic water demands involved a large amount of data analysis. It was, therefore, decided to allow this analysis to be made public by including it in the Appendix of this thesis. Note: the Appendix number relates to the Chapter number. Hence, Appendix 4A relates to Chapter 4).

Appendix 3A Attributes of the district meter areas in Wales.

Appendix 3B Daily domestic water consumption in the district meter areas of Wales.

Appendix 3C Daily domestic water consumption in the small water supply areas of Yorkshire.

Appendix 3D Daily domestic water consumption for individual households in Yorkshire.

Appendix 3E Daily domestic water consumption for individual households in and around the London area.

Appendix 3F Daily domestic water consumption for individual households in Essex, Suffolk and Norfolk.

Appendix 3G Household questionnaire in the Essex and Suffolk Water study.

Appendix 3H Household questionnaire in the Thames Water study.

Appendix 3I Household questionnaire in the Yorkshire Water study.

Appendix 3J Descriptions used to classify areas in the GB Profiler system.

Appendix 3K Daily weather data for London, Wales and Yorkshire.

Appendix 3L Histograms and z-scores for water consumption and weather data in the small water supply areas of Yorkshire.

Appendix 4A Characteristics of the district meter areas of Wales using small area statistics.

Appendix 4B Characteristics of the district meter areas of Wales using GB Profiler.

Appendix 4C Time-series plots of water consumption in the district meter areas of Wales.

Appendix 4D Time-series plots of water consumption in the small water supply areas of Yorkshire.

Appendix 4E Descriptive statistics of water consumption in the district meter areas of Wales and the small water supply areas of Yorkshire.

Appendix 4F Per capita consumption in the district meter areas of Wales and the small water supply areas of Yorkshire.

Appendix 4G Environmental factors and water demands in the district meter areas of Wales (linear regression).