AN EVALUATION OF THE HISTORICAL APPROACHES TO UNCERTAINTY IN THE PROVISION OF VICTORIAN RESERVOIRS IN THE UK, AND THE IMPLICATIONS FOR FUTURE WATER RESOURCES PLANNING

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ABSTRACT

Attitudes to large Victorian reservoir schemes range from being unnecessarily grandiose to being grateful for a wonderful legacy. The sizing of three Victorian reservoir schemes at Thirlmere for Manchester, Lake Vyrnwy for Liverpool, and Elan Valley for Birmingham, was strongly influenced by ambitious Corporations, and the Victorian engineers' judgment of the demand forecast, respectively JF Bateman, Thomas Hawksley and James Mansergh. In this research, the "risk averseness" of design size is used as a surrogate for uncertainty, and a novel lag-time method, which involves extraction of data from supply and demand balance diagrams, enables comparisons. The full Elan scheme design is found to be the least risk averse, and the original Thirlmere scheme design the most risk averse. In comparison with a contemporary large reservoir design, the tentative conclusion is reached that using the lag-time model approach, the recent proposal by Thames Water Utilities for a 100 Mm^3 design for an Upper Thames Reservoir, in terms of future supply and demand, is a more risky design size than any of the Victorian designs. Water resources planners would be interested in the analysis and comparison of risk averseness and efficiency of design for other types of historical and modern schemes.

DEDICATION

I dedicate this thesis to my wife Maxine, who has been very patient throughout the four years it has taken me to get to the finishing line.

I would also like to dedicate it to the Victorian engineers who were responsible for leaving us a remarkable legacy of upland reservoirs and gravity aqueducts. In the photograph below, James Mansergh (on horseback) was the water engineer who designed and constructed the Elan scheme in Mid-Wales. Elan has supplied nearly all the water needs of Birmingham for the past 108 years, and the scheme is expected to do so for many years to come.

INSPECTION BY ENGINEERS AND GEOLOGISTS IN ELAN VALLEY IN CONNECTION WITH BIRMINGHAM CORPORATION WATER BILL, 1892.

R.E. Tickell — James Mansergh — Edward Michael Eaton — J. Gale — Henry Rofe — Sir Frank Bramwell — Thomas Hawkesley (Chair) — G.H. Hill — Prof. Topley — Charles Hawkesley — Prof. Boyd Dawkins — J.W. Gray

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The historic photographs are published by kind permission of the Radnorshire Museum, Llandrindod Wells.

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Finally, I would like to acknowledge Dr. Roy Ward of The University of Hull, Professor Mike Hamlin of the University of Birmingham, and Dr. Terry Kitson – deceased, of Severn Trent Water who inspired me to become an engineering hydrologist.

ABBREVIATIONS

AAR	Annual Average Rainfall
AOD	Above ordnance datum
BWCo	Birmingham Waterworks Company
CBWD	City of Birmingham Water Department
CEO	Chief Executive Officer
DCM	Domestic Consumption Monitor
DEFRA	Department of Environment, Food and Rural Affairs
DO	Deployable Output
DoE	Department of the Environment
DWI	Drinking Water Inspectorate
DWRMP	Draft Water Resources Management Plan
EA	Environment Agency
EEC	European Economic Community
ELoL	Economic level of leakage
EU	European Union
FRS	Fellow of the Royal Society
GARD	Group Against Reservoir Development
HoC	House of Commons
HoCSC	House of Commons Select Committee
HoL	House of Lords
HoLSC	House of Lords Select Committee
ICE	Institution of Civil Engineers
LCC	London County Council
LTM	Lag-time model
LTOA	Lower Thames Operating Agreement
Mg	Million gallons
Mgd	Million gallons per day
Ml	Megalitres
Ml/d	Megalitres per day
mm	Millimetres
Mm^3	Million metres cubed
MWB	Metropolitan Water Board
NGO	Non-governmental organisation
NRA	National Rivers Authority
Ofwat	Water Services Regulation Authority
ONS	Office of National Statistics
OPCS	Office of Population Censuses and Surveys
PCC	Per Capita Consumption
rdWRMP	Revised draft Water Resources Management Plan

SR	Service Reservoir
STW	Severn Trent Water
TDA	Thirlmere Defence Association
TH	Target Headroom
TW	Thames Water
TWL	Top Water Level
TWU	Thames Water Utilities
UKWIR	UK Water Industry Research
UTR	Upper Thames Reservoir
UU	United Utilities
WAFU	Water Available For Use
WHO	World Health Organization
WIA	Water Industry Act 1991
WRB	Water Resources Board
WRMP	Water Resources Management Plan
WW1	World War I
WW2	World War II

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CHAPTER 1 INTRODUCTION

“Perhaps the heaviest responsibility resting on any local government is the establishment and maintenance of a proper supply of water for those under its care. How unpardonable a failure in this all important matter! Yet how vast the task”

(This quote is the first paragraph of “The Future Water Supply of Birmingham”, 1891, by Thomas Barclay. He was a member of the Water Committee at Birmingham City Council).

1.1 Why is this project being undertaken?

The tone of Barclay’s words reminds us how far our society has developed over the past century. As today’s domestic customers of private water companies, a clean and constant water supply is taken for granted. An increasing proportion of us are paying for water by meter, and water is now becoming a commodity rather than an essential. The great majority of us that live in the UK have little idea about the vastness of the tasks that have been undertaken over a long period of time. It is the successful completion of these tasks by water engineers, and the maintenance of these assets, that enables us all to open a tap connected to the mains with unquestioned certainty in the quantity and quality of what appears. The particular focus for this thesis is an essential part of the front end of this process; that is, uncertainty in the planning for long term water resources. The scope of this project is limited to public water supply.

There are still many examples in the UK, particularly in its cities, of Victorian infrastructure that are in use today. This observation leads to a question: how and why has this happened? With regard to large Victorian water schemes, they are a very valuable legacy that we enjoy today, and it would be interesting to know how they did it so that we might leave as good as, and if not a better legacy to future generations.

The Victorian infrastructure subject area chosen for this project is the planning and design of reservoirs in England and Wales that are remote from the cities they serve, and connected to them by gravity aqueducts. The particular uncertainty that has been researched is in the long term forecast of water supplies and demands made at the planning and design stage for these schemes.

The importance of this work, the author believes, is that it has led to a robust yet simple way of comparing, in terms of supply and demand, the relative risk averseness of reservoir design, to enable comparison with the performance of historic schemes. A lag-time method is suggested that uses forecast and actual supplies and demands, and then judgements are made of the scale and timings for schemes that use the supply and demand balance diagram. By learning about how the Victorian engineers approached uncertainty, it is believed that this research will help to contribute to better and timelier decisions about future reservoir schemes.

The reasons for selecting the type of reservoir scheme for research were:-

1. Late Victorian reservoir and gravity aqueduct scheme designs were regarded by opponents at the time as grandiose and hugely damaging to the environment. More than a century later, many of these schemes are still operational, and have become a valuable legacy today providing clean, cheap and reliable water supplies. These schemes operate with a small carbon footprint, and they are expected to continue working long into the future.

2. Huge lead times, sometimes measured in decades, have been needed to span the time of conception to the delivery of reservoir schemes. This fact magnifies the challenge of addressing uncertainty in making supply and demand forecasts. New long-term

uncertainties, like the impact of rising temperatures due to climate change, are adding to the challenge of planning and designing modern reservoir schemes.

3. Critical analysis of reservoir schemes can be informed and improved through the use of the supply and demand balance model.

The reasons for selecting the three Victorian schemes for research appear in Chapter 2, Literature Review. They are:

- The Elan scheme for Birmingham appears in Section 2.1.
- The Thirlmere scheme for Manchester, and Vyrnwy for Liverpool, are in Section 2.2.
- The modern scheme chosen for research is Thames Water Utilities (TWU) proposed Upper Thames Reservoir (UTR) in Oxfordshire for securing supplies in London, which is covered in Section 2.3.

The other two main types of water resources schemes are abstractions from groundwater and from rivers. They were considered with comparative research in mind, but the variety of forms and sizes of schemes made the selection process complex, and therefore were not considered further.

A Glossary of Terms is provided in Appendix A.

1.2 Setting the Scene: Victorian and modern water supply service

Table 1.1 shows a summary of Victorian and modern scenes for ten categories in the provision of a water supply service. The comparisons are interesting and will be reflected upon within this thesis. For example, in the ownership category, the privately owned Victorian companies were taken over by the Corporations because of the variable service offered by the companies during and after drought, and greater investment was badly needed to meet the drivers of rapidly increasing population and economic activity, and for improving public health.

Then more than a century later, the companies were returned to the private sector in 1989 so they could raise funds through the stock market, or from new owners, for further huge programmes of investment that were primarily aimed at the sewerage and sewage treatment functions. With many polluted urban rivers, at that time, Britain had acquired the sobriquet of "the dirty man of Europe".

The scene also needs setting by knowing how the institutions of government, and the responsibility for water supply, have changed. Table 1.2 shows the change from late Victorian to modern times, and summarises the principal drivers for change. The main issues identified in Table 1.2 will be addressed in the body of the thesis.

A peer reviewed paper about Victorian water demand forecasting was published in February 2010. The paper is based on the research reported in Chapter 3, and is titled "A review of the 1892 water demand forecast for Birmingham" by Bradford, Gaterell and Bridgeman. It was published in the ICE's Journal of Engineering History and Heritage, Volume 163, EH1, and an offprint is included as Appendix G.

Table 1.1 – Victorian and Modern Scenes; water supply service

Provision of WATER SUPPLY Service	Setting the VICTORIAN scene	Setting the MODERN scene
Ownership and Responsibility	Water supply was a political issue during and after drought. Many private water companies were purchased or transferred to Local Authorities over a 50 year period.	Today's 10 private Water and Sewerage Companies in England and Wales were created in 1989. 19 relatively small private water supply companies remained. Mergers mean there are now 14 "water only" companies.
External Regulation	Government persuasion of individual water undertakers to improve quantity and quality of supplies.	Government Regulators: Financial – *Ofwat.* Environment and Abstraction Licensing – *Environment Agency*. Treated Water – *DWI.*
Water Supply - Quantity	Intermittent supplies to consumers slowly improved to become constant supplies. Homes with WCs started to grow rapidly.	Constant supplies for all, and infrequent restrictions on customer hosepipe and sprinkler use in droughts.
Water Supply - Quality	River abstractions often poor and variable until storage and filtration introduced. Preference by industry and domestic users for soft water.	Compliance required to high bacteriological and chemical World Health Organisation (WHO) and European Economic Community (EEC) standards. Aesthetics of taste and odour important.
Investment decisions	Made by Corporations. The powers to construct schemes were obtained by Acts of Parliament.	Made by Water Companies for inclusion in their 5 yearly Business Plans submitted to Ofwat.
Drivers for Water Resources and Supplies Investment	Increasing population, Economic growth, Deteriorating raw water quality of existing sources, Better treated water quality, Better public health.	Increasing population, Economic growth, Better treated water quality, Better security of supply, Improve the environment, Impacts of climate change.
Finance	Income from customer bills Long term loans from Government Sale of bonds to the public.	Customer bills. Borrowing from banks. Investment from owners.
Water Resources Planning Approach	A "single track" approach, build a new reservoir.	A "twin-track" approach of demand management and water resources schemes.
Water Resources Planning Methodology	Empirically based engineering judgement (see Chapter 4)	Set by EA for Water Companies to produce their 5 yearly Water Resources Management Plans.
Water Resources Planning Long Term Horizon	Up to 63 years (in the case of Birmingham)	25 years (required by EA guideline)

Table 1.2 - Institutional comparison and drivers; late Victorians and today

Institutions	Victorians	Victorian Drivers	Today	Today's Drivers
Central Government	Royal Commissions	Cholera and typhoid outbreaks in London and other cities	Improve ecology of water environments	Green image. EU Directives. Climate Change. Public health not an issue.
Local Government	Took responsibility for water supply by purchasing local private water companies	Sustain population and economic growth, and improve public and moral health	Victorians remembered for the major contribution to civic pride. Water Authorities set in 1974 and privatised in 1989.	Central government wants the privatised water companies to deliver major investment programmes, and be successful businesses.
Water Companies	Supplied those who could afford to pay. Not interested investing for the long-term.	Maximise income, minimise expenditure, and pay dividends to owners.	Heavily regulated. Some water companies now wholly owned by foreign investors.	Meeting regulatory targets at least cost. Maximize profit, and pay good dividends to shareholders. Build a reputation for good customer service and good value for charges.
Consumers	No formal representation.	Philanthropists recognised poor health and affordability issues	Consumer Council for Water now represents the interests of consumers.	Government appointed, and independent of water companies and regulators.
Economic Regulator	None	None	Economic regulator Ofwat created in 1989	Government established Ofwat to set water charges that are fair, and to monitor water companies' "contracts" with their customers.
Environmental Regulator	None	None	The EA sets guidelines and monitors water companies' 25 year plans. Controls water abstractions by a licensing system. The government champion for environmental improvement.	The Government wants to act responsibly in the interest of businesses and households, and create sustainable water environments. Through Defra and the EA, the government wants to ensure that the water companies have appropriate, robust and affordable water resource plans in place.
Drinking Water Quality Regulator (DWI)	None	No controls	DWI monitors drinking water quality, and approves schemes for improvement.	Reporting high compliance standards to government. Incident management.

1.3 Setting the Scene: Response to Drought

In the modern age, until a serious summer drought in 1995, water companies' investment in water resources and supplies had a low profile. The 1995 drought was followed by a dry winter, and this experience exposed significant deficiencies in the nation's water resource availability and supply flexibility, particularly in the north of England, and deficiencies too in the process of making water resources plans. The latter issue was addressed by government's "Agenda for Action" published in 1996, which is covered in some detail in Chapter 6.

At present (March 2012), in the south and east of England, including London, after two dry winters, there is a developing drought, and a hosepipe ban for domestic consumers is planned to start on 5 April 2012. For many domestic consumers, this the second time in eight years that a ban has been imposed. This is more frequent than the water companies tell their domestic customers is their target level of service (see Chapter 6). How will Government, the regulators and water companies respond? In the short term, the major uncertainty is whether the drought of 2012 turns out to be, or not to be, worse than the previous worst in 1976. This will depend on the extent of the geographic variation of rainfall, and the water resource types that are particularly affected.

When the capital faces a water shortage, and the rain falls copiously further west and north, a question often asked is why we do not have national water grid. The EA remains clear that the practicalities are enormous, the costs exceed the benefits, and local developments are better (EA, 2006). However, as will be discussed in this thesis, the Victorian water engineer had a greater influence on decisions than his modern counterpart.

Against this backdrop, the thesis starts with a Literature Review in Chapter 2. The identification of the knowledge gap, and the project aims and objectives to fill the gap are presented in Chapter 3. The Victorian approach to uncertainty in the long-term planning and design of the chosen remote reservoirs is discussed in Chapter 4. In Chapter 5, a novel lag time model is used to judge the risk averseness of the Victorian reservoir designs. The modern approach to long term water resources and supplies planning, and how uncertainty is addressed, appears in Chapter 6. In Chapter 7, the lag time model is applied to the proposed 100 Mm^3 storage Upper Thames Reservoir scheme. The Discussion of the findings is presented in chapter 8, and the Conclusions to this research appear in Chapter 9.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction to the Literature Review

This Literature Review contains factual material, analysis and comment derived from the author's engagement with historic and modern UK water supply and water demand literature.

The structure of Chapter 2, Literature Review, appears in Section 2.1.1. The reasons why the particular Victorian schemes were chosen for analysis are outlined in Sections 2.1.2 (Elan) and 2.1.3 (Thirlmere and Vyrnwy). Section 2.1.4 explains why the proposed Upper Thames Reservoir (UTR) was chosen as the modern scheme for analysis.

The literature review helps to identify a knowledge gap. The aims and objectives of this research that address the knowledge gap appear in Chapter 3.

2.1.1 Structure of the Literature Review

Section 2.2 provides historical context about the Victorian industrial cities of Birmingham, Manchester and Liverpool. As explained in Section 2.1.2, there was more contextual material found for Birmingham than for the other two cities.

Section 2.3 contains further historical context about the Victorian water engineers themselves, who directly or indirectly made such a difference for their client Corporations, and for the improvement in public health. The methods and parameters they used for making forecasts of demand, and assessing reservoir yield, are introduced.

Section 2.4 reviews the literature available about the three Victorian schemes. The critical analysis of historic water supply and demand forecasts that relate to the three Victorian schemes has been enabled by valuable data, information and reflection recorded by the

Victorian engineers. These have been found in published technical papers, and in the reports presented by Victorian water engineers to Local Authority and Government committees.

There is a detailed Victorian chronology in Appendix B of events relevant to 19^{th} century water supplies in Birmingham and London. This chronology is a reminder about the pace of change as social, economic, technical and political influences impacted on the planning and design of schemes.

Section 2.5 contains modern context for how today's planning and design of water resources and supplies infrastructure is undertaken by the water industry. The way that uncertainty is factored into the supply demand balance forecasts by the use of target headroom is introduced. The Government's lead with a vision for a wide range of stakeholder interests in water is acknowledged.

Section 2.6 is focussed on the literature associated with Thames Water Utilities proposed new reservoir, and in particular for the Public Inquiry in 2010.

The Literature Review finishes in March 2011, when the Secretary of State officially informed Thames Water Utilities that all the recommendations of the Planning Inspector had been accepted. The major recommendation was the rejection of a pumped storage UTR of 100 Mm^3 in Oxfordshire, which was the company's preferred solution to London's long-term supply and demand problem. Other scheme options were put forward by the Inspector for further investigation, including a smaller UTR of 50 Mm^3. The outcome from the Public Inquiry appears not to have satisfied either the promoters, or the objectors.

2.1.2 Selection of the Elan Reservoirs Scheme for analysis

Research was proposed by the author for studying the late Victorian Elan scheme located in mid-Wales, which has supplied very nearly all of the water demand in Birmingham for the past 107 years. The choice of the Elan scheme was approved for funding by Dr John Bridgeman of the University of Birmingham, and by Professor Robert Sellin of University of Bristol, who was acting as a Trustee of the ICE's Research and Enabling Fund.

Professor Sellin asserted that "Birmingham appears to have got things right". Reflection after the discussion with Professor Sellin prompted the question "Can we quantify how "right" or "wrong" Birmingham Corporation got it, and can we compare this with other Corporations that developed similar schemes?" This idea then led to a more specific question involving uncertainty: "When making this comparison, can we learn anything about the way Victorian water engineers' approached the factoring of uncertainty into their supply and demand forecasts?"

Elan was regarded as the major scheme for this project, and a great deal of local documentation and historic data was found in Birmingham about this highly controversial scheme. There is significantly more material and analysis presented in this thesis about the Elan scheme than for the other schemes chosen for analysis.

2.1.3 Selection of Thirlmere and Vyrnwy Schemes for analysis

For comparative analysis with Elan, the selection was made of the Thirlmere scheme and the Vyrnwy scheme as all three are of the same type and scale. They comprise of remote upland raw water storage that is naturally filled, and connected to their distant cities by gravity aqueducts. All were planned, designed and constructed in the late Victorian era for the supply to the three largest cities in England outside of London. All three schemes are still working today at maximum capacity. Their locations relative to the industrial cities they serve are illustrated in Figure 2.1.

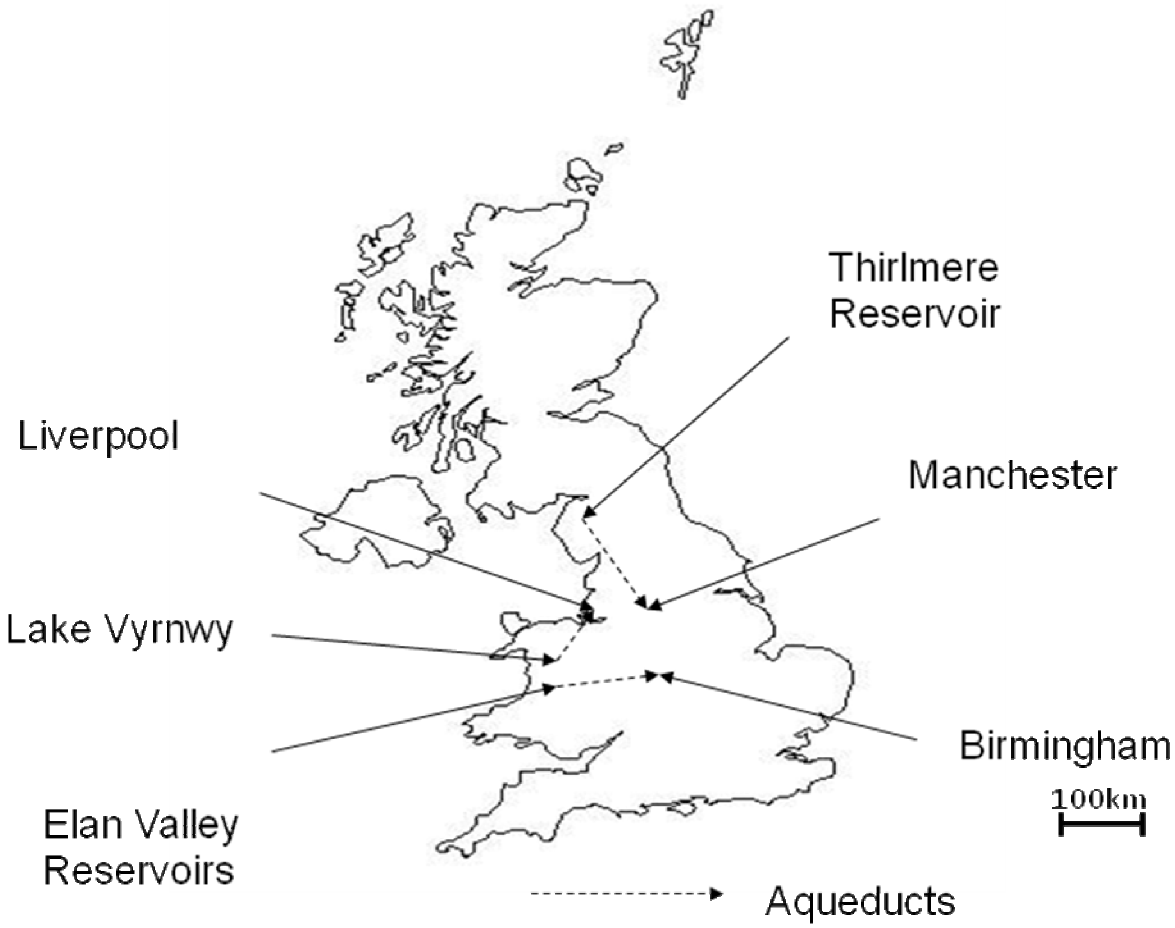

Figure 2.1 - Location of the schemes, aqueducts and cities

A high level factual summary of the sizes, dates, and the names of the principal Victorian engineers involved is shown in Table 2.1a. A similar summary is shown in Table 2.1b for two other major Victorian schemes in the UK that might have been included in this project; they are Loch Katrine (Glasgow) and the Derwent Valley Reservoirs (East Midlands).

Table 2.1a. Thirlmere, Vyrnwy, Elan: High level summary; Table 2.1 b. Other major Victorian schemes, Loch Katrine and Derwent Valley Reservoirs.

a

Victorian Reservoir Scheme	Corporation	Leading Water Engineers	Final Scheme Capacity	Date of Parliamentary powers	Date of first flow
Thirlmere	Manchester	JF Bateman. (then GH Hill)	37,000 Ml	1878	1894
Lake Vyrnwy	Liverpool	T. Hawksley (then G Deacon)	59,000 Ml	1879	1893
Elan Reservoirs	Birmingham	J. Mansergh	99,000 Ml	1892	1904

b

Victorian Reservoir Scheme	Corporation	Leading Water Engineers	Final Scheme Capacity	Date of Parliamentary powers	Date of first flow
Loch Katrine	Glasgow	JF Bateman.	25,500 Ml	1855	1859
Derwent Valley Reservoirs	Sheffield, Nottingham, Derby, Leicester.	Derwent Valley Water Board	47,000 Ml (including Ladybower)	1899	1916

During the literature search, two papers were found that were presented to the same Institution of Civil Engineers (ICE) meeting in 1896 about the newly commissioned sources at Thirlmere and Vyrnwy (Hill, 1896; Deacon 1896). After these presentations had been made, the discussion was started by James Mansergh, who compared the physical characteristics of the two schemes with his Elan scheme, which at that time was under construction. Figure 2.2 is a cartoon that was used during the discussion by Mansergh.

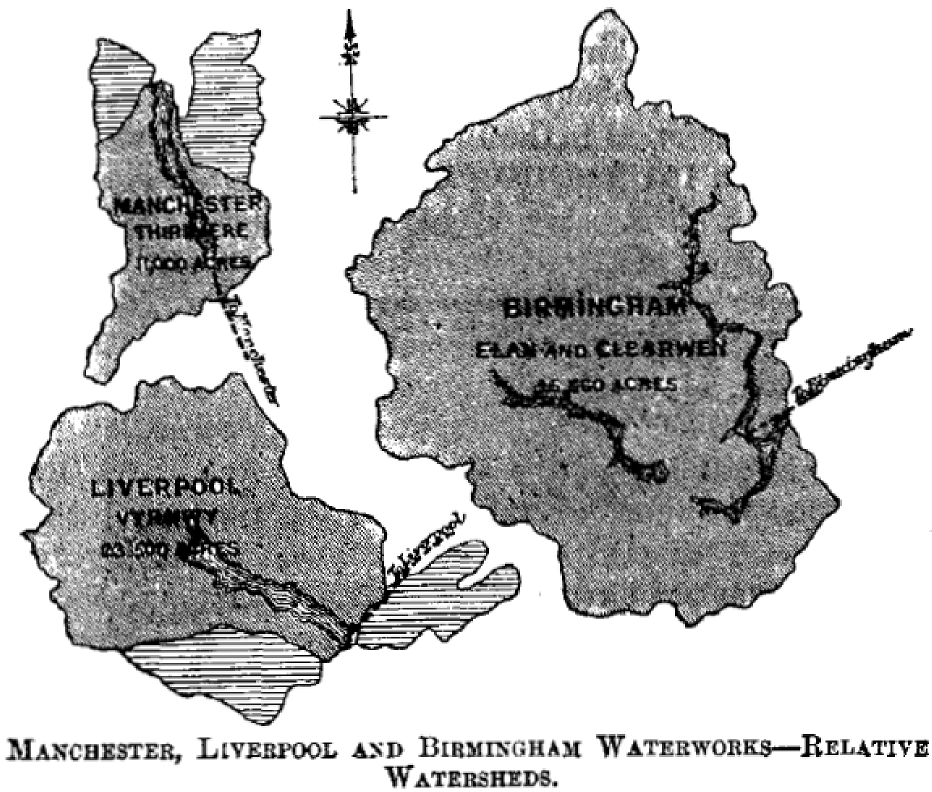

Figure 2.2 - Mansergh's Three Catchments – ICE 14 April 1896

This ICE discussion was an inspiration to the author for knowing that the same three schemes were selected for comparison 116 years ago.

2.1.4 Selection of the proposed Upper Thames Reservoir for analysis

For a modern scheme in the UK, the intention was to choose a strategic reservoir scheme that was at the planning stage, and then apply the new comparative method developed for the Victorian schemes. The largest scheme proposal in the UK that is at the planning stage is for a 100 Mm^3 pumped storage scheme Upper Thames Reservoir (called UTR or Abingdon). Thames Water (TW) has proposed the scheme, and it features in the company's preferred plan (rDWRP, 2009). In the past different storage sizes that increase the long term security of supply to London have been suggested. The scheme works by being filled in winter by abstractions from the nearby River Thames, and releasing water back into the same river during summer to travel to London, and then re-abstraction before treatment and supply. The extra deployable output is 185 Ml/d, and the average daily demand in London is about 2,000 Ml/d. The fact that the UTR is filled in a different way to the Victorian schemes was judged to be not material for this project.

A Public Inquiry was held in the summer of 2010 into the company's revised Draft WRMP produced in September 2009. The documents presented by the company and by objectors (led by the EA) have provided useful material for this project. The most significant document was the Planning Inspector's report that gave the reasons for rejecting the company's preferred plan for a UTR 100 Mm^3 scheme for completion in 2026.

The arguments for and against the UTR scheme involves different drivers and planning uncertainties to those faced by the Victorians. Meeting the demands from a growing population and enabling future economic growth remain common drivers. However, the Victorian driver to improve public health is no longer an issue. It has been replaced by a drive for environmental improvement, and much of this improvement will depend on reducing and reallocating existing water abstractions for public supply back to the natural water environment. There are very significant uncertainties about the quantities involved.

2.2 Historical Context, Victorian Cities

2.2.1 Britain's Victorian Cities

In the Victorian railway age of the nineteenth century, Britain witnessed huge political social and economic changes with the emergence of its great industrial cities. Britain's Industrial Revolution of urban growth had its economic foundation in a rapidly expanding population coupled with booming industrial development. However, this growth brought social problems that impacted most adversely on the public health of the poor. The primary physical causes of poor health were bad and overcrowded housing, an inadequate water supply, polluted drinking water, and the lack of proper sanitation. Population growth was the most significant indicator of the scale of the challenge.

Table 2.2 shows that the times of maximum population growth rate for the three cities did not coincide. Comparatively, Manchester witnessed the greatest growth rate in the first half of the 19th century, Liverpool was greatest in the second half of the 19th century, and Birmingham grew the fastest in the first half of the 20th century.

Table 2.2 – Resident Population Growth in Birmingham, Manchester and Liverpool

Cities and rounded resident Population supplied.	Year 1801	Year 1851	Growth 1801 to 1851	Year 1901	Growth 1851 to 1901	Year 1951	Growth 1901 to 1951
Birmingham	75,000	230,000	x 3.1	520,000	x 2.3	1,110,000	x 2.1
Manchester	90,000	350,000	x 4.4	660,000	x 1.9	700,000	x 1.1
Liverpool	80,000	250,000	x 3.1	660,000	x 2.6	806,000	x 1.2

A Victorian chronology for Birmingham and London of water supply related events, including reference sources, is given in Appendix B. Information contained in this chronology is used in Section 2.2.2 for London, Section 2.2.3 for Birmingham, and referred to in Section 2.4 that describes the three Victorian reservoir schemes.

2.2.2 London

In London, the River Thames wastewater crisis developed in the first half of the 19th century, evidenced by the well documented outbreaks of cholera, and culminating in the Great Stink of 1858. This event demonstrated that the public health of all classes was threatened, and raised the political will sufficiently for Government to seek improvement (Hardy, 1984). Halliday's "The Great Stink of London" celebrates Sir Joseph Bazalgette's substantial and lasting contribution to better sanitation in London through his design and delivery in the 1860s and 1870s of the intercepting sewers on either side of the River Thames (Halliday, 1999).

The population of London was growing rapidly, and during the second half of the 19th century, proposals were made for new raw water storage west of the capital (Bailey Denton, 1866). In 1869, a Royal Commission chaired by the Duke of Richmond into London's future water supplies examined distant solutions, particularly from Wales (Walters, 1936). Richmond recommended increasing abstractions from the non-tidal River Thames upstream of London where river flows could be further exploited. To enable this to happen, the science of river water treatment was improved, and new bankside storage was constructed in west London. The debate about developing new storage remotely from London continues today some 140 years after Richmond. The proposed UTR is introduced in Section 2.6, and critically analysed in Sections 6.4 and 6.5.

Also in the second half of the 19th century, there was growing demand for clean soft water to enable economic growth in Manchester, Liverpool, and Birmingham. Unlike London, these three cities are not located near to large non-tidal rivers. Deteriorating existing local surface and groundwater sources in both quantity and quality eventually stimulated water engineers and their client Corporations to search further afield (Hassan, 1998). Over a century later, all three cities now enjoy the legacy of a relatively cheap, clean and reliable water supply.

2.2.3 Birmingham

In the latter half of the 18th and early 19th centuries, Birmingham was developing its manufacturing base for small specialised items, and water for domestic and industrial use came from wells. At the same time, a group of physicians, scientists, entrepreneurs and engineers known as the Lunar Society met regularly in Birmingham to discuss freely their thoughts on scientific experimentation and discovery which would be good for mankind, and good for business (Uglow, 2002). Thus Birmingham became a centre for innovative and non-conformist thinking away from the institutionalised constraints of London. This gave Birmingham an integrity which did not depend on the capital, and also marked its difference from Manchester, Birmingham's main rival manufacturing city to the north.

By the 1850s and early 1860s, Birmingham had lost ground to other cities with a succession of councils making a virtue of spending little money on public amenities and thus public health (Briggs, 1968). Birmingham's period of strongest economic growth at near 4% per year occurred in the latter part of the 19th century.

The social, economic and political historian Asa Briggs (1968) suggests that the root of the public health problem in the early 1870s was the Corporation's difficulty in reconciling economic individualism and common civic purpose. However, Ward (2005) identifies that the civic gospel had a religious foundation of caring for the poor, and was key to local government in Birmingham being described by others in the 1870s as "the best in the world". Briggs emphasises the significance to Birmingham's economic development of figures such as successful entrepreneur Matthew Boulton (a Lunar Society member), and revered politician Joseph Chamberlain, whereas local social historian Professor Carl Chinn (2003) stresses the substantial and sometimes undervalued contribution made by skilled and adaptable ordinary people. The two approaches are seen by Chinn as complimentary.

2.2.4 Birmingham Institutions

The story of Birmingham's water supply planning is linked to developments in improved sanitation and drainage. In chronological order, the key institutions for the planning and delivery of water and wastewater services were:

1) **The Streets Commissioners**; first appointed by Government in 1769 with a duty to cleanse and light streets. By the Improvement Act of 1812, the Streets Commissioners became the first public health authority for the town.
2) **The Birmingham Waterworks Company**; created by act of Parliament in 1826, and the responsibility for supply remained in private hands until 1875. (Mathews, 1886)
3) **The Committee of Public Works of the Birmingham Borough Council**; appointed to implement the Birmingham Improvement Act of 1851, and thereafter took over the work of the Streets Commissioners. This committee took an interest in, but were not responsible for, water supplies. (Macmorran, 1973)
4) **The Water Committee of the Council**; formed in 1875 on the takeover of the responsibilities and purchasing the assets of the Birmingham Waterworks Company. The Water Committee recommended building the Elan scheme to the City Council (CBWD, 1973).
5) **Severn Trent Water Authority** took over the responsibilities and the assets from the City Council as part of the wider restructuring of Local Government in 1974. There was hostility towards the new Authority from Birmingham inhabitants who felt the Authority had stolen the Elan scheme, and at the same time, domestic water bills in Birmingham had risen significantly.

6) **Severn Trent Water Ltd**; the responsibilities and assets for water and waste were transferred back into private hands in 1989 after 114 years in local government.

Estimates of the population served are not consistently reported in the literature. The city boundaries were substantially extended in 1891 and 1911, and the figures quoted by Dick (2005) are used. Population data for Birmingham is discussed in Section 4.3.5, and census data for the decades from 1801 to 1961 are shown in Figure 4.11.

2.2.5 Birmingham Decision Makers

There were six Victorian engineers who undertook water resources planning and design for Birmingham, and who were the most influential in the improvement of public health.

John Pigott-Smith, highways engineer to the Streets Commissioners, who become Borough Surveyor reporting to the Council's new Public Works Committee up to 1857. He had a passion for drainage, and achieved much during the period when Council spending was miserly. Pigott-Smith was aware of how poor drainage in the Black Country was a threat to the quality of the River Tame, which was a significant source of drinking water for Birmingham. Following a pollution event in the River Tame at Willenhall in 1854, he shocked the members of the Public Works committee when he took them to see what was normally being discharged into the river above the abstractions for Birmingham (Macmorran, 1973).

Robert Rawlinson, sanitary engineer, who advised the Streets Commissioners and then the Public Works Committee from 1848 up to at least 1871. He first came to prominence in 1849 when he reported to the Government's new Central Board of Health about the poor state of Birmingham's public health. Rawlinson (1849, 1854, 1871) understood the link between clean water, proper drainage and public health, and his first report to the Council on water resources in 1854, co-authored with Pigott-Smith, recommended alternative local surface sources to replace the River Tame. His paper on future water resources in 1871, for which the Council asked him to consult James Mansergh, brought Elan to the Council's attention as the best site for a clean and plentiful gravity supply. Sir Robert Rawlinson's role provided continuity in addressing Birmingham's problems over a crucial period that lasted over 20 years.

Richard Hassard, civil engineer, who in 1870 was the first to propose to the Public Works Committee that Birmingham's water supply should come by gravity from distant new storage to the west. His first recommendation was the River Teme (Herefordshire), and he proposed an aqueduct route that turned out to be very close to that eventually built for Elan. As well as the supply to Birmingham, a supply could be made available to the neighbouring South Staffs Waterworks Co. After Rawlinson's paper of 1871, Hassard revised his recommendation to a new site on the River Ithon, which is close to Elan. In this latter paper, Hassard expressed his disappointment that Rawlinson had used many of his ideas without proper acknowledgement (Hassard, 1870, 1871).

Thomas Hawksley, civil engineer, advised the Birmingham Waterworks Company on a River Blythe abstraction just east of Birmingham. Abstractions from the Blythe are made today for the supply to Nuneaton in north Warwickshire. Hawksley advocated the development of local groundwater sources for public supply. He was a lone but persuasive voice about the use of groundwater (Mathews 1886).

J. W. Gray, the City Engineer, provided 50 year supply and demand projections from 1890 to 1940, which were developed by Mansergh to justify the need for a scheme the size of Elan to the City Council. (Barclay, 1898)

James Mansergh, civil engineer; Mansergh strongly recommended the Elan site for reservoir development to the Council, first in support of Rawlinson's paper of 1871, and then again in 1891 for the land purchase. He had assessed the Elan and Claerwen valleys as far back as 1862, possibly with a view to a future supply for London. Mansergh was in charge of construction of the Elan scheme starting in 1892 (Mansergh, 1894) up to its commissioning in 1904. In 1862, Mansergh had the foresight to get rainfall records started at Elan.

Of the many politicians over time who cared about improving public health in Birmingham, and for the City's economic prosperity, there are three administrators who stand equal with the engineers in making the Elan scheme happen:

Joseph Chamberlain was the charismatic Mayor and Cabinet Minister, who was responsible for taking over the gas and water companies for the citizens of Birmingham in 1874 and 1875 respectively. He was the leader of the "civic gospel" which revolutionised the role of local government in Britain. Whilst at Westminster, he steered the Bill authorising the construction of the Elan scheme through both Houses in one sitting in 1892. His status in Birmingham could not have been higher (Ward 2003, 2005).

Thomas Avery, businessman and Councillor, who from 1862 up to 1892 was a well respected and influential chair at various times of the Finance, Sewage, and Water Committees, as well as Mayor. It was Avery who in 1869 gave the Council the wake-up call about their responsibilities about public health (Avery, 1869). Soon after 1869, he successfully negotiated the financial detail for the Council to purchase the Birmingham Waterworks Company. Avery was steadfast in 1893 when an ageing Joseph Chamberlain warned the Council in 1893 that the Elan scheme might prove too much for the City's finances. (Ward, 2005)

Thomas Martineau, was the chairman of the Council's Water Committee in 1890 who successfully convinced the Council that James Mansergh's scheme was the right one for securing Birmingham's long term water supply (Barclay, 1898).

2.2.6 Manchester water supplies prior to Thirlmere

Manchester witnessed major growth similar to that of Birmingham, but half a century earlier. The chapter title in Briggs (1968) "Manchester; Symbol of a New Age" signifies that Manchester was in the vanguard of Britain's Victorian urban industrialisation. Whilst there was no "civic gospel", moral philanthropy existed like the founding in 1833 of the Manchester and Salford Provident Society "for the encouragement of frugality and forethought…and the occasional relief of sickness"

The industrial picture was of large mills owned by wealthy men that employed lots of expendable people. This picture was in direct contrast to Birmingham's mass of small works that employed skilled workers.

A chronology of the water supply events in Manchester and Liverpool, given in Table 2.3, shows how similar the water supply history is of these two great urban developments situated in north-west England.

Table 2.3 - Chronology of Liverpool and Manchester Water Supply, 1847 to 1900

Year	Liverpool	Manchester
1847	Corporation acquires both local water companies.	Corporation acquires local water company.
1850 - 1857	Thomas Hawksley's Rivington Pike reservoirs scheme built near Bolton (ultimate max 55 Ml/d); first flow 1857. Liverpool demand 30 Ml/d.	Bateman's Longdendale reservoirs scheme constructed east of the city (ultimate max 90 Ml/d); first flow 1855. Manchester demand 36 Ml/d.
1865	Liverpool demand 72 Ml/d. Drought, supplies down to 2hrs per day and intermittent thereafter.	
1868	In spite of house to house inspections, supplies remain intermittent until 1874 (shut-offs normally for 9-12hrs per day).	Manchester demand 60 Ml/d. Drought, 12 hour supply for 84 days. Then a return to constant supplies.
1873	Liverpool demand and max water supply 80 Ml/d. "Special operations for the prevention of waste" (Parry 1881) reduces losses, and constant supply returns in 1875.	Demand increase to over 70 Ml/d was viewed as soon to exhaust Longdendale, and the next major source needed.
1875	Liverpool demand managed down to 67 Ml/d. Constant supplies reinstated. Bateman proposes Ullswater.	Manchester demand 80 Ml/d. Bateman makes 30 year forecast of 4.5 Ml/d per year.
1876		Manchester turns down joint development with Liverpool at Ullswater. Bateman proposes Thirlmere.
1879	Hawksley and Bateman independently are of the opinion that Vyrnwy better than Haweswater.	TDA challenge overcome and powers for Thirlmere obtained using Bateman's 4.5 Ml/d per year forecast.
1880	Powers for Vyrnwy obtained using Hawksley's 36 year forecast of a doubling of population using 30 gallons/head/day by 1916. Current supply population 703,000.	Current supply population c.900,000. Larger than Liverpool as supply area included surrounding towns in Lancs. and Cheshire.
1892	First flow from Vyrnwy scheme	
1894		First flow from Thirlmere scheme. Manchester Ship Canal opened.
1898	Parry asked by Corporation to review the supply demand balance, and to cost a second Vyrnwy main.	
1900	Liverpool demand 124 Ml/d.	Harwood report says current demand is 145 Ml/d, and forecast demand would reach supply capability of 340 Ml/d in 1935. Second main required soon.

The first large scale example of a gravitation works in this country was at Longdendale, some 18 miles east from Manchester (Hassan, 1998). This scheme formed, at the time, probably the largest system of artificial lakes in the world, and had a reliable yield of between 109 and 113 Ml/d (24 and 25 Mgd). Undertaken by Bateman, the full scheme took over 20 years to develop because of the engineering problems caused by poor ground conditions. In spite of these difficulties, Bateman was trusted by Manchester Corporation. In the 1860s, Bateman had undertaken a project to source water 35 miles north at Loch Katrine for Glasgow (Binnie, 1981).

Before Longdendale, local groundwater sources and canals were used as sources.

2.2.7 Liverpool supplies prior to Vyrnwy scheme

Victorian Liverpool was a commercial town with merchants, and was rather different character to the industrial town of Manchester with its large mills.

Pollution and overuse of groundwater sources lead to a pressure group of councillors called the Pikeists who wanted a new source on the edge of the Pennines at Rivington. The Pikeists prevailed, but only because of a projection of 100 Ml/d (22 Mgd) available from the scheme that was made by Thomas Hawksley (MWH, 2008). This assessment was subsequently found to be a significant over-estimate. Hawksley had used average rainfall for his analysis, and the drought yield of the Rivington sources was near 77 Ml/d (17 Mgd).

The first flow from the Rivington scheme occurred in 1857, and constant supplies were started in 1858. During a drought in 1865, it was with dismay that intermittent supplies had to be reintroduced and to last for another seven years (Deacon, 1875).

The long timescale to deliver a new water resource forced the Corporation to take the view that leakage and waste reduction was the only way forward in the short and medium term.

This situation was turned into an opportunity by the corporation's engineer George Deacon, who invented a distribution meter that produced a chart, and interpretation helped prioritise leakage reduction efforts. Deacon's innovative approach was successful in the areas where it was implemented, and formed the beginning of what is now called "active" leakage control.

Poor public health remained an issue (Roberts, 2000), and after some unsuccessful attempts to develop new sources nearer to home, the civic leaders of Liverpool chose to develop a site in North Wales, 68 miles away at Lake Vyrnwy. It was completed in 1891 as the largest artificial dam in Britain at the time, and the first to have a high masonry embankment (Hassan, 1998). The success that Liverpool Corporation had with the Vyrnwy scheme helped to give Birmingham Corporation the confidence that upland reservoir storage and aqueduct schemes were achievable.

2.3 Historical Context; Victorian Water Engineers and Methods Used

2.3.1 Britain's Victorian Water Engineers

The vision and work of many of the water engineers engaged by the Corporations to propose and design new water schemes are described and celebrated by Binnie (1981). Binnie's use of the word "early" in the title perhaps infers that they were not the water engineers of the mid to late Victorian era, but this is not the case. Binnie devotes detailed biographic chapters to two of the giants of water engineering in John Frederick Bateman FRS (1810-1889), who was responsible for planning the Thirlmere scheme to supply Manchester, and Thomas Hawksley FRS (1807-1893) for planning the Vyrnwy scheme to supply Liverpool.

James Mansergh FRS (1834-1905), who proposed designed and constructed the Elan scheme for Birmingham, came later and is not covered by Binnie. Other documents have been found that provide enough detail to gain an understanding of Mansergh and his work, in particular Thomas Barclay's "The water supply of Birmingham" (1898).

Bateman, Hawksley and Mansergh were all made FRS, and Presidents of ICE for the then normal two year tenure. Their Presidential Addresses provide insight to their character, and their obituaries published in the ICE proceedings provide helpful reflection on their careers.

In his Presidential Address of 1900, James Mansergh reflected on what had been achieved by water engineers in the 19th century. Mansergh counted Simpson, Bateman and Hawksley, plus two other past presidents, Sir Joseph Bazalgette and Sir Robert Rawlinson, whom he felt had made exceptional contributions to water supply engineering. Table 2.4 summarises the key dates for the water engineers revered by Mansergh, and the summary for Mansergh himself.

Table 2.4 - Seven Victorian water engineers who were past Presidents of ICE

President of ICE, Water Engineer	**Years of Birth and Death**	**Life**	**Year of Presidential Address**	**Age when President**	**References** (Binnie = "Early Victorian Engineers" by G. M. Binnie, 1981, London, Thomas Telford)
James SIMPSON	1799 - 1869	70	1854	55	Binnie chapter 5 (1981), ICE obit
Thomas HAWKSLEY	1807 - 1893	86	1872	65	Binnie chapter 8 (1981), "Pure and Constant" (2008), ICE obit
John Frederick BATEMAN	1810 - 1889	79	1878	68	Binnie chapter 9 (1981), Smeaton Lecture (2011), ICE obit
Sir Joseph BAZALGETTE	1819 - 1891	72	1884	65	Halliday "The Great Stink" (1999), ICE obit
Sir Robert RAWLINSON	1810 - 1898	88	1895	85	Binnie chapter 10 (1981), ICE obit – not found
James MANSERGH	1834 - 1905	71	1901	67	Barclay, "The water supply of Birmingham" (1898), ICE obit
Sir Alexander BINNIE	1839 – 1917	78	1905	66	ICE Presidential Address and ICE Obit.

James Simpson pioneered the filtration process of water treatment, and thus enabled the continued and growing use of River Thames water to supply the Lambeth and Chelsea water companies in London.

Thomas Hawksley specialised in designing many water supply and pumping schemes. MWH (2008) describes Thomas Hawksley's legacy of schemes, some of which are operational today. His success in designing pumping systems led to Hawksley also becoming president of the Institution of Mechanical Engineers.

John Frederick Bateman designed and constructed many earth filled dams, including the Longdendale reservoirs scheme in the valley of the River Etherow for Manchester Corporation. The Longdendale scheme was the largest of its type in the UK, and it preceded the Thirlmere scheme. Russell (1981) shows there are some 28 schemes that Bateman constructed in NW England, about half of the total in which he was involved. Russell's talk to the Newcomen Society provides an excellent record of Bateman's life and achievements. It was used and acknowledged by Professor Moffat from the University of Newcastle to inform his presentation for the ICE's annual Smeaton lecture about Bateman (Moffat, 2010).

Sir Joseph Bazalgette was knighted for his contribution to sanitary improvement in London. Halliday (1999) emphasised Bazalgette's extraordinary patience and competence to deliver the re-sewering of London. Sir Joseph used his Presidential Address (1884) to benchmark London water supplies by comparing statistics gathered from cities across the world.

Sir Robert Rawlinson invented the title "sanitary engineer" for himself. He primarily worked for the Government and was knighted for his substantial contribution to the improvement of military and public health. Sir Robert had a passion for improving the health of the poorest in society. He assumed the Presidency at the surprising age of 85. All the

Victorian water engineers mentioned reached at least 70 years old, which was comparatively long lived at that time.

James Mansergh had not completed the Elan scheme for Birmingham Corporation at the time he became President of ICE at the turn of the century. Mansergh used his Presidential Address as an opportunity to expand Sir Joseph's Bazalgette's high level comparisons of world cities. Mansergh collected more detailed numbers about water supply from cities at home and abroad, and he published them in an Appendix to his Address. The data and information brought together by Mansergh is a snapshot of water supply at the end of the 19^{th} century, and is a valuable legacy for analysts.

Sir Alexander Binnie was a civil engineer, and has been included in Table 2.4 for his passionate interest in rainfall statistics. This led for the first time to a better understanding of their uncertainty. His contribution is discussed in Section 2.3.4. Sir Alexander was knighted for building the Blackwall road tunnel under the Thames. Another significant achievement was leading the team that ensured the Metropolitan Water Board came into being. Alexander Binnie and James Mansergh were known to each other from their younger days having worked on the same Welsh railway projects in the 1860s.

There are significant contributions to the development of Victorian water engineering in the cities of interest to this project by four other engineers and a meteorologist. These are noted below:

George Henry Hill was for many years Bateman's assistant in Manchester. He was responsible for completing the Thirlmere project after Bateman's death, and presented a paper to ICE about the scheme in 1896. The Manchester based dam building consultancy that bore his name remained in business until the 1980s.

George Deacon became Chief Engineer to Liverpool Corporation**.** Deacon completed the design and construction of the Vyrnwy dam after Hawksley refused to work on the scheme as an equal. Deacon presented a paper to ICE in 1896 about the Vyrnwy scheme at the same session that Hill presented the Thirlmere scheme. Deacon came to London to work in private practice with Sir Alexander Binnie.

Joseph Parry was a water engineer who worked under George Deacon at Liverpool Corporation. He implemented Deacon's leakage control project, and its success was due to Parry's interest in analysing the data. After Deacon's move to London, Parry was made Chief Engineer. In 1881, Parry published a useful and readable handbook "Water, its composition collection and distribution."

Dr William Pole was a mathematician, engineer and linguist who worked on his own. Such was his mathematical prowess that other water engineers asked him to confirm that their engineering calculations had been carried out correctly. As a water engineer who was disinterested in the technical solutions to London's water supply problems, he was made the Technical Secretary to the Richmond Royal Commission in 1869 that heard Bateman advocated powerfully for supplying London from new storage in Wales. Thereafter, Dr Pole gave objective and convincing evidence to Parliament in support of proposals for new remote reservoir schemes for other Corporations.

GJ Symons FRS was the meteorologist who started the publication of British Rainfall statistics, and was a good friend of Sir Alexander Binnie. Symons standardized the process of rainfall data collection, and recruited several thousand volunteer observers. Symons' contribution to rainfall science made Britain at that time the world leader in the collection of rainfall data.

2.3.2 Victorian estimates of demand

As is described in Section 2.4, population forecasts, judgement of about how much per capita demand was due to grow, and linear trend extrapolation were the most commonly used ways of making a demand forecast.

There was often little actual flow data other than a daily estimate of supply, and the "per capita demand" was usually calculated by dividing the estimate of the total supply by the estimate of the population served. A figure of 25 gallons per person per day was regarded as a reasonable figure to plan for in urban situations, and judgement was used to estimate how quickly water closets and hot water systems would penetrate the housing stock. This was an early attempt to do component forecasting, but without any of the data available today.

When Sir Robert Rawlinson was engaged by Swansea Corporation for a reservoir design, he refused to make any demand forecast believing that the responsibility for creating the forecast must stay with the client (Binnie, 1981).

The "Decremental ratio of Increase" method was used by Mansergh to construct a demand forecast for Birmingham in 1892 (Bradford et al, 2010). This began the move towards estimating the components of demand. Population forecasts were generally over-estimated, perhaps as a buffer against the many uncertainties. Appendix C contains the parameters used by Mansergh for his demand forecast, and the parameters used today.

2.3.3 Victorian estimation of water supply reservoir yield

Thomas Hawksley relied on the estimation of annual average rainfall alone to assess the yield available of 100 Ml/d (22 Mgd) from the Rivington Pike scheme for Liverpool's water supply. The anticipated 22 (Mgd) turned out to be an overestimate, as in practice, the reservoirs were only able to produce 75 Ml/d (16.5 Mgd) during droughts in the mid 1860s

(MWH, 2008). Hawksley developed his empirical "three dry years" reservoir yield rule for an impounding reservoir for a water supply. Hawksley clarified his method in his evidence to the Richmond Commission in 1868 with the quote below, and reprised by Binnie (1981) page 154.

"The first thing to be done is to ascertain the average of the rainfall over a very large number of years. From that deduct one sixth, that being the quantity which will inevitably be lost over the waste weir…The next thing to do, from the residual quantity is to take off the amount of evaporation…..We find by the reservoirs of the great magnitude which I'm going to mention we can store and regulate (that is the thing wanted) the rainfall of three consecutive dry years, and we find (and it is a very curious fact again, but it comes in justification of what I have already said) that the average rainfall of the three consecutive dry years … is exactly one sixth less than the average of the whole."

Following a series of droughts in the 1880s, Hawksley's rule was amended empirically in 1892 by Alexander Binnie, who suggested that one fifth rather than one sixth should be removed from the annual average rainfall. G Binnie goes on to say on p156 that "the stage was reached of numerically estimating the yield from 80 per cent of the average rainfall, which became known as the "reliable yield"…..this rule was one that laymen could readily understand…The value is equivalent to the runoff in a hypothetical 80% rainfall year."

The storage required is then obtained from "the ordinary formula" below (Rippl, 1883). In the absence of flow data, the method depends on rainfall data. Having estimated the Three Dry Years annual average rainfall (in millimetres), the number of days supply required, Z, determines the amount of storage required:

$$Z = \frac{1000}{0.198 \times \sqrt{R}}$$

Equation 2-1

The volume of water to be stored in one day, T, is:

$$T = B + C + V - D$$

Equation 2-2

where B is the demand of the town, C is the compensation to the stream, V is the loss by evaporation, and D is the dry weather flow into the reservoir in million gallons per day. Rippl states that in England, Z is normally 100 to 250 days, that the formulae are suitable only for English conditions, and that C is regulated by law, being usually one third to one quarter of the available supply from the catchment.

Rippl's paper is helpful to our understanding of the developing science of estimating storage requirement. He describes another method of deriving storage capacity requirement based on the lowest calendar year of rainfall on record. He correctly criticises the method for not taking a longer period than a year, and for excluding the possibility that a mid-year start and end date may be more critical. Rippl then proposes a graphical simulation of storage method where the start and end dates, and the length of time considered are not constrained.

In the Victorian era, the estimation of storage requirement method remained largely empirical, and there was a paucity of flow data on which to base such estimates. Thus as the surrogate, it was the estimation of rainfall that began to attract scientific attention, in part because it was cheaper to collect than flow.

2.3.4 Awareness emerges of Uncertainty in Rainfall data estimation

Rippl asserted in 1883, without explanation, that at least 35 years of rainfall data is required to make a robust estimate of mean annual average rainfall. Nine years later in 1892, the issue about record length and possible error was addressed by A. R. Binnie (1892) in a paper to ICE. Binnie’s statistical analysis produced the results that are summarised in Table 2.5.

These results show, for example, that the error band for a 15 year record, mean annual average rainfall is likely to be estimated within ± 5%, and for 35 years within ± 2%. Clearly a 35 year record will have a smaller error band, but a ± 5% error might be sufficient as an assumption, depending on the application.

Table 2.5 - Deviations around the Mean AAR for different rainfall record lengths (after Binnie, 1892)

Years of Annual Average Rainfall Data Record	Percentage Deviation Range from the estimate of the mean of AAR
1 year	+ 51% to – 40%
5 years	± 15%
10 years	± 8.22%
15 years	± 4.75%
25 years	± 2.75%
35 years	± 1.78%

Sir Alexander Binnie’s passionate interest in rainfall estimation continued until his death in 1914. His series of lectures in 1912 on Rainfall, Reservoirs, and Water Supply was an epitaph that captured his long experience as a water engineer. The preface to these lectures contained:

“…..not a complete treatise on Waterworks Engineering, but merely an attempt to illustrate some of the salient points connected with one of the most difficult branches of Engineering; and if he (i.e. Binnie) succeeds in impressing upon the reader the difficulties of laying down any exact stereotyped rules, and how dependent the Engineer is on meteorological, geological and chemical data, he will feel that his work has not been thrown away in the interests of sanitary science."

The "difficulties of laying down any exact stereotyped rules" suggests Binnie's sensitivity to inherent uncertainty. Sir Alexander Binnie's professional life lasted more than 50 years, and when these lectures were delivered at ICE in 1912, he was aged 73. Perhaps this was the point in time when the era of the 19th century Victorian water engineer drew to a close.

2.4 The Three Victorian Reservoir Schemes; Description and Data Sources

2.4.1 Summary Description of the Three Schemes

As noted in Section 2.1.2, the three schemes were considered as a comparable group by Mansergh in the Discussion that took place after the papers by Deacon (1896) and Hill (1896). Mansergh compared their catchment areas, as shown in Figure 2.2, and rainfalls alongside that for the Elan scheme, which at that time was under construction. Mansergh pointed out that the catchment area for Elan was approximately double that of Vyrnwy, and four times the area draining into Thirlmere, whilst the average annual rainfall estimate for Thirlmere was approximately 25% higher than for the other two. The estimated populations served at the turn of the century were Manchester 1.10 million, Liverpool 0.97 million, and Birmingham 0.74 million.

The physical data for the three Victorian schemes are shown in Table 2.6 (metric units) and Table 2.7 (imperial units). The sources in which they were found are presented in Table 2.8.

Table 2.6 - Physical data for the three Victorian schemes (metric units)

Metric **Measures**	**Thirlmere** **Reservoir** (One new dam raised existing lake level)	**Lake Vyrnwy** (One new dam impounded the River Vyrnwy)	**Elan Reservoirs** (Original design was for 6 new dams – see numbers below. For Stage 1, three new dams impounded the River Elan.)	**Elan** (After 1952, for Stage 2, one new dam was added to impound the River Claerwen for Full Elan scheme)
Catchment area	4,452 hectares	9,204 hectares	18,842 hectares	
Reservoir area	321 hectares	454 hectares	628 hectares	
Average Rainfall	2591 mm (1877) (later 2159 mm)	1655 mm	1753 mm	
"3 Dry Years" Average Annual Rainfall	2150 mm (1877) (later 1798 mm)	1386 mm	1397 mm	
Storage	37,000 Ml	59,000 Ml	79,000 Ml	99,100 Ml
Drought Yield to supply	227 Ml/d (1877) (later 164 Ml/d)	182 Ml/d	314 Ml/d	341 Ml/d
Compensation	25 Ml/d	61 Ml/d	123 Ml/d	123 Ml/d
Total Drought Yield	252 Ml/d (1877) (later 189 Ml/d)	243 Ml/d	437 Ml/d	464 Ml/d

Table 2.7 - Physical data for the three Victorian schemes (Imperial)

Imperial Measures	**Thirlmere Reservoir**	**Vyrnwy Reservoir**	**Elan Reservoirs (original design)**	**Elan (after 1952)**
Catchment area	11,000 acres	22,742 acres	46,560 acres	
Reservoir area	793 acres	1,121 acres	1,552 acres	
Average Rainfall	85.7 inches	65.2 inches	69.5 inches	
3 Dry Years Rainfall	70.8 inches	54.6 inches	55.5 inches	
Storage	8,135 Mg	12,131 Mg	17,915 Mg	21,800 Mg
Drought Yield to supply	50 Mgd (later 36 Mgd)	40 Mgd	69 Mgd	75 Mgd
Compensation	5.5 Mgd	13.5 Mgd	27 Mgd	27 Mgd
Total Drought Yield	55.5 Mgd (later 41.5 Mgd)	53.5 Mgd	96 Mgd	102 Mgd

Table 2.8 -Physical data for the three Victorian schemes (Sources)

References for physical data	**Thirlmere Reservoir**	**Vyrnwy Reservoir**	**Elan Reservoirs (original design)**	**Elan (after 1952)**
Catchment area.	GH Hill, 1896 Mansergh, 1896	Mansergh, 1896 Discussion	Mansergh, 1896 Discussion.	
Reservoir area.	GH Hill, 1896	Deacon, 1896	Mansergh, 1912	
Average Rainfall.	Mansergh, 1901	Mansergh, 1901	Mansergh, 1896 Discussion	
3 Dry Years Rainfall.	GH Hill, 1896 Mansergh, 1901	Mansergh, 1901	Mansergh, 1896 Discussion. Mansergh,, 1912	
Storage.	GH Hill, 1896	Deacon, 1896	Mansergh, 1896 and Discussion	Birmingham Post, 23/10/52
Drought Yield to supply.	i) GH Hill, 1896 ii) Walters, 1936	Mansergh, 1901	Mansergh, 1896 Birmingham Corporation, 1940	Birmingham Corporation, 1940
Compensation.	GH Hill, 1896.	Mansergh, 1896	Mansergh, 1896 Discussion.	Mansergh 1896 Mansergh 1912
Total Drought Yield.	Yield + Comp	Yield + Comp	Yield + Comp	Yield + Com

2.4.2 Description of the Elan Scheme for Birmingham

In late Victorian Britain, Birmingham was developing into one of the nation's foremost industrial cities and Birmingham Corporation was anxious not to let the lack of water threaten the city's burgeoning economic growth. By 1892, growth in water demand was 3% per annum and the headroom of water supply availability over water demand in Birmingham was rapidly approaching zero. The average annual demand for public water supply was 73 Ml/d (16 Mgd) (Barclay, 1891) and a summer peak demand of 20% above average could add up to a further 14 Ml/d (3 Mgd). The maximum output from local surface and groundwater sources was 87 Ml/d (19 Mgd). More detail about supply and demand prior to the Elan scheme is given in Section 4.2.3.

The opportunities perceived at the time for developing new local sources were limited, perhaps providing for no more than another 10 to 20 years; existing lowland sources were also experiencing an increasing risk of deteriorating raw water quality. The primary conditions identified by Birmingham Corporation were for a new gravity supply of exceptionally good quality, and "there must be a sufficiency for the district 50 years hence at least". (Barclay, 1891) In the recent past, Manchester and Liverpool Corporations had built new remote gravity schemes, and similar proposals were being considered for meeting London's growing water needs.

Thus the Elan impounding reservoirs and aqueduct scheme located in the unspoiled mountains of Mid-Wales was proposed, designed, and constructed for Birmingham Corporation by the civil engineer James Mansergh. The scheme has since provided a plentiful, reliable, clean and inexpensive water supply. Today, whilst at many water abstraction sites in the UK there is debate about the level of environmentally sustainable abstraction, the Elan scheme continues to operate at maximum capacity with its small operational carbon footprint and appears to be taken for granted by all.

The Elan Scheme provides a gravity supply to Birmingham, the highest large city in the UK, and was built in stages to become one of the largest water resources and supply schemes in the country. The general location of the Welsh reservoirs is shown in Figure 2.3. A schematic diagram of the reservoir system is shown in Figure 2.4, and Figure 2.5 is a schematic illustration of the Elan Aqueduct, which links mid-Wales with Birmingham. Figures 2.6, 2.7 and 2.8 are historic photographs of Craig Goch dam, pipeline construction and Frankley reservoir on the western edge of Birmingham. Tables 2.9 and 2.10 summarise the physical data and the stage dates.

Table 2.9 - Summary of physical data for the Elan scheme: Welsh dams and reservoirs

Dam and reservoir	Dam height, m	Dam length, m	Reservoir capacity, Ml	Reservoir area, ha	Reservoir TWL, m AOD*	Date completed	Storage phase
Caban Coch	37	186	33530	202	250.5	1904	1
Pen-y-Garreg	37	161	6050	50	288.0	1904	1
Craig Goch	36	156	9220	88	317.0	1904	1
Claerwen	56	355	48300	263	368.8	1952	2
Total capacity, Ml			99100				

Notes:

*TWL, top water level; AOD, above ordnance datum

Mansergh's original plan for stage 2 was for three reservoirs in the Claerwen catchment

The submerged dam at Garreg-Ddu is within Caban Coch reservoir

Releases are made from Claerwen reservoir for transfer to Caban Coch. These releases use the Dol-y-Mynach tunnel, which was constructed as part of stage 1

Table 2.10 - Summary of physical data for the Elan scheme: Elan Aqueduct, 118 km from Mid-Wales to Birmingham

Construction	Length, km	Size mm	Capacity, Mld	Gradients	Date completed	Supply phase
Tunnels and cut-and-cover	59	~2 m deep ~2.5 m wide	340 (design capacity)	1 in 3000 1 in 4000	1904	1
Siphon pipelines (2 no.)	59	1050 mm dia.	114	1 in 1570 1 in 1760	1904	1
Reinforcement (1 no.)		1500 mm	+136		1920-1939	2
Reinforcement (1 no.)		1500 mm	+114		1949-1961	3
Total	118		364			
Notes: Mansergh's original plan was for six pipelines of 1050 mm dia. Reinforcements were made using a cross-over system to enable incremental increases in capacity Total capacity is approximate, depending on aqueduct maintenance and operation						

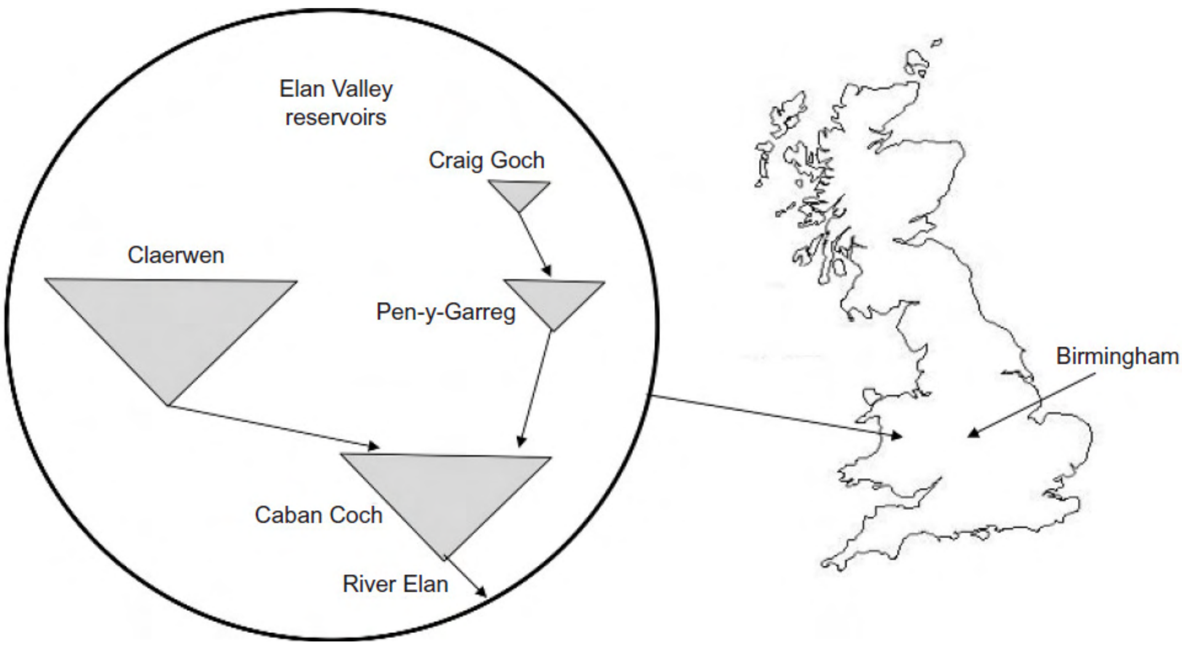

Figure 2.3 – Location of Elan

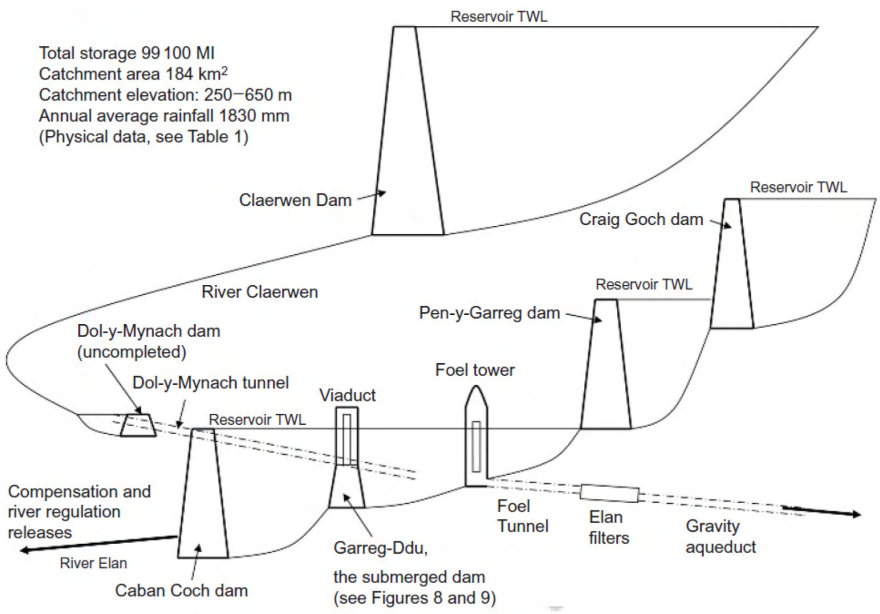

Figure 2.4 – Schematic of the Elan reservoirs

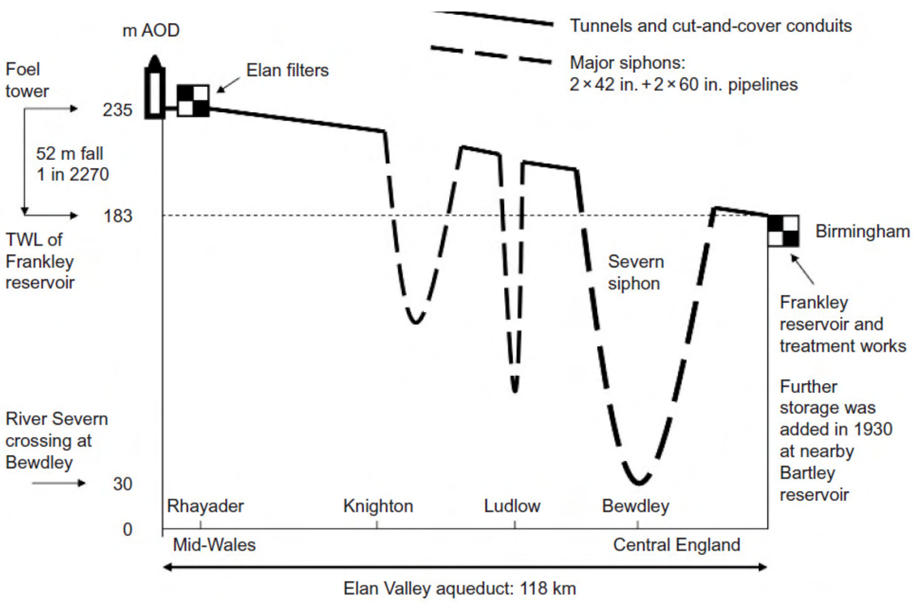

Figure 2.5 – Schematic of the Elan aqueduct

Figure 2.6 – Craig Goch Dam in the early 1930s

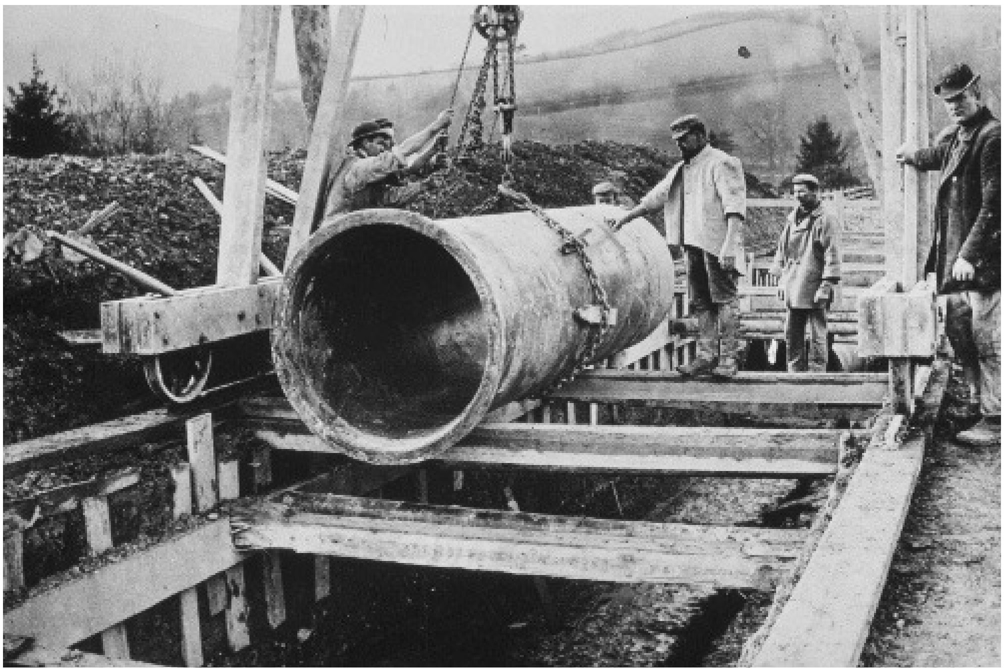

Figure 2.7 – Construction of Elan aqueduct

Figure 2.8 - Frankley reservoir under construction

Figure 2.9 - Foel tower and the viaduct at Garreg-Ddu

Figure 2.10 - The submerged dam at Garreg-Ddu emerges in autumn 2003

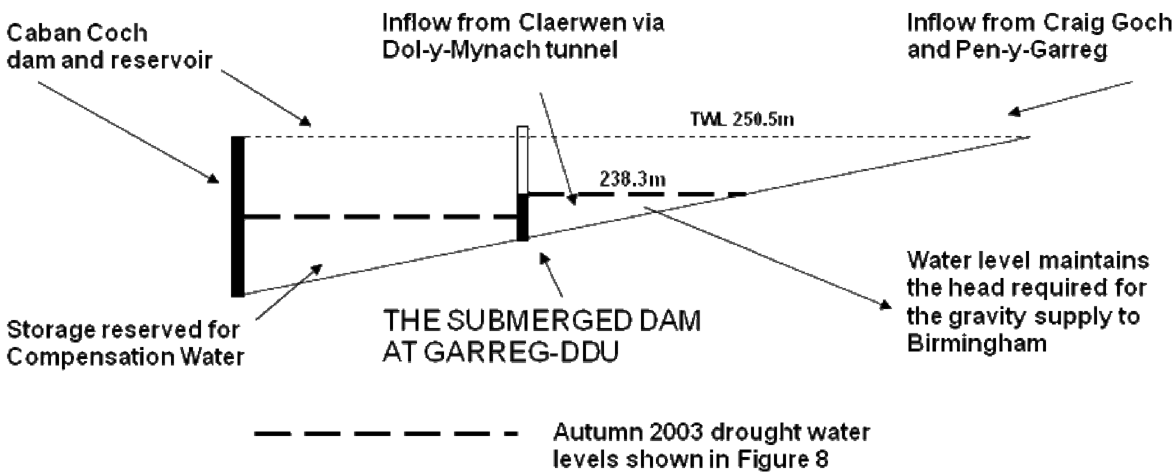

Figure 2.11 - Schematic of the submerged dam at Garreg-Ddu

The Elan scheme is capable of supporting a critical drought year water supply output to Birmingham of approximately 330 Ml/d, and also provides for compensation flows and river regulation support to the River Elan and River Wye. As shown in Table 2.10, the Elan Aqueduct can convey up to 364 Ml/d. Elan will continue to meet the demand from Birmingham's 1.15 million inhabitants well into the twenty-first century, far beyond original expectations.

The evidence presented in 1892 to the House of Commons Select Committee (HoCSC, 1892) to convince Parliament of the need for this controversially large scheme included the 63-year water demand forecast to 1955 formulated by Mansergh. This forecast turned out to be pivotal to the Corporation's case for obtaining the powers to construct the full Elan scheme established in the Birmingham Corporation Water Act of 1892.

As well as proposing a phased scheme, which spread the costs, Mansergh's inclusion of a submerged dam within Caban Coch reservoir at Garreg-Ddu was also influential to obtaining the parliamentary powers. The dam, shown in Figures 2.10 and 2.11, ensures a division between an upper compartment, where a minimum head of 52m at Foel Tower (Figure 2.9) maintains the gravity flow in the aqueduct to Birmingham, and a lower compartment, where the water is available only for compensation and river regulation. The submerged dam was clearly visible in the drought of autumn 2003 (Figures 2.10 and 2.11) when storage at Elan was drawn down to near 30% full. By making the division observable when storage becomes depleted, Mansegh's design gave the scheme credibility.

Mansergh estimated in 1892 that his proposed full scheme and the first phase would be ready in 10 years time at a cost of nearly £4 million. Phase one, having cost £5.8 million, was formerly opened by King Edward VII in July 1904. It consisted of the elements shown in

Tables 2.9 and 2.10, the Foel Tower and primary filtration at Elan Filters. The first phase also included storage of 909 Ml and slow sand filters at Frankley, the storage being enhanced by another 2275 Ml in 1930 at nearby Bartley Reservoir.

James Mansergh died in 1905, and it was left to his sons to record the engineering challenges and solutions for the Institution of Civil Engineers in 1912. (Mansergh EL, Mansergh WL, 1912)

A critical review of the history of the Elan scheme must consider the reasons why the choice was made to develop a water resource in Wales. At the time, the intention was to have water resources available which were sufficient to meet demands in Birmingham for the next 50 years. A fruitful line of inquiry that exposed the reasons for the political tensions before and after the Elan scheme was constructed, was to address the issue of the scheme's location, "Why Wales?"

2.4.3 Why Wales? Support for the Elan scheme

From the technical point of view, Rawlinson's and Mansergh's advice was pivotal to Birmingham Corporation's decision a) to go to Wales, and b) specifically to the Elan and Claerwen valleys. This was the advice to the council in 1871, when water purity was the principal technical driver, and it was same again in 1890, when the council believed that it only had sufficient water to meet demands for the next ten years.

Rawlinson expressed concerns in his paper of 1871, based on the BWCo's experience of using the River Tame, about the medium and long term risks of deteriorating raw water quality of local rivers. He was also of the view that there was insufficient groundwater locally to meet demands for the next 50 years. He considered the River Derwent in Derbyshire and the River Severn, but discounted them both on the grounds of both purity and pumping requirements. He also considered the Rivers Ithon and Teme suggested by Hassard, but thought that the local disruption would be significant. He concluded that within a one hundred mile radius, Elan and Claerwen fulfilled his criteria of quality, quantity (up to 182 Ml/d or 40 Mgd) and elevation.

Although he wrote little, Mansergh's contribution in 1894 to Eustace Tickell's book "The Vale of Nantgwilt" provides us with the evidence that it was the contraction of the Elan river valley at Caban Coch, the opening out of the valleys above it, and the impermeable bedrock, which made it "a comparatively easy problem for a water engineer" to recommend. Elan was judged by Mansergh as clearly the best site (and possibly the only practicable site) for an upland storage gravity scheme to supply Birmingham.

Rawlinson (but not Hassard) had been asked by the Corporation in 1871 to consult Mansergh, and again Mansergh was the consultant in 1890, so it was no surprise that Elan remained the scheme of choice. Mansergh was also clearly of the view that if Birmingham did not move to secure the Elan catchment, then London would step in.

Mansergh's assessment made in the early 1890s about the amount of water which could be made available to supply from Elan is very close to what it is believed today. A 20 year daily rainfall record at Nantgwilt was available to him, and showed an annual average rainfall of 1830 mm/year, some three times the rainfall in Birmingham. He deduced that the 184 sq kms (71 square miles) of catchment could produce an average of 454 Ml/d (100 Mgd) over a three consecutive dry years period assuming 82,000 Ml (18,000 Mg) storage. He split this into 331 Ml/d (73 Mgd) to supply, and 123 Ml/d (27 Mgd) for compensation to the River Wye.

Barclay (1898) provided the definitive summary of the reasoning behind the selection of Wales to provide Birmingham's water supply. Barclay was a member of the Water

Committee, and at least three editions of his book exist; the first being prior to the Birmingham Corporation Water Act of 1892, and the third dated 1898 some six years before opening. On the balance of supply and demand projections, Barclay describes how in 1890, the City Engineer, J. W. Gray, produced 25 and 50 year demand projections of 118 Ml/d (26 Mgd) for the year 1915 and 241 Ml/d (53 Mgd) for 1940. Average demand in 1890 was 68 Ml/d (15 Mgd) and a peak day demand at 100 Ml/d (22 Mgd), with recent growth of 3% per annum. The supplies available were about 91 Ml/d (20 Mgd). The demand forecast was updated in 1892, and the new projection of "probable daily demand for water" for Birmingham showed 305 Ml/d (67 Mgd) for the year 1955, i.e. not far from Mansergh's assessment of what the Elan scheme could support. Hence the city believed it had the justification for the full scheme.

Mansergh not only saw the site for its utility, but also an opportunity to create something of beauty which enhanced the landscape. Its popularity as a place to visit has over time meant that the reservoirs (or lakes as they were first called) have become accepted locally and regionally as beneficial.

Just before World War 2, a drought in 1937 gave the impetus to constructing the second tranche of storage in the Claerwen valley. Construction was due to start on Claerwen dam in 1939, but because of WW2, the start was delayed until 1946. Claerwen Dam was completed in 1952 apparently without opposition. A supplement to the Birmingham Post issued on the opening day (Birmingham Post, 23 October 1952) celebrated the young Queen Elizabeth's visit to officially open the dam, and carried articles extolling the foresight of Birmingham and Mansergh in creating such a wonderful asset for the city.

2.4.4 Opposition to the Elan scheme

Double Service Water Committee (1892) advocated groundwater for domestic supplies, and local river water for street cleansing, and raised issues regarding the cost, asserting that their solution would cost only one tenth of the Welsh scheme (there are no workings in the paper). In addition, the document raised objections to the abandonment of the existing sources – especially the constant and mineral rich groundwater. It was believed that the fast rising water demand was in part created by the Water Department in declaring 4,600 private wells unfit to drink “at the very time Birmingham was considered one of the healthiest large towns in England”. Altogether, Double Service Water Committee (1892) raised 16 technical, economic and political reasons for opposing the Elan scheme, and the authors were unable to mount a successful challenge to the Corporation’s position.

Popular opposition to the scheme was expressed through cartoons which appeared in Birmingham’s “Town Crier” magazine. Figure 2.12 “Wells not Wales” captures the mood of discontent over the cost, and also concern for water quality about the reaction of upland water on lead pipes. The face of the robed figure pointing to Wales bears a likeness to Mansergh.

During the period of construction for stage 1, the local newspaper covering Rhayader (The Brecon and Radnor Gazette) displays remarkably little local opposition to the scheme. It was seen as a source of income, improved water supplies would be provided, and it was a matter of great local pride that King Edward VII was coming to perform the opening ceremony.

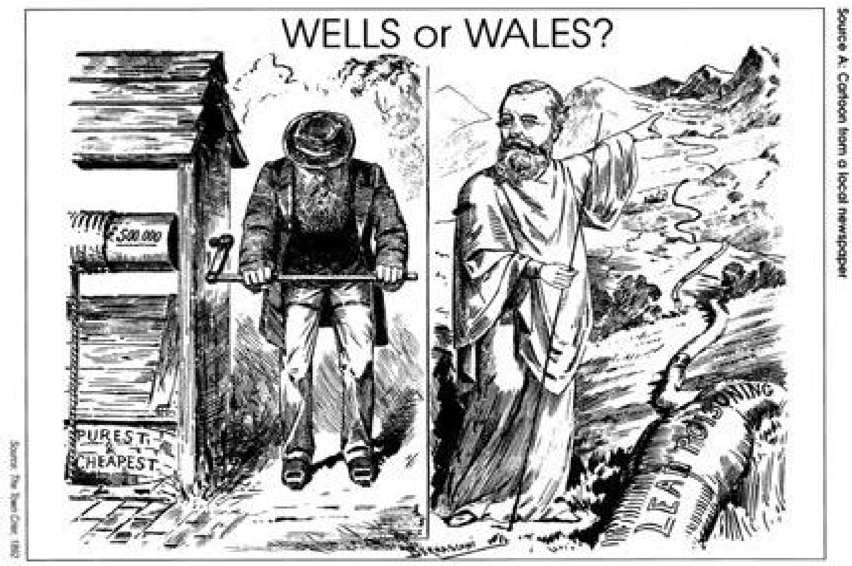

Figure 2.12 - Wells not Wales cartoon, from Birmingham's "Town Crier" magazine 1892

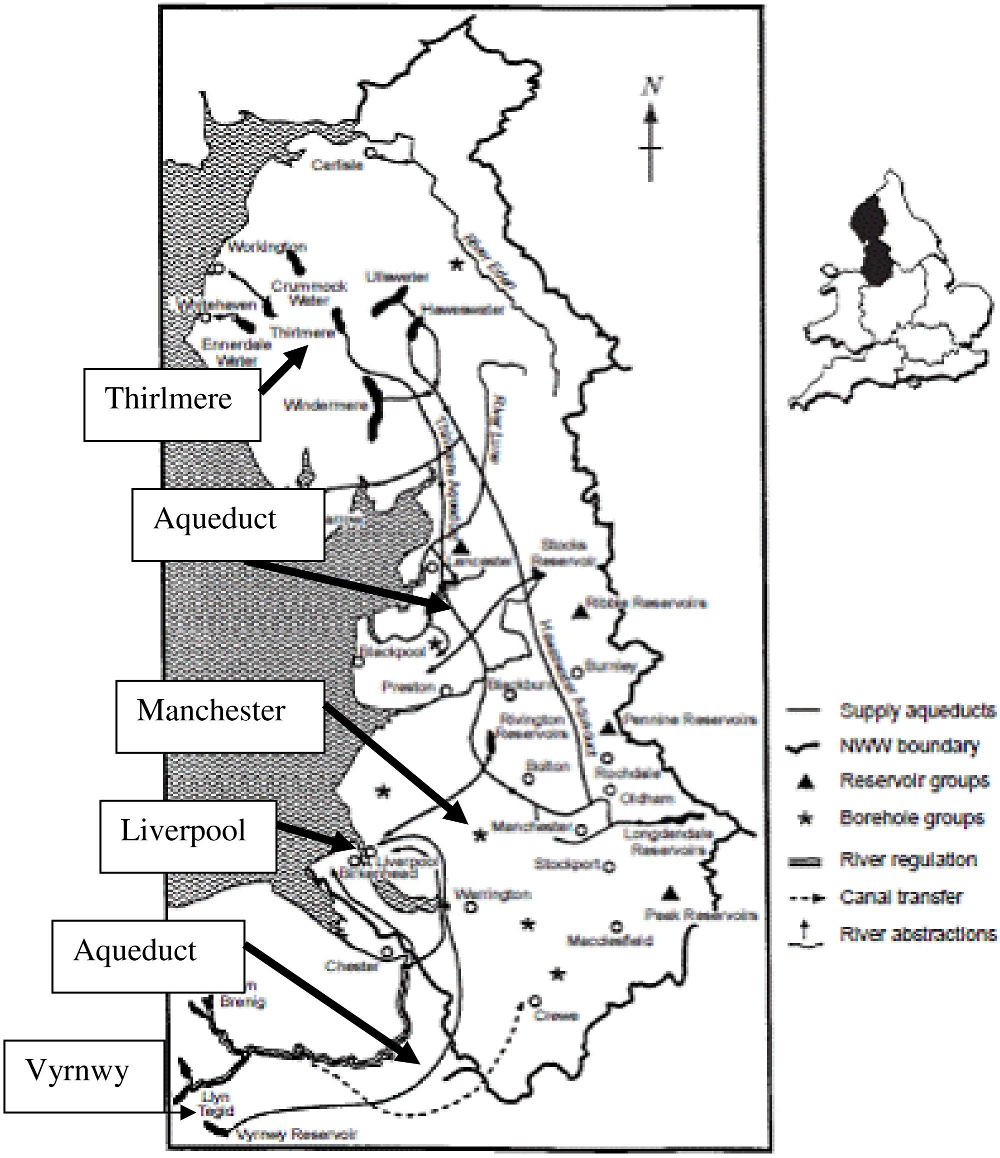

Figure 2.13 - Schematic of strategic links in North West England

2.4.5 Description of the Thirlmere Scheme for Manchester

The Manchester Corporation Waterworks Act of 1879, which provided the powers to construct Thirlmere was the first of the three schemes under review to be authorised by Parliament. The scheme differed significantly from the other two by being an enlargement of an existing natural lake in the Lake District of England; the reservoirs at Vyrnwy and Elan are bodies of water created by new dams in steep sided rural Welsh valleys. Thirlmere is located in the upper half of the schematic Figure 2.13 near the centre of the Lake District, and is connected by a gravity aqueduct 154 kms long to Manchester.

To raise the level of Thirlmere, Bateman designed a new masonry dam some 261m (857 feet) long located at the northern end of the existing lake, as shown in Figure 2.14 (b). The new dam raised the lake level by 15.2 metres (50 feet), and more than doubled the surface water area of Thirlmere from 133 hectares (328 acres) to 317 hectares (793 acres). The additional body of water of 37,000 Ml (8,135 Mg) between 162m (533 feet) and 178m (583 feet) above OD was made available for supply by a gravity aqueduct 154 kms (96 miles) long running south to Manchester. Five pipelines each with a capacity of 45 Ml/d (10 Mgd), and 227 Ml/d (50 Mgd) in total, were planned to be built in stages as required (Harwood, 1895). The castellated architecture of the draw off tower is shown in Figure 2.14a.

To protect the existing lake, there was a condition in the Act of 1879 that no water was to be abstracted to cause Thirlmere to fall below its original level. In the early years of the scheme, whilst demand had yet to grow to exceed the first pipeline capacity of 45 Ml/d (10 Mgd), the lake level was raised by a maximum of 6 metres (20 feet).

Two years after the scheme was opened, Hill (1896) recalls the intended scale of the scheme, and an important data issue:

"In 1878, when the Bill was before Parliament, there were no records of the rainfall upon this drainage-area, it therefore had to be estimated by the examination of the returns in other parts of the Lake District. The quantity of water obtainable for the city was, after allowing 5,500,000 gallons per day as compensation water to the river, assumed at about 50 million gallons per day."

In the years that followed, the collection of local rainfall data showed that Bateman's assumption of the drought yield to supply of 227 Ml/d (50 Mgd) was too high (Holme Lewis, 1921). Walters (1936) reported that the drought yield figure was revised to 164 Ml/d (36 Mgd), but did not disclose who made the revision, and when. The uncertainty for the design of Thirlmere introduced by not having accurate rainfall data was significant, and the principal implication of this for Manchester Corporation was that another major water supply scheme (which turned out to be a similar scheme using a neighbouring lake at Haweswater) would be needed at an earlier date than planned.

Bateman's over-estimated drought yield number for Thirlmere was peer reviewed in the year that the scheme first went before Parliament. The discussion of the review at ICE was led by Mansergh (1878), who remarked under the heading of "Droughts":-

"Without going further into figures, it is pretty clear that all the circumstances are very favourable for the collection of a large quantity of water:-

1st The rainfall is very great;

2nd The loss by evaporation and absorption is small;

3rd The droughts are short;

4th The storage capacity is large.

We may safely concur with Bateman's opinion that 50,000,000 gallons (227 Ml/d) may be taken to Manchester after making a fair provision for the discharge of compensation water to the river." The four "very favourable" circumstances led to an opinion where there was little hard data to support the 227 Ml/d (50 Mgd) number.

The attempt made to estimate the average annual rainfall for the Thirlmere catchment is instructive. Using just 10 months data from a single rain-gauge in the catchment, Bateman's estimate was made of the average annual rainfall at 2,590 mm (102 inches).

The average rainfall figure used in this peer review started with an estimate for the year of 1877 at 3,225 mm (127 inches). Then one fifth was deducted as 1877 was 20% wetter than the mean annual figure for rain-gauges "over a long series of years in this district" to provide a revised average annual estimate of 2,590 mm (102 inches).

After 18 years with local rainfall data, Mansergh (1896) stated that the mean annual average rainfall figure for the Thirlmere catchment was now 2,160 mm (85 inches), and the three dry years experienced in the mid 1880s was 1,803 mm (71 inches). Similar numbers of 2,177 mm (85.7 inches) and 1,798 mm (70.8 inches) were reported again by Mansergh (1901). By chance, a 30% difference between the 1878 annual average rainfall estimate of 2,590 mm, and the three dry years average in 1896 of 1,798 mm, is similar to the yield reduction from 227 Ml/d (50 Mgd) to 164 Ml/d (36 Mgd) is 28%.

Symons, from a meteorologist's perspective, thought at the time that the lengths of droughts in the Lake District lasted a maximum of only two months. This view conveyed the idea that in upland areas, reservoirs will be more resilient to drought than those at lower elevations. We know now, but they did not know then, how to develop operating rules to cope with droughts of different lengths and intensities.

a).

b).

Figure 2.14 - a). Thirlmere draw-off tower and b). Thirlmere dam

2.4.6 The Thirlmere Defence Association

Opposition to the Thirlmere scheme was organized by the Thirlmere Defence Association (TDA), which was one of the first examples in Britain of an environmental pressure group. In 1877, one year before the Thirlmere Bill went before Parliament, the TDA identified that “the lake country belongs in a sense, and the widest and best sense, not to a few owners of mountain pasture, but to the people of England” (TDA, 1877.) Ritvo (2003) points to even wider interest from lovers of the Lake District from throughout the English speaking world who wished to resist, in the TDA’s words, “the industrialization” of Thirlmere.

The TDA (1877) argued that the proposal was unjustifiably large, and smaller alternative schemes nearer to Manchester were better matched to meet rising demands for the next 20 years. There was no explanation as to why a horizon of 20 years was chosen. For a forecast, the TDA’s estimate of the current population supplied of around 800,000 would be assumed to grow at the current rate (about 2% per annum) to c.1,125,000 by 1897. The total demand 20 years hence in 1897 would be 128 Ml/d (28.1 Mgd), which was arrived at by assuming a “maximum” per capita rate of 25 gallons per head per day. Since Bateman believed the Longdendale source to yield 25 Mgd, the TDA argued that the additional 50 Mgd from the proposed Thirlmere scheme “would be sufficient to supply the whole County of Lancaster” with a population of 3 million. The Corporation’s aspiration, the TDA rightly contended, was to sell water to new customers.

There was criticism of Bateman’s approach to giving evidence to the House of Commons Select Committee. “He declines to be bound by a single statement in any previous reports, however solemnly made at the time, should such statement conflict with his present assertions. Human wisdom, it seems, so imperfect and uncertain 30 years ago, has now, in the very nick of time, attained perfection and certainty” (Credat Judeas, 1878). Bateman’s dismissal of alternative schemes was "magisterial", and "additional proof that sturdy semi-sarcastic assertion is often more efficacious than argument". Bateman's standing as the leading water engineer of his generation, and the inability of the TDA to present substantive technical arguments, were pivotal to Manchester Corporation's acquisition of the powers in 1879 for the Thirlmere scheme.

2.4.7 Description of the Vyrnwy Scheme for Liverpool

Lake Vyrnwy is situated at the headwaters of the River Vyrnwy, which is a tributary of the River Severn. Physical data is given in Table 2.6, and pictures of the lake and draw-off tower are shown in Figures 2.15a and 2.15b.

The potential of the Vyrnwy valley for a water resource was first identified by Bateman in the late 1860s. The exact position of the dam was chosen by Deacon as the most suitable ground conditions for watertightness, and Deacon's 1896 paper presented to the ICE provides information about the construction of the whole scheme.

Even though the need for a new water resources scheme was clear, the proposals were taken to Parliament because of concerns raised by the owners of the Bridgwater Canal for the planned arrangements for the aqueduct crossing under the canal. Once this issue had been resolved, the 1880 Vyrnwy Works Act authorised the construction of the dam and the aqueduct.

The drought yield is 182 Ml/d (40 Mgd), and the piped sections of the 107 km aqueduct were designed to carry this flow in three pipes of equal discharge volumes. The first pipe could carry rather more than one third at 68 Ml/d (15 Mgd) (Parry, 1899), and was deliberately over-sized to accommodate problems of encrustation inside pipes.

a).

b).

Figure 2.15 - a). Lake Vyrnwy, and b). Vyrnwy draw-off tower

The compensation water arrangements were also a matter for debate. The provision of "freshets" on fixed dates from the reservoir during summer months was agreed for sustaining fisheries. Those with interests in the River Severn as far down as Gloucester were placated with monetary compensation.

2.4.8 Liverpool; Intermittent Supplies 1865 to 1873

Well before the Vyrnwy scheme, water supplies in Liverpool from 1865 to 1872 were intermittent, with many consumers having to cope with no running water for up to 10 hours a day. This level of service was due to the conjunction of insufficient water resources, growing demand, and a high level of leakage and waste. The challenge for the Corporation's water engineers was clear; the next water resource would take a long time to deliver, and the city was losing business because of lack of water. The innovative answer was provided by Deacon to develop a method of reducing demand by targeting the Corporation's resources to areas with the most leakage and waste.

By comparison, consumers in late Victorian Manchester and Birmingham fared rather better than those in Liverpool. A reflection on what was called then "The Evils of an Intermittent Supply" (Parry, 1881) were generated by water standing in uncovered cisterns becoming badly polluted by dirt and refuse. Also, the dust jacket of G. M. Binnie's "Early Victorian Water Engineers" (Thomas Telford, 1981) says that the book tells "the story of the grudging acceptance of the need for constant unpolluted water supplies and the many problems, human and technical that had to be faced in meeting that need". Intermittent water supplies were commonplace in early Victorian urban Britain, where the poorer districts were either not supplied at all or only intermittently from standpipes or water carts.

The questioning of the acceptability of intermittent supplies gained momentum with the Health of Towns Commission (1844). The Commission's proceedings were dominated by Sir Edwin Chadwick, as he came to realise that "to provide drains and sewers was not enough; there must also be a constant water supply available in every tenement." (Binnie, 1981).

Binnie recounts conflicting evidence about the impact of intermittent supplies presented to the Health of Towns Commission. Thomas Wicksteed, Engineer of the East London Waterworks, argued against a constant supply at high pressure on the grounds of expense, in that larger diameter pipes would be needed to meet the increase in demand, and that lead piping in poor areas would soon disappear. This argument was countered by Thomas Hawksley from recent experience of constant supplies for domestic and fire-fighting purposes in Nottingham. He correctly contended that not all houses make their maximum demand for water at the same time, so large diameter pipes were not needed, and the lead pipes also remained in place. Hawksley's view was that a pressurised water pipe acted as "a police on the pipe". A year later in 1845, in a letter to Chadwick, Hawksley alleged that the London Water Companies delivered an intermittent supply as the only way they could manage with inadequate water resources (Binnie, 1981).

In 1852, a scheme for Liverpool was designed by water engineer James Simpson to provide a high pressure system solely for fire-fighting; he was against extending the scheme into a constant supply for all purposes to all the inhabitants. Simpson had written that that it would be expensive and useless: "what dependence can we place on it? I answer, at once, little or none, because its thousands of pipes and cocks in private places are not susceptible of hourly and immediate inspection and control" (Binnie, 1981).

The concern expressed by Simpson was for the increase in the amount of waste and leakage rising to the point where the availability of water resources dictated that a constant supply was unsustainable. His concern turned out to be prophetic. As was noted in Section 2.2.7, Liverpool first received a constant supply service in 1858, but was forced to reinstate intermittent supplies from 1865 to 1872 (Parry, 1881). Parry followed Deacon to become Liverpool Corporation's Water Engineer. The time had arrived for water engineers to follow Hawksley's maxim that supplies should be "Pure and Constant".

2.5 Modern Context

2.5.1 Government Vision

The Government documents presented in Table 2.11 below are those which were consulted for this project. Three of these documents are particularly visionary. First, the 1963 Water Resources Act, which enabled national and local long term water resources planning, and brought together for the first time issues of river water quantity and quality (Tebbutt, 1971). Second, the plans for England and Wales developed and published by the Water Resources Board in 1973, which proposed a series of major water resources schemes and inter-basin transfers to meet projected demands in 2001. Third is Future Water (2008) that presents the Government's aspiration of reducing domestic per capita demand by 20% in order to reduce abstractions, and thereby make a significant step towards the delivery of sustainable water environments. The emphasis on demand management in Future Water is in contrast to the strategic water resource scheme options suggested by the WRB, and refined in Nature's Precious Resource report from the National Rivers Authority (NRA) in 1994.

One year after the NRA report, the summer drought of 1995 occurred in England and Wales, which continued in some areas into the following winter. The Government response was an

"Agenda for Action" that was published in 1996 by the Department of the Environment. This report contained actions for all the major stakeholders in the planning and use of raw water. They are set out in Section 6.2.

The next notable drought to cause anxiety was a series of dry winters in the early 2000s that affected South East England. Water levels in the chalk aquifers were low due to the lack of winter recharge, and consequently base river flows were low. Flows in the River Thames were adversely affected, and domestic customers in south-east England were banned from using hosepipes and sprinklers in the summer of 2006.

There was a pivotal change in 2007 for the WRMP process (covered in more detail in Section 2.5.3) with the mandatory introduction of a public consultation process for the Draft WRMP, followed by a statement of consultation responses report to Defra. If these responses were not acceptable, the Secretary of State has the powers to call a Public Inquiry. On 3 August 2009, Thames Water was informed on that there would be an Inquiry into their revised DWRP of September 2009, as shown in Table 2.11.

Table 2.11 - Government documents consulted

Date	Source	Title	Comment
1960	Ministry of Housing and Local Govt.	River Severn Basin, Hydrological Survey.	Set 727 Ml/d (160 Mgd) as the minimum flow of the River Severn at Bewdley to dilute 91 Mld of sewage effluent from the Black Country joining the Severn at Stourport. Bradford (1980).
1963	MHLG	Water Resources Act 1963	Major legislation that created the Water Resources Board and River Authorities with powers to undertake long term planning.
1973	Water Resources Board	Water Resources Plans for England and Wales	Proposals made with costs for major reservoir developments and inter basin transfers including the Craig Goch scheme for London.

Date	Source	Title	Comment
1994	National Rivers Authority	Water, Nature's Precious Resource	Environmentally sustainable strategic water resources scheme options for E+W.
1996	Department of the Environment	Water Resources and Supply: Agenda for Action.	Post 1995 drought actions for Govt, Regulators, water companies, consumers.
2007	Government legislation	Parliamentary WRMP and Drought plan Directions for water companies	Water company plans are made statutory, including public consultation.
2007	Environment Agency	Water resources planning Guideline (and subsequent revisions)	Guidance to water companies for WRMP.
Feb 2008	Defra	Future Water.	Government vision for the water environment and aspiration for reducing domestic use to 130 litres per head per day by 2020.
Mar 2008	EA	Draft of Water for the people and the Environment	Public consultation document
June 2008	EA	Climate change Adaption Strategy;	
2008 to 2010	EA module reports	Water resources in E+W, current state and future pressures. Managing water in SE England. Climate change and river flows in the 2050s. Planning ahead for an uncertain future; (i) in the 2050s; (ii) water in the 2100s.	These reports were produced to explain EA thinking to other parts of Government, and to add to the WRMP Guidance for water companies.
Mar 2009	EA	Water for the People and the Environment, final report	Areas of Water Scarcity, and Restoring Sustainable Abstractions action sites identified
3 Aug 2009	Defra	Letter to Thames Water Utilities (TW) to announce Public Inquiry into TW Draft WRMP	Key documents to and from EA and Defra to TW are covered in Table 2.13.
2009	EA	River Basin Management Plans	Plan for the Thames catchment issued in December 2009.
Dec 2009	Defra	Independent review of charging (the Anna Walker report)	Charges to stay as per household, too difficult to charge per person.
Mar 2010	EA	EA strategy; water resources action plan for E+W	
Summer 2010	EA, Ofwat evidence	Thames Water evidence.	Public Inquiry held in Oxford: started June, ended August 2010.
Dec	Planning		Recommendation to SoS to reject

Date	Source	Title	Comment
2010	Inspectorate		TW's revised Draft WRMP.
1 Mar 2011	Defra	Decision letter to TW that the SoS had accepted all 25 of the Planning Inspectors recommendations, and proposed further work on scheme options.	TW Draft WRMP deemed not to meet Directions, and 100 million cubic metres storage for an Upper Thames Reservoir rejected.

The documents that cover the engagement of Thames Water with government before and during the Public Inquiry appear in Table 2.15.

2.5.2 Demand forecasting developments in the 20th century

Since 1975, there has been huge technical development in the methodologies for making long term demand forecasts. Estimates of component water use based on measurement are now made for the individual components that make up demand (see Appendix C). The milestones when methods and data have improved are summarised in Table 2.10. Birmingham is used as the example.

Table 2.12 - Milestones of water demand forecasting for Birmingham, 1890 to date

Milestone **Number, and dates**	**Forecast made by:-**	**Time Horizon of forecasts:-**	**Evolving Demand Forecasting Approach (for different timescales as required, e.g. Average Year, Dry Year, Peak Week) :-**
1. Early 1890s	James Mansergh for Birmingham Corporation (Justifies the storage size of the Elan scheme)	60 years (to 1955)	Mansergh's extrapolation of total demand trend uses "Decremental Ratio of Increase" (Barclay, 1898, and Section 4.3.6 for detail) Range of over-estimated population forecasts made by judgement.
2. Mid 1960s to early 1970s.	Water Resources Board (WRB,1973) (National water resources plans for Government, see Table 2.11)	30 years (to 2001)	More systematic, but still over-estimated, population forecasts. Extrapolation of total demand, and separate forecasts made for metered and unmetered use. Leakage treated as part of unmetered demand, and also extrapolated. (Sharp, 1967)
3. Mid 1970s to late 1980s	Severn Trent Water Authority (Demand forecasts are made that are significantly lower than WRB forecasts)	20 years (to 2001)	New data from domestic water use studies in Malvern and Mansfield (Thackray, Cocker, Archibald, 1978). Metered use forecast for disaggregated industrial and commercial sectors (Thackray, Archibald, 1981: Archibald, 1983). STW's Domestic Consumption Monitor (DCM) of households paying unmetered water bills started in 1984. First modern attempt at quantifying micro components for domestic use (National Water Council, 1982). Leakage estimated as a residual of total supply.
4. Mid and late 1990s	Severn Trent Water (National Rivers Authority disbanded; responsibilities passed to new EA)	25 years (to 2021)	Econometric modelling used for metered use forecast. Unmetered household water use trends derived from STW's DCM data. Leakage data and information collected at district metered area level to enable "active" leakage control. (DoE, 1980)
5. After 2000 to the Present Day	Severn Trent Water (All water companies required to use EA Guidelines; EA responsible to Defra for regional water planning)	25 years (most recent is 2010 to 2035)	Micro-components used to produce unmetered domestic forecast. Another DCM of metered domestic consumers set up by STW allows further disaggregation in the forecast. Climate change impact on demand. Water efficiency savings modelled. Leakage forecast linked to asset renewal.

Three items in Table 2.12 are expanded below:

1. At 60 years, the late Victorian demand forecast time horizon is double those used over the past 40 years. The confidence that James Mansergh had in Birmingham's continued burgeoning economic development in the 20th century is reflected by the 60 year horizon. There is critical analysis of Mansergh's forecast in Chapter 4.

2. A step change in water demand forecasting, both of a new component based methodology and the acquisition of data, was started at Severn Trent Water Authority in the mid 1970s. A step change in the forecasts themselves also occurred as Britain had entered a post-industrial age where water demand from traditional heavy industries was in rapid decline. Thus the new water demand forecasts were considerably lower than those produced by WRB, and led to the indefinite deferral of the proposed scheme to increase the storage of Craig Goch reservoir in the Elan system (Halcrow, 1973) for a to supply London via the River Severn and River Thames. This idea was first suggested in the 1860s, and the issue of water transfers from Wales to London was raised in Parliament in the early 1890s at the time when Birmingham Corporation was seeking the Parliamentary powers to construct the Elan scheme. Hansard (1892) records the discussion in which the issue of water from Wales should be treated first as a national question, whilst other objectors to the Birmingham scheme believed that the needs of the metropolis should come first. Sir Joseph Bailey (MP for Hereford) correctly identified a key institutional problem that "London is not allowed to make up its mind as there is no public body which is allowed to speak for London". The argument made by Joseph Chamberlain based on the urgency of Birmingham Corporation's need ultimately prevailed following scrutiny by a Select Committee.

3. Present day water demand forecasts made by the water companies in their Water Resources Management Plans are expected to follow the EA Guideline (EA, 2008). Thames Water Utilities deviated from the Guideline, and at Public Inquiry in 2010 (see Section 6.5), the company was judged to have failed to provide enough evidence to justify the deviation, which was an inclusion by the company of a “long term risk” factor of 100 Ml/d beyond 2035. Although not legally binding, in practice the EA Guideline now has an equivalent status.

2.5.3 Deployable Output replaces Reservoir Yield

A major improvement in the way water resources and supplies are accounted for took place in 1997. This improvement formed part of the industry’s response to the Government’s “Agenda for Action”, which was triggered by the experience of drought in 1995 (see Section 6.2).

The traditional reservoir yield figure in the 20th century represented the output that could be sustained with a probability of failure, usually of once in 50 or 100 years. It had served the industry well; however, with the greater interconnection of sources, reservoir yield had become a less fundamental statistic to water resources planners. Increasingly flexible water supply networks were constructed that enabled reservoir, river and groundwater sources to be operated conjunctively. There were other constraints on resource use that were not reflected in reservoir yield, and many water companies had computer based water resource and supply simulation models with long historic data sets that could test the impact of constraints.

Deployable Output became the new parameter, and it is defined by the EA in the glossary (Appendix A) as “The output of a commissioned source, or a group of sources….constrained (if applicable) by:

- Abstraction licence (the terms and conditions thereof).
- Pumping plant (capacity) and/or well/aquifer properties.
- Raw water mains (capacity) and/or aquifers.
- Transfer and/or output mains (capacity).
- Treatment (capacity and capability)
- Water quality (raw water quality, blending constraints)”.

From the total Deployable Output for a Resource Zone (defined in the glossary as “The largest possible zone in which all resources, including external transfers, can be shared and hence the zone in which all customers experience the same risk of failure from a resource shortfall”), an estimate of Outage is subtracted, and the resulting figure is called Water Available For Use (WAFU). The supply and demand balance diagrams produced by water companies for their WRMP use the appropriate critical demand period for the Resource Zone (e.g. Dry Year, or Peak Week), and the corresponding WAFU. Table 2.13 summarises the key issues that add to the uncertainty of the future WAFU available of the three principal types of water resource.

Table 2.13 - Summary of water resources types that contribute to WAFU on the "supply" side of the Supply-Demand balance in a Resource Zone

Water Resources Types	Impounding Reservoirs	River Abstractions	Groundwater Abstractions
Water resources and supplies planning issues	Direct supply reservoirs (eg Elan for Birmingham). Reservoirs for river support (eg. Llyn Clywedog supporting low summer flows in the River Severn.)	River intakes, often pumped into raw water storage prior to treatment (eg King George reservoirs filled from the River Thames for London)	Boreholes and wells. (eg Chalk and Limestone in south and east of England, sandstone in parts of central and northern England.)
Environment and Quality	Many existing reservoirs have become important scientific and recreational sites.	EU Water Framework Directive requires rivers to be of good ecological status. Full impact not yet known.	EA's "Restoring Sustainable Abstractions" policy, i.e. reducing existing abstractions
Climate Change	More wet winter refill, less inflow in dry summers. Simulation models used to vary inflows to assess the impact on Deployable Output.	Flows reduced in dry summers. Especially at risk are rivers with already low base flows.	Generally more drought resistant than surface sources. Possible higher winter recharge
Long-term Outlook	New reservoirs politically unpopular. Dry year output from existing reservoirs may become less reliable.	Potentially the most significant reductions in the water available for public supply.	Reductions in annual licensed quantities likely. Aquifer storage and recovery can increase output. Very site specific.

2.5.4 Water Resources Management Plan (WRMP) and Resource Zones

The WRMP is produced and updated by every water company at five-yearly intervals, in which the company presents and justifies its preferred plan at annual intervals for 25 years. The process for developing the plan is set down by the EA, and a simplified process diagram is shown in Figure 2.16.

Draft and Final WRMPs are cast by all water companies at Resource Zone level. Data tables are required by the EA that cover the detailed supply and demand components for each Resource Zone.

Data acquisition for this project has been aided by Birmingham being a single resource zone in the Severn Trent Water WRMP, and likewise London is a single resource zone in Thames Water. United Utilities have cast Liverpool and Manchester into a single large resource zone which covers nearly all of the company's supply area; Figure 2.13 shows a schematic.

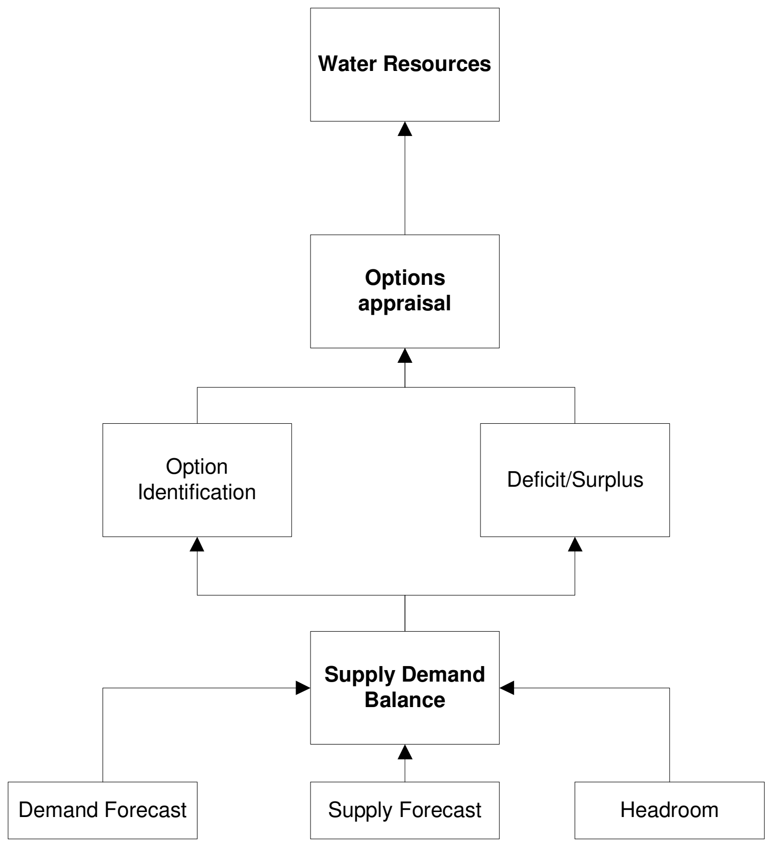

Figure 2.16 - Components of a Water Resources Management Plan (from EA Guideline April 2011)

2.5.5 Uncertainty in Target Headroom

The EA defines target headroom (shown as “Headroom” in Figure 2.16) as the buffer between supply and demand to cater for specified uncertainties. The optimum position in the plan for a Resource Zone is to have a least cost plan where the actual headroom equals the target headroom throughout the plan period. Figure 2.17 is an indicative example showing how actual headroom can be above, equal to, and below target headroom over the plan period.

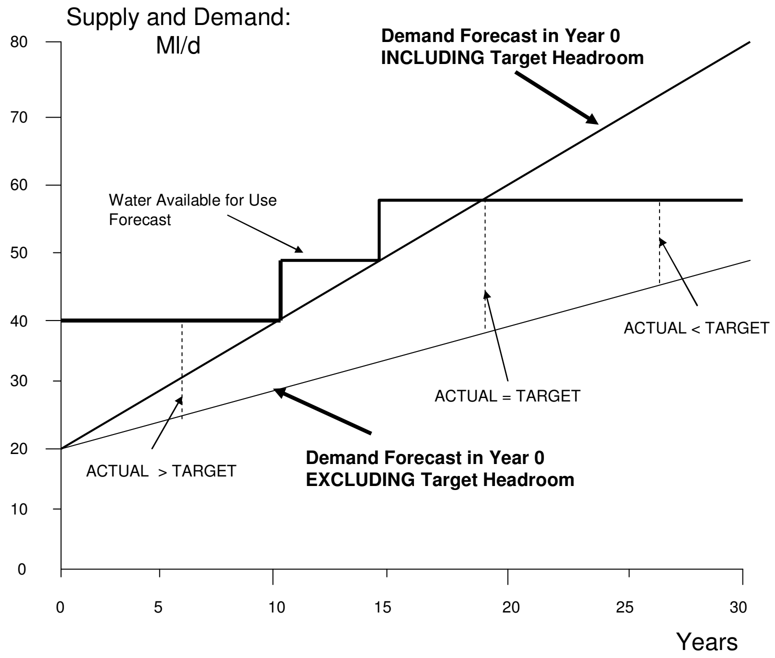

Figure 2.17 - Actual and Target Headroom: Indicative example

In this indicative example in Figure 2.17, there is a forecast made in year 0 for supply (Water available for use, or WAFU) that shows two additions of about 10 Ml/d each in years 10 and 15. There are two forecasts of demand, one with and one without the buffer to cover uncertainty. When the target headroom is added to the demand forecast, for the first 20 years, the actual headroom is either greater than or equal to the target headroom, and the supply demand balance is acceptable. However for years 20 to 30, the Year 0 plan needs to address the increasing shortfall.

The modern probabilistic target headroom methodology (UKWIR, 2002) enables a link to be made between uncertainty (the amount of target headroom required) and risk to the company's chosen level of service. This issue is returned to in Chapter 6.

2.5.6 Today's forecast supply and demand data and information

The water companies are required by Ofwat and EA to complete a series of data tables with a substantial amount of detail about supply and demand to accompany their Draft and Final WRMPs. Now that water companies are legally obliged to consult publically, and to make the narrative and data tables available on the internet, there is a large amount of data and information available for research. The principal data table used in this project is from the Thames Water revised Draft WRMP (2009), with the reference of WRP-FP; Final Planning Supply and Demand Components for the Dry Year in the London Resource Zone, and using the company's levels of service. The narrative contains the assumptions used by the company for the forecasts, and information on sizes, dates, and costs about the company's preferred scheme options.

2.6 Thames Water proposed UTR for London

2.6.1 London and Levels of Service

Thames Water Utilities is the largest water and sewerage company in the UK serving over 13 million people in London and the Thames Valley. About 8 million are served in the company's London Resource Zone, which is shown in Figure 2.18, and has a daily average total demand of near 2000 Ml/d.

London's principal source of water is the lower River Thames upstream of Teddington Weir. The Lower Thames Operating Agreement (LTOA) in combination with abstraction licences determines how much water can be abstracted from the Lower Thames, and informs the introduction of water use restrictions in London during a drought. The drought of 2005 and 2006 tested the effectiveness of the LTOA as a drought management tool. The results of a review of this Agreement will impact both on the WRMP and the Company's Drought Management Plan. The most significant issue for supply is the ecological impact on the water environment of the Lower Thames abstractions, and for demand, the correct application of the most up-to-date assumptions on demand savings during drought periods.

All companies now tell their customers the level of service for which the company plans. The levels of service set by Thames Water are given in Table 2.14, which shows the frequency with which the company believes it needs to impose from time to time for different types of water use restrictions during periods of water shortage. These levels of service are applicable to London, and as the severity of drought increases, so do the actions taken by the company that reduces the risk of future supply failure, and minimizes environmental damage.

Table 2.14 -Thames Water; Levels of Service to customers in droughts (Source: Thames Water, revised Draft WRMP, September 2009)

Level	**Action**	**Frequency (drought severity)**
1	Media campaign, additional water efficiency campaign, enhanced activity and restrictions to reduce risk to water supply.	One in five years
2	Enhanced media campaign, customer choice / voluntary constraint, sprinkler ban.	One in 10 years
3	Hosepipe ban, Non essential use ban, Drought Orders	One in 20 years
4	Severe water rationing	Never

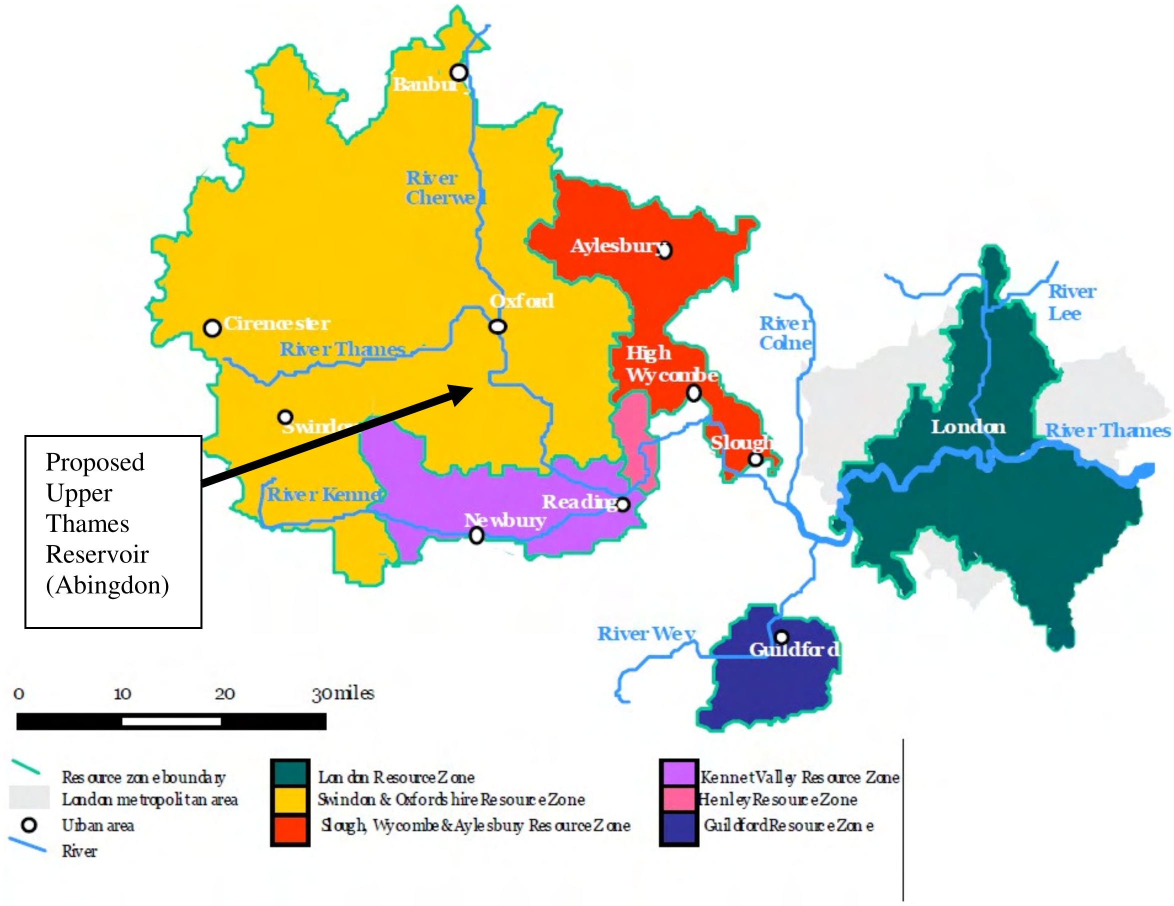

Figure 2.18 - Thames Water Resource Zones (from Thames Water Resources Management Plan, 2009)

2.6.2 The 2010 Public Inquiry

By calling for a Public Inquiry into Thames Water's revised Draft WRMP (September 2009), the Secretary of State started a process that demanded engagement between the EA and TW, and a great deal of preparation.

Two issues of particular interest for the research reported in this thesis were:

1. The approach taken by the company that introduced "long term risk" to cover particular uncertainties beyond the plan horizon year of 2035.

2. The reasons given by the Planning Inspector (Wendy Burden) to reject the Thames Water plan, and thereby company's preferred scheme, which was for 100 Mm^3 of new raw water storage near Abingdon, Oxfordshire (i.e. the UTR) in 2026.

The EA led the case for the objectors. The Inquiry took place in Oxford during the summer of 2010, and the Inspector's report was published in December 2010. The decision letter from Defra to the company was dated 1 March 2011. An abridged list of the documents available, which has been limited to those that were of particular relevance to the arguments explored in this research, appears in Table 2.15.

Table 2.15 - Chronology of reports associated with the Public Inquiry

Date	Government	Thames Water	Comment
Feb 2009		Statement of Consultation Responses report to Defra.	The company's responses to issues raised by the public.
May + June 2009	EA Advice reports to Defra about TW's Statement of Consultation Responses		EA believes TW has not adequately addressed issues raised by the consultation.
3 Aug 2009	Defra letter to TW announces that a Public Inquiry has been called.		
Sep 2009	EA letter to TW identifies 21 "Outstanding Issues"		Letter in response to a TW asking for clarification about EA Advice to Defra
Sep 2009		TW releases "revised" Draft WRMP that contains 100 Ml/d of "long term risk" after 2035.	Greater demand reductions were shown than in previous DWRMP.
Jan 2010		TW and EA agree a "Statement of common ground"	Register of 49 issues, 10 of which are unlikely to be agreed before Inquiry
Feb 2010		TW publishes "Statement of Case"	Many of the 49 issues now resolved.
March 2010		TW and Ofwat agree a Statement of common ground	
April 2010	Parliamentary briefing organised by GARD, the largest NGO opposing		GARD water engineers are John Lawson (ex Halcrow) and Chris Binnie (consultant)
15 June	EA Proofs of Evidence and	TW Proofs of Evidence and	CEO Richard Aylard: Levels

Date	Government	Thames Water	Comment
to 18 Aug 2010	rebuttals, primarily: Ms Pauline Smith and Ms Vicky Carpenter	rebuttals, primarily: Dr Chris Lambert and Dr Yvette de Garis	of Service. Chris Lambert: Supply and Demand planning. Yvette de Garis: Environmental issues.
13 Dec 2010	Planning Inspector's report.		TW not fully compliant with Directions, insufficient evidence to sustain "long term risk" of 100 Ml/d, 100 Mm^3 UTR scheme rejected.
1 Mar 2011	Decision letter from Defra to TW, Secretary of State accepts all of the Inspectors conclusions and recommendations		A further letter of 13 May contained a programme of work that met all 25 of the recommendations.
	Thesis ends March 2011: later entries for information:		
Dec 2011		New Draft Final WRMP issued for public consultation	No UTR.
Jan 2012	EA and Ofwat publish reports "The case for change" on future water availability and reform of abstraction management.		Support information for Defra White Paper "Water for Life"

Argument about the significant issues raised at the Public Inquiry, which refer to the documents listed in Table 2.15, appears in Chapter 6.

2.7 Summary of the Literature Review

This section summarises the key elements of the Literature Review to take forward into this thesis:-

Introduction to the Literature Review: The scope of the project is the planning for raw water reservoir schemes that have been built for public supply.

The naturally filled Elan Valley Reservoirs storage (99,000 Ml) and gravity aqueduct scheme is located in uplands of mid-Wales where there is high rainfall, and was chosen for study because it has provided the water for public supplies in Birmingham for over a century. The first flow from the Elan scheme to Birmingham occurred in 1904.

For comparisons to be drawn with Elan about uncertainty, the Thirlmere reservoir (37,000 Ml) and gravity aqueduct scheme located in the English Lake District, and the Lake Vyrnwy reservoir (59,000 Ml) and aqueduct scheme located in Mid-Wales were chosen for study. These schemes serve Manchester (first flow 1894) and Liverpool (first flow 1892) respectively. Both schemes are of a similar type to Elan, and were constructed at the end of the 19^{th} century. Many reports and papers were found containing data and information about the Elan scheme.

Thames Water's proposed pumped storage and river regulation scheme called Upper Thames Reservoir (100,000 Ml) was chosen as a modern scheme to compare with the Victorian schemes because of its strategic significance in long term plans for the supply of London. Thames Water's revised Draft Water Resources Management Plan published in September 2009, and a recent Public Inquiry generated a substantial amount of useful literature.

Historical context: Victorian Cities: The Industrial Revolution generated rapid population growth and burgeoning economic development in the UK's industrial cities. Greater investment in new assets for water supply and drainage was needed. Private water companies were bought by the ambitious Corporations to deliver the investment that supported economic growth, and the improvement of public health. Good references were found that explained the political, social and economic background for the three cities under review.

Historical context; Victorian engineers and methods: Bateman and Thomas Hawksley were well respected late Victorian water engineers involved with the designs of Thirlmere and Vyrnwy respectively. Insufficient rainfall data was used to calculate the yield of reservoirs, and mistakes were made that led to over estimated source yields. Mansergh had good rainfall data, and correctly estimated the yield of Elan. Uncertainty in the estimation of average annual rainfall began to be understood at the end of the 19th century, but little information was uncovered about the Victorian engineers approach to other uncertainties. From material found about the engineers themselves, and their forecasting methods, it appears that Victorian engineers were expected to recommend solutions with uncertainty implicit in their empirically based judgements.

Description of the three Victorian reservoir schemes and data sources: More data and information was found for Elan and Birmingham than for the other two schemes. The researcher has had a paper published about the 1892 water demand forecast for Birmingham based on work done for the thesis (Appendix E). Liverpool suffered intermittent supplies until innovative leakage and waste control was introduced. Mansergh asserted to a House of Commons Select Committee in 1892 that “there was no preventable waste in Birmingham” and was believed. Manchester Corporation’s proposals for Thirlmere were objected to by the Thirlmere Defence Association, the first example of an environmental organisation. The verbatim reports from the Parliamentary Select Committees have allowed greater insight to the way the Victorian engineers did their work.

Modern context: Government and regulators play an influential role. Water resources planning undertaken by UK water companies to guidelines set by the Environment Agency. Significant technical development in supply and demand forecasting has been made; rather than reservoir yield, a water resources and supply system now has a Deployable Output, and demand is disaggregated. Uncertainty in the supply and demand forecast is accounted for in probabilistic target headroom of supply over demand based on level of service. There is a great deal of literature produced by Government, Regulators and water companies.

Thames Water proposal of an Upper Thames Reservoir: In their revised Draft Water Resources Management Plan of September 2009, Thames Water proposes a 100 Mm^3 pumped storage reservoir near Oxford. Raw water would be released back into the River Thames in summer to support abstractions for supplies in London. The Planning Inspector for a Public Inquiry held in 2010 into Thames Water's proposals rejected the notion of a "long term risk" argument put forward by the company. However, compared with the independent Victorian Parliamentary committee system, the freedom of decision making in today's Public Inquiry system has become significantly more constrained by the change in the socio-economic background over the past century, and by the development of a regulatory framework.

The Literature Review has revealed descriptive material that compares the three Victorian reservoir schemes of Elan, Thirlmere and Vyrnwy. Sufficient actual and forecast supply and demand data for the three industrial cities of Birmingham, Manchester and Liverpool has been found to construct historic supply and demand balance diagrams. There is a wealth of material about supply and demand for Thames Water's proposed UTR (or Abingdon) reservoir, and future supplies to London. No material has been located that attempts to evaluate and compare uncertainty at the planning stage for the sizing of schemes. This finding informs the specification of the knowledge gap for this project, the statement of the project aim, and the setting of the objectives, which appear in Chapter 3.

CHAPTER 3 KNOWLEDGE GAP, AIMS AND OBJECTIVES

3.1 Knowledge Gap

A. The Victorian water engineers and their client Corporations are generally admired for their technical ability and vision, but is this admiration founded on fact, or does it reflect today's growing nostalgia for Victorian civic achievement? There is knowledge of the physical detail of individual Victorian reservoir and gravity aqueduct schemes, and some of the empirically based judgements made by those engineers. However, for long term reservoir schemes, no analysis has been found, in terms of supply and demand, that considers how well, or how badly, these schemes have actually performed.

B There has been no retrospective attempt in the past to compare either empirically or systematically the relative supply and demand performances of different Victorian reservoir schemes. Could analysis of data, which can be derived from supply and demand diagrams, produce a method that would allow sensible comparisons to be made, and not be confounded by uncertainty?

C. An assessment of the supply and demand risk averseness of modern scheme designs has never been attempted. Could the same model used to address B above be able to compare the relative risk averseness (resource lasts beyond date expected), or the inefficiency of design (resource does not reach date expected) of modern and Victorian schemes?

Comment on actions required for A:- To provide an informed view, critical analysis is needed, which is based on the comparison of actual demand data with the original demand forecasted to justify the scheme. By getting to know the character of the Victorian engineers, an appreciation can be formed of how uncertainty in the demand forecast was approached.

Comment on actions required for B: A novel method has been developed that uses ratios of flows, and the years when intersections occur of the planned supply with the actual demand in the supply and demand balance diagrams. From these variables, the relative "risk-averseness" of the original scheme designs can be assessed. The more risk averse, the safer the original scheme design turned out to be, but perhaps the design was larger than necessary.

Comment on actions required for C: There is a conceptual difficulty, which is that no demand history exists for a modern scheme. As an alternative, in its Water Resources Management Plan (WRMP), Thames Water shows a range of demand forecast scenarios to 2035. Using extrapolated supply and demand beyond 2035, "what if" demand scenarios can be tested. Comparison of these results with the Victorian results provides an understanding of the degree of risk averseness that is being planned for. London's supply and demand balance diagrams have relatively flat supply and demand projections compared with the Victorian examples, and therefore the results for London will be less accurate.

3.2 Aim and Objectives

Aim:

The aim of the research reported in this thesis is to determine whether Victorian approaches to uncertainty in water resources and supply planning offer any lessons for planning water resources and supply schemes today.

Objectives:

The over-arching aim is underpinned by a set of carefully constructed objectives as shown in Table 3.1.

Table 3.1 – Project objectives, and key elements of work

Objectives	**Key Elements of work: these also reflect how the Knowledge Gap has been addressed.**
1. To undertake a detailed examination of the historical development of the Elan water resources and supply scheme for Birmingham UK to understand the technological, social, economic, environmental and political context within which they were provided.	Much of the Victorian water infrastructure is still in use today more than a century since its construction. A literature search has been undertaken, and historic supply and demand data analysed for the Elan Reservoirs and aqueduct scheme, and research into Birmingham's water supply history.
2. To elucidate the philosophy and quantify the Victorian approach to understanding issues of uncertainty in the forecasting of water demand by comparing the approaches used by Birmingham with Manchester and Liverpool for the planning and design of remote upland large reservoir schemes.	Why did Victorian engineers build what they did? Did they plan for uncertainty and longevity, and if so how did they quantify these issues? The demand forecasts were researched and analysed that justified the proposed size of the Elan scheme, and for two similar schemes, at Thirlmere for Manchester, and at Vyrnwy for Liverpool. The work done for Elan and Birmingham has been published. Using forecast and actual supply and demand, the comparative risk averseness of the original designs is evaluated. This uses a novel lag-time model approach, which has been developed in this project for this purpose.
3. To consider whether historical approaches to dealing with uncertainty continue to inform current infrastructure design and planning and to determine the consequences for providing effective and sustainable infrastructure.	Using the Thames Water Upper Thames Reservoir as an exemplar, and the information from the recent Public Inquiry, to consider how we currently plan and size reservoir schemes, and how our modern approaches compare to those of the Victorians.
4. To critically appraise the influence of Victorian infrastructure on the development of the water supply system, and to determine how this legacy could continue to influence this fundamental area of engineering and public health.	Given that future supply and demand profiles are very uncertain, are there lessons we can learn from historical approaches to planning and designing for uncertainty that ensures the infrastructure we construct now remains useful in the future?

CHAPTER 4 VICTORIAN APPROACH

Chapter 4 addresses the first objective in Table 3.1, and Knowledge Gap A, which is the detailed examination of the historical development of the Elan scheme. Part of the second objective, and Knowledge Gap B are addressed, which is the widening of the examination to the Thirlmere and Vyrnwy schemes.

4.1 Introduction to the Victorian Approach

The purpose of this chapter is:

1. To show and analyse Victorian water supply and demand data for the years that predate the time when the decisions were made to build the three Victorian schemes. The reasons for the choice of schemes are given in Sections 2.1.2 and 2.1.3.

2. To explain the three different demand forecast approaches taken that justified the need for the three schemes.

3. To compare observed supply and demand data with the original forecasts.

4. To synthesise the analysis of 1, 2 and 3 and thus draw conclusions regarding the Victorian approach to addressing supply and demand issues.

The value of this work is to gain an understanding of the information that was available at the time to the Victorian water engineers; how these data were used as the basis for the demand forecasts; and to find out how accurate, or otherwise, the forecasts turned out to be.

A summary chronology of event dates leading up to the planning and design, and then the construction and commissioning of the three schemes, is shown below in Table 4.1. Descriptions of the three schemes can be found in Section 2.4.

Table 4.1 - Chronology for the three schemes from 1847 to 1904, including reprise of Table 2.3.

Years	Thirlmere for Manchester Corporation	Lake Vyrnwy for Liverpool Corporation	Elan Valley for Birmingham Corporation
1847	Takeover of private water company; water supplies were from wells and canals.	Takeover of private water companies; water supplies were from springs and wells	Birmingham Water Company supply since 1830 had been from River Tame abstractions.
1850 to 1857	1855: first flow from Bateman's Longdendale scheme, at the time the largest reservoir scheme of its type in the UK.	1857: first flow from Hawksley's Rivington reservoir scheme near Chorley.	1851: powers obtained to purchase water company; but not used until 1875. 1854: Rawlinson first suggests using River Blythe for supply.
1865 to 1874	1868: drought supplies of 12 hours per day for 84 days, then constant supplies resumed. 1873: Bateman said Longdendale will become exhausted in 10 years and next scheme needed. Yield of wells reducing and becoming polluted.	1865: drought supplies down to 2 hours per day. Supplies remained intermittent, with shut offs normally 9 to 12 hours per day. 1873: Introduction of "special operations for the prevention of waste". 1874: Waste reduction successful and constant supplies gradually introduced. Yield of wells reducing and becoming polluted.	1862: Mansergh first sees Elan as potential reservoir site. 1864: Hawksley proposes use of better quality local groundwater instead of increasingly polluted Tame. 1865: Bateman proposes large reservoirs schemes in Mid-Wales to supply London. 1872: River Tame abstraction ceased, replaced by supplies from new wells.
1875 to 1883	1875: Bateman proposes Ullswater scheme for Manchester + Liverpool. 1876: Bateman proposes Thirlmere for Manchester. 1879: Thirlmere Defence Association object, but Thirlmere powers obtained	1876: Ullswater scheme rejected by both Corporations. 1879: Lake Vyrnwy a better scheme than Haweswater independently agreed by Hawksley and Bateman. 1880: Powers obtained to construct Lake Vyrnwy.	1875: Birmingham Water Company purchased by Birmingham Corporation. 1883: New treatment works opened at Whitacre supported by bankside storage filled from the Rivers Bourne and Blythe.
1892 to 1904	1894: First flow from the Thirlmere scheme in the same year that the Manchester Ship Canal is opened.	1892: First flow from the Lake Vyrnwy scheme. At the time, the largest masonry dam in the world.	1892: Powers obtained to construct the Elan scheme. 1904: First flow from the first stage of the Elan scheme.

Table 4.1 shows that the lengths of time from the acquisition of Parliamentary powers to commissioning were similar for the three schemes. Thirlmere took 15 years, from 1879 to

1894, Vyrnwy took 12 years from 1880 to 1892, and Elan took 12 years from 1892 to 1904. At the outset, Vyrnwy was expected to take six years, and Elan seven years.

Noted in Table 4.1 under Elan for 1865 is Bateman's contribution to the Royal Commission chaired by the Duke of Richmond which advocated new storage in the upper River Severn catchment in Mid-Wales to serve London. Bateman paid for the investigations himself, and his proposals were well received. Whilst not recommended at the time for London, the discussion raised awareness that developing remote upland reservoirs could be the right approach for other conurbations

In 1876, Table 4.1 records that Bateman proposed Ullswater in the Lake District as a source that could supply both Manchester and Liverpool. Liverpool Corporation's need was more urgent, and being unsure of the commitment Manchester Corporation had to the scheme, Bateman's proposal was dropped. Manchester's next proposals for an upland development remained in the Lake District, whilst Liverpool turned towards the development of catchments in Wales.

The Manchester and Liverpool experiences are presented before Birmingham throughout Chapter 4, as the planning for the Thirlmere and Vyrnwy schemes occurred over a decade earlier than for Elan. The supply and demand history is presented for each Corporation in Section 4.2. This analysis provided the basis for the approaches taken to produce long-term demand forecasts for the future described in Section 4.3. In the mid to late 1870s, Bateman and Hawksley are shown to have used trend-based approaches, whilst in 1892, James Mansergh for the Birmingham demand forecast 63 years ahead, used a method called the Decremental Ratio of Increase (DRoI). The DRoI approach is explained in Section 4.3.

With the three schemes in place, comparisons of forecast and outturn demands for the three Corporations are covered in Section 4.3. The well matched forecast and outturn for Birmingham provided the impetus to report this work in a peer reviewed paper (Bradford et al., 2010): an offprint is located in Appendix G.

4.2 Historic Supply and Demand data prior to Reservoir Schemes

Historical water supply and demand information is shown in Figures 4.1 (Manchester), 4.2. (Liverpool), and 4.3 (Birmingham).

4.2.1 Longdendale and Manchester

The demand data which John Frederick Bateman presented to Manchester Corporation in February 1875 formed the technical basis for the justification of a new water resource. These data appear in Harwood (1895). The data for Figure 4.1 is an example; the comments on the diagram have been added by the author.

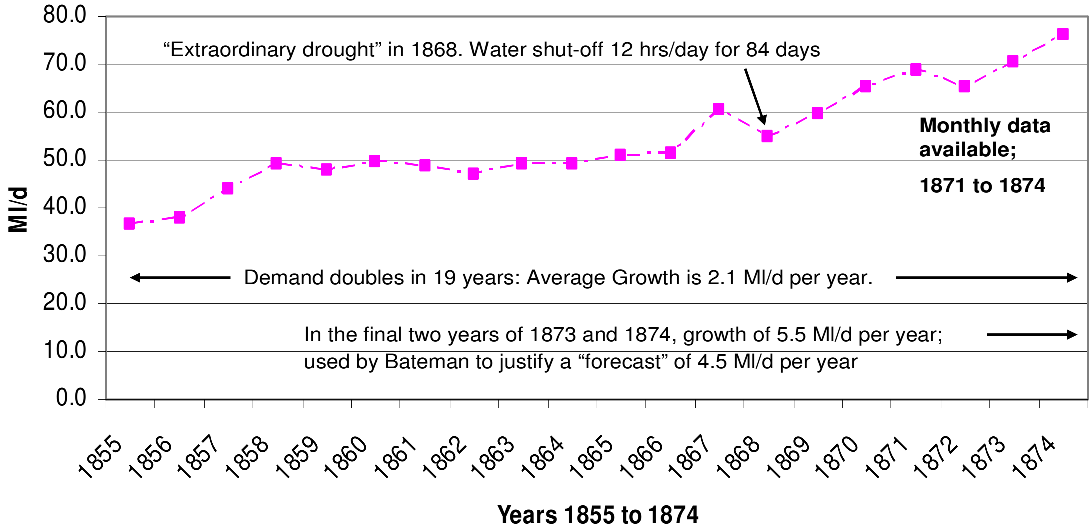

Figure 4.1 – Manchester Supply Area, Annual Average Demand, 1855 to 1874 (Bateman Feb 1875)

Bateman was responsible for the design for the Longdendale scheme, which is a series of reservoirs in the valley of the River Etherow immediately to the east of the city, the first of which was opened in 1855. Bateman did comment on an important "Extraordinary drought" feature in 1868, when he records that water was shut off for 12 hours a day for nearly three months, which was insignificant to the years of intermittent supplies endured at this time in Liverpool. Another set of data that Bateman showed was the monthly data shown in Figure 4.2 for the four years 1871 to 1874. These data were shown by Bateman to demonstrate seasonal demand effects. Bateman was an advocate of designing schemes that maintained supplies during peak demand periods.

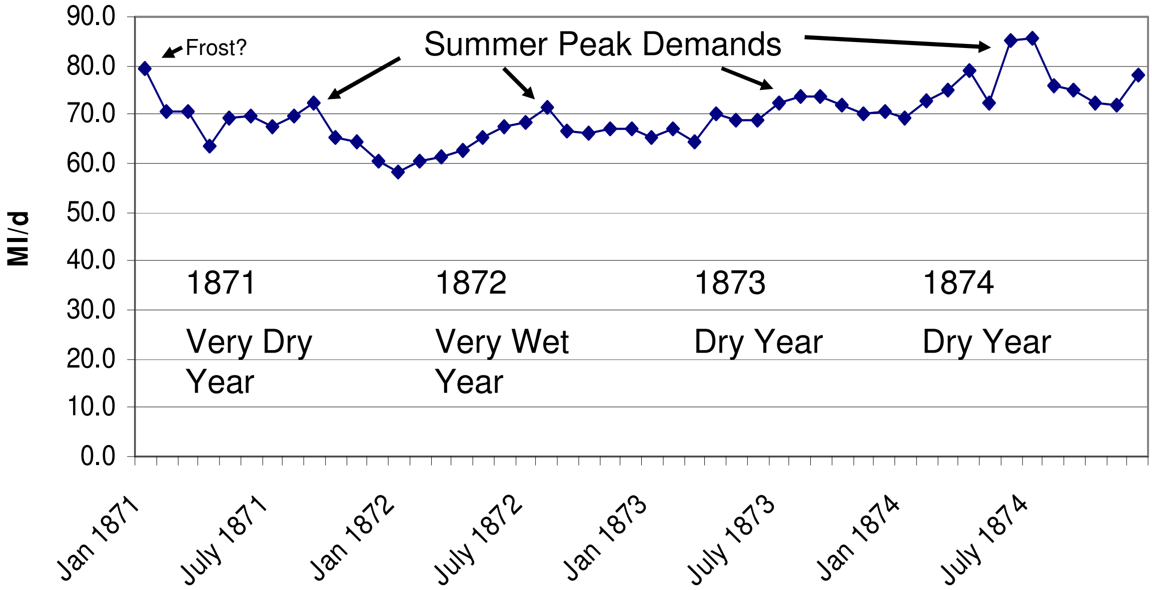

Figure 4.2 – Manchester Supply Area, Monthly Water Demands, Jan 1871 to Dec 1874 (Bateman Feb 1875)

The wet and dry year descriptions are Bateman's, based on local annual rainfall statistics. The summer monthly peak at near 85 Ml/d was further amplified by Bateman in the text by quoting the peak summer demand week ending 22 June 1874 at 89 Ml/d. An even higher peak week of 95 Ml/d had occurred in frosty weather in the week ending 11 January 1875. The annual average water demand met by Manchester Corporation from 1855 to 1879 shows demand doubling from 40 to 80 Ml/d, as shown in Figure 4.3. There appears to be no evidence of Bateman factoring peak demands into his demand forecast in 1875.

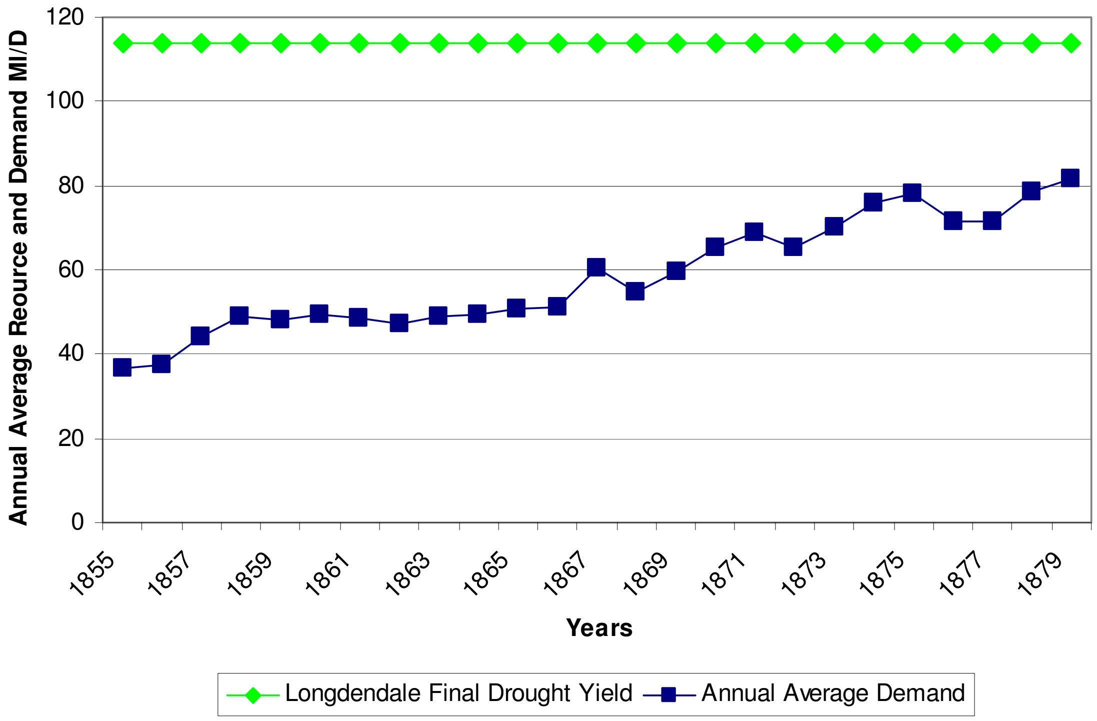

Figure 4.3 – Manchester, Annual Average Resource and Demand, 1855 to 1879

The existing resource availability was estimated by Bateman to be no more than 114 Ml/d. Demand growth was fastest in the latter half of this period at near 4% per annum, and on the evidence of growth in the last two years of this period, Bateman advised the Corporation that growth of 4.5 Ml/d per year (1 Mgd per year) should be used as a planning forecast. Thus he concluded that the available supply would shrink to zero in eight years.

The starting year of 1855 in Figure 4.3 marks the date of the first flow from the Corporation's new scheme at Longdendale. Although Longdendale was a staged scheme that Bateman finally finished in 1877, Figure 4.3 shows for simplicity just the final drought yield. Binnie (1981) reports that the drought yield to supply of the Longdendale scheme was estimated by Bateman at between 106 and 114 Ml/d.

The finishing year in Figure 4.3 is 1879, when the powers to develop Thirlmere were obtained. Construction of the Thirlmere scheme started some time later in 1884.

4.2.2 Rivington and Liverpool

The picture for Liverpool Corporation is rather different, as presented in Figure 4.4.

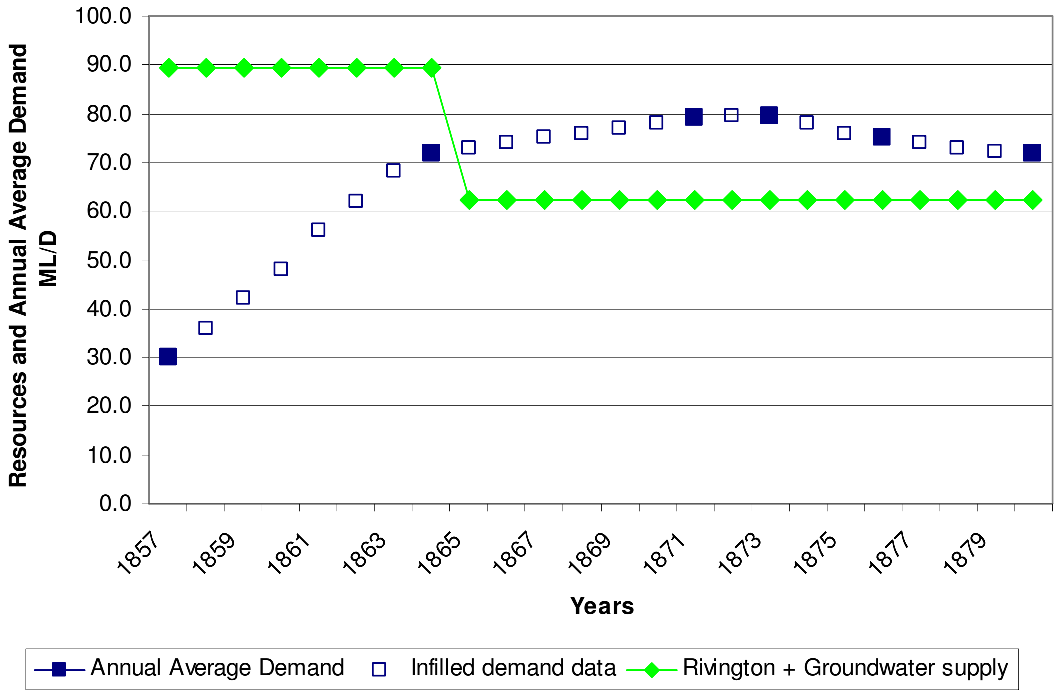

Figure 4.4 – Liverpool, Annual Average Resources and Demand, 1857 to 1880

Between 1857 and 1864, Figure 4.4 shows there was strong demand growth from 30 to 70 Ml/d, which is over 10% per annum. After 1864, demand slowly rose up to the year 1873, and then fell so that in 1880, demand had returned to 70 Ml/d, the same level as it was 16 years earlier. Over the 23 year period from 1857 to 1880, growth averages three percent per annum.

Changes over time in the numbers population served can occasionally explain movements in demand, but not for Liverpool in the 1870s. At the time water demand was falling, the population served rose from 614,000 in 1873 (Beloe, 1875) to 703,000 in 1880 (Parry, 1881).

As has been alluded to in Sections 2.2.7 and 2.4.8, the falling demand was due to the successful implementation of innovative leakage detection. The most common approach taken by 19th century water undertakings to limit demand was the introduction of intermittent supplies.

The perilous supply demand balance position for Liverpool is made clear in Figure 4.4. Table 4.2 shows that the estimated drought resource for Liverpool had to be revised by a downward 27 Ml/d, or some 44% of the total.

Table 4.2 – Drought Yield of Sources supplying Liverpool, 1857 and 1865

Row References	**Resources**	**Drought Yield in 1857**	**Drought Yield in 1865**	**Change**
A	Rivington Supply and Compensation	100.0 Ml/d	72.7 Ml/d	- 27.3 Ml/d
B	Rivington Compensation	37.7	37.7	0
C = A - B	Rivington Supply to Liverpool	62.3	35.0	- 27.3
D	Local Wells	27.2	27.2	0
E = C + D	Liverpool Supply (shown in Fig 4.4)	89.5	62.2	- 27.3

Hawksley's estimate of the Rivington drought yield (including compensation) was 100 Ml/d (22 Mgd) (Binnie, 1981), which is shown in row A in Table 4.2. After subtracting the compensation flow (line B) of 37.7 Ml/d (8.3 Mgd), the drought year supply from Rivington to Liverpool was 62.3 Ml/d (row C). Another 27.2 Ml/d (6 Mgd) (Duncan, 1853) was deemed as obtainable from local wells (row D), thus the total drought year supply figure for Liverpool in 1857 shown in line E was 89.5 Ml/d (19.7 Mgd).

After experiencing more serious droughts than Hawksley had imagined at the planning stage of the scheme, the overall drought yield from Rivington was reduced by 27.3 Ml/d from 100 Ml/d to 72.7 Ml/d (Binnie, 1981), as shown in row A of Table 4.2. With the amount of compensation staying the same at 37.7 Ml/d, the drought supply available from Rivington to Liverpool was cut from 62.3 Ml/d to 35.0 Ml/d (7.7 Mgd).

The amount of supply headroom over demand that Liverpool Corporation thought it had shows a dramatic change in a short space of time. In 1857, there appeared to be 60 Ml/d of headroom, which was double the current demand of 30 Ml/d. Eight years later, Figure 4.4 shows that the headroom had become negative, and explains why the Corporation's intermittent supply policy lasted so long.

4.2.3 Local Sources for Birmingham

The chronology of key water supply events in the 19th century for Birmingham and London appears in Appendix B.

Up to the early 19th century, all water supplies in Birmingham were drawn from privately owned local wells. Piped water supplies began in 1831, and at the same time, the newly formed Birmingham Waterworks Company (BWCo) started abstractions from the River Tame just to the north of the town. The abstracted water was settled in a reservoir at Aston at a site now covered by the junction of the M6 motorway and the A38.

In 1854, a pollution incident on the Tame upstream of Aston at Willenhall showed the vulnerability of this supply, and prompted the Council to examine alternatives, even though it had no direct responsibility for water supply. Public health was the Council's responsibility, and a report by sanitary engineer, Robert Rawlinson, recommended abstraction from the River Blythe at Whitacre, some 12 miles east of Birmingham (Rawlinson, 1854).

To replace the polluted River Tame abstractions, the engineer Thomas Hawksley advised BWCo in the 1860s that groundwater stored in the Triassic Sandstones underlying much of Birmingham was a suitable alternative. Whilst there were some failures in trying to liberate the groundwater, successful wells provided constant and good quality supplies. A small number of spring sources with comparatively low output were also used. In 1871, abstractions from the River Tame for domestic supply had to cease by statute, and before then, some 32 Ml/d of varying quality was being supplied, but only to those who could afford it.

In the early 1870s, the Council was becoming concerned about rising demand, continuing public health problems, and that the Birmingham Water Company BWCo was not investing sufficiently in new water supplies for the future. As Mayor of Birmingham, Joseph Chamberlain acquired the responsibility for water supply in 1875 by purchasing the BWCo. Chamberlain also took over the responsibility for gas supplies, and after his death in 1902, the grateful citizens of Birmingham expressed their gratitude in a citation that stands today on his memorial in Chamberlain Square.

Most of the abstracted and treated water from the local Birmingham sources was pumped to Aston, and then pumped again, either to a service reservoir west of the town centre at Monument Lane, or directly into distribution. In 1883, some 80% of properties connected within the supply area used 54 Ml/d of mains water (Mathews, 1886).

Table 4.3 shows the total yield of the sources, estimated at that time by Mathews and Barclay, was 82 Ml/d. If treated water storage was also factored in, a further 12 Ml/d could be added to make the water supply available total 94 Ml/d. Whilst preparing the Parliamentary evidence for the Elan scheme, Mansergh reduced the total from 94 Ml/d to 87 Ml/d on the grounds that there was insufficient pumping capacity to deploy all of the well water. The latter figure has been quoted for use in supply calculations (Bradford et al, 2010).

Table 4.3 – Estimated Yields of Birmingham Local Sources in 1891

Groundwater Sources: Wells	**Mathews (1886) and Barclay (1891), Ml/d**	**Million Gallons per Day**
Aston Well	13.6	3.0
Witton Well	11.4	2.5
Kings Vale	1.1	0.25
Perry Well	9.1	2.0
Selly Oak Well	5.7	1.25
(Anticipated output from new Longbridge Well)	7.0	1.5
Wells Total	47.9	10.5
Surface Water Sources: Streams		
Plants Brook	9.1	2.0
Perry + Witton Streams	4.5	1.0
Rivers Bourne and Blythe	20.5	4.5
Surface Water Total	34.1	7.5
Total Output from Wells and Streams	**82 Ml/d**	**18.0 Mgd**
Additional From Storage (Barclay)	**12 Ml/d**	**2.75 Mgd**
Theoretical Maximum Output	**94 Ml/d**	**20.75 Mgd**
With Mansergh's downward adjustment of 7 Ml/d made in 1891	**87 Ml/d**	**19.25 Mgd**

In 1886, with the recent introduction of abstractions from the Rivers Bourne and Blythe for treatment and pumping at Whitacre, Mathews (1886) concluded optimistically that "It would appear, therefore, that we need have no anxiety for the future". This optimism quickly evaporated, as by 1890, demand reached 70 Ml/d, and a growth rate of three percent per annum. Peak demands were assumed to be up to 20% higher, which would require an output capability from all the Birmingham sources of 84 Ml/d. Average annual demand data for Birmigham is given in Table 4.4.

Table 4.4 – Birmingham annual average demands from 1876 to 1891

Year	Annual Average Ml/d	Annual Average Mgd	Comment
1876	37.4	8.30	Corporation acquired the Undertaking
1877	37.9	8.33	
1878	40.6	8.93	
1879	44.7	9.84	
1880	44.7	9.84	
1881	51.9	11.42	
1882	49.5	10.88	
1883	52.3	11.51	
1884	54.7	12.04	
1885	53.7	11.82	
1886	57.7	12.70	
1887	63.9	14.05	Dry summer
1888	63.6	13.98	
1889	64.9	14.28	Mansergh uses 1883 to 1889 data for 3% per annum growth trend in forecast
1890/91	76.5	16.82	Winter high demand – subsequently written down to 70.4 Ml/d (15.5 Mgd)

Table 4.4 shows that from 1876 to 1890, demand in Birmingham had doubled in 15 years. For 1891, matching the supply in Table 4.3 with demand in Table 4.4, it can seen that the average demand of 76.5 Ml/d was 5.5 Ml/d below total output of sources.

The 1890/91 demand was significantly enhanced by extra leakage and wastage caused by a particularly bad winter. For trend analysis, the demand figure was written down to 70 Ml/d (15.5 Mgd). The explanation for assuming the figure of 70 Ml/d has not been found.

For Birmingham Corporation, the demand profile is shown in Figure 4.5. It is similar to Manchester.

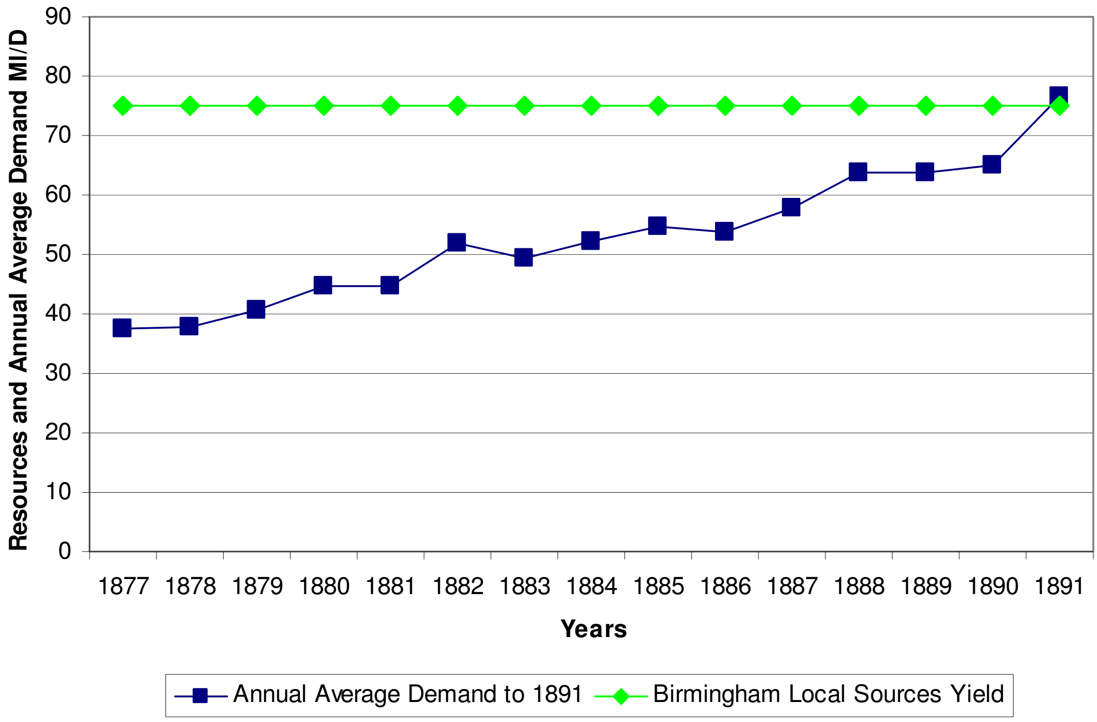

Figure 4.5 – Birmingham, Annual Average Resources and Demands, 1877 to 1891

The starting year of 1877 is two years after the Corporation took over the responsibilities for water supply from the Birmingham Water Company. The yield of the local sources available to Birmingham was shown by Mathews (1886) as 75 Ml/d (16.5 Mgd). Mathews figure was derived from 41 Ml/d (9 Mgd) from 5 deep wells, and 34 Ml/d (7.5 Mgd) from four surface streams.

In 1883, 2000 Ml of new pump filled raw water storage became available at Shustoke for treatment at Whitacre works on the eastern boundary of Birmingham. At the time, Mathews suggested that the new storage at Shustoke added another 45 Ml/d (5 Mgd) to 91 Ml/d (10 Mgd) to the yield, but later Mansergh was sceptical (again) of this claim as the extra yield could not be deployed throughout the whole of the supply area. Figure 4.5 shows 75 Ml/d, which is the yield figure used by Mansergh in 1892 for the presentation of the case for Elan.

In 1891, with a rapidly closing supply and demand balance, the chairman of the Council's Water Committee, Thomas Martineau, asked the City Engineer J. W. Gray to produce projections for Birmingham's water demand 25 and 50 years hence. Gray reported that by 1900, demand would outstrip the supply provided by the existing water resources. Martineau turned to Mansergh for his advice, which was unequivocal. Mansergh's recommendation for a new remote reservoir storage and gravity aqueduct scheme at Elan some 120 kilometres distant in Mid-Wales was accepted by the Council (Barclay, 1898).

4.3 Approaches used and Forecasts produced

The historic supply and demand data prior to the decisions taken by the three Corporations to develop the Thirlmere Vyrnwy and Elan schemes were presented in Section 4.2. This section focuses on how the three water engineers arrived at their demand forecasts that justified these schemes. A summary of the three methods are:

Bateman for Manchester – extrapolate recent trend of demand for 40 years.

Hawksley for Liverpool – extrapolate recent trend of population growth and multiply by 30 gallons per head per day for the next 36 years.

Mansergh for Birmingham – A model called the Decremental Rate of Increase is used in 1892 to forecast demand 63 years ahead to 1955.

Comparisons are made of the forecasts and actual demands in Section 4.4. Bateman for Manchester:

There are three water demand forecasts of note for Manchester made by Bateman. In summary, with comments about forecast accuracy, these are:-

1. **1847:** Demand was near 30 Ml/d, and growth in demand was 2 Ml/d per year. Bateman forecast in 1847 that demand 20 years hence in 1867 would be between 55 and 68 Ml/d, and Bateman used this forecast as evidence of the need for the Longdendale scheme. Actual demand in 1867 was 60 Ml/d, and the accuracy of his 1847 forecast was pointed out with some pride by Bateman to the Waterworks Committee in October 1868 (Bateman, 1868).

2. **1868:** In October 1868, Bateman forecast that demand would increase by 4.5 Ml/d per year, and reach the water resource drought yield capacity of Longdendale of c.110 Ml/d "in about 8 or 9 years". Also, there had been a drought in the summer of 1868 when there was a temporary intermittent supply (for 12 hours a day for 84 days), and was evidence to support the urgent need for a new scheme. Actual growth remained near 2 Ml/d per year, and the forecast demand was only reached 22 years later.

3. **1875:** Bateman forecast growth of 4.5 Ml/d per year, and that demand of 182 Ml/d (40 Mgd) or 227 Ml/d (50 Mgd) "or even more" would occur in the next 20 or 30 years. The basis for this forecast was a linear projection based on the most recent past two years where there had been growth in total demand of 5 Ml/d per year. Bateman presented his forecast as evidence to Parliament for the need for a remote storage scheme in the Lake District. 30 years later in 1905, actual demand reached 155 Ml/d. Bateman encouraged investment in water resources for the long term, and at the same

time was an advocate for building capacity to meet summer and winter peak demands. An extrapolated forecast beyond 30 years using 4.5 Ml/d per year is shown in Figure 4.6 starting in 1879 when the Bill with the powers to construct Thirlmere was obtained. This shows that the gradient of his forecast matched the gradient of actual demand up to the end of World War 1, some 40 years later. In the presentation of the series of diagrams that follow, the actual annual average demand data is split to accentuate the relatively short data sets that the Victorians had on which to base their long term demand forecasts.

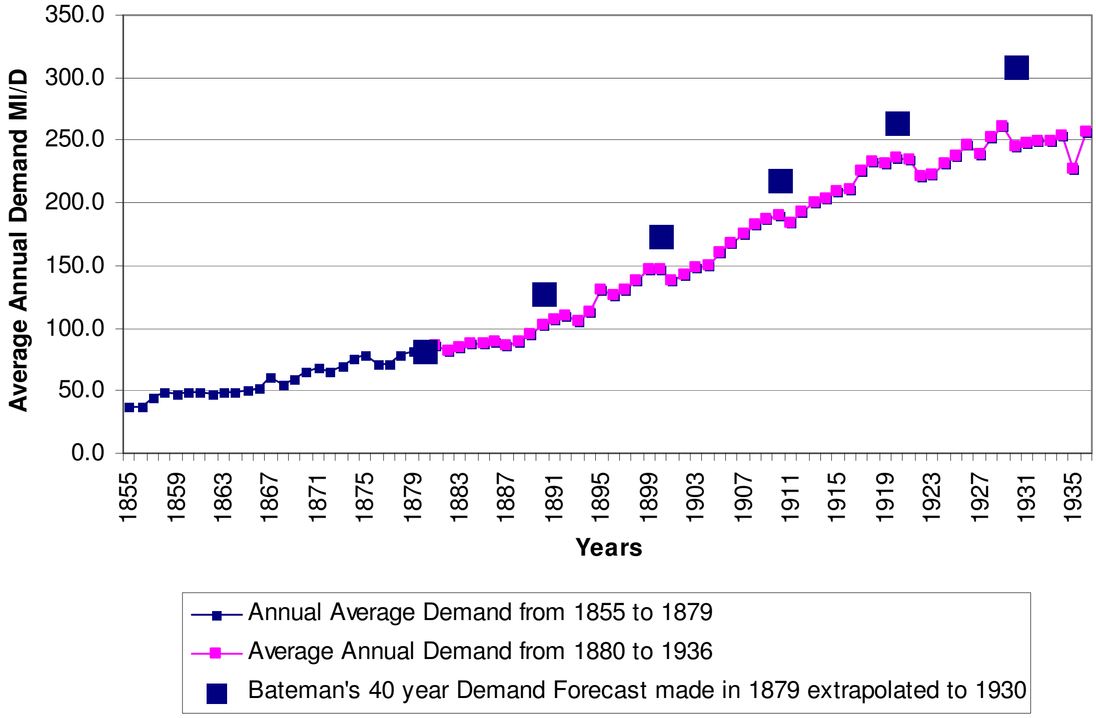

Figure 4.6 – Manchester, Annual Average Demands from 1855 to 1936, and forecast to 1930 made in 1879

4.3.1 Thirlmere; Parliamentary Debate 1878

The HoCSC Select Committee for the second reading (the first reading collapsed because of administrative errors) of the Manchester Water Bill, were instructed on Friday 15 February 1878 thus:-

1. That they have the power to inquire into and report upon the present sufficiency of the water supply of Manchester, and its neighbourhood, and of any other sources available for such supply.

2. To consider whether permission should be given to make use of any of the Westmoreland and Cumberland lakes for the purpose; and if so, how far, and what conditions.

3. To consider the prospective requirements of the populations situated between the Lake District and Manchester.

4. To inquire and report whether any, and if so which, provisions should be made in limitation of proposals for the exclusive use of the water of any of the said Lakes.

The Committee reported:

1. The population within the statutory area of supply is estimated at “nearly a million”. The available supply from Longdendale “will not be far from 25 Mgd (114 Ml/d) or about 25 gallons per head of the population within the area”.

2. “Your Committee assume that 25 gallons per head form a fair supply for a district, and hence Manchester has at present a sufficient quantity of water for the city and its statutory area of supply”.

3. “But the population is rapidly increasing. The houses within the inner district, supplied with water in detail, increase in number 5,300 annually, and the outer district supplied in bulk, by 2,200”.

4. “Calculating 5 people to a house, in 10 years more, there may be a population of 1,337,000 with a water supply sufficient for 1,000,000. Considering that that a period of 10 years is not a very long time to bring a new system of water supply to a large district into efficient operation, your Committee came to the conclusion that Manchester is justified in seeking additional sources of supply”.

5. “The question still remained whether it could not obtain this supply in its own vicinity, without going to the Lake District of Cumberland”.

The following summarises the key points that arose during the hearing.

Regarding rainfall records in Thirlmere catchment, Bateman disclosed that he had used 17 years of data in a neighbouring catchment at Seathwaite to work out the inflow to Thirlmere. As noted in Section 2.2.6, the lack of adequate local rainfall data turned out to be major weakness, as the drought yield to supply from Thirlmere was reduced about 25 years later, from 227 Ml/d (50 Mgd) to 164 Ml/d (36 Mgd) (Walters,1936).

The key piece of evidence about the demand forecast from Bateman read: “What I estimate is that at least 1,000,000 gallons a day (increase per year) will be required to meet the demand upon the Manchester Corporation for water”.

Bateman’s view of the Thirlmere scheme was given: with a scheme for 227 Ml/d (50 Mgd) in mind, “there is no fear of the water supply failing the wants of Manchester for a very long period; the time will come if Manchester goes on prospering, and after our time, when more water will be required than even Thirlmere will give, but that will be a long time hence”.

Dr William Pole gave evidence in support of Thirlmere. Regarding an estimate of total demand by Bateman, Dr. Pole remarked “I think, all things considered, Mr Bateman’s calculation of 30 gallons is not out of the way, considering one third of it is intended for trade, and only 20 gallons for domestic supply…..taking the year where there has been greatest consumption, and allowing for the probability of the increase in demand (baths and water closets) it is not an excessive quantity to provide for".

The Select Committee accepted 7,500 new houses per year growth and an occupancy rate of 5 persons per household. Thus the annual growth is of 37,500 people, and using a range of demand for total demand of 25 to 30 gallons per head per day:

1. At 25 gallons/head/day, growth is 937,500 gallons/day/year.
2. At 30 gallons/head/day, growth is 1,125,000 gallons/day/year.

The growth forecast is very dependent on the assumed occupancy rate as, for example, an assumption of 4 persons per household and 30 gallons per head, the growth rate is 900,000 gallons per day per year.

4.3.2 Hawksley for Liverpool

The only demand forecast considered in this project is that made in 1880 in support of Liverpool Corporation's successful attempt to secure the powers to build the world's largest masonry dam in the valley of the River Vyrnwy in North Wales.

A discontinuous dataset of annual average demands for the Liverpool Corporation supply area has been constructed from 1857 to 1946. Figure 4.7 below shows these data with the 36 year demand forecast presented by Thomas Hawksley in 1880 to evidence the need for the Vyrnwy scheme. The 36 year horizon for this forecast was set by first assuming six years to construct Vyrnwy, and then adding 30 years as the period of time this asset was intended to last. The data set in 1880, which was significantly influenced by waste reduction, effectively ruled out demand based trend analysis for the forecast.

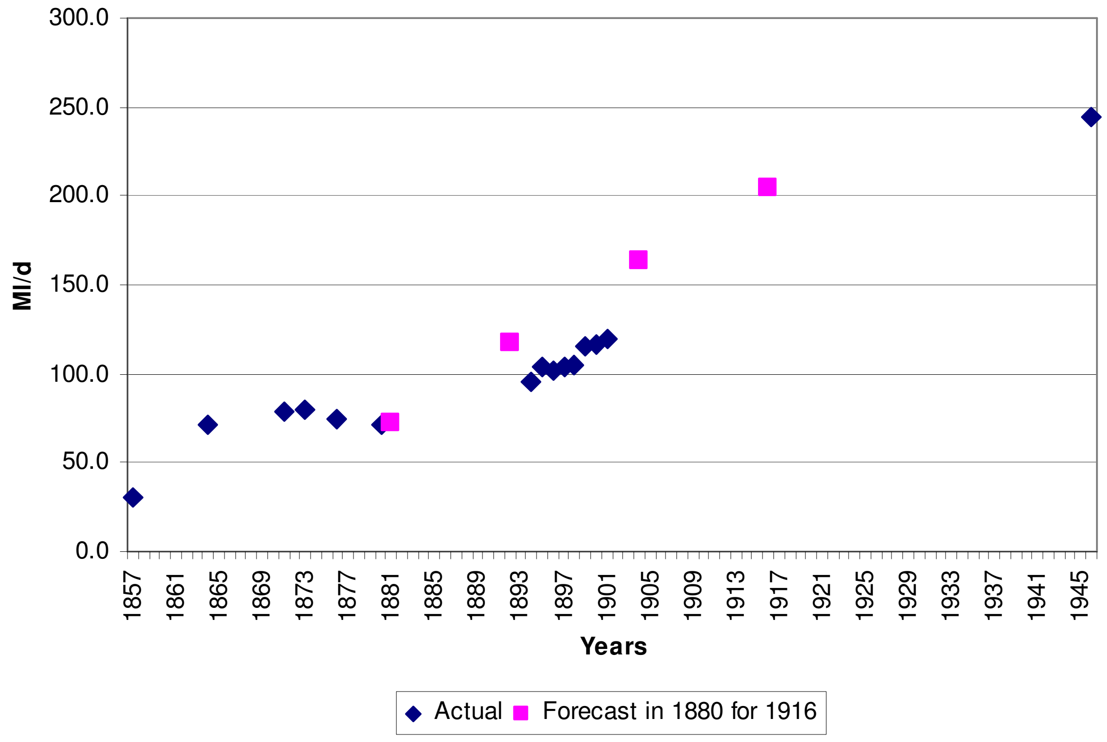

Figure 4.7 - Liverpool Corporation, Annual Average Demands, 1857 to 1946

The data for 1857 and 1873 come from Beloe (1875), for 1864 to 1880 from Parry (1881), for 1894 to 1880 from Parry (1899), for 1899 to 1900 from Liverpool Council proceedings, and the data for 1946 are derived from Liverpool Corporation's "Red Book".

There are fewer actual demand data for Liverpool than for Manchester as there was poorer documentation of summary annual demand data at the Liverpool Records Office.

The 1880 demand forecast was produced by making a forecast of population growth based on the recent growth trend (Figure 4.8), and multiplying the population forecast by a forecast of per capita demand (Figure 4.9), which includes all water use.

The population forecast of 1.5 million people for 1916 is shown in Figure 4.8, and by 1916, the diagram shows that the forecast was a substantial over-estimate of around 50%.

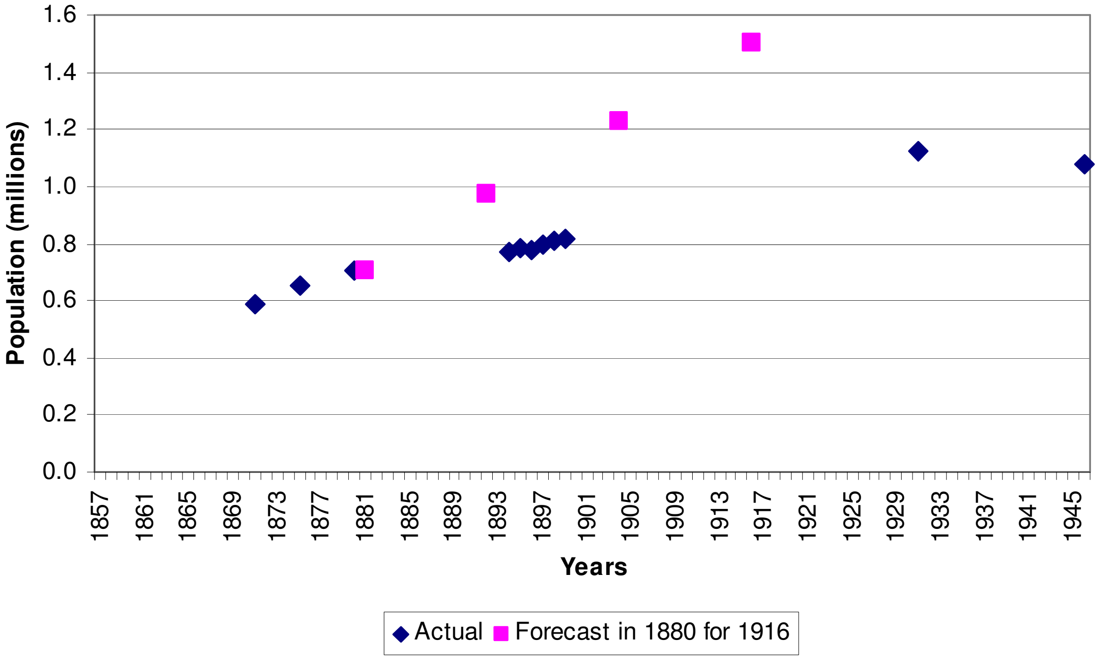

Figure 4.8 – Liverpool, Water Supply Population, Actual 1871 to 1946, and Forecast for 1916 in 1880

The data source for the population forecast is Hawksley's evidence given in 1880 to the Select Committee for the Liverpool Corporation Waterworks Bill (HoCSC, 1880)

Expressing demand in a standardised gallons per head per day allowed the Victorians to make comparisons in respect of year on year change, and for showing the rank of the water supply undertaking against others. The latter use was made both by Liverpool and Birmingham to demonstrate to their respective Select Committees that consumption was relatively low.

In 1880, with Liverpool demand at 22.5 gallons per head per day, Hawksley argued that 30 gallons was a fair forecast as London was already at 32.5 gallons (Parry, 1881). Parry also noted that the Manchester number was at the time only 20 gallons, but the Select Committee was given the explanation that Liverpool was asserted to be a "water closet city", whereas Manchester was not (Parry, 1881).

Demand of 30 gallons per head per day had already been observed in 1864, and occurred again in the late 1890s, as shown in Figure 4.9.

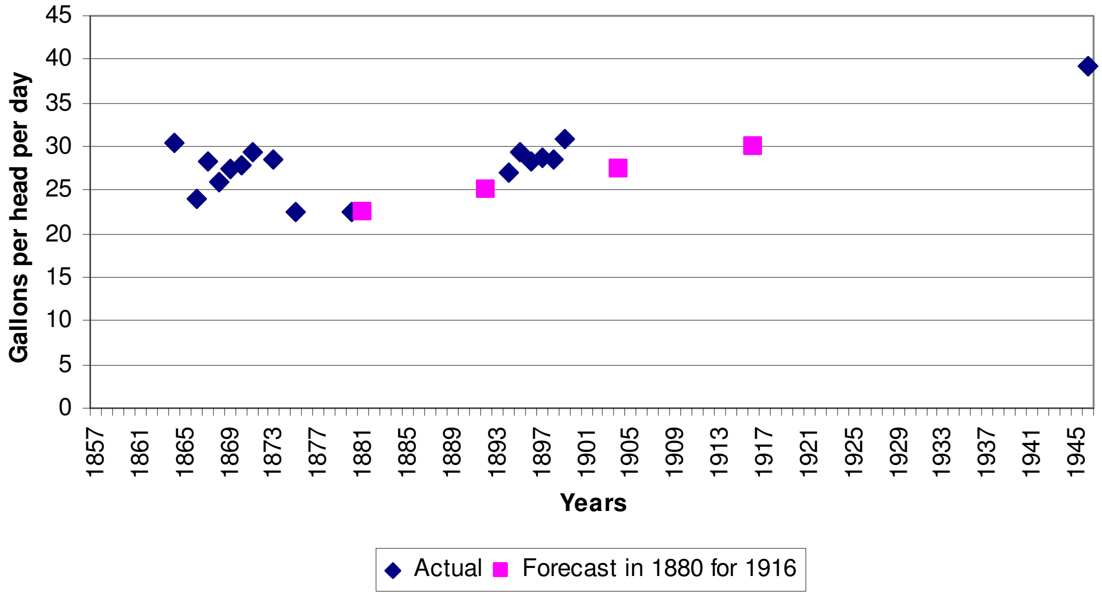

Figure 4.9 - Liverpool Corporation, Actual Annual Average Demand expressed as Gallons per Head per Day from 1864 to 1946, and Forecast to 1916 from 1880

Some new demand analysis which has been undertaken during this project, which is reported in Appendix E, has established that the two sets of Parry's data are consistent, and that the 30 gallons per head per day demand figure in 1864 is confirmed as the result of high losses rather that high consumption. The year on year changes observed from 1865 to 1873 are likely to be due to data inaccuracy during this period when the Corporation could only offer an intermittent supply. The 1875 figure of 22.5 gallons per head per day is confirmed by the new analysis to be a significant reduction in waste.

The comparison of the 1880 demand forecast for Liverpool with those observed is shown in Figure 4.10. The gradient of the actual demands is shallower than the gradient of the.forecast.

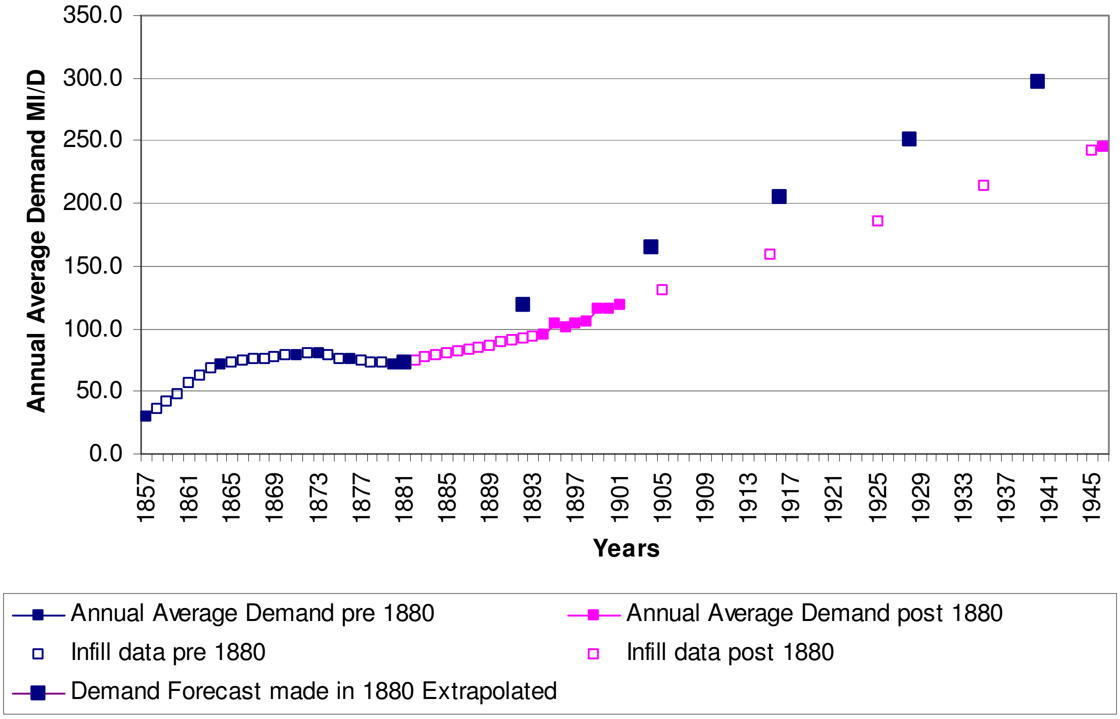

Figure 4.10 – Liverpool, Annual Average Demand and Forecast, 1857 to 1946

4.3.3 Vyrnwy; Parliamentary Debate 1890

The case for Liverpool Corporation, which proposed the construction of the Vyrnwy dam and aqueduct scheme in North Wales, was made to a HoCSC in June 1880. Some comments that are relevant to supply and demand are summarised below.

The present population supplied was 720,000, and assuming a demand of 25 gallons per person per day, a supply of at least 82 Ml/d (18 Mgd) was needed now. However, Counsel for the Corporation said "...no large town is satisfied with 25 gallons – it will do in moderately wet years, but not in dry years." The requirement of a new scheme was made clear: "...any supply which could not give us water for 30 years after we commenced impounding would not be sufficiently large,…and it would be wise not to calculate on less than 30 gallons per head per day for all uses."

A projection of 6 years was made by both Hawksley and Bateman for the Vyrnwy scheme to come into operation, and thus the time for which the scheme was intended to meet growing demand was 6 + 30 years = 36 years. The current date was 1880, so the planned date for which the Vyrnwy should last was 1880 + 36 = 1916.

Arriving at the population forecast for 1916 of 1,600,000 was described thus: "We have taken it from the number of consumers at the present moment, with additions at the average rate of increase over a period of 5 years, and in that way we should very nearly reach about 1,600,000. 1,500,000 would be under the mark, and about 218 Ml/d (48 Mgd) for an adequate supply of water."

Hawksley himself provided assurance to the Select Committee; "I have no doubt that the population, plus the increments of the use of water for their own domestic purposes, will bring about the results that are contemplated by this Bill, namely the use of 218 Ml/d (48 Mgd) within the districts supplied by Liverpool."

Many of the objectors to the scheme were given financial compensation in the Act after amendments. These included interests along the River Severn, as the River Vyrnwy is a major tributary.

4.3.4 Population data for the Birmingham supply area

A reliable estimate of current population in the supply area is always important for establishing the base for a demand forecast. In 1892, Birmingham Corporation produced estimates based on census data and house counts back to 1871, and as summarized in Table 4.5.

Table 4.5 – Birmingham Corporation water supply population and housing estimates for 1871, 1881 and 1891

Year	Supply Area: Inhabited Houses	Supply Area: Population
1871	89,457	449,384
1881	109,813	561,537
1891	129,188	647,972

In 1891, Inhabited Houses (the term used by the Corporation) and Supply Area Population were both 45% higher than in 1871. After 1891, boundary changes to the city (in 1909 and 1911) increased the number of inhabitants by about 200,000, but the population in the area supplied remained substantially unchanged. The two data sets are plotted in Figure 4.11.

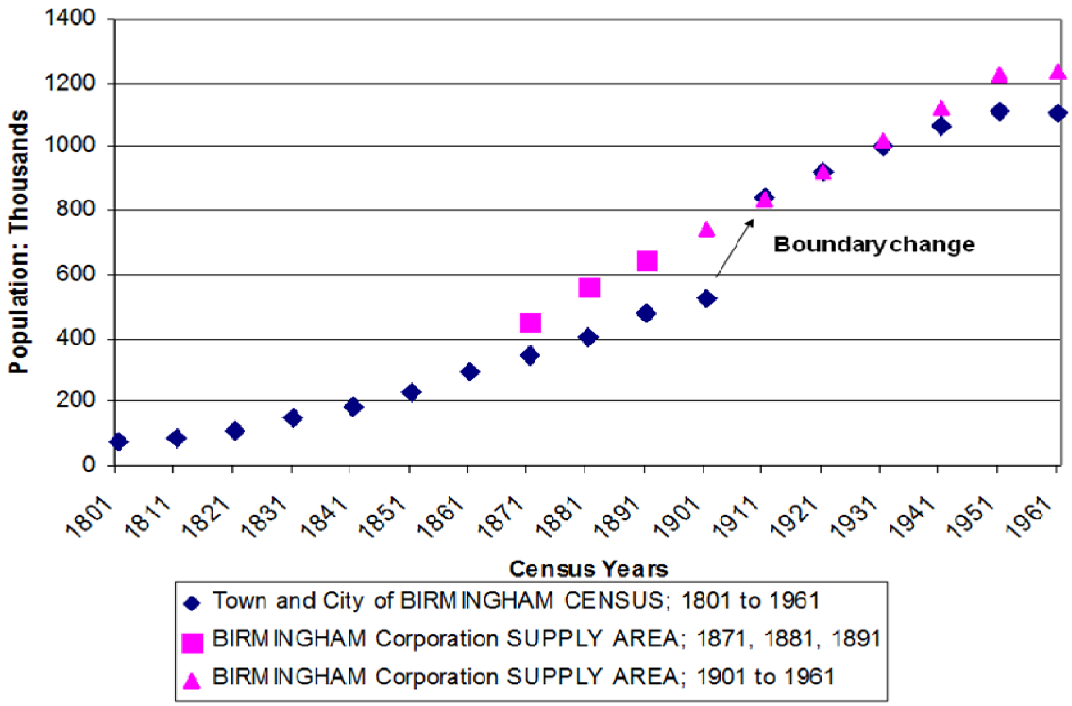

Figure 4.11 – Population of Birmingham, 1801 to 1961

Figure 4.11 shows that the resident population estimates for the supply area from 1911 up to the 1930s were similar to the census figures for the city. In the 1940s and 50s, population grew faster in the dormitory towns such as Solihull, which were within the supply area, but not within the city. The 1801 – 1961 census data for the City of Birmingham is listed by Dick (2005), and the supply area population data appear in the annual accounts of the City of Birmingham Water Department (CBWD). There was no 1941 Census; the missing data in Figure 4.11 are interpolated.

4.3.5 Mansergh for Birmingham

In 1891, Mansergh assumed the responsibility for producing the 25 and 50-year total water demand forecasts for Birmingham. His method was to establish a base position of total demand, and then make an extrapolation. Rather than fit a straight line, or use a single percentage rate of increase, Mansergh started the extrapolation for years 1 to 10 with a compound rate of increase of 3% per annum (the current growth rate), and then reduced the rate by 0.25% in each succeeding decade, using a model that Mansergh termed the Decremental Rate of Increase (DRoI). Table 4.4 contains the profile of the DRoI parameters chosen by Mansergh, but it is not known exactly how Mansergh translated his forecast of measured and unmeasured demand into his choice of DRoI parameters. It is considered that judgement must have played a significant part.

Table 4.6 – Mansergh's annual growth factors for the Decremental Rate of Increase (Barclay, 1898)

10 yrs @ 3.00% compound from 1890/91 to 1899/00
10 yrs @ 2.75% compound from 1900/01 to 1909/10
10 yrs @ 2.50% compound from 1910/11 to 1919/20
10 yrs @ 2.25% compound from 1920/21 to 1929/30
10 yrs @ 2.00% compound from 1930/31 to 1939/40
10 yrs @ 1.75% compound from 1940/41 to 1949/50
5 yrs @ 1.50% compound from 1950/51 to 1954/55

Figure 4.12 shows the comparison of Mansergh's DRoI based demand forecast made in 1892 using the percentages in Table 4.2. The forecast is continued beyond 1955 up to 1985 using the reductions of 0.25% in 10 year intervals to reach a percentage growth rate of 0.75% in the 1980s. The impression given by Figure 4.11 is that there was a remarkably similar rate of forecast and actual growth for over half a century.

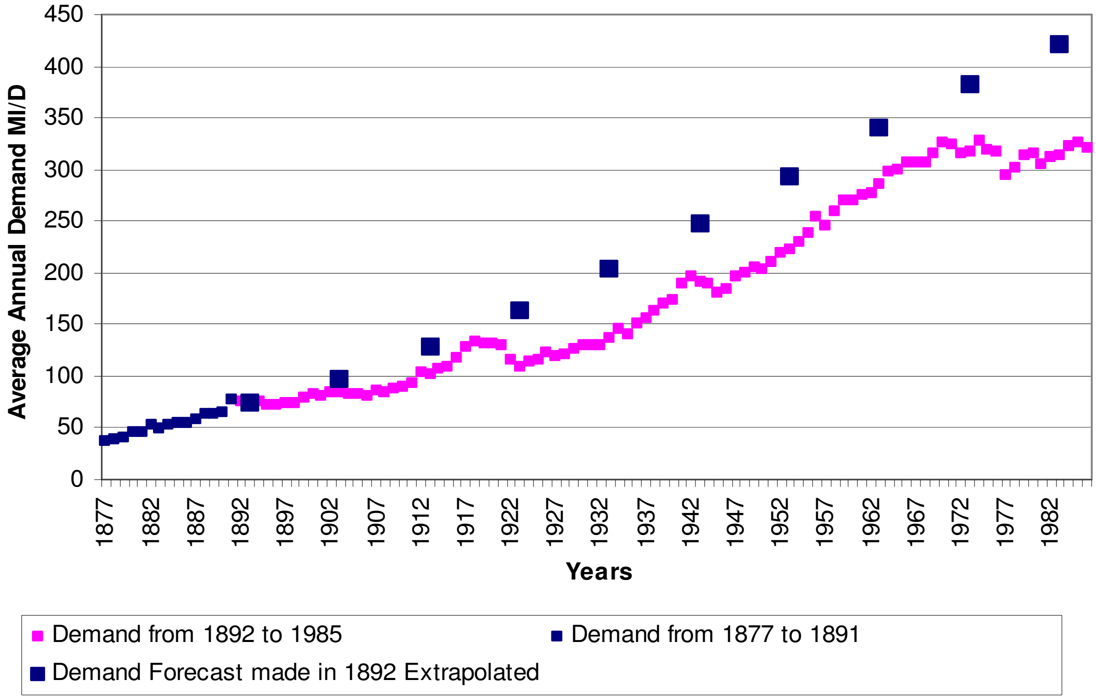

Figure 4.12 – Birmingham Demands from 1877 to 1985; Mansergh's 1892 Demand Forecast extrapolated to 1985

It is interesting and constructive to consider the downward step applied by Mansergh to the growth factor in the "Decremental Ratio of Increase" forecasting model. For example, an arbitrary 0.5% step produces a lower forecast profile than for 0.25%. Both are shown in Figure 4.13 together with the straight-line projection based on the 15 years of actual data from 1876 to 1891.

A comparison of the three projections in Figure 4.13 for the first 20 years to 1912 shows that there is little difference between them. Thereafter, an increasing gap develops between the 0.25% and 0.5% profiles, especially after 1942 when the 0.5% profile flattens as it approaches its maximum at 190 Ml/d. The 0.25% profile at this time is growing at its maximum rate of near 5 Ml/d per annum, which is the same as the growth rate of actual demand through to 1955.

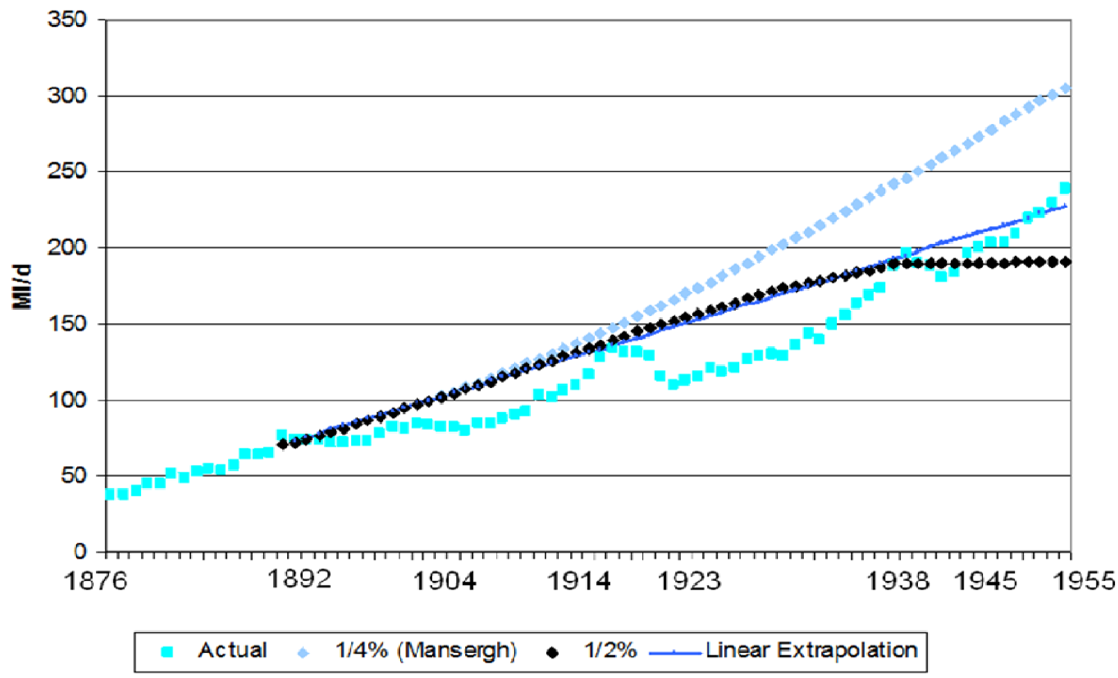

Figure 4.13 – Decremental rate of increase – comparison of 0.25% and 0.5% growth rate reductions at 10 year intervals

There was no challenge by the HoCSC to Mansergh's assumption of 0.25% steps or the 10 year intervals. The first phase of Elan storage was worth 205 Ml/d (45 Mgd) as a drought year water supply, and had Mansergh adopted the 0.5% profile showing a maximum demand of 190 Ml/d, the case for developing the second phase of storage at Claerwen could not have been made. The linear extrapolation in Figure 4.13 is close to the 0.5% profile up to the late 1930s, and by 1955 is very close to actual demand. This result is a coincidence, and not indicative that this straight line forecast should have been used. Conceptually, a demand forecast derived by using the DRoI method is more attractive than an infinitely long straight line as it can produce an upper limit of growth. This appears to have been tacitly accepted by the Corporation although there is no solid evidence for this.

Mansergh at first provided the HoCSC a 50 year forecast for the year 1940 of 237 Ml/d (52 Mgd). However, he advised the HoCSC that his time horizon for the full scheme could be 60 or 70 years as “the end of the world is not to come in 1940”. This comment was made to emphasise that if the Corporation was to make provision for at least 50 years, the need was for the full Elan scheme. From then on, the HoCSC considered Mansergh’s annual average demand forecast for 1955 of 305 Ml/d (67 Mgd). Using Mansergh’s population forecast of 1.62m for 1955, his implicit daily average total per capita demand forecast was 188 litres per head (equivalent to 41 gallons per head).

Mansergh approached his forecast by producing a trend of observed average annual supply. He selected the most recent data from 1883 to 1889, which gave him a growth factor of three percent per annum, and the starting growth figure shown in Table 4.1. Data prior to 1883 existed, but he explained that in the late 1870s and early 1880s, public water supplies grew abnormally quickly at more than 4% per annum. At this time, the Corporation condemned many polluted private wells, and replaced these supplies with mains water. This high rate replacement had already diminished, and he dropped these data from his analysis. For within-year weather related demand effects, Mansergh referred to the City Engineer, J. W. Gray‘s experience that a dry summer could add another 20 to 25% to demand, and that this level of demand would very shortly be unsupportable by the existing water sources and storage. Birmingham’s situation was in such trouble that Mansergh told the HoCSC that it was “palpable that some works must be done at once”.

Mansergh argued that water demand in Birmingham was relatively low compared with London and Glasgow. He assessed the average daily domestic demand per head for Birmingham at 77 litres (17 gallons); his calculation took the total average daily supply of 117 litres per head (25.75 gallons per head), and then subtracted 40 litres per head (8.75

gallons per head) for trade use, public sanitary purposes, sand washing, fountains, fires, flushing mains and street watering. However in more affluent London, the average daily domestic demand had been recently estimated to be 112 litres per head (24.75 gallons per head). The 77 litres (17 gallons) domestic per capita figure for Birmingham was described by Mansergh as “a very reasonable amount, and in future will be considerably increased. Nowadays, baths and hot water apparatus are being put into houses of much smaller rental than they used to be”. Mansergh estimated that domestic demand in towns with no water closets was 59 to 65 litres per head per day (13 to 14 gallons per head per day).

Glasgow’s total average daily supply of 214 to 227 litres per head (47 to 50 gallons per head) was much higher than in Birmingham, which Glasgow city engineer James Gale said was due to the influx of new industries attracted by the introduction of soft water supply from Loch Katrine; industrial demand had trebled reaching 77 litres per head per day. This evidence fortified the belief that soft water from Wales would have the same effect in Birmingham; starting from a higher base than Glasgow, Mansergh assumed 91 litres per head per day for the Birmingham forecast. The social and economic reasons for the greater potential for industrial growth in late Victorian Birmingham compared with Manchester has been highlighted by Briggs (1968) as being the great diversity of occupations, a skilled workforce and small workshops rather than large factories.

Although it is not clear how he used these figures to develop his forecast, Mansergh confirmed that in his experience, his demand assumptions were “reasonable” and the way he used them in his evidence demonstrated that he understood their significance. However, he did not present an accurate view of losses. He asserted, “I am quite certain that there is no preventable waste (in Birmingham) at all”. The success of the waste control initiatives that were introduced during the construction period for Elan contradicts Mansergh's view. Clearly a statement like this would not go unchallenged today.

The usual response by a water undertaker at that time to the prospect of growth outstripping supply was to develop new supplies, but there were few suitable local opportunities in Birmingham. A substantial waste minimisation programme was started in the 1890s, and continued after the first phase of the Elan scheme was commissioned in 1904. Section 4.4 concludes that without the waste minimization programme before World War I, the surge in demand to meet the war effort would have presented an even more serious supply problem.

4.3.6 Elan; Parliamentary Debate 1892

Even though requested to do so by the HoCSC Select Committee, Mansergh refused at an early stage of the hearing to give a population forecast for Birmingham in 1955 on the grounds that he had not explicitly used a population forecast to develop his demand forecast. However, some speculative population forecasts for 1955 were offered to the HoCSC by Howard Smith, (an internal auditor appearing for the Corporation), of between 1.35 million and 2 million. When pressed later by the House of Lords, Mansergh reluctantly suggested a figure of 1.62m (a compound increase of 1.5% per annum) as "not unreasonable". As we now know, these estimates all turned out high, but they were compensated in the forecast by under-estimates of per capita demand growth. Figure 4.11 shows the supply area population peaked and flattened in the 1950s at 1.25 million and since then, the population stabilised.

With regard to rainfall estimates, Mansergh recognized that in the past "great mistakes have been made by overestimating the quantity of rainfall" and that "I am not more careful than my experience leads me to be." On several occasions when giving evidence, and under cross examination, Mansergh used the first person "I" to confirm that the opinion and experience was his, and the word "safe" to imply that his approach was balanced. Mansergh admitted that his judgment might, in the fullness of time, prove to be wrong.

Potential uncertainty in the under-estimation of the 3 dry years rainfall on the Elan catchment was raised in cross-examination of Mansergh. After clarifying that a minimum quantity of 450 Ml/d was assumed as the 3 dry years runoff figure from the Elan and Claerwen catchments, Moon (Counsel for the opposition) asked Mansergh that if he subsequently found out that "Mr Lloyd's water gauges (i.e. rain gauges) have led you astray, and that more water falls on that area than you expect, what might be the under-calculation? A little perhaps?" The dialogue (HoCSC, 1892) continued thus:

Moon – "545 Ml/d (120 Mgd)?"

Mansergh - "Certainly not."

Moon – "500 Ml/d (110 Mgd)?"

Mansergh – "Certainly not."

Moon – 477 Ml/d (105 Mgd)?

Mansergh – "I might go to 477 Ml/d (105 Mgd)"

Mansergh was confident in the knowledge that 20 years of rainfall records was a huge advantage to narrow the range of error. His judgment at the time, based on the short dialogue above, was that an under-measurement of 6% was possible. It is interesting to note that in Binnie's estimation of annual average rainfall paper to ICE in 1892, the range of error with 20 years of record is given as ± 3%. Assuming that the percentage rainfall error approximates to the runoff error, Mansergh could have justified an upper range of 464 Ml/d (102 Mgd).

However, Binnie's paper was presented on 22 March 1892, just 9 days before the start of Select Committee's hearing on 31 March.

Mr Pember, the Counsel for opponents London County Council, argued that a decision about Birmingham's scheme should be deferred for a year until the latest Royal Commission had reported about the much larger issue of London's future water supply. Pember asked Mansergh that if Birmingham was allowed to develop the Elan scheme, how many people could be served from potential reservoirs elsewhere in Wales. Mansergh's response was "Oh dear, about 200 million." Summarizing his argument recommending that Parliament should pause, Pember's primary objections were:

1. The Elan scheme is too large for Birmingham;
2. There are other places that need water;
3. Birmingham is safe for the next 10 years.

Pember suggested Mansergh's demand forecast of 67 Mgd for 1955 was too high, and that a more realistic forecast range was from 30 Mgd minimum to 40 Mgd maximum. Pember's view was based on a population forecast assumption of 1.6 million people, which had been tacitly accepted by Mansergh as possible. There was an inferred range of 19 to 23 gallons per head per day of per capita demand, which were comparatively low.

The range of uncertainty in the demand forecast for 1955 can be assessed using the data and information presented by witnesses to the Select Committee. The matrix in Table 4.7 assumes a range for the population forecast from 1.3 to 2.0 million, and a range for Non-Domestic use between 8.75 and 20.25 gallons per head per day. Average domestic demand is assumed to be

25 gallons per head per day, and +20% of average domestic demand to produce a peak demand.

Table 4.7 – Matrix showing the range of alternative demand forecasts for Birmingham that could have been made in 1892 for 1955

Non-Domestic Scenarios:	1955 Pop Forecast: 2.0 x 0.65 (1891) **1.3 m (+10k /year)** Demand Forecast Average (Peak)	1955 Pop Forecast: 2.5 x 0.65 **1.6 m (Mansergh)** Demand Forecast Average (Peak)	1955 Pop Forecast: 3 x 0.65 **2.0 m (H Smith)** Demand Forecast Average (Peak)
1. 1891 existing: **8.75 g/head/day**	44 Mgd (50)	54 Mgd (62)	67 Mgd (77)
2. 2 x 1891 **17.5 g/head/day**	55 Mgd (61)	68 Mgd (76)	85 Mgd (95)
3. 1891 plus Gale **20.25 g/head/day** **Or 91 litres/head/day**	58 Mgd (64)	72 Mgd (80)	90 Mgd (100)

The matrix in Table 4.7 shows the minimum average demand forecast is 44 Mgd, and the maximum is 90 Mgd. This range is clearly above Pember's estimate for 1955 of 30 to 40 Mgd. Mansergh's figure of 67 Mgd is mid-range.

4.4 Supply and Demand Outcomes

In Section 4.3, the Victorian engineers' long-term demand forecasting approaches were researched, and the accuracy of their forecasts was examined. The planned and the actual water resource availability are now brought together with the forecast and the actual demands.

4.4.1 Thirlmere and Manchester – Supply and Demand Balance 1855 to 1936

Whilst the powers to develop the Thirlmere scheme were obtained in 1879, the Corporation did not start construction until 1884. There was a summer drought that year, and Bateman warned the Corporation that the Longdendale reservoirs may not refill over the following winter. Bateman's report triggered the Corporation into action.

The actual construction period over-ran the planned period by five years. This is shown in Figure 4.14 by the five year difference of the planned (1889) and actual (1894) years for Thirlmere to come on stream. For the total water resource in Figure 4.14, Bateman's planned drought yield of 227 Ml/d for the Thirlmere scheme has been added to 111 Ml/d for Longdendale, and the total plotted as 339 Ml/d. The Thirlmere scheme had a "planned life" of 55 years from 1879 until 1934, the latter year being when the extrapolated demand forecast meets the planned drought availability.

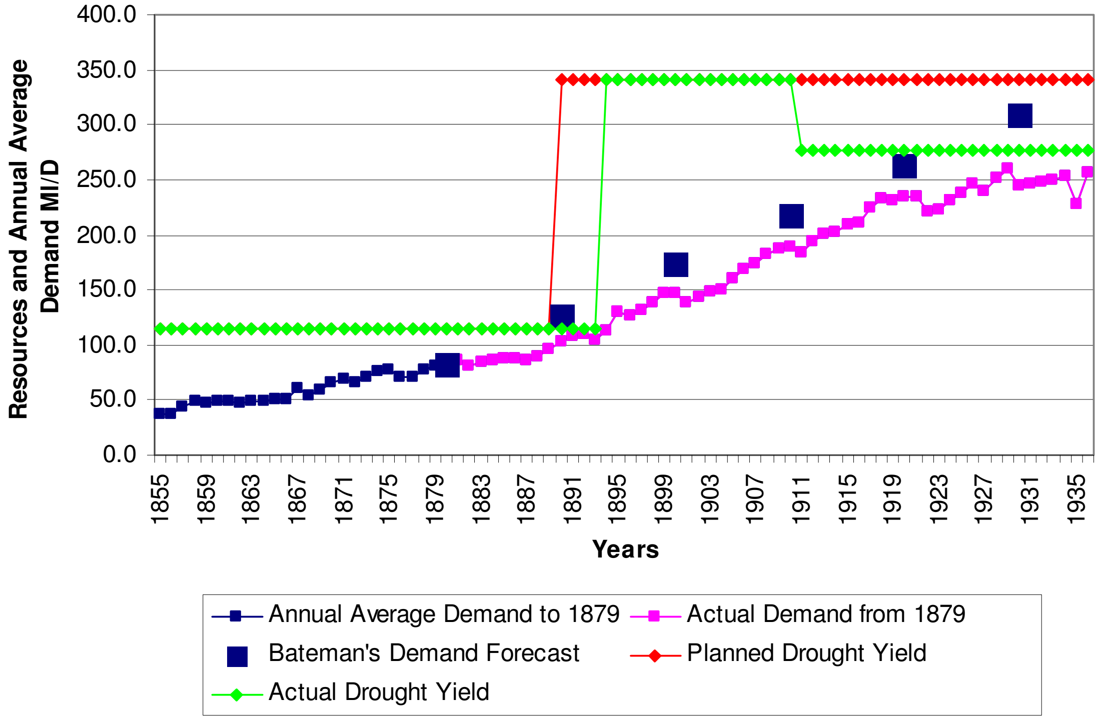

Figure 4.14 – Thirlmere and Manchester, Resources and Demands, 1855 to 1936

The reduction of the Thirlmere drought yield from 227 Ml/d to 164 Ml/d (Walters, 1936) reduces the planned life to 42 years, as it lasts from 1879 to 1921. It has been shown indicatively in Figure 4.14 as occurring in 1910. No formal announcement about the reduction has been found.

4.4.2 Vyrnwy and Liverpool – Supply and Demand 1857 to 1946

The drought yield figure from 1894 onwards is plotted in Figure 4.15 as 232 Ml/d. The three components are Rivington 35 Ml/d (7.7 Mgd), Vyrnwy 182 Ml/d (40 Mgd), and local wells 15 Ml/d (3.3 Mgd) (Mansergh 1901).

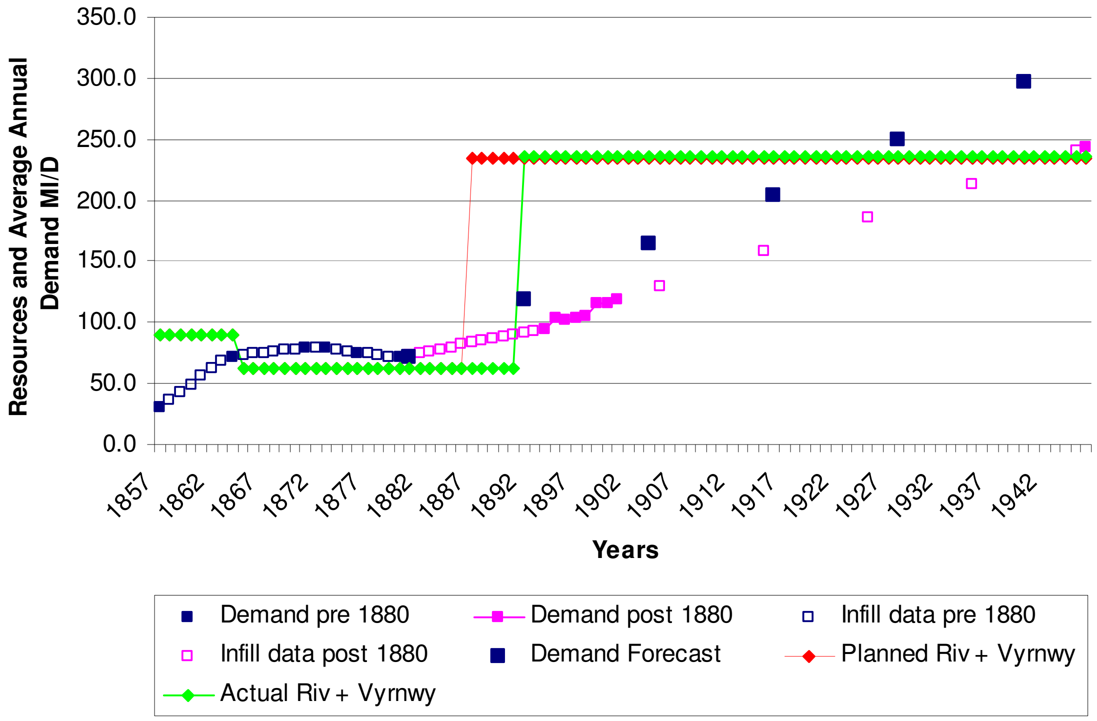

Figure 4.15 – Liverpool Vyrnwy, Resources and Demands, 1857 to 1946

Figure 4.15 shows how critical the Vyrnwy scheme was to Liverpool Corporation. The intersection of the demand forecast and the enhanced water resources occurs in 1925, which is 31 years after the first flow from Vyrnwy. The Corporation wanted a scheme to last for a minimum of 30 years, and this objective was met.

4.4.3 Elan and Birmingham – Supply and Demand 1877 to 1984

A similarity of Elan with the two other Victorian schemes is the over-running construction phase. In 1892, Mansergh believed that the first stage of the Elan scheme could be constructed in 8 to10 years, and in fact it took 12 years to reach the first flow to Birmingham in 1904. From 1904 onwards, the drought yield figure plotted in Figure 4.16 contains only the Elan yield. All the local sources operating before 1904 are assumed to be decommissioned, mothballed, or available only in emergency.

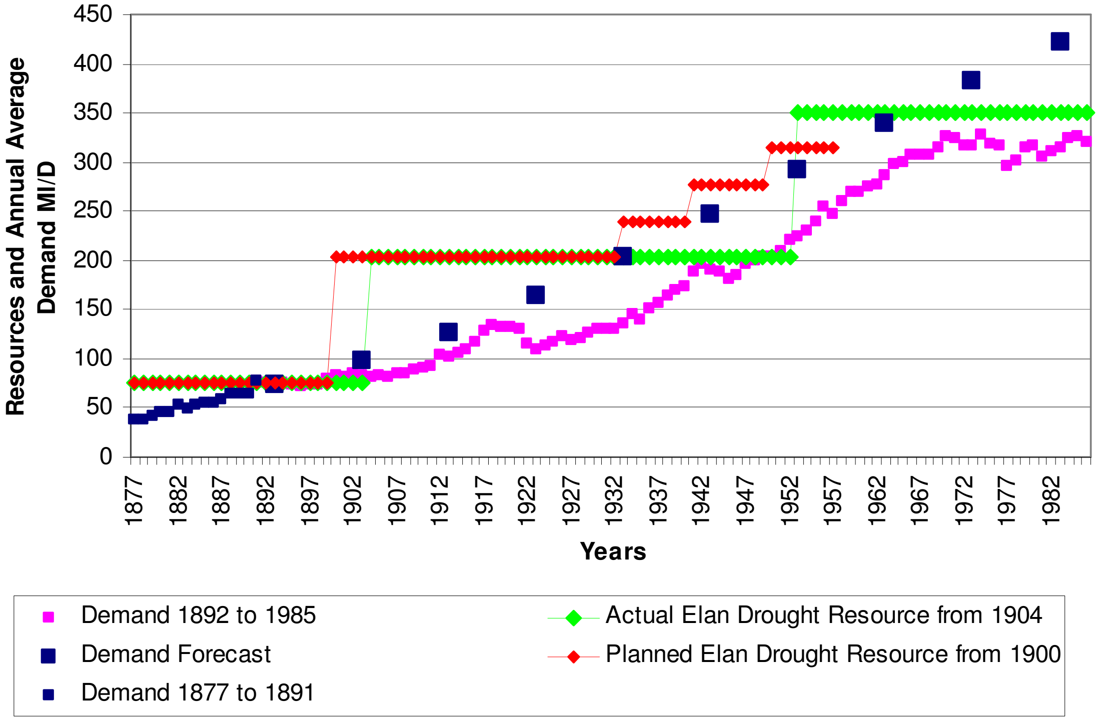

Figure 4.16 – Birmingham Elan, Resources and Demands, 1877 to 1985

The second stage of reservoir development saw one large reservoir at Claerwen that exceeded the original storage provision, and provided more drought resource. The schematic in Figure 2.4 shows the full scheme including Claerwen.

4.4.4 Birmingham; Disaggregated Supply and Demand 1897 to 1955

For this comparison, the 63-year period of the forecast and observed demands were divided into 6 sub-periods, as shown in Figure 4.17, and summarized in Table 4.8.

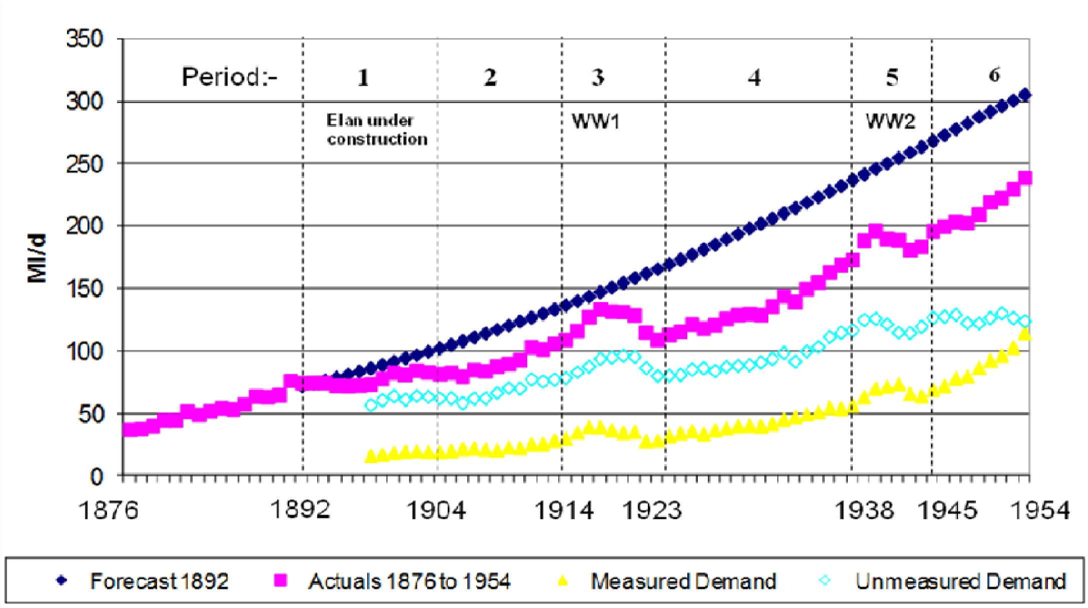

Figure 4.17 – Birmingham Water Demands: Mansergh's 1892 forecast and actual demands from 1876 to 1955

Table 4.8 – Summary of six periods for comparison shown in Figure 4.17

Period	No of Years	Key Features
1. 1891 - 1903	12 yrs	Demand flat, growth held by demand management
2. 1904 – 1913	10 yrs	Actual growth = Forecast growth
3. 1914 – 1922	9 yrs	Peak in 1917/18 during WW1, then fall.
4. 1923 – 1937	15 yrs	Actual growth = Forecast growth
5. 1938 – 1944	7 yrs	Peak in 1942/43 during WW2, then fall
6. 1945 – 1954	10 yrs	Actual growth = Forecast growth
1891/2 – 1954/5	63 years	Actual growth 180 Ml/d; Forecast growth 240 Ml/d

The datasets used to construct Figure 4.17 come from the annual reports produced by the City of Birmingham Water Department (CBWD). The annual total water supplied and the annual measured demands are derived from meter readings. The average annual unmeasured water demand (mostly household water use, some trade and industry, and waste) is the residual from the subtraction of the measured demand from the total water supplied. Their movements over these six periods help to explain how Birmingham developed in the first half of the twentieth century.

Period 1: 1891 to 1903 - From 1891 up to 1903 before Elan first came on stream, measured demand was steady. Unmeasured demands grew more slowly than might have been expected given that population growth at this time was approximately 20,000 per annum, or 3% per year. The explanation for this lies in the response made by Birmingham Corporation when faced with an increasing risk of running out of water during the Elan construction period. The Water Committee had two strategic options; either to invest in the enhancement of output from local sources, or attempt to control demand. Barclay describes how the Water Committee felt at that time that something should be done to increase supply. After the failure of trial borings, "it is feared that there are no other sources of supply on which the Corporation can draw, and the Water Department will find it very difficult to keep the population fully supplied".

The introduction of demand management was more successful. In 1893, the Water Committee instructed that all 155,000 properties in the supply area should be inspected to prevent as much waste as possible. This serious undertaking was, as reported by Barclay in 1898 as "abundantly justified by the result" since it had quickly provided an annual saving of 6 Ml/d (500 million gallons per year), and also saved the Corporation pumping costs. The annual statement of accounts for 1898 from the CBWD shows that the new team of waste inspectors found 14,000 cases of waste from faulty fittings per year. By 1904, the figure had reached 31,000 cases per year. The throughput at an existing testing facility for water fittings was increased – some 57,000 were tested in 1898 rising to 160,000 in 1904. By 1904, these activities had the desired effect of constraining total demand growth by up to 14 Ml/d.

Period 2: 1904 to 1913 - Elan water was first introduced in 1904, and the growth in this period was primarily unmeasured demand. The population continued to grow at 3% per year, and waste prevention continued at the pre-Elan rates, but measured demand remained steady for the 10 years until the onset of World War 1. This could be considered unexpected as one of Mansergh's arguments for the Welsh scheme was that new industry would be attracted by the soft water, it being preferable for use in boilers.

Period 3: 1914 to 1922 - With the onset of World War I, dramatic rises occurred in both measured and unmeasured demand. The increase in total demand (5% per year) was the fastest since the Corporation took over the Birmingham Waterworks Company in 1875. Birmingham had the companies, skills and the workforce to manufacture the needs for war. Furthermore, waste inspections were curtailed, the CBWD accounts showing in 1916 that only 11,000 cases of faulty fittings causing waste were found. In May 1916, total demand was 120 Ml/d and rising, the maximum capacity of the twin piped aqueduct was surpassed, and full use was being made of standby sources. In his Annual Report for 1915/16, Antony Lees, the Secretary to the Water Committee stated:

"It is now realised that the consequence of the increase in consumption of water being more rapid than anticipated, exceeding in fact the rate of increase for revenue, the third main on the aqueduct will be required earlier than was expected…. as regards the immediate future, it is clear that in view of the war conditions, the provision of the third main must be indefinitely postponed…..the increased consumption entails the cost of additional pumping from old sources….a considerable expenditure at Plants Brook (an old local surface source) will have to be faced to render that station again available for use. On the above grounds, it seems to me impossible to make a forecast which will be of any practical value".

Mansergh's original plan was for the third main to be available by this time, but the Water Committee had been overtaken by events, and total annual average demand peaked in 1917/18 at 134 Ml/d. Following the war, both measured and unmeasured demands were in sharp decline until 1922/23, when demand returned to the 1914/15 level.

Period 4: 1923 to 1937 - The inter-war period witnessed population growth of near 1% per annum; in 1929/30, the number of people supplied by the Corporation was estimated to have reached 1 million. In spite of the Great Depression, the total demand growth rate returned to that forecast by Mansergh, and the actual demand increase over the period of 80 Ml/d being equally split between measured and unmeasured demand. The third main was completed, and after a summer drought in 1937, the Corporation begun the preparation for the second phase of raw water storage provision for the single reservoir at Claerwen. Mansergh's original plan had been for three small reservoirs.

Period 5: 1938 to 1944 - The outbreak of World War II caused the construction of Claerwen to be deferred. A spike in demand occurred again, peaking this time at 200 Ml/d in 1942/43, followed by another fall.

Period 6: 1945 to 1955 - The period from 1945 to 1955 saw total demand growth returning to the Mansergh forecast rate. Nearly all of the growth of 50 Ml/d was measured demand, and it was the fastest sustained growth outside of wartime at any time since 1892. Unmeasured demand growth became flat as the supply area population levelled off.

In summary, over the 63 years from Mansergh's forecast in 1892 to the end of the forecast period in 1955, population supplied doubled from 600,000 to 1.2 million. Unmeasured demand more than doubled from 60 Ml/d to 135 Ml/d, and measured demand increased by a factor of 7 from 13 Ml/d to 105 Ml/d. The proportion of unmeasured to measured demand in 1892 was approximately 85%:15%, and by 1954/55, it was approaching 50%:50%, thus showing how significant industrial and commercial growth has been to the development of Birmingham's economy. Total demand increased by a factor of 3.5 from 70 Ml/d to 239 Ml/d, whereas the forecast was near 4.5 times higher at 305 Ml/d. In 1955 this represents a positive gap of 28%, which is shown in Table 4.9.

Table 4.9 – Annual average actual and forecast PCC for Birmingham in 1955

	Actual in 1955	**Actual PCC Litres per head per day**	**Mansergh Forecast for 1955**	**Implied Forecast Litres per head per day**	**Per Cent Difference; Forecast vs. Actual**
Population	1.23 million		1.62 million		+ 32%
Total Supply	239 Ml/d		305 Ml/d		+28%
Total as PCC		194		188	- 3%
Unmeasured		101		97	- 4%
Measured		93		91	- 2%

There may be evidence that Mansergh's implied PCC forecasts for 1955 were well judged. In row 3 in Table 4.7, the measured forecast PCC of 91 litres was Mansergh's estimate. The unmeasured forecast of 97 litres is the subtraction of 91 from 188 litres. However, the close match of PCC figures is only possible using Mansergh's overestimated population forecast. Looking at sensitivity, to produce a similar match using the actual population figure implies a much higher total supply PCC value of 248 litres. Or, using the 1955 actual supply figure with Mansergh's population forecast implies an improbably low PCC of 148 litres. Without experience, using judgement to produce a joint PCC and population forecast carried a high risk of getting the long-term final year average annual demand seriously wrong.

The profiles of forecast and actual growth from 1904 to 1955 become closer with the removal of the observed demand management effects prior to the commissioning of Elan. This is shown in Figure 4.18 where Mansergh's forecast has been translated from an 1892 start to begin in 1904.

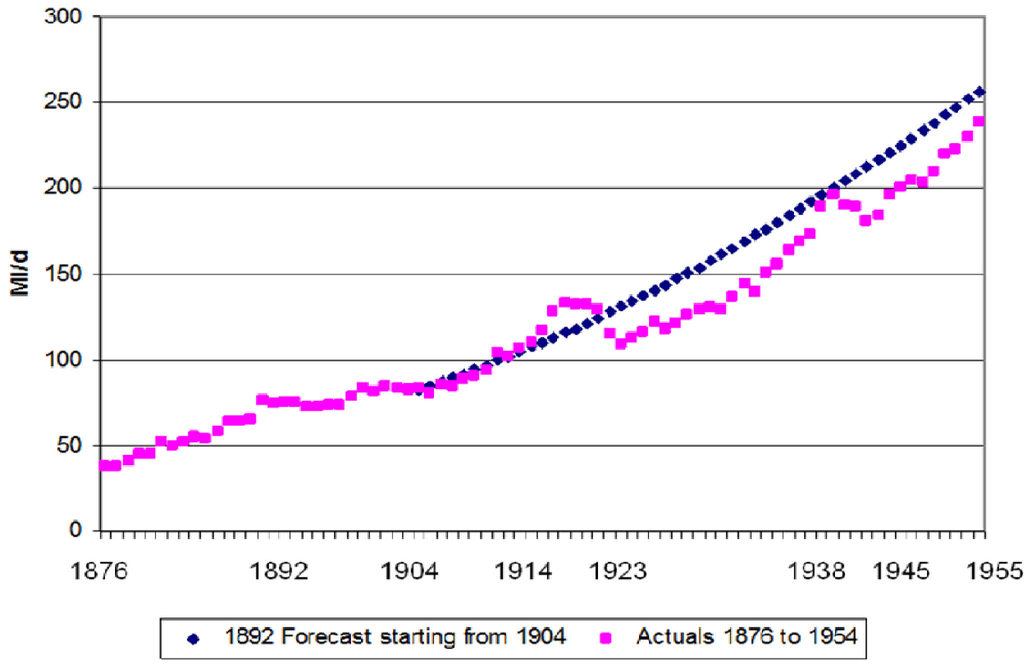

Figure 4.18 – 1892 forecast translated to 1904 start compared with actual demands

The gap between forecast and actual demand in 1955 is then reduced to only 7%, which is remarkably close and a testimony to Mansergh's judgement.

4.4.5 Modern critical review of the Elan scheme

Coopey (2000) and Roberts (2000, 2006, 2007) provide a contemporary Welsh reflection on English dam developments, particularly in North Wales. A key theme is the importance of the English perception of Welsh water purity. Along with Liverpool, Birmingham Corporation marketed the notion of the purity of Welsh water to convince a sceptical public of the need for an expensive scheme, and that the resultant cleansing would be moral as well as physical. Roberts remarks that even today, bottled water from Wales is branded as coming from a desolate rural place with its consumption leading to better health.

Far from the unchallenged admiration of the Birmingham engineers by many earlier writers, Coopey sees the Elan scheme as a "reflection of the power of the political-engineering nexus in Birmingham between 1870 and 1890 and its ambitions and ideologies." The picture Coopey presents is of the Corporation exhibiting imperialism and determination. The Corporation defeated the local opposition by presenting the science and engineering data, and the demographic projections, as certainties which could not be resisted. Today, with much better organised and resourced interest groups, an understanding of the uncertainties of supply and demand projections are pivotal to the arguments supporting and opposing new water resource schemes.

Coopey describes how objectors on the River Wye were pacified by Mansergh's "pre-emptive engineering" of the Carreg-Ddu dam design, which ensured that the storage in lower Caban was for compensation to the Wye, and not for supply to Birmingham. Whilst agreeing that Mansergh was a clever engineer, Coopey does not express admiration.

Coopey gives us his insight to the self-interested motives of the civic politicians and engineers, but he does not pass judgement on whether the Elan scheme was worthwhile. He does, however, assert that Hassard's alternative Ithon and Teme scheme was "cheaper, less risky, more useable water, and less disruptive of local communities." This is not referenced, and so remains an assertion. Perhaps his motive was to place doubt in the reader's mind about

Birmingham's competence to choose the most economic and least environmentally damaging scheme.

Roberts's recent papers argue that the commemoration of waterworks was for the display of civic unity, and that 19th century dam building was an exercise in modernisation and the progress of mankind. This was at a time when Welsh nationalism was focussed more on playing a part in the government of the British Empire than opposing the English Victorians notion of modernity.

Roberts notes an inter-war ideological shift when the nationalists showed a clear anti-modern anti-urban streak. Nationalist opposition in the 1950s and early 60s to Liverpool's reservoir at Llyn Celyn produced a defining moment at the opening ceremony. The nationalists sabotaged the microphones, and the event only lasted three minutes. As a reflection of our now more enlightened environmental age, Liverpool issued an apology in 2005 for forcing this scheme through. It is believed that in recent times, the issue of an apology from Birmingham for Elan has not been raised.

4.5 Summary of the Victorian Approach

The analysis presented in this chapter has provided the pictures of supply and demand before and after the three Victorian reservoir schemes were built. There is a focus on the analysis of the demand forecasts made, and the approaches used by the Victorian engineers. Bateman used extrapolation from historic supply data for Manchester's demand forecast. For Liverpool, Hawksley used the population growth trend, and Mansergh used a novel method for Birmingham called the Decremental Ratio of Increase. The growth profiles of forecast and actual demand for Birmingham are surprisingly good.

A conclusion is emerging that the Victorian engineers did not explicitly quantify and factor in risk and uncertainty into their demand forecasts. They recognised that there were risks, but their approaches were pragmatic and necessarily deterministic because alternative statistical approaches were only in their infancy.

For this project, a method is required for expressing quantitatively the risk and uncertainty of a reservoir design size. A novel "lag-time" approach is developed that uses the actual and forecast supply and demand balance. The approach is explained and applied to the three Victorian reservoir schemes in Chapter 5.

CHAPTER 5 LAG-TIME MODEL

Chapter 5 develops an approach that enables comparisons to be made of the relative risk averseness of the Victorian schemes design storage sizes. The method is based on data abstracted from supply and demand graphs, and is novel. This new lag-time model approach has been developed for this project to address Knowledge Gap B, and to meet the quantitative elements of the second project objective.

5.1 Introduction

In order to quantify the relative effectiveness of a scheme design, a mechanism that involves extracting data from the supply and demand diagrams has been devised by the author. A lag-time model, which requires the evaluation of a novel "planned life" and "lag-time" for each scheme, is developed in Section 5.2.

The planned life is defined as the period of time which starts in the year when the powers to construct a scheme are obtained, and finishes in the year when the intersection occurs between supply and demand plus target headroom. The lag time is defined as the period of time that starts in the year when the planned life ends, and ends when actual supply and demand lines intersect. The actual life of a scheme is the sum of the planned life and the lag time.

To help explain the new terminology, an indicative supply and demand diagram is given in Figure 5.1. The planned life of scheme A is 14 years (from year 1 to 15 on the x-axis), and the lag-time of scheme A is 15 years (from year 15 to year 30). The actual life of scheme A is 29 years, which is the addition of planned life and lag-time. This interpretation of the supply demand balance is new, and makes use of a model that is used widely to portray forecast and observed water supply and water demand data.

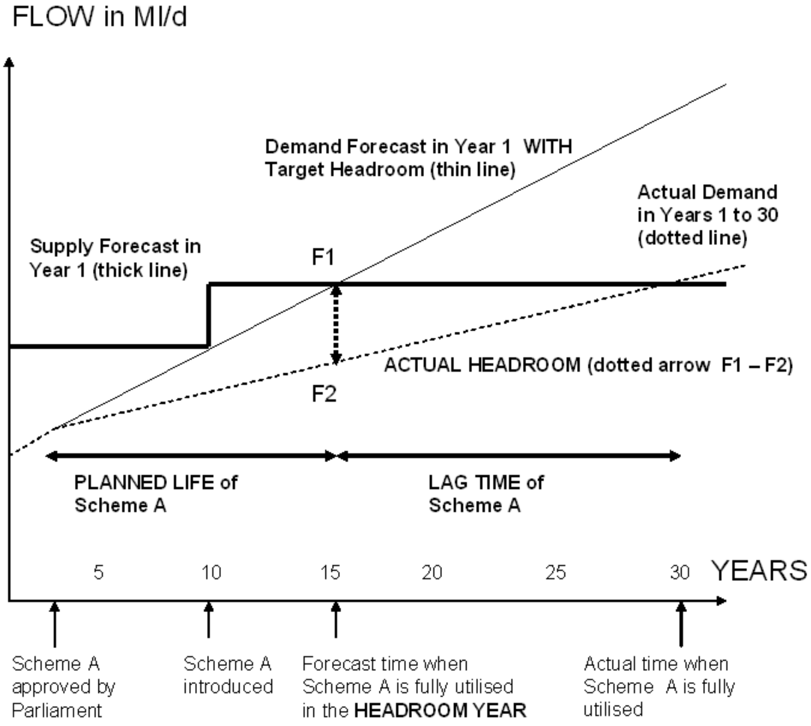

Figure 5.1 - Indicative Supply and Demand Diagram showing how the Planned Life and Lag-Time for Scheme A are estimated.

Simplified annotated diagrams are shown in Sections 5.3, 5.4 and 5.5 that identify the start and finishing times for estimating the planned life and lag-time for each of the three Victorian schemes of Thirlmere Vyrnwy and Elan schemes. The more detailed supply and demand diagrams from Section 4.4 are reprised below each annotated diagram to assist the analysis.

To enable comparisons of scheme effectiveness, two new expressions of normalised "Time Ratios" and "Flow Ratios" are derived in Section 5.6 for each scheme, and the results are analysed and discussed in Section 5.7.

5.2 Planned Life and Lag-Time

5.2.1 Planned Life

The planned life of a scheme could start at any time over a range of years. For comparing the planned lives of schemes, the starting year needs to be selected in a systematic way. The starting points that were considered are:

1) The time when the Corporation chose to develop the scheme.
2) When the scheme was first taken to Parliament.
3) When the Bill that authorised the scheme received Royal Assent.
4) When construction started.
5) When the first flow occurred.
6) When the scheme was fully commissioned.

Number 3 was chosen as it has a specific date, and the Bill will include any special conditions required by Parliament. The reasons for rejecting the other 5 options were as follows:

Number 1 is interesting for comparing the lead times of schemes, but can be difficult to define accurately enough from historic documents.

Numbers 2 and 3 are similar, but Number 2 would miss the occasions when there were failures at the Parliamentary stage.

Number 4; defining the time when construction started begs the question of which element of the scheme was started.

Number 5 was next best, as the time is specific. However, the time is not linked to the time during which the planning and design stages were undertaken.

Number 6 is similarly removed from the planning and design, and has the added uncertainty of being unable to find a date which formally commissions some or all of the water resources elements of the scheme.

The end of the planned life of a scheme occurs when the drought output from a scheme was forecast to be fully utilised. This is at the intersection in the supply and demand diagram of the projected additional drought yield of the scheme with the demand forecast. The demand forecast includes the target headroom calculated when the scheme gained parliamentary approval. The target headroom in Figure 5.1 for scheme A is shown as the distance from Point F2 to Point F1.

To obtain the intersection that marks the end date for the planned life, the horizons of the demand forecasts need to be extended. The forecasts for Manchester and Liverpool were linearly extrapolated beyond their 40 and 36 year horizons up to 50 years. For Birmingham, using Mansergh's parameters in his Declining Ratio of Increase forecasting method, the forecast was extended by 10 years from 63 years to 73 years. Whilst these extrapolations appear reasonable, more uncertainty is introduced to the accurate estimation of the end-date. Summarising, the end date of the planned life is the same as the start date of the lag-time.

The length of the planned life provides an indicator of boldness and confidence in a scheme. The longer the planned life, the greater the uncertainty as to when the planned life will actually end. The length of time it takes to deliver such long-term infrastructure investments, and estimating how long they will last, was a judgment call by the Victorian engineers. They were not to know, and factor in, the timing and impact on water demand of wars, and of economic boom and bust. For all three schemes, there was ultimately a margin of safety. This margin is the Lag-Time of a scheme.

5.2.2 Lag-Time

The lag-time is the period of time from when the planned life ends to when the actual full utilisation of the scheme occurs. Therefore lag-time can only be calculated in retrospect, and is an indicator of how well, or how badly, the design and the outcome are matched. The end-date of the lag-time occurs when the drought year water resource capability of the scheme under review intersects with actual demand in the supply demand diagram.

Actual demands in most years will be near normal, but the effect of prolonged hot weather, or thawing after winter frosts, normally lead to demands that are well above normal. During abnormally warm weather and with an intermittent supply, there is uncertainty about what the true unconstrained demand might have been. Peak week summer demands in Birmingham, where there was a constant supply, were reported to be over 20% greater than average during the late 1880s. Analysis of Bateman's monthly demand data from Manchester shows that it is reasonable to add up to a further 5% to the annual average demand in a dry year.

5.3 Application of LTM to the Three Victorian Schemes

5.3.1 Thirlmere: Application of Lag-Time Model

Two scenarios of water resource availability are modelled. Scenario A uses the Thirlmere output of 227 Ml/d (50 Mgd) assumed by Bateman in his original design. Scenario B is for the revised output of 164 Ml/d (36 Mgd). This revision is shown in the reprised Figure 4.14 as occurring at an arbitrary time of 1910, but the choice of the date is immaterial to the estimation of planned life and lag-time shown below.

From Figure 5.2, the planned life of scenario A is 54 years (from 1879 to 1934), which is from the year when the parliamentary powers were obtained, up to the year where the horizontal supply line intersects Bateman's extrapolated demand forecast at Point A1.

The planned life of scenario B is shorter at 40 years (1879 to 1919), which again assumes the scheme start date of 1879, but this time there is an intersection with the extrapolated demand forecast that occurs at Point B1.

The lag-time of A starts at 1933, but the end date cannot be estimated as actual supply and actual demand fail to intersect. The lag-time for B is 10 years, which is shown in Figure 5.2 from the planned intersection at Point B1 in 1919, along to the actual "lagged" intersection at Point B2 in 1929.

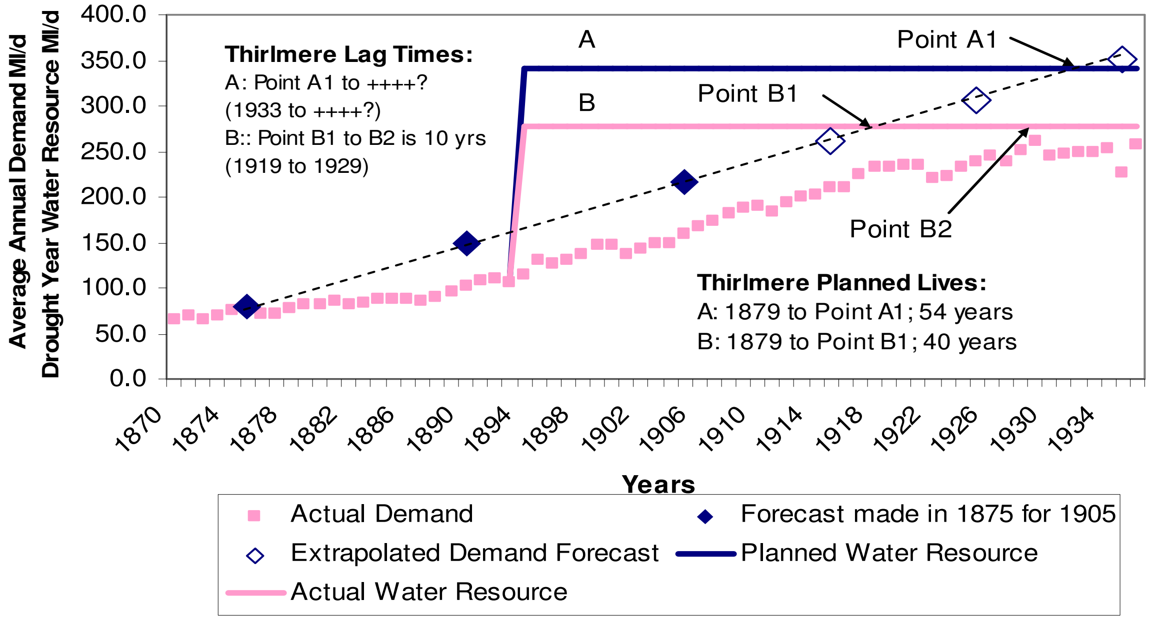

Figure 5.2 - Thirlmere: Planned life and Lag-Time

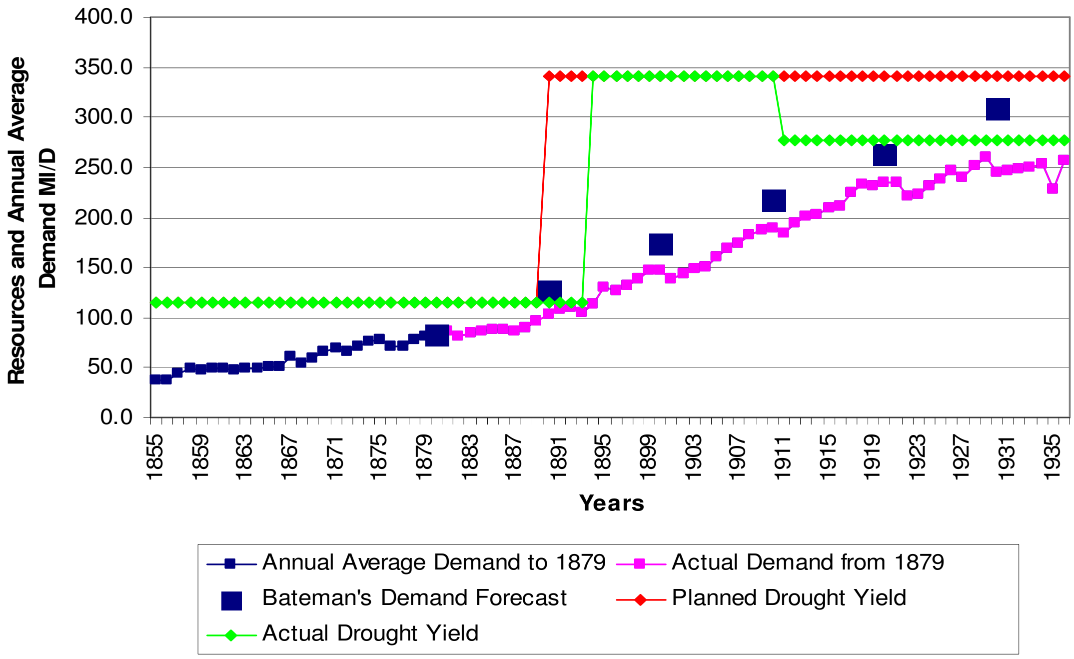

Figure 5.3 - Thirlmere reprise of 4.14

The lag-time for Bateman's planned scheme is likely to be more than 50 years, and so the actual life would be at least 100 years. With the revised lower Thirlmere drought output capability, the lag-time is about 10 years from the early 1920s to the early 1930s, and the actual life working out at near 50 years.

5.3.2 Vyrnwy: Application of Lag-Time Model

The Vyrnwy Works Act was passed in 1880, and a 12 year construction period followed. The planned construction period was 6 years, and this difference is shown in Figures 5.3 and 5.4.

An extrapolated linear demand forecast is required to calculate the planned life of Vyrnwy at 45 years (from 1880 to 1925). The lag-time is 15 to 20 years (from 1925 to the early 1940s); a figure of 18 years is used in later calculations. The actual life becomes 63 years. A refinement of this range could be achieved with more actual demand data in the 1920s and 1930s.

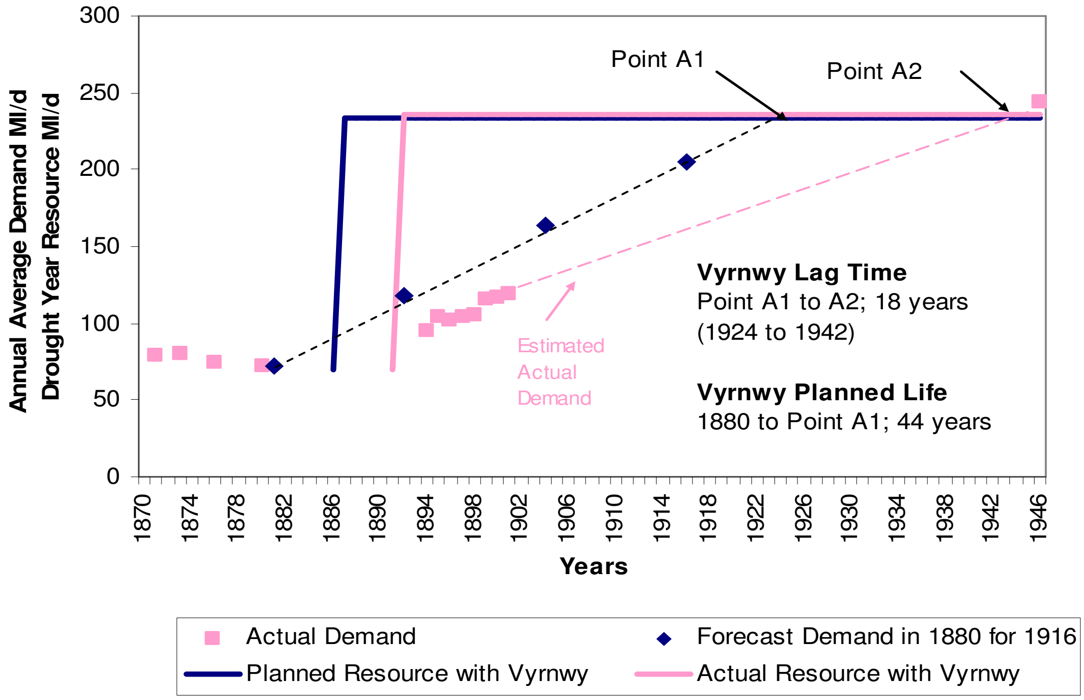

Figure 5.4 - Vyrnwy Planned Life and Lag-Time

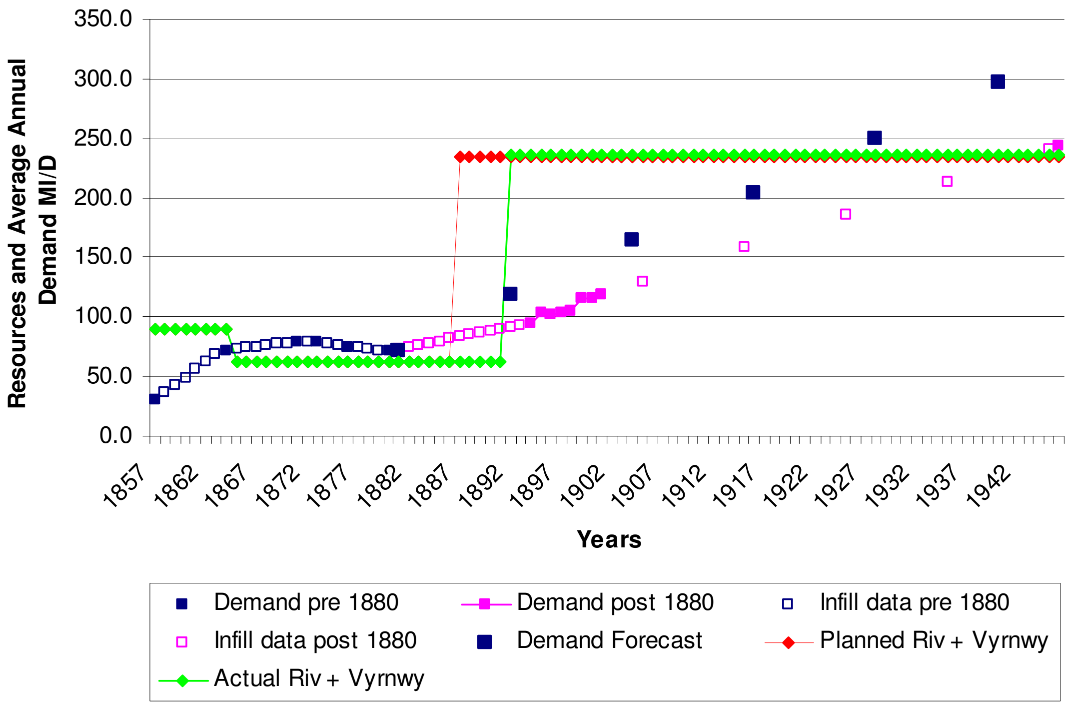

Figure 5.5 - Vyrnwy reprise of 4.15

5.3.3 Elan: Application of Lag-Time Model

As described in Chapter 2, there were originally six dams in Mansergh's design for Elan. The first three dams had a drought yield of 205 Ml/d (45 Mgd), and are referred to here and in Figure 5.6 as Stage 1.

Using Figure 5.6, the planned life for Stage 1 (labelled A in Figure 5.6) of Mansergh's design was 40 years (from 1892 to 1932 shown as Point A1 in Figure 5.6. There is a lag-time of 10 years from 1932 to 1942 (Point A1 to Point A2 in Figure 5.6.), making the actual life of 50 years.

Stage 1 plus Stage 2 (labelled B in Figure 5.6) of Mansergh's original design was for a drought yield of 314 Ml/d. The planned life is 65 years (from 1892 to 1956/1957), and the lag-time 10 years (from 1956/57 to 1966/67), which makes the actual life 75 years.

For the actual full Elan scheme, the planned life is 70 years. This figure assumes the continuation of Mansergh's demand forecast using the Decremental Rate of Increase.

The lag-time for the actual full scheme is about 10 years from the early 1960s to the early 1970s, and therefore the actual life of the actual full Elan scheme is 80 years.

The lag-time for Stage 1 is 10 years between the early 1930s and early 1940s. This might have been longer but for the rise in demand which took place during WW2. The lag-time for Stages 1 and 2 is also 10 years between the early 1960s and early 1970s. It is reasonable to assume that during dry years, average annual demand will show higher than in a normal year provided constraints on demand are not introduced.

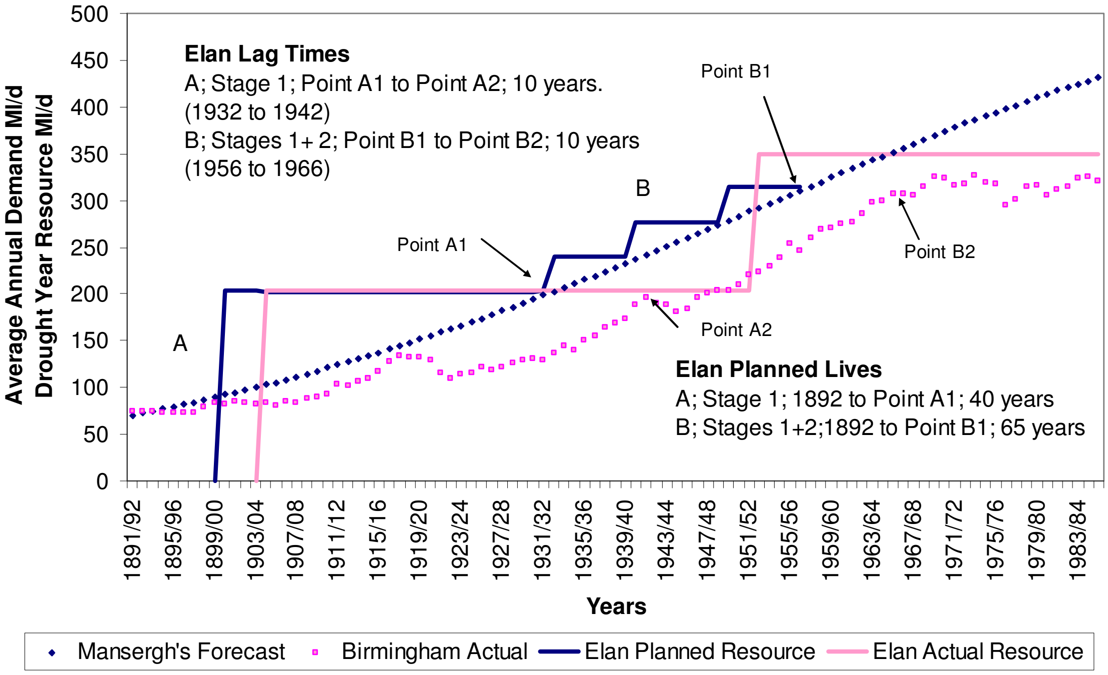

Figure 5.6 - Planned Life and Lag-Time for Elan Stages 1 and Stages 1+2

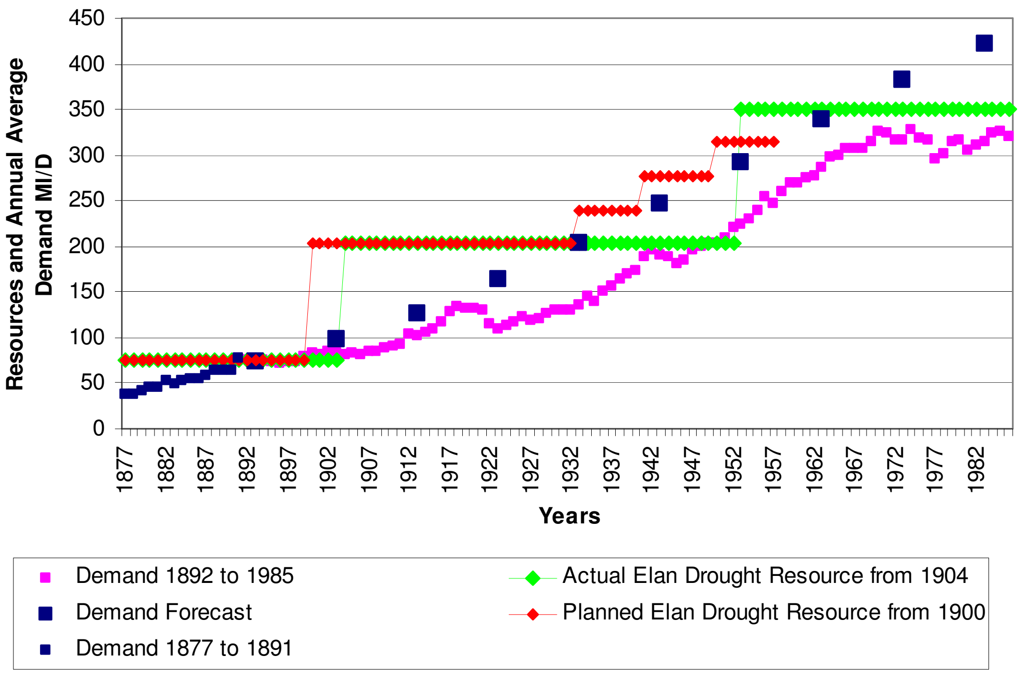

Figure 5.7 - Elan reprise of 4.16

Whilst there is insufficient data here to develop all but the simplest mathematical relationships, the ratio of lag-time over planned life (in Section 5.6 called the Time Ratio) has been used in this study to normalise the risk averseness of scheme designs.

Also in Section 5.6, a normalised Flow Ratio has been used to reflect the scale by which the headroom volume in the forecast demand has exceeded the actual demand.

5.4 How risk-averse were the scheme designs?

In the following tables that compare scheme design risk-averseness, Thirlmere has been considered as two different schemes using Bateman's original design of 227 Ml/d, and the subsequent 164 Ml/d drought yield.

Elan is also considered as two schemes. Stage 1 has a reservoir yield of 205 Ml/d. Stage 1 plus Stage 2 of Mansergh's original scheme has the drought yield to supply of 314 Ml/d. This was the yield anticipated by Mansergh for the completed scheme.

Vyrnwy is one scheme with a drought yield to supply of 182 Ml/d.

The risk averseness of scheme design is ranked in three ways:

1) by normalizing time into a Time Ratio,
2) by normalizing flows into a Flow Ratio,
3) by absolute Planned Life.

5.4.1 Time Ratio

Time ratio is a new concept developed as part of the research reported in this thesis, and is calculated by lag-time divided by planned life. A relatively low time ratio indicates less risk aversion. Table 5.1 shows the comparisons, with Thirlmere 227 clearly the most risk averse design, and Elan 314 the least risk averse.

Table 5.1 - Time Ratios of schemes

Scheme, Drought Yield in Ml/d **(Start year for Planned Life)**	**Planned Life (PL)** **in years**	**Lag Time (LT) in years**	**Time Ratio** **(LT/PL)**	**Rank of Risk Averseness** **(Time Ratio)**
Thirlmere 227 (1879)	54	>50	c. 1	5. Most Averse = Less Risky
Vyrnwy 182 (1880)	44	18	0.41	4
Elan 205 (1892)	40	10	0.25	2 =
Thirlmere 164 (1879)	40	10	0.25	2 =
Elan 314 (1892)	65	10	0.15	1. Least Averse = More Risky

There is no surprise in seeing Bateman's original design for Thirlmere as the most risk averse, and an outlier. Had the yield of 227 Ml/d remained, it would have been difficult for Manchester Corporation to make the case for their next water resource at Haweswater. The revised yield of 164 Ml/d brought the scheme exactly into line with Elan Stage 1, but this must be chance.

5.4.2 Flow Ratio

Flow ratio is also new and developed for the research reported in this thesis. To produce the flow ratio, the flows that make up the actual headroom (marked as F2 minus F1 in Figure 5.1) are used. The flows are read off the supply and demand diagrams, and the Flow Ratio is F1 divided by F2. A relatively low flow ratio figure indicates less risk aversion.

To make the Flow Ratio calculation, the year at the end of the planned life is identified. In Figure 5.1, this year is called the headroom year. The headroom year is noted for each scheme in the first column of Table 5.2.

The ranking of schemes for the flow ratio in Table 5.2 portrays a different picture to that shown in Table 5.1 for the time ratio. Elan 205 becomes the most risk averse, and Thirlmere 164 the least risk averse. The explanation lies in where the economic cycle is when the headroom year occurs. In the case of Elan 205, this is in 1933 during the Great Depression, and the actual water demand is depressed. The Headroom Year for Thirlmere 164 is 1919, and therefore before the world economy was in recession. The actual headroom is shown in Table 5.2. Thirlmere 227 has by far the largest actual headroom of 92 Ml/d.

Table 5.2 - Flow Ratios of Schemes

Scheme, drought yield Ml/d (Headroom Year)	**Flow (F1) in Ml/d**	**Flow (F2) in Ml/d**	**Actual Headroom (F1 – F2)**	**Flow Ratio (F1/F2)**	**Rank of Risk Averseness by Flow Ratio**
Thirlmere 227 (1934)	341	249	92 Ml/d	1.37	4
Vyrnwy 182 (1924)	237	183	54 Ml/d	1.29	3
Elan 205 (1933)	205	136	69 Ml/d	1.50	5. Most Averse = Less risky
Thirlmere 164 (1919)	277	232	46 Ml/d	1.19	1. Least Averse = More Risky
Elan 314 (1956)	314	254	60 Ml/d	1.24	2

Up to now, the drought yields of Longdendale and Rivington have been included in the flow F1 for the Thirlmere schemes, and the Vyrnwy scheme, respectively. The F1 figures for the two Elan schemes contain only the Elan drought yields. A check was made to see if the ranking was altered by the removal of the Longdendale and Rivington schemes from the calculation. Table 5.3 shows Thirlmere 227 returning to the most risk-averse scheme, and the full Stage 1 + Stage 2 Elan 314 is the least risk averse.

Table 5.3 - Flow Ratios minus Longdendale and Rivington

Scheme, drought yield Ml/d, (Headroom Year)	Flow (F1) in Ml/d, minus Longdendale and Rivington	Flow (F2) in Ml/d, minus Longdendale and Rivington	Actual Headroom (F1 – F2)	Flow Ratio (F1/F2)	Rank of Risk Averseness (Flow Ratio)
Thirlmere 227 (1934)	227	135	92 Ml/d	1.68	5. Most Averse
Vyrnwy 182 (1924)	182	128	54 Ml/d	1.42	3
Elan 205 (1933)	205	136	69 Ml/d	1.50	4
Thirlmere 164 (1919)	164	118	46 Ml/d	1.39	2
Elan 314 (1956)	314	254	60 Ml/d	1.24	1. Least Averse

5.4.3 Overall Rank of Risk Averseness

For an overall ranking of risk averseness, the planned life length has been introduced to Table 5.4 to reflect the greater uncertainty of schemes with longer planned lives. Weights were considered for achieving the total rank score, but were difficult to justify. With equal weighting for all three parameters, Elan 314 and Thirlmere 164 schemes are clearly the least risk averse.

Table 5.4 - Rank of overall Risk Averseness including Longdendale and Rivington

Scheme, Drought Yield Ml/d	Rank Time Ratio Tab 5.1	Rank Flow Ratio Tab 5.2	Rank Planned Life Tab 5.1	Total Rank score	Rank of Overall Risk Averseness
Thirlmere 227	5	4	2	11	4 = Most Averse
Vyrnwy 182	4	3	3	10	3
Elan 205	2 =	5	4 =	11	4 = Most Averse
Thirlmere 164	2 =	1	4 =	7	2
Elan 314	1	2	1	4	1 Least Averse

Table 5.5 uses the same ranks as Table 5.4 except the flow ratios from Table 5.3, which excludes the Longdendale and Rivington schemes. The total rank scores are similar, but the Thirlmere 227 scheme is not so much of an outlier as the scheme was in the time ratio results.

Table 5.5 - Rank of overall Risk Averseness minus Longdendale and Rivington

Scheme, Drought Yield Ml/d	Rank Time Ratio Tab 5.1	Rank Flow Ratio (minus Long & Riv) Tab 5.3	Rank Planned Life Tab 5.1	Total Rank score	Rank of Overall Risk Averseness
Thirlmere 227	5	5	2	12	5. Most Averse
Vyrnwy 182	4	3	3	10	3 =
Elan 205	2 =	4	4 =	10	3 =
Thirlmere 164	2 =	2	4 =	8	2
Elan 314	1	1	1	3	1 Least Averse

As will be suggested in Chapter 6, the principles of the lag time model method could be used to allow an “historical perspective check” on schemes.

5.5 Summary of risk averseness ranking exercise

The purpose of the exercise was to quantify comparative risk averseness of the Victorian reservoir scheme designs. The objective is a better informed discussion about the perception that large Victorian reservoir schemes were grandiose.

The clear least risk averse design was Mansergh's full Elan scheme, and Bateman's Thirlmere 227 scheme was the most risk averse. Hawksley's Vyrnwy scheme was never the least or most risk averse.

Historically, Bateman's Thirlmere scheme design predates Vyrnwy and Elan. Mansergh's Elan scheme came after both of the other two. We also know that Mansergh's demand forecast was developed with a better understanding of the water use behaviour, and this is possibly one of the reasons that the full Elan scheme design was the least risk-averse. Demand forecasters believe that the purpose of developing demand forecasts is to try to reduce uncertainty, and this exercise appears to sustain this view.

CHAPTER 6 MODERN APPROACH

Chapter 6 lays the foundations for addressing the first part of Knowledge Gap C, and the third project objective, by first explaining the current public water supply planning process that is undertaken by water companies. The current statistically rigorous UKWIR methodology for calculating target headroom that represents uncertainty is introduced. The novel lag-time approach is regarded as complimentary to the UKWIR methodology rather than a replacement. Thames Water's revised Draft Water Resources Management Plan of September 2009, which contained a proposal for a new large reservoir of 100 Mm^3 of new storage as part of the company's preferred strategy for the next 25 years, was the subject of a Public Inquiry in 2010.

6.1 Introduction

The modern approach starts in 1996 with the publication of the "Agenda for Action" in which central government addressed all the major stakeholders in the water industry after the national drought in 1995. In response, significant actions included the overhaul of the water resources planning process used by the water companies, and a systematic approach to express uncertainty in headroom.

The truest test of the technical and political issues occurs at a Public Inquiry. Evidence presented at the Public Inquiry into Thames Water's revised Draft WRMP in summer 2010 is analysed, as are the reasons for the Planning Inspector to reject the company's plan, and thereby, rejection of the proposed UTR scheme. Appendix D contains a chronology of the many documents that were produced by the Environment Agency, Defra and Thames Water leading up to the call for a Public Inquiry, and the aftermath.

Whilst the EA has done much work to improve its approach to forecasting water demands, their expertise is necessarily working at catchment level, and for a much wider range of water users than a water company's customers.

6.2 Water Resources Planning, and the "Agenda for Action"

The final move away from a "predict and provide" planning approach, and its replacement by a "twin-track" approach to long term water resources planning in England and Wales, was triggered by the experience of water supply difficulties that were encountered in the summer drought of 1995. In October 1996, the Government (The Department of the Environment) took the lead by launching "Water Resources and Supply: Agenda for Action". The then Secretary of State John Gummer said in the Foreword:

"The drought of 1995, which affected large parts of England and Wales, and continued into 1996 in many areas, focussed attention on water resources. The question also arose of whether this drought is a manifestation of climate change. This was the background to the commissioning of this paper on the arrangements for securing sufficient supplies in the longer term. The paper confirms that the framework for those arrangements is sound."

The arrangements were underpinned by Government, which would retain the responsibility for the legislative and policy framework within which the water companies and their regulators would operate. The objective was "to ensure that the water we need in the longer term is provided effectively, efficiently, and in an environmentally sustainable way." To make this happen, Agenda for Action recommended actions to be undertaken by water companies, regulators, Government, manufacturers of water using appliances, and water consumers. The Secretary of State concluded with "sustainable development (of water resources) is a matter for each and every one of us as individual members of the community. This Agenda for Action is for all of us."

The tables below list the actions with a summary of progress since 1996.

Table 6.1 - Central Government

Reference **pp 42**	**The Government will**	**Actual Actions**
12.2 a	Bring forward modifications to the legal framework if required.	Water companies 5 yearly Water Resources Management Plans have been made statutory.
12.2 b	Continue to promote research into climate change.	Through UKWIR (UK Water Industry Research).
12.2 c	Revise regulatory requirements in respect of water conservation	Specifications set for enabling sustainable housing.
12.2 d	Assist in the promotion of efficient use of water.	Support for Waterwise.
12.2 e	Review the process for Drought Order applications	Water Companies Drought Plans made statutory. EA now made aware of the detail for a Drought Order much earlier in the process.
12.2 f	Consult on use of economic instruments in relation to water abstraction.	"Water for Life" white paper of Dec 2011; consultation planned in 2013 about new water abstraction regime.
12.2 g	Introduce legislation as necessary for compensation arrangements for customers affected by supply interruptions or low pressure	Water companies now operate Guaranteed Standards schemes to compensate customers.

The Government (through DEFRA) has been active developing debate, and providing leadership for water resources and supplies planning. "Future Water" makes clear the Government's approach should be primarily demand management. Targets are set for reducing domestic per capita demand from the current 140 to150 litres per person per day down to 120 or even 110 litres per person per day by 2035.

Table 6.2 - Environment Agency

Reference	The Environment Agency should:	Actual Actions
12.3 a	Co-ordinate the fresh estimating of the reliable yields of water resource systems, and publish.	Water companies undertook the work in 1997 in calculating new "Deployable Output" for systems.
12.3 b	Lead the testing of these estimates against climate change scenarios.	Water companies and EA input range of rainfalls into simulation models to arrive at range of Deployable Outputs for systems.
12.3 c	Revise as necessary its national and regional water resources strategies in consultation with the water companies	EA produced national and regional strategies, and updates.
12.3 d	Be fully involved with water companies new resource development plans.	Undertaken within the Water Resources Management Plan Annual Updates, and 5 year review.

The EA has many duties in national and regional water resources planning and operations. These duties include being Defra's specialist advisor, particularly with regard to the assessment of water companies Water Resources Management Plans and Drought Plans. The EA operates the national raw water abstraction licensing system, determines abstraction licence applications, develops River Basin Management Plans, Catchment Abstraction Management plans, and is also the environmental regulator of the water companies. With responsibilities too for river water quality, pollution control and fisheries, the existence of EA and water company plans would be expected to reduce the risk of conflicts of interest, particularly during a drought.

Table 6.3 - The Office of Water Services

Reference	The Office of Water Services should	Actual Actions
12.4 a	Monitor and as necessary enforce water companies' performance of their duty to promote the efficient use of water by their customers.	Legal duty on water companies to promote water conservation in the 1995 Environment Act. All water companies have water saving initiatives, which are reinforced during droughts.
12.4 b	Monitor, report, and as necessary, take further action on leakage control.	Incoming Government in 1997 empowered Ofwat to set water companies mandatory annual leakage targets. Severn Trent Water fined in 2008 after referral by Ofwat for deliberately misreporting leakage in 2002 and 2003.
12.4 c	Be fully involved with water companies' resource development plans	Presentations by water companies leading up to Periodic Review
12.4 d	Consider the financial implications of new water resources and supply schemes as necessary in the course of its normal price regulation activities.	The East Worcestershire Waterworks Company was taken over by Severn Trent as new water resource schemes were needed that would have produced unacceptably high charges to East Worcs customers.

Ofwat's primary role is to assess water companies 5 yearly Business Plans, and to set the level of water charges to customers in that 5 year period. Ofwat also ensure that the water companies fulfil their side of the "contract" with their customers. Even though the EA may determine an abstraction licence for a scheme in a water company's favour, Ofwat are under no obligation to allow the funding to the water company involved.

Table 6.4 - Drinking Water Inspectorate

Reference	The Drinking Water Inspectorate will:	Actual Actions
12.5 a	Check that all water supplies are monitored in accordance with and meet regulatory quality requirements	Business as usual
12.5 b	Check that water treatment processes comply with regulatory requirements	Target dates agreed with water companies for implementing water treatment improvement, and approval for water companies to be funded.
12.5 c	Take enforcement action if regulatory requirements not met.	Business as usual

The Drinking Water Inspectorate (DWI) has a clear role in monitoring and reporting on the companies' compliance with treated water quality standards. Variable and deteriorating raw water quality (e.g. nitrates) can impact on the availability of water in water resources planning assumptions. The DWI is involved in evaluating risk, authorisation of the appropriate treatment solution, blending solution, and approving the timetable and costs for scheme delivery.

Table 6.5 - Water Companies

Reference	Water Companies should	Actual Actions
12.6 a	Prepare fresh estimates of the reliable yields of water resources systems.	Deployable Output for every system calculated for the first time in 1997 (a huge task).
12.6 b	Establish further detailed measurements of household water use.	Severn Trent Water added a large sample of households paying by meter to an existing monitor of daily use in households paying unmeasured charges.
12.6 c	Conduct further studies on the implications of climate change on the demand for water	UKWIR programme of climate change impact research.
12.6 d	Extend the penetration of metering	Significantly extended in water stressed areas of South East England
12.6 e	Develop more sophisticated tariff structures.	The technology is available, but industry standards difficult to agree.
12.6 f	Increase efforts to promote water conservation	All water companies are proactive. Severn Trent has recently offered a water conservation kit for free.
12.6 g	Improve leakage measurement, control and reporting	Huge improvement since 1996 investing in new meters, data capture, methods and analysis.
12.6 h	Enter into dialogue with customers about security of supply	Consultation with customers is part of the statutory requirement for WRMP and Drought Plans.
12.6 i	Draw up plans for timely development of new water resources where demand cannot be managed to remain within existing resource capability.	The 5 yearly WRMP planning process that looks forward 25 years ensures that supply demand balance deficiencies are identified, and that water companies develop a least cost plan to remedy the shortfall.

Table 6.6 - Manufacturers of Water Using Equipment and Fittings

Reference	Manufacturers of water using equipment and fittings should	Actual Actions
12.7 a	Continue to develop and market energetically more water-efficient products.	White goods now carry information about water use
12.7 b	Continue innovation in the field of water recycling systems.	Recycled water is used in non-households to cut costs. In households, technology exists for grey water recycling, but cost, practicality, and attitude are barriers that will take time to change.

Table 6.7 - Water Consumers

Reference	Water Consumers should	Actual Actions
12.8 a	Take full notice of information from water companies and other organisations on the need for water efficiency and how to achieve it.	Huge efforts have, and are being made, to encourage water efficiency. Difficult to measure the impacts reliably in large samples.
12.8 b	Recognise the environmental significance of water conservation	Education centres teach children about the link between water conservation and environmental improvement.
12.8 c	Take every opportunity to use water wisely.	With the increasing penetration of household metering, water is becoming just another commodity. "Using water wisely" can get forgotten during droughts.

6.3 The current water resources planning approach used by Water Companies

The "twin-track" approach of demand management and capital schemes is now used by all water companies to update and develop their preferred programmes for the least cost mix of demand management initiatives and new schemes. Demand management can be more expensive than new small water resources schemes, but to encourage companies to do more, Ofwat now funds schemes that deliver measurable reductions of water demand. Water companies are also expected to align their draft WRMPs with the assumptions made in other parts of the company's Business Plan that affect supply, demand and projected costs (e.g. metering policy and forecast of uptake).

The process for the production by water companies of their 25 year horizon WRMPs is provided as Guidance from the EA. Water companies are expected to follow the Guidance, unless a deviation is clearly justified by the evidence. As will be shown later, a deviation by Thames Water that included for "long-term risk" beyond 25 years was deemed inadmissible by the Inspector at Public Inquiry for insufficient evidence and justification. A closer analysis of the reasons given for this decision that are given in Section 6.5.5 is helpful to meeting the objectives of this study.

6.3.1 EA's Water Resources Management Plan Guidance introduces Headroom

In its Introduction, the EA Guidance states what a Water Resources Management Plan is for, and the recommended approach to delivering a robust plan:

"A water resources plan shows how a water company intends to maintain the balance between supply and demand for water over the next 25 years."

"Companies should set out a baseline forecast of demand for water for 25 years, assuming current demand policies. This should include Defra/Welsh Assembly Government policy and any forthcoming changes in legislation about demand management."

The first area of uncertainty mentioned by EA is about the uncertain impacts of climate change on supply and demand, and in the same paragraph, introduces the idea of "the required level of headroom"

"Companies should also consider the impact of climate change on demand.

This should then be compared against a baseline forecast of available water supply, assuming current resources and future changes that are known about. Companies also should consider the impact of climate change on supply and forecast the required level of headroom to allow for uncertainty in the assessment."

The EA Guidance goes on to explain what is meant by headroom:

“Headroom is a buffer between supply and demand designed to cater for specified uncertainties. This gives a calculated surplus or deficit of water for each year. This is known as the baseline supply-demand balance and companies aim not to have a deficit.

Where there is a deficit, companies should choose water management options (i.e. on both sides of the twin track) to meet the difference.”

In practice, the deficit referred to above by EA is by how much the available headroom of supply over demand falls short of the target headroom.

“A company’s water resources plan should consider the costs and benefits of a range of options and justify the preferred option set. The company should then prepare a final supply-demand balance, taking into account its preferred options for water management, to demonstrate that the plan meets the forecast demand.” The message that the EA is communicating here is that it expects to see water company plans that just meet target headroom in 25 years time, and no more. The Agency’s guidance continues:-

“A company’s water resources management plan should be a stand-alone document that provides a realistic strategic plan for managing water resources. Companies should provide evidence in their plans in support of their preferred strategy and full details of the assumptions they have made.”

The EA’s use of the word “realistic” is open to interpretation that depends on technical and regulatory judgement. “Companies should demonstrate a clear understanding of the performance of their systems, the main factors affecting their supply-demand balance, and how their preferred plan is both flexible and robust to the various risks and uncertainties, including the potential impacts of climate change.”

In chapter 9 of the EA's Guidance, the EA explains that there are two methods of calculating the headroom requirement (i.e. the target headroom) to allow for uncertainty:

1 "A Practical Method for Converting Uncertainty into Headroom (UKWIR, 1998), is a pragmatic approach that…does not provide sufficient evidence to justify the development of new resources to meet the calculated target headroom. This approach is most suitable for resource zones where there is a healthy supply demand balance for at least the next ten years."

2 "An Improved Methodology for Assessing Headroom (UKWIR, 2002) addresses the shortcomings of the 1998 methodology by taking a more rigorous approach to determining headroom uncertainty through probabilistic simulation. The uncertainties of each headroom component are defined as probability distributions, and combined using Monte Carlo simulation. Much more work is required to apply this approach but it is sufficiently rigorous to support the justification for developing new resources."

The headroom components included in the 2003 methodology are shown in Table 6.8.

Table 6.8 - Supply and Demand related components for Target Headroom calculations

Ref.	**Supply related**	**Ref**	**Demand related**
S1	Vulnerable surface water licences	D1	Accuracy of sub-component data
S2	Vulnerable groundwater licences	D2	Demand forecast variation
S3	Time-limited licences	D3	Uncertainty of impact on climate change on demand.
S4	Bulk imports	D4	Uncertain outcome from demand management measures.
S5	Gradual pollution of sources causing a reduction in abstraction.		
S6	Accuracy of supply-side data		
S7	Single source dominance (dropped as included in Outage)		
S8	Uncertainty of impact of climate change on source yields.		
S9	Uncertain output from new resource developments		

Probability distributions are chosen for each of the parameters shown in Table 6.8 for a Monte-Carlo analysis.

Not only is the 2003 approach preferred for its rigour, the model output is presented in a probabilistic way, as shown in Figure 6.1, that links to the confidence level of meeting a water company's stated level of service. To be 100% certain of meeting the level of service (a hypothetical assumption), target headroom would be very large, and the plan would have to be made up from an undeliverable set of non-optimal and very expensive actions.

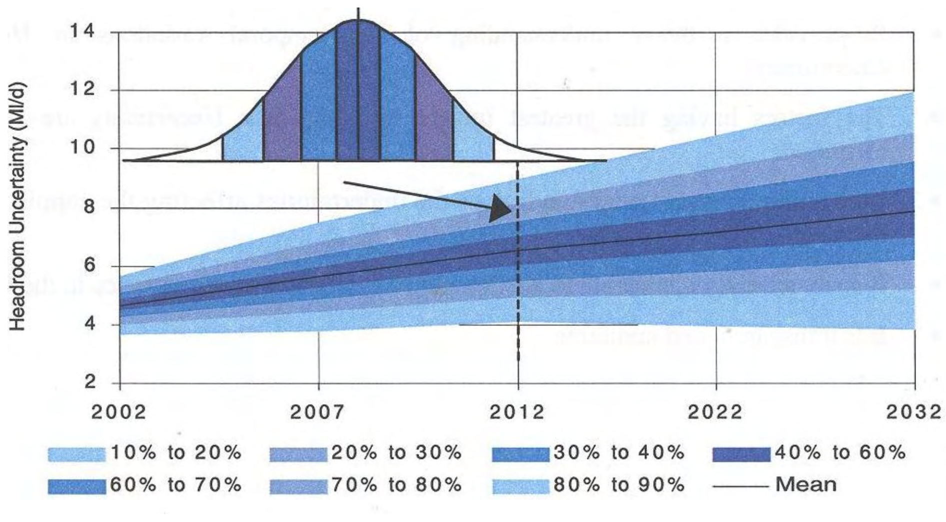

Figure 6.1 – Typical results from headroom analysis (UKWIR, 2002)

The application of the novel lag-time model is not regarded as an alternative to this methodology, but as complimentary to it, by providing an "historic perspective check".

There is also danger of going too far in the other direction, perhaps to reduce expenditure. The EA recognise that there is a judgement to be made here as "water companies should not take unnecessary risks by applying too low target headroom." This judgement involves selecting the level of risk (e.g. the frequency in years for applying a hosepipe ban) that a particular company has chosen for its customers, and explaining the cost versus risk issues in public consultation documents. However, whilst the UKWIR headroom assessment methodology enables a flexible approach to be taken, the range of judgements that are necessary for selecting the shape and range of the error functions used in the Monte-Carlo analysis, the range of choice of the degree and the timing of level of service failure probability, and uncertainties in the original assessment of the Deployable Output of supply systems, it is possible to force a given outcome for the target headroom calculation.

There are different types of risk and their associated cost pressures which water companies have to manage. For example, there is regulatory risk in failing to meet reductions in operating costs that have been previously agreed with Ofwat. This failure turns into a business risk when Ofwat factors such failings into the five-yearly price review. The balance of risks and costs in both water and wastewater sides of the business helps to determine the company's priorities for expenditure. Capital expenditure on new water resources and supplies is normally a small part of a water company's capital programme, and the five yearly price reviews do not encourage inter-generational expenditure.

The EA's components of the WRMP process, including headroom, is shown in Figure 6.2.

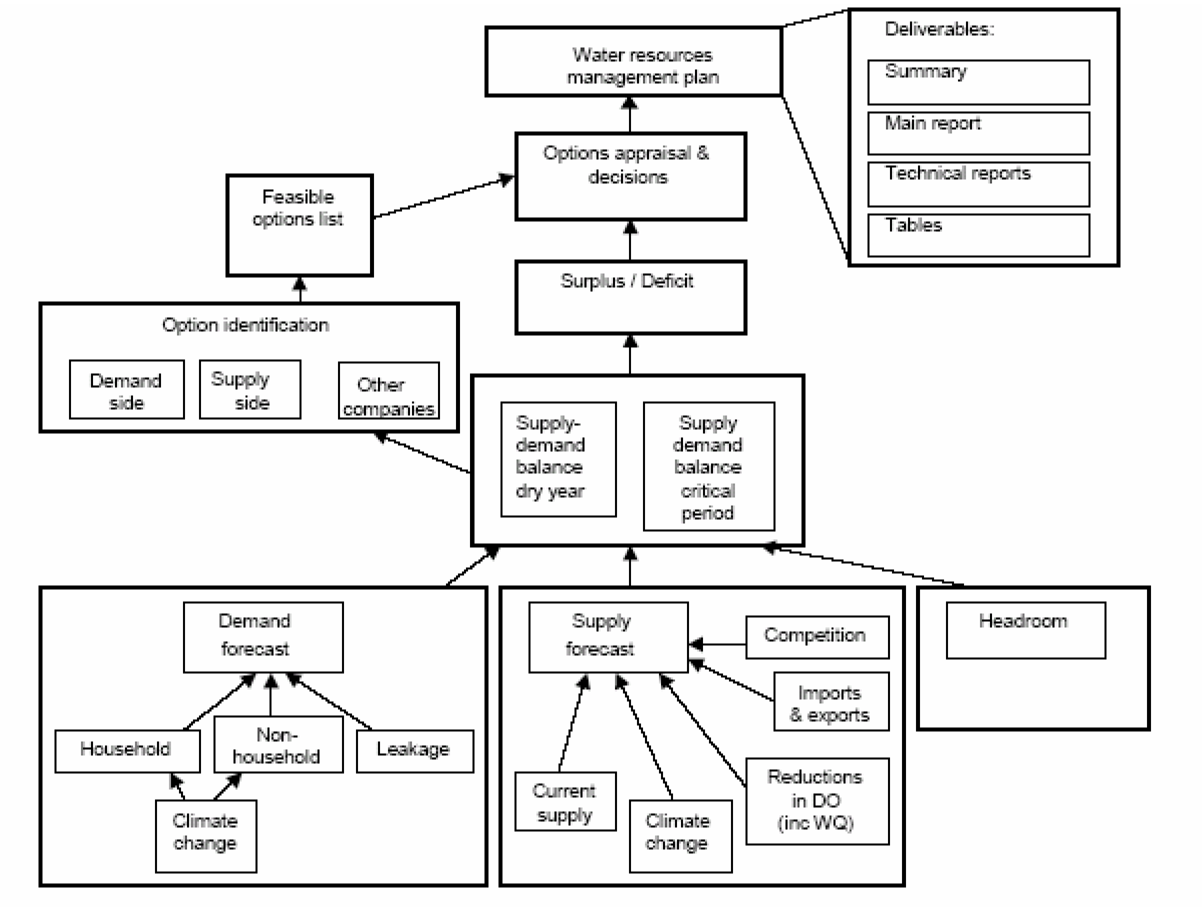

Figure 6.2 - Components of a Water Resource Management Plan (from EA, 2007)

6.3.2 Target Headroom

For each Resource Zone within a water company, a baseline supply and demand position is set first. Then the supply and demand forecasts are made along with the target headroom (TH), which is then used to plan the scale and timing for an optimal least cost set of water resources and demand management schemes. TH will be relatively small in the early years of the plan, but as the planning horizon extends, the target headroom of supply over demand will grow. However, as real time moves forward, the TH for a particular year in future is likely to decrease.

To illustrate the declining target headroom for a given year as real time moves forward, Figure 6.3 is used as a hypothetical and a much simplified supply and demand balance diagram. It is an indicative example that shows:

1. In Year 10, a new 10 Ml/d Scheme A is commissioned.
2. Also in Year 10, Actual Headroom (simply supply minus demand, and excluding the X axis, the lowest line in Figure 6.2.) is boosted by 10 Ml/d to a total of 20 Ml/d. At this point in year 10, available headroom is 10 Ml/d above target headroom.
3. The small dotted lines show how the demand forecast + target headroom for year 30 gradually reduces in real-time from 80 Ml/d to 50 Ml/d in 5 year intervals
4. Target headroom is just met in year 15. By year 30, available headroom is zero
5. As real-time reaches year 30, and without Scheme B, actual headroom and target headroom fall to zero. There is now a significant risk of failing to meet levels of service as there is no allowance for uncertainty.

6. Scheme B might have been regarded in Year 0 as optimal for providing supplies for the next 40 to 50 years. Its deferral runs the risk of having to bring forward a sub-optimal scheme.

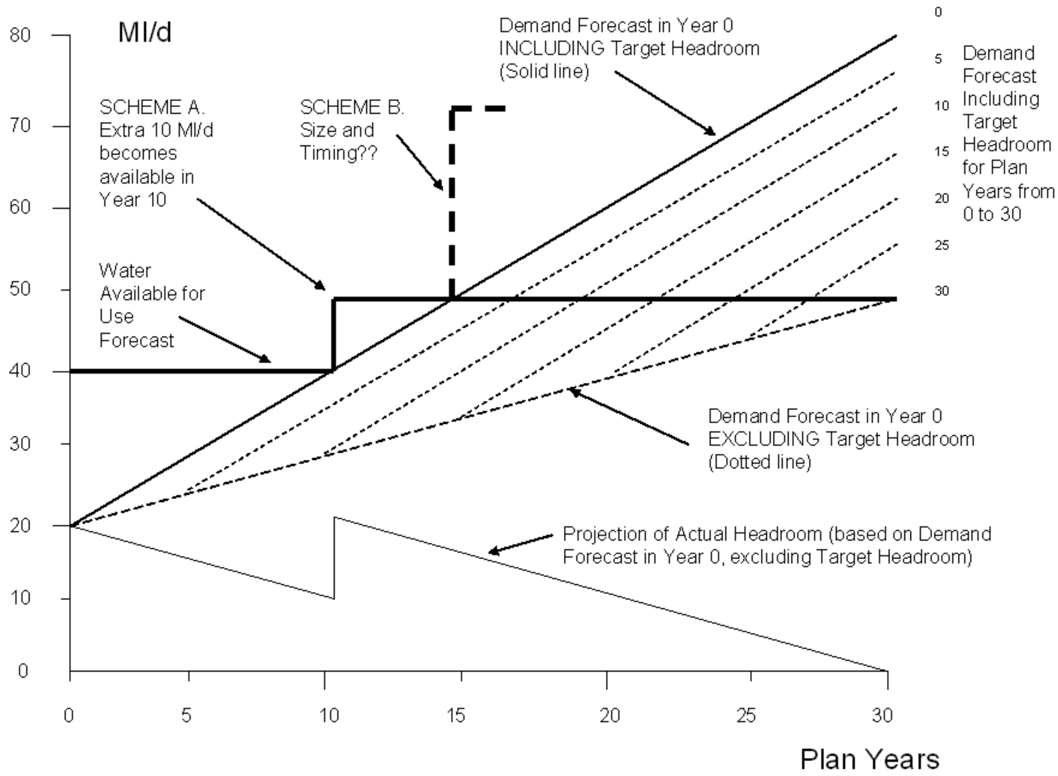

Figure 6.3 - Indicative Supply and Demand Forecasts

In Figure 6.3, the initial supply and demand forecasts are made in Plan Year 0. The “Water Available for Use” is the supply forecast. There are two demand forecasts, one includes target headroom (TH), and the other excludes TH. Using the Plan Year 0 demand forecast that includes target headroom, Scheme A is due in Plan Year 10, and provides an extra 10 Ml/d of Water Available for Use (from 40 to 50 Ml/d in Figure 6.2). The Plan Year 0 forecast to meet TH shows that Scheme B is due in Plan Year 15, but what should be the size and timing for this scheme?

In real time, by Plan Year 15, if the simplifying assumptions are made of rolling forward the same profile of TH, and also the assumption of steady linear demand growth, the interpretation of Figure 6.2 shows that Scheme B is now required between Plan Years 20 to 25. Looking further forward to the production of the plan in Plan Year 30, the supply and demand forecasts intersect, which indicates that Scheme B (or something else) should not be deferred any further. Figure 6.2 shows that with Scheme A, but without Scheme B, the projected Actual Headroom (AH) in Plan Year 30 becomes zero.

If Scheme B is a major resource for the long-term, the plan in Plan Year 0 ought to bring out the issues around the forecasts, alternative solutions, and the development of the scheme. However, the current approach to target headroom implies that the selection and timing of schemes that is optimal for meeting target headroom from Plan Year 0 becomes non-optimal in future years. Also, as the 25 year horizon approaches, and there is a constraint on the inclusion of a scheme that is optimal, for example from year 20 to year 40. This is precisely the situation that Thames Water had when developing their plan.

The regulatory and public scrutiny of water company plans and proposals for new reservoir schemes is rightly challenging. The technical complexities are substantial, judgment of detail is still involved, and there is much more data now to be judged.

6.3.3 Climate Change

In the past 10 years, there has been questioning about whether rising temperatures due to climate change is really happening, and if it is, there are other factors than man that are the cause. Sceptics mistrust the science, and in response, The Royal Society (2010) produced an objective evidence based summary of the science. The Society concludes that there is a warming trend, and that man's activities are the dominant cause, but because of the uncertainties that will always be apparent, climate science must be the essential basis for planning. Hulme (2007) argues that climate scientists need to improve their communication with the public to explain the science, and that it is in fact healthy and expected in the scientific world for scientists to disagree.

Over the past 15 years, much research work has been undertaken by UKWIR and EA that enables better quantification of the potential impacts of climate change on the deployable output of surface and groundwater sources. The results of this research have helped EA to formulate advice to the water companies when developing their WRMPs. This Section 6.3.3 reports on early work to quantify the impacts, which was undertaken by Severn Trent Water and published by ICE (Crookall and Bradford, 2000). Aspects of the work done by Thames Water for their Draft WRMP (2009) are also described.

Water resources system simulation models have played a central role in this quantification, and these models were employed by Severn Trent Water using rainfall factors produced from the UKCIP98 scenarios. For 2020 and 2050, all the surface sources tested showed a reduced deployable output. In 2050, the Elan catchment showed a relatively small range of reduction of between – 9 to -12 Ml/d for the “wet” and “dry” scenarios, whilst the sources dependent on the River Severn showed a larger range of -40 to -85 Ml/d.

The conclusion in the paper was that the impact on surface water sources is highly dependent on the nature of the catchment, and on the volume of storage available. Groundwater source deployable outputs showed small increases, which to most people would be beneficial. Compared to the impact on surface water supplies, the impact of climate change on annual water demand is thought to be relatively small.

The south-east of England is the area where climate scientists believe the warming will be greatest in the UK, and Thames Water (2009) state that "by far the biggest uncertainty factor is the impact of climate change". To demonstrate the range of rainfall uncertainty, the company made projections of monthly rainfall for the 2020s using six different climate models. The results are shown in the company's Table E.3 (2009), and reproduced in this thesis as Figure 6.4. The evidence from the "wet", "dry" and "mean" profiles clearly show the wetter winters and drier summers, and there is a gap between the average wet and dry scenarios that is approximately 25% for each of the 12 long term monthly averages.

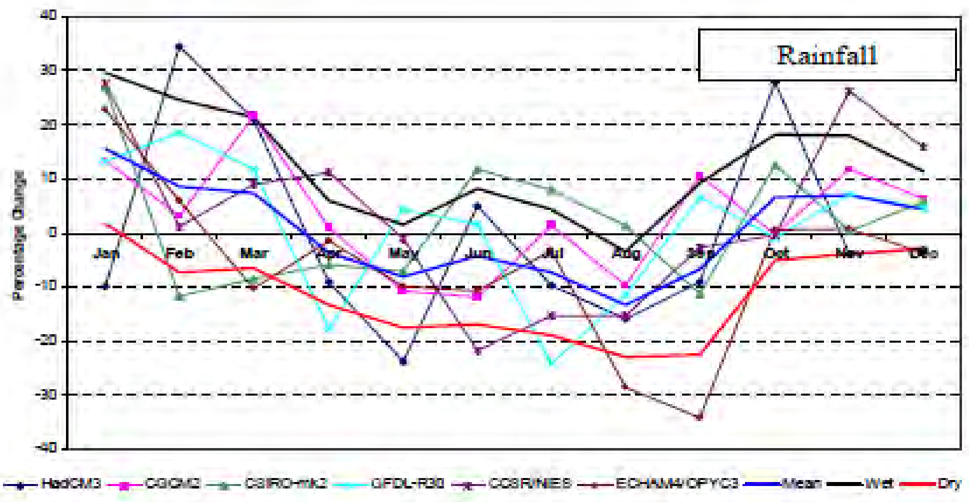

Figure 6.4 - Comparison of rainfall factors, from Thames Water (2009) Figure E.3

The UKCIP09 (2011) regional findings for the 2080s, which use the Medium Emissions Scenario, show for London that the gap is wider at 42%. The central summer mean rainfall estimate is -22% below the long term mean, and the central winter mean rainfall estimate is +20%. However, these figures conceal runs of years with below average rainfall (IH, 1994) that impact negatively on the yield of groundwater resources, and result in lower than average base flows to rivers. Future water resource plans for water companies in south-east England that assume runs of years with low rainfall, would be very expensive to implement, and face major political difficulties.

Thames Water also presents a comparative summary table from two climate models in the revised Draft WRMP (2009). The results in the company's Table E.3 show the deployable output reductions that are entirely due to climate change. The company's Table E.3 is shown as Table 6.9 for the London resource zone.

Table 6.9 - Results of the latest UKWIR06 climate change modelling (WRMP) compared to WR06 - Thames Region, London from Thames Water (2009) Table E.3

Thames Region					
	WRMP			WRP06 (Previous)	
Scenario	Nov 2007 - London DO with CC impacts (Ml/d)	CC diff from base (Ml/d)	Scenario	Mar 2006 - London DO with CC impacts (Ml/d)	CC diff from base (Ml/d)
Base (No CC)	2007	-	Base (No CC)	2121	-
Dry	1520	-487	Medium	1840	-281
Mid	1908	-99	Warm & Wet	2057	-64
Wet	2202	195	Cool & Wet	2132	11

Table 6.9 demonstrates that there is still much uncertainty in the assessment of deployable output. The mid-point planning lines are 182 Ml/d apart (i.e. 281 – 99), which is equivalent to the deployable output of the UTR, and therefore the loss of a major resource.

6.3.4 Ofwat Approach

The twin track approach to water resources planning is accepted by water companies and the regulators. An Ofwat view of this approach was presented in 2010 by Dr Mike Keil (2010), Head of Climate Change Policy at Ofwat using a fictional indicative example as shown in Figure 6.5.

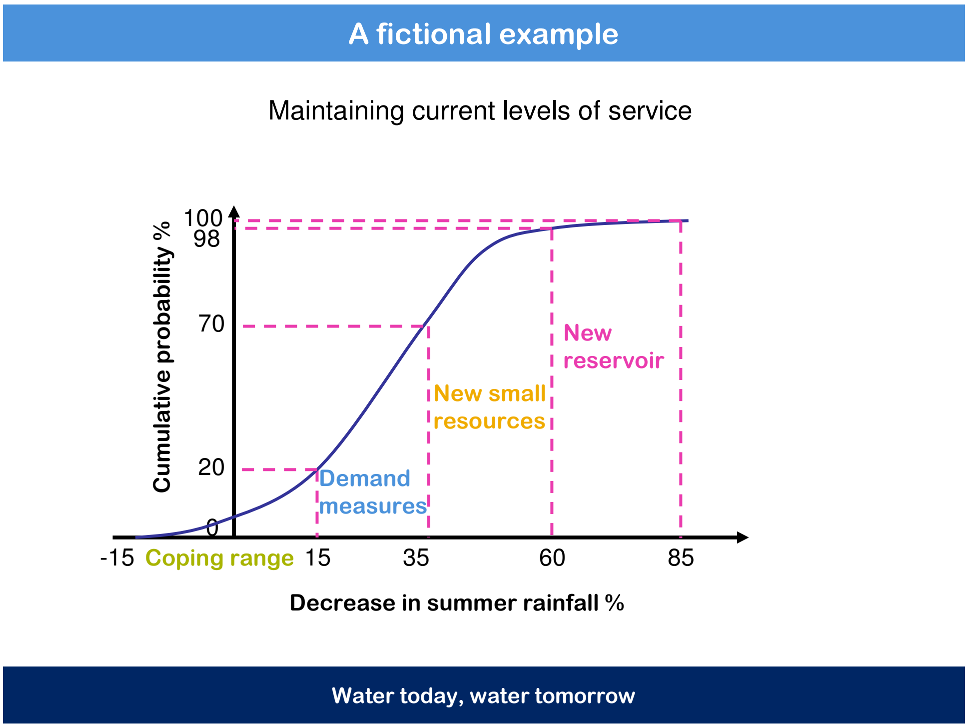

Figure 6.5 – Ofwat view of the twin track planning approach

An "S" curve shows the relationship of the cumulative probability of maintaining current levels of service on the Y axis, with the reduction of summer rainfall caused by climate change on the X axis. The diagram also shows that after the "coping range", the first remedial measure is demand management.

The impression given by Figure 6.4 is that a new reservoir is the least attractive option because the high cost raises the cumulative probability from 98 to 100%. "New reservoir" also comes last if the climate models project an extraordinarily large reduction in summer rainfall. There is no question that achieving 100% is going to be very expensive, but the optimal twin track programme of schemes might not produce the order of remedial action shown.

6.4 Thames Water revised Draft WRMP September 2009

In terms of numbers of customers, Thames Water is the UK's largest regulated water supply company. The operational area covered is around 8,000 square kilometres and stretches from the Cotswolds in the west to the East of London. Approximately 2,850 Ml/d of water are put into supply each day, supplying an estimated 8.56 million drinking water customers. Thames Water, as a statutory water undertaker, has a duty under the Water Industry Act 1991 (the WIA) to provide an effective and efficient water supply. Every five years Thames Water is required to produce a Water Resources Management Plan which sets out how the company intends to provide water to meet customers' needs while protecting the environment over a 25-year period. The Plan presents forecasts for water demand within Thames Water's supply area for a 25-year period from 2010 to 2035. It sets out the company's strategy, and the options available to manage demand for water and the schemes to provide water resources. Three of Thames Water's tables listing the options in the company's revised Draft WRMP of September 2009 are numbered 8.3, 8.4 and 8.6, and are shown in Appendix F.

6.4.1 Thames Water preferred Plan

In Thames Water's Table 8.3, the company sets out alternative twin track programmes for nine scenarios the London resource zone. One scenario was least cost, three were optimal for environmental and social issues such as carbon emissions, and five provided for long term security of supply risk. All scenarios contained implementation of targeted compulsory domestic metering, and at least 1000 km of mains replacement to reduce leakage. The company's preferred programme up to 2035 was for one of the long term risk scenarios that includes another 1000kms of mains replacement up to 2020, and a new UTR reservoir of 100 Mm^3. The preferred programme leaves 127 Ml/d of surplus resource in 2035, whilst the least cost scenario leaves 1 Ml/d.

The financial NPV costs given in the Thames Water Table 8.4 shows a range from £1,295m for the least cost scenario, to £2,480m for a long term risk scenario that relies on many small water resources schemes, and leaves a surplus of 130 Ml/d in 2035. The preferred programme cost is £1,769m, which is 3rd cheapest of the scenarios. With the addition of monetised environmental and social costs, the preferred programme becomes the second cheapest behind the least cost scenario. The difference in cost is largely explained by a lower mains replacement rate of 500 km up to 2020 in the least cost scenario. Thames Water emphasise that no costs are incurred in the preferred programme for a new reservoir until 2015.

The Capex cost for a new UTR reservoir of 100Mm^3 of £725m is shown in Thames Water's Table 8.6. The extra deployable output that Thames Water calculates is 185 Ml/d, and thus the unit cost is approximately £4m per Ml/d. For comparison, the Elan reservoirs and aqueduct scheme cost £6m a century ago, which is approximately £600m today. The dry year deployable output for the first stage of the Elan development is approximately 200 Ml/d (CBWD, 1940), and thus the resulting unit cost is £3m per Ml/d. Using this coarse comparison, unit cost appears not to rule out immediately the possibility of future development of reservoir storage schemes in mid-Wales.

6.4.2 Thames Water Sensitivity Testing of Scheme Dates

In their revised Draft WRMP, Thames Water presented the results of sensitivity testing of scheme commissioning dates. Eight scenarios were used, covering a range of population growth, the degree of downward movement of domestic PCC demand, the demand saving by domestic metering, and the impact on demand of the economic downturn. The results are shown in Table 6.10.

Table 6.10 - Sensitivity Testing Results for the London Resource Zone

	Final Plan Programme London RZ	**Population - High**	**Population - Low**	**PCC Movement - High**	**PCC Movement - Low**	**Selective Metering Savings - 5%**	**Selective Metering Savings - 15%**	**Economic Downturn - High**	**Economic Downturn - Low**
Change in supp/demand 2019 / 20 (Ml/d)	0	54	- 33	14	- 15	12	- 12	20	- 28
Change in supp/demand 2034 / 35 (Ml/d)	0	106	- 65	71	- 86	19	- 19	20	-29
East London Resource Development (1 Ml/d)	2020/21	2012/13	2033/34	2014/15		2018/19	2026/27	2012/13	
Northern New River 1 (1.8 Ml/d)	2020/21	2012/13	2033/34	2014/15		2018/19	2026/27	2013/14	
AR – SLARS (19.0 Ml/d)	2021/22	2014/15		2020/21		2020/21		2019/20	
100Mm3 Reservoir Abingdon (173 Ml/d)	2026/27	2026/27	2033/34	2027/28		2026/27	2026/27	2026/27	2028/29
Southwark (1.5 Ml/d)		2012/13		2018/19		2019/20		2013/14	

	Final Plan Programme London RZ	**Population - High**	**Population - Low**	**PCC Movement - High**	**PCC Movement - Low**	**Selective Metering Savings - 5%**	**Selective Metering Savings - 15%**	**Economic Downturn - High**	**Economic Downturn - Low**
ASR Darent Valley 2		2018/19		2024/25				2025/26	
ASR Darent Valley 3		2013/14		2019/20		2020/21		2014/15	
AR - Kidbrook		2013/14		2019/20		2019/20		2013/14	
East Croydon (1.5 Ml/d)		2013/14		2019/20		2019/20		2014/15	
Deephams STW Reuse (25 Ml/d)		2018/19		2025/26					
Hogsmill B		2013/14							
NPV compared to Final Plan programme	100%	119%	95%	104%	79%	102%	98%	104%	96%

Analysis of the results in Table 6.10 shows;

1) The range of the change in Distribution Input from the first Draft WRMP for 2019/20 was from +54 Ml/d to -33 Ml/d, which is 87 Ml/d. Fifteen years later in 2034/35, the range more than doubles to 181 Ml/d, from +106 Ml/d to -75 Ml/d. The forecast Distribution Input for London in 2034/35 is 1,900 Ml/d, so the total range is near 10% spread between +5.5% and -4.5%. These numbers are for identifying the range used for this particular sensitivity test, and not for estimating target headroom.
2) A comparison of the sensitivity test flow range with target headroom is instructive. In 2034/35, the target headroom shown in Figure 7.3 for the London Resource Zone is 200 Ml/d. The forecast Distribution Input is 1,900 Ml/d, and the addition of the 200 Ml/d target headroom increases the supply requirement to 2,100 Ml/d, which is also near 10% more. Thus the sensitivity test range, and the amount of target headroom is similar, and the positive deviation of the sensitivity test (+106 Ml/d) is well within the target headroom of 200 Ml/d. This finding demonstrates that the sensitivity test has used reasonable conservative values.
3) The sensitivity test shows that the requirement and timing of schemes is more sensitive to the assumptions for population growth and domestic per capita demand, rather than metering savings and allowance for the economic downturn. Significant reductions in PCC is the primary item for attention in the Government’s policy, and the delivery demands a major shift in the attitude to water use in the home. Should these reductions not occur fast enough, much of the risk of supply failure is carried by the water companies and their customers.

The proposed reservoir for 100 Mm^3 (called Abingdon in Table 6.10 rather than Upper Thames Reservoir) is required in seven out of the eight scenarios. The date this scheme is most often required is 2026/27 in five out of the eight scenarios. The extra 173 Ml/d deployable output from this scheme means that there is a large supply surplus over demand at the end of the planning period. A major issue here is the acceptability of such a surplus to the Regulators. The TW preferred plan in the company's rDWRMP is shown below.

The grey WAFU bars Figure 6.6 show the UTR coming into the plan in 2026. The Demand and the Demand + Target Headroom lines can be seen separately in Figure 7.3.

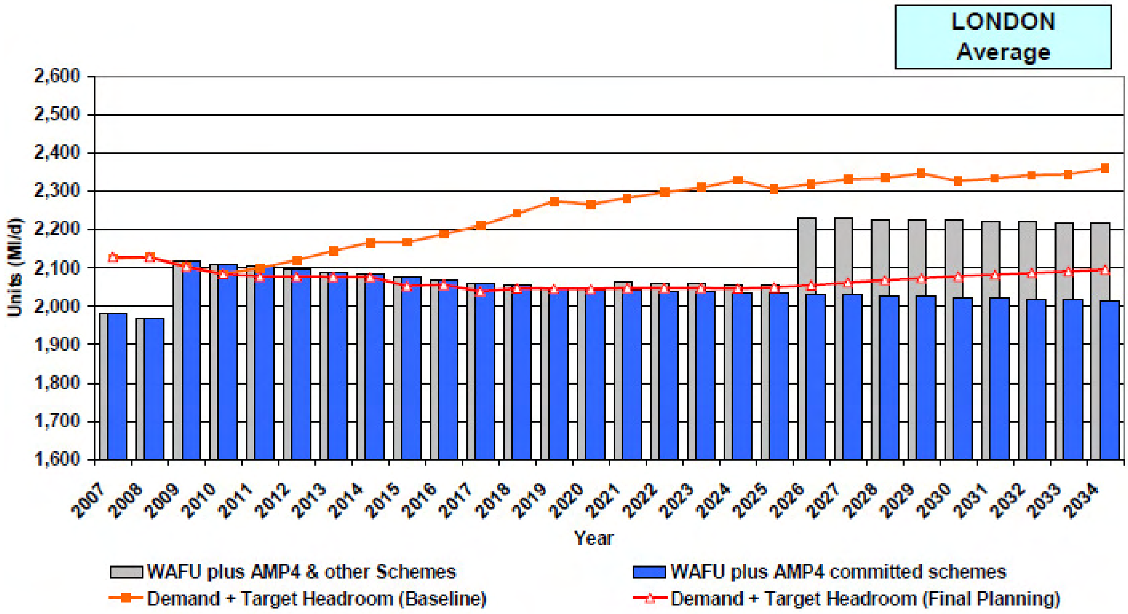

Figure 6.6 – London Resource Zone Dry Year Average preferred plan (TW Figure 9.5 rDWRP September 2009)

6.4.3 Thames Water Approach to Uncertainty

Throughout the development of the company's plan, Thames Water used the EA's WRMP Guideline and the recommended UKWIR 2002 methodology for converting supply and demand uncertainties into target headroom. However, in February 2009, after the public consultation on the Draft WRMP, the company indicated in its "Statement of Response" to Defra, that there was a need to plan for further than the 25 year planning horizon. The company called this "long-term risk" beyond 2035, and a judgement was made by the company that a further 100 Ml/d should be added to target headroom for risk items that the company believed were not adequately covered in the EA Guidance.

The most significant extra risk item was the potential loss of deployable output due to environmental sustainability reductions in abstraction, for compliance with the ecological standards required by European legislation, and for the EA's programme of "Restoring Sustainable Abstractions". The Guidance stated, and the advice was repeated in letters from the EA to Thames Water, that the company should not include any reductions in target headroom calculations that had not been confirmed by the EA. Confirmation by the EA about the scale and timing of these reductions will be made in 2013. For sensitivity testing only, the EA provided the company with a potential but unlikely upper limit of 600 Ml/d. This figure would have a very negative impact on Thames Water's supply demand balance, being about 30% of the company's water resources assets.

Whatever the actual SR figures turn out to be, the EA confirms that the company would be given sufficient time to deliver replacement water resources before implementing the reduction. The EA's confidence in its ability to influence the timetable could be misplaced as the Agency does not grant planning permission, or approve the expenditure needed to develop the replacement sources.

Thames Water's addition of long-term risk to their Plan proved to be pivotal to subsequent events that impacted on Thames Water's plan. Also it is of significance to this research as the inclusion of long-term risk to cover long-term uncertainty, and Thames Water's justification for its inclusion, proved at Public Inquiry to be unacceptable to the Secretary of State.

6.5 Public Inquiry

In a letter dated 3 August 2009 from Richard Wood (Head of Water Supply and Regulation Division at Defra) advised David Owens (CEO Thames Water Utilities Ltd) that the Secretary of State was minded to call for a Public Inquiry into the company's Draft Water Resources Management Plan.

The Inquiry took place in Oxford in the summer of 2010, and the Inspector, Wendy Burden, presented her report in December 2010. The Secretary of State accepted all 25 of the Inspector's recommendations.

6.5.1 Why was a Public Inquiry called?

In the letter of 3 August, Mr Wood says that the reasons for calling an Inquiry were:

"Your Statement of Response and additional information does not provide adequate justification for your preferred options or the decision process in reaching that preferred programme of options. You do not provide enough detail on some of the changes made in your plan, especially in relation to household demand. In addition, some directions and representations still remained unaddressed…concerned mainly with the options appraisal and your preferred programme."

Whilst arguments about the option appraisals and the decision processes occupied a significant part of the Inquiry, this project concentrates on the argument about long term risk, and the company's selection of an Upper Thames Reservoir scheme.

6.5.2 The case for Thames Water

The evidence for the current and forecast supply demand balance, and the need to take a longer term view beyond 25 years was presented by Dr. Chris Lambert of Thames Water. The explanation of the company's position with regard to potential future environmental sustainability reductions, and the judgement for the inclusion of another 100 Ml/d to allow for longer term uncertainty was made by Yvette de Garis of Thames Water. Dr. Lambert said that the company was prioritising demand management in the first 15 years by the delivery of the extremely challenging programmes for further leakage reduction, and the substantial increase in household metering. These programmes were challenging not only in the relatively short time taken to implement them, but there was a significant risk that the planned reduced demand might not be achieved. There is uncertainty that the actual headroom would be sufficient, and Dr Lambert contended that the company should plan to include new water resources schemes that are optimal for the remaining 10 years and into the longer term.

Ms de Garis's evidence dealt with the uncertainty of sustainability reductions, and the delivery by the water company of the requirements of the Water Framework Directive. With regard to the inclusion by Thames Water of an allowance above target headroom of long term risk, Ms de Garis told the Inquiry that "an informal judgement was taken to make an allowance for an additional 100 Ml/d." Informal was perhaps not the best word to use here.

6.5.3 The case against UTR

The EA took the lead for the opposition. The EA's argument against the company's decision to include for long-term risk was advanced by Ms Vicky Carpenter.

Ms Carpenter's argument was:

1) The "long term risk" uncertainties identified by Thames Water are manageable risks.

2) Thames Water's approach is contrary to the water resources planning guideline.

3) The "long term risk" uncertainties identified by Thames Water do not, when critically assessed, provide any sound justification for the significant surplus planned for.

4) These "long term risk" uncertainties should have been taken into account through sensitivity analysis.

5) Thames Water has failed to properly justify or explain the change in its approach from that adopted initially in its draft WRMP to the revised draft WRMP (2009).

The rebuttal from Dr Lambert dealt with each item, that from a water resources planning viewpoint for Thames Water, it would be "irresponsible" for the company to ignore long term risk, and that strict adherence to the existing EA's guideline horizon of 25 years did not encourage optimal long-term planning for a large water company like Thames Water. A similar point was made in 1892 by Mansergh when he told the House of Commons Select Committee during the hearing for the Birmingham Corporation Bill that "the world does not end in 40 years". The committee agreed, and as described in Chapter 4, Mansergh then extended his planning horizon to 63 years.

Dr Owen Turpin for the Agency criticised Thames Water's process for arriving at the optimal least cost programme without full appraisals of other solutions.

Two well known and respected UK water engineers gave technical evidence on behalf of GARD, the Group Against Reservoir Development. John Lawson (ex Halcrow) provided information about alternative schemes, especially regional transfers, which he believed that Thames Water had not thoroughly appraised. Dr. Lambert explained that transfer schemes involving the lower River Severn would face significant environmental opposition as there many sites in the Severn Estuary that are protected under the EU's Habitats Directive.

Chris Binnie (consultant water engineer) gave technical evidence for GARD about Thames Water's demand forecast. Binnie's principal point was that he believed that the company's population forecast was inflated. Other detailed demand related issues were raised by the EA, but either because of the complexity, or the uncertainty, or the perception that upward and downward pressures on the numbers tended to cancel out, Thames Water's demand forecast was not viewed by the Inspector as a key area of concern.

6.5.4 The Inspector's recommendations December 2010

The recommendations reflect the arguments put forward by the EA.

"The main deficiencies in the rdWRMP which I consider require change in order to secure a plan which is fit for purpose and legally compliant relate to the following key matters:

i) The deletion of the premise of 'long term risk'

ii) The deletion of all programmes which have the objective of meeting 'long term risk'.

iii) A wider range of feasible options.

iv) Changes in the methodology for programme appraisal to bring it in line with good industry practice, with a clear description of the process set out in the plan.

v) Sensitivity analysis to cover the potential for future sustainability reductions together with identification of a choice of options from the feasible options list to meet different levels of sustainability reductions.

6.5.5 The reasons for the rejection of Thames Water's revised Draft WRMP

Analysis of the dialog from the Inquiry helps to achieve an understanding of why the Inspector made her recommendations.

The Inspector records below the company's view of whether it is appropriate for Thames Water to plan for long-term risk, and to factor in potential future sustainability reductions.

Para 2.4:

Whether it is appropriate for Thames Water to plan for long-term risk, including indicative sustainability reductions, in the revised plan. Dr Lambert, who has more expertise and experience in water resource management planning than any other witness, explained on Day 1 of the Inquiry, that "a Water Resource Management Plan is a strategic plan for the short, medium and long-term and it would be improper not to take account of long-term risk". He observed that an element of subjective judgment was inevitable, although the Inspector is invited to conclude that Dr Lambert's subjective judgment is not merely that but reinforced by his considerable experience in water resource management planning. He explained that where, as here, there is a degree of uncertainty about the long-term, Thames Water's experts have had to face the task of making a judgment based on the best knowledge available at the time. This they have done in respect of potential sustainability reductions. There is nothing strange or startling about this. It is the very essence of planning. If all was certain there would be no scope and indeed no need for judgment.

The Inspector then records the company's contention that the results of sensitivity analysis will be ignored by the parties that reject the inclusion of long-term risk.

Para 2.4.36:

…Thames Water submits that the adopted position of the main parties in rejecting the inclusion of long-term risk in the appraisal process but accepting the need to carry out a sophisticated sensitivity analysis of long-term risk elsewhere in the plan, which is then not planned for but ignored, is untenable….It cannot be appropriate to recognise that consideration needs to be given to assessing a risk but then to ignore the outcome of that consideration.

The Inspector expresses disagreement with the company's view of what would happen if sensitivity testing is undertaken.

Para 2.4.4:

With this process of review; with sensitivity analysis in the current plan; and with ongoing investigations of alternative options to meet different levels of Sustainability Reductions (SRs); I consider that the risk of harmful consequences to water consumers or the UK Government as feared by Thames Water would be avoided.

The Inspector makes a judgement about which party's assessment she believes about the amount of evidence.

Para 3.3.32:

Notwithstanding the very significant experience of Dr Lambert, I agree with the EA that there is a major deficit in the evidence available to justify planning for a specific level of SRs in the rdWRMP

The Inspector takes a view on the integrity of the company's position

Para 3.3.15; 5.1.2; 5.3.12:

This causes me to have some sympathy with concerns expressed at the Inquiry that the rdWRMP has been produced in order to support the UTR project, with the 100 Ml/d allowance selected specifically to justify the UTR.

The Inspector makes a clear statement about the short-coming of the company's plan, and that the scheme would fail to justify a National Policy Statement.

I find insufficient weight in the Company's argument that unknown SRs must be planned for through the inclusion of a large scheme in the preferred programme, and prefer the approach put forward by the Environment Agency to deal with uncertainties arising from future unknown SRs through sensitivity analysis and the investigation of alternatives to meet different levels of SRs.

Para 13.2.26

Furthermore, I find inadequate evidence to support the assertion that an additional 100 Ml/d is required to deal with future unknown SRs, bulk supplies to other Water Companies and any shortcomings in water demand management measures. As a result, I find that the need for the UTR is not sufficiently demonstrated in the rdWRMP to justify the weight that would be given to that need.

The Inspector made her position clear, which was that Thames Water did not make a strong enough case for her either of the merit of planning for long term risk, or of the additional 100 Ml/d of long term risk. This was a difficult case to make, but without sufficient justification from Thames Water, it was understandable that the Inspector would regard the Agency's WRMP guideline as equivalent to a legal document, and discount long term risk because it does not feature in the guideline. The Inspector's view hardened as the Inquiry progressed that she had “some sympathy” with those who felt that the 100 Ml/d long term risk was only there to justify the 100 Mm^3 UTR scheme.

The Inspector supported the EA’s technical evidence, but recognised that having no firm quantification of SRs made TW’s planning difficult. Thames Water will have to wait for the proposed sensitivity analysis and investigations into alternative sources to be completed before another strategic view of the long term can be taken. The Inspector recommended that further work for Thames Water should include an appraisal of a UTR scheme with 50 Mm^3 storage.

6.6 Where do the risks lie?

The modern twin track approach to water resources and supplies planning is conceptually sound, but perhaps the way the method is being implemented, and the Public Inquiry process has perhaps unnecessarily created uncertainty. The Government is clearly supportive of demand management by metering and building water efficient homes to drive down domestic PCC from 150 litres to l20 litres per head per day. The time this will take is unknown as so much depends on attitude to water, but it is to be hoped that today’s infants grow up in a world that understands the value of water. The challenge is there for Government, regulators and water companies and their customers.

The role that refurbished and new physical assets play appears to be less well understood, but these will be needed more than ever should the planned demand management savings remain as an aspiration. The risk here is likely to be borne by water company customers as levels of service deteriorate, but hopefully not to see the return of intermittent supply. Hillier (2009) suggests that the reintroduction of intermittent supply in London ought to feature as an option to cope with the impact of climate change on water resource availability. Less dramatically, Eden (2010) is of the view that a hosepipe ban is the price water customers have to pay for having inefficient water companies. Natural monopolies, like the water companies, are more likely to breed inefficiencies than where there is competition, and it is up to the companies and the regulators to deliver cost optimal investment efficiently. Economic competition does not replace the need for strong leadership to ensure that, along with all the best practice for reducing water demand, the right assets are built for the right reasons at an affordable cost.

6.7 Summary of the Modern Approach

Whilst every UK water company has to update its WRMP once every five years to the guideline set by the Environment Agency, it appears that larger companies that propose strategic reservoir developments that are optimal for horizons that exceed 25 years are likely to face legal challenge. The current planning process of 5 yearly review of prices by Ofwat forces a short term rather than a long term perspective to be taken by the UK water companies to water resources and supply planning. There appears to be no room in the current planning process for cost effective inter-generational expenditure, something that the Victorians planned for, and that led to the legacy of schemes we enjoy today.

Whilst mindful of the constraints on decisions that can be made after a Public Inquiry, and whether or not the 100 Mm^3 UTR is the right scheme, the Planning Inspector's report about the Thames Water Inquiry shows that water engineering judgements are less valued now than the judgements of his Victorian forebears. It is believed that a better understanding by the public of historical context and comparative risk would raise the perception of water engineer's value to society.

This project now moves on in Chapter 7 to the application of the lag time model to London and the 100 Mm^3 UTR scheme, and comparisons are made with the Victorian schemes.

CHAPTER 7 APPLICATION OF LAG-TIME MODEL TO THE LONDON RESOURCE ZONE AND 100 Mm^3 UPPER THAMES RESERVOIR

Chapter 7 addresses Knowledge Gap C and both the third and fourth project objectives. The shape of the supply and demand projections for Thames Water's London resource zone are very different to those made before the Victorian schemes were built. Demand in London is set to continue falling as the mains replacement programme reduces leakage and domestic metering is extended. A view is formed that the UTR scheme is more likely to fall short of its design life (ie a shortfall rather than a lag-time) using the lag-time model with a range of demand forecasts in place of actual demands.

7.1 Introduction

Having developed a Lag-Time Model (LTM) to compare the relative risk averseness of the Victorian reservoirs designs, consideration was given as to whether this model might be used effectively to assess the risk averseness of Thames Water's 100 Mm^3 scheme. A range of extrapolated demand forecasts for London are used instead of observed data.

Chapter 7 starts with background information about population growth, household size, and the company's planned switching of domestic customers from unmeasured to measured charges in Thames Water's revised Draft Plan of September 2009.

7.2 Projections of Population and Housing Growth in the London Resource Zone

Attention to the final planning projections of population and households provides insight into Thames Water's thinking.

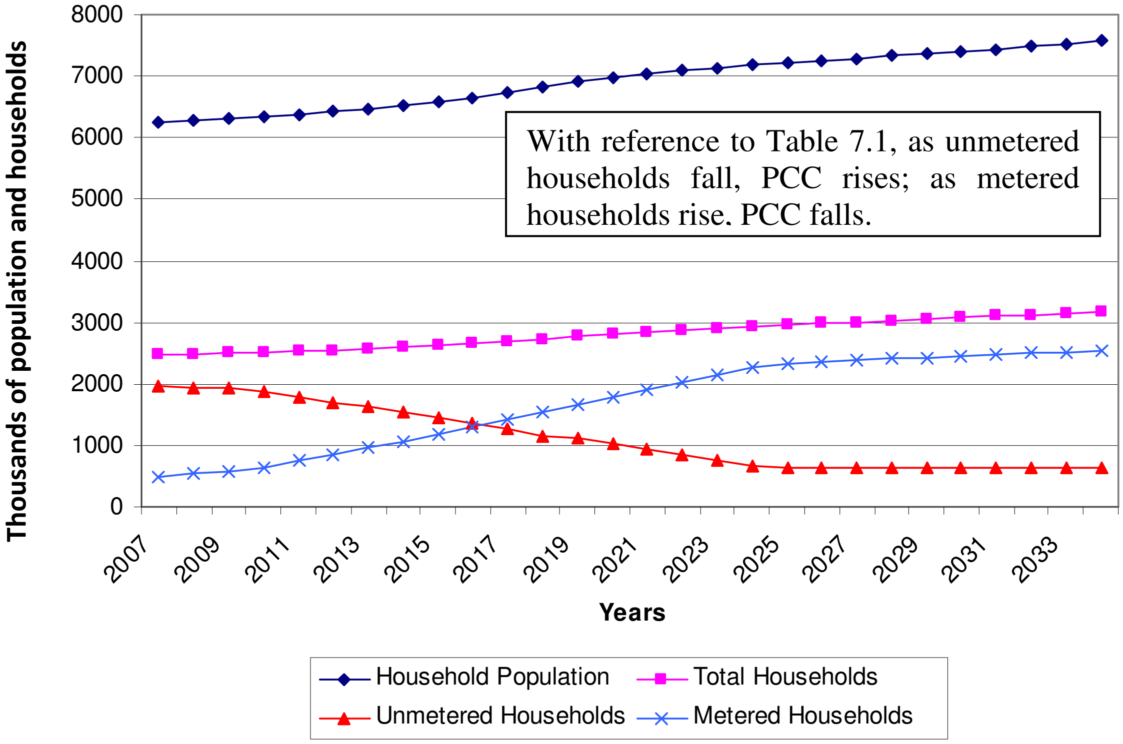

Figure 7.1 - Households and Population Projections for London, 2007 to 2035 (Source; Table WRP4 – FP, London Dry Year, Thames Water Draft WRMP Sept 2009)

Figure 7.1 shows the Company's final planning annual profiles for household population, and total numbers of households split between unmetered and metered properties. Table 7.1 below shows the changes from 2008 to the planning horizon in 2035, including actual and projected PCC. A cautionary note: the numbers shown in Table 7.1 have been superceded by TW's updated DWRMP that was published in December 2011 for consultation in January 2012. The key Distribution and Target Headroom numbers are very close. The updated WRP4-FP Final Planning table of supply-demand components for London Dry Year Average can be directly accessed by a weblink given in the References. The table itself is on page 7 out of 15, and was successfully accessed on 1 April 2012. Distribution Input is on Line 11, and Headroom is Line 52. Both were used to construct Figure 7.3.

Table 7.1 - Dry Year: Population, Households and PCC, London, 2008 and 2035 (Line numbers refer to Thames Water, Draft WRMP 2009, Table WRP4 –FP)

	2008 (Baseline)	2035 (Final Planning)	Percentage of Total; 2008	Percentage of Total; 2035
Population living in households				
Unmetered (line 18)	5,100,967	1,704,480	81.5%	22.5%
Metered (line 21)	1,156,287	5,871,194	18.5%	77.5%
Total (million)	6.25 million	7.57 million		Growth + 21%
Numbers of households				
Unmetered (line 19)	1,975,639	625,005	80.0%	19.7%
Metered (line 22)	493,833	2,542,635	20.0%	80.3%
Total (million)	2.47 million	3.17 million		Growth + 28%
Household Per Capita Consumption; Litres / head / day				
Unmetered (line 36)	164.5	172.3		Growth + 4.7%
Unmetered h/hold Occupancy Rate (line 20)	2.58	2.77		Growth + 7.4%
Metered (line 40)	155.2	133.8		Reduction: -13.8%
Metered household Occupancy Rate (line 23)	2.34	2.08		Reduction: - 11.1%
London (line 40.1)	162.7	142.4		Overall; - 20.3 litres, or – 12.5%

Over the planning period, Table 7.1 shows there is a reversal of the proportions for unmetered and metered households and population between 2008 and 2035 from close to 80% and 20%

to near 20% and 80%. Figure 7.1 shows that the period when most of the switching takes place is before 2025, one year before the proposed UTR scheme is ready.

Based only on comparisons of the average unmetered with the average metered PCCs, conclusions drawn about the amount of water saved by switching are not reliable. The reason is that the occupancy rates for both classes are different, as shown in Table 7.1.

The lower occupancy rate for measured households has been influenced by self selected households that have opted to pay metered charges rather than unmetered charges. This group tends to have lower occupancy as the potential reduction in water charges is greatest. A reduction of 10% in average water use attributed to metering was measured over 25 years ago as part of the National Metering Trails in an experiment involving a large sample of households that were compulsorily metered in the Isle of Wight. There must be a risk that the Government's aspiration for 20 to 30 litres reduction may not be delivered by 2035. The scale of these reductions at water company level, or for a resource zone, has never been attempted before.

The impact of the metering programme, which includes new tariffs and changes in attitudes to water use, is projected by Thames Water to reduce the overall London domestic PCC by 20 litres from 163 to 143 litres per head per day, as shown in Table 7.1. The annual profile of the reduction that appears in Figure 7.2 shows PCC continuing to fall after 2030, when the switching of unmetered to metered properties is small.

The step change reduction of about 5 litres in 2017 for PCC, as shown in Figure 7.2, is the company's estimate of the effect of introducing varying volumetric tariffs that encourage reduced consumption.

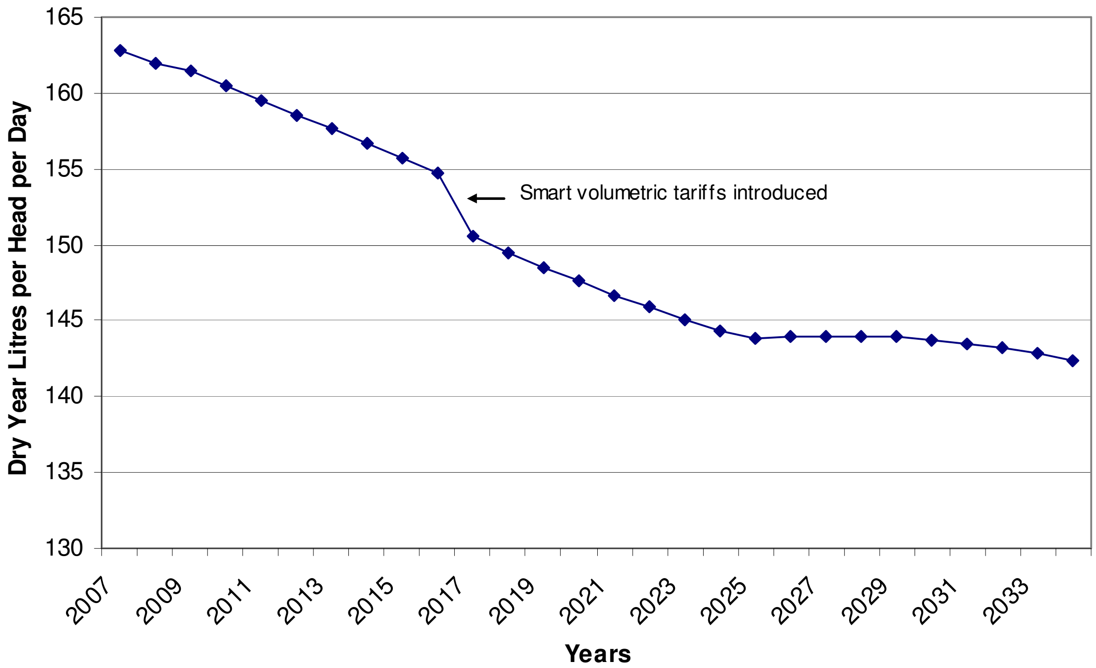

Figure 7.2 – Projected Domestic Per Capita Consumption from 2007 to 2035

Thames Water has factored the Government target of a 20 litres per person per day reduction into its final planning scenario. The company has not assumed an absolute PCC target figure of 130 litres as Thames Water's domestic demands have consistently been reported to Ofwat at a higher level than the national average.

The use of PCC for setting the target rather than using household consumption makes for difficulties of estimation, as the number of people living in each household is hard to obtain accurately. For the same reason, the conclusion to use household rather than PCC targets was also reached in Anna Walker's independent review of charging for water services (2009).

7.3 Supply Demand and Target Headroom for London to 2035 and 2050

The fall in the forecast of distribution input from 2007 to 2019 is shown in Figure 7.3. This is explained by the anticipated reduction of leakage delivered by the company's mains replacement strategy, and reductions in domestic PCC noted in Section 7.2. In Figure 7.3, Thames Water shows an increasing absolute volume of target headroom from 2007 to 2020 growing to 200 Ml/d.

Beyond 2020 up to 2035, a judgement was made by the company to present target headroom as flat at 200 Ml/d thereafter. The reason given by Thames Water was that further increase in target headroom would eventually trigger another scheme because of uncertainties about the UTR scheme. Target headroom would normally continue expanding as the planning horizon lengthens into the future (see Figure 6.1), but in some cases, the numbers become very large and meaningless for planning and design. Target headroom continuing at 200 Ml/d is assumed in this project from 2035 to 2050, as shown in Figure 7.3.

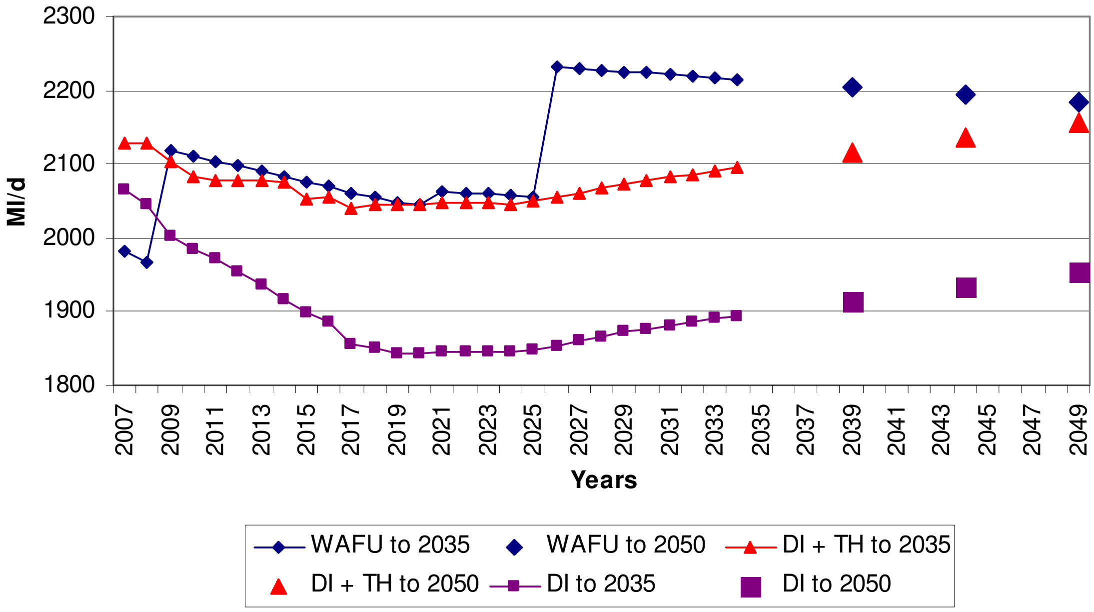

Figure 7.3 – London: Supply Demand and Target Headroom, 2007 to 2050

The Water Available for Use (WAFU) in Figure 7.3 shows that the recently commissioned desalination plant enabled the company to just meet target headroom in 2009. After 2009, WAFU falls due to the supply side impacts of climate change. Then in 2026, an increase of

178 Ml/d of WAFU is shown as the additional resource created by the Upper Thames Reservoir. After 2026, climate change is assumed to continue eroding WAFU.

By 2050, the downward linear extrapolation of WAFU is about to cross the upward linear extrapolation of distribution input plus the 200 Ml/d of target headroom. An example of a profile that shows the potential range TW's target headroom is shown below in Figure 7.4. The company used 90% confidence up to 2015, falling to 70% by 2035. (TW, 2009)

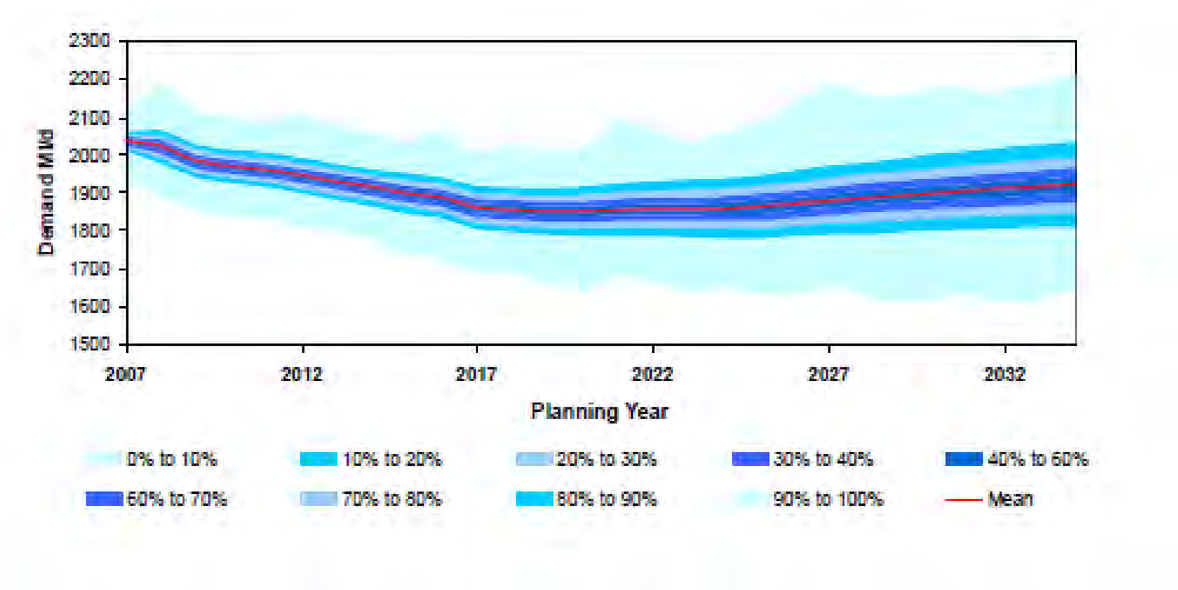

Figure 7.4 - An example of a final planning demand forecasting uncertainty profile for London

Beyond 2035, using the linear extrapolation approach is arbitrary, but an argument for using another arbitrary approach is less important than having an understanding of the relative sensitivities of the forecast parameters. The assumption about the value of domestic PCC is clearly significant, as a fall of 10 litres rather than the projected 20 litres per head per day is equivalent to an increase in demand of 75 Ml/d in 2035. There are also uncertainties in the timing and scale of as yet unconfirmed abstraction licence reductions, and the impact of climate change on WAFU. As the extrapolated demand line is close to flat, the intersection of the WAFU line with the distribution input plus target headroom line could be plus or minus 20 years.

7.4 Supply Demand Balance Points for Three Demand Scenarios

Three demand scenarios have been chosen to enable comparisons to be made of planned lives and lag-times for the UTR scheme, and for comparisons with the Victorian schemes. The three demand scenarios are called “Baseline”, “Mid point” and “Final Planning”. The baseline and final planning demand scenarios to 2035 appear in TW’s Draft WRMP of September 2009. The midpoint scenario is half way between the two, and are shown in Figure 7.5. These demands do not have target headroom added. The reason is that for comparison with the Victorian scheme designs, which do not have explicit allowances for uncertainty in the demand forecast.

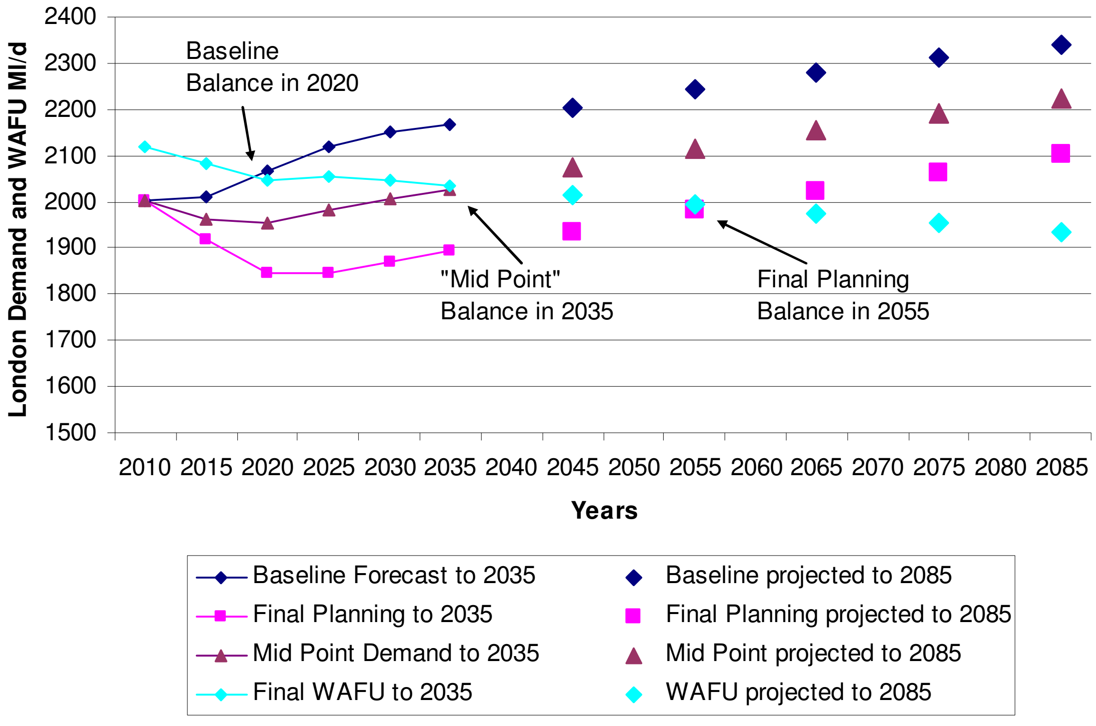

Figure 7.5 – London, Three Demand Scenarios to 2085

In Figure 7.5 beyond 2035, all three demand scenarios have been linearly extrapolated up to the year 2085. Also shown in Figure 7.5 are “balance points” marked with the date when the projected WAFU and demand are in balance. The intersections occur for the baseline scenario in 2020, for the mid-point scenario in 2035, and the final planning scenario in 2055.

The baseline scenario is the company’s pre-2009 forecast, and assumes the continuation of the existing demand management practices, and the existing rate of mains replacement. The final planning scenario is assumed to be the first choice that reflects the company’s preferred Business Plan. The mid-point scenario represents a partial delivery of the planned enhancement of demand management and leakage control savings. The range between the baseline and final planning projections shown in Figure 7.5 is approximately 250 Ml/d.

The WAFU does not contain the UTR, nor any assumption about the loss of abstraction licences to the environment. The impact of climate change is the cause of the falling profile of WAFU.

In Figure 7.6, the introduction of the UTR moves the intersection dates back to 2045, 2065 and 2085. The end of planned life for the UTR is 2085.

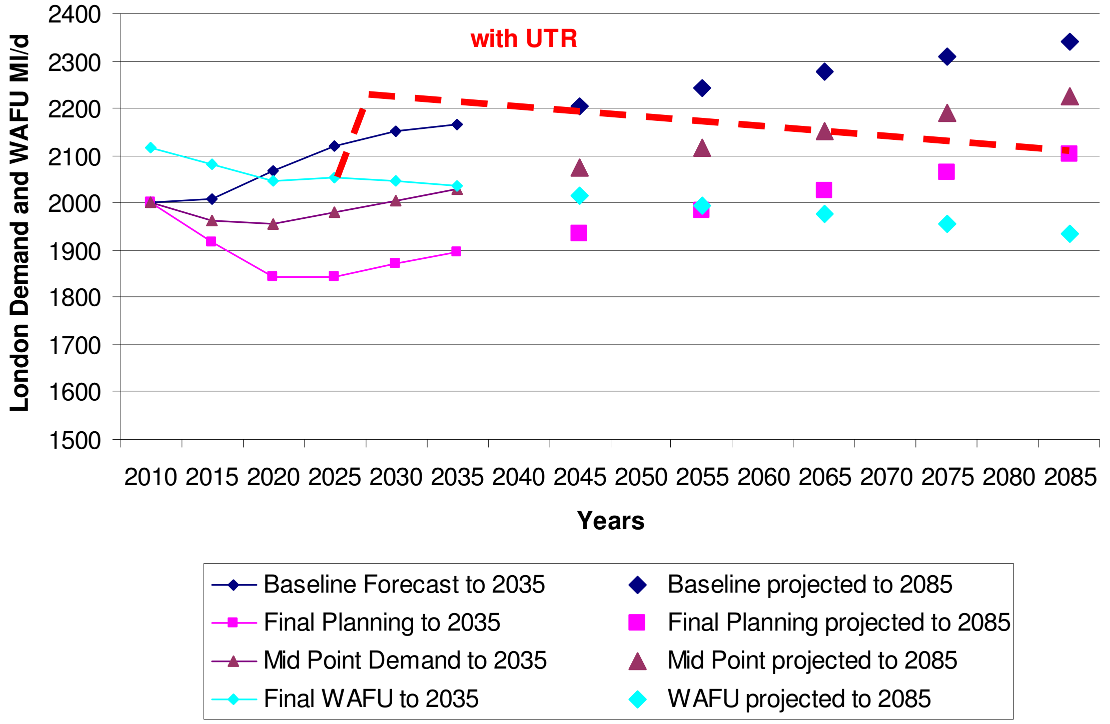

Figure 7.6 – Three Demand Scenarios and the Upper Thames Reservoir

The start date for calculating the planned life has been assumed in this research as the time when the powers are obtained to construct a scheme. The UTR start of planned life is assumed to be 2015, and so the planned life of the UTR scheme is 70 years.

Instead of using observed actual demands, the three demand scenarios can be used as surrogates to give an idea of the range of lag-times for the UTR scheme. The notion of lag-time used in Chapter 5 represents a period of time that a scheme has been able to last beyond its planned life, but here the representation also includes a scheme that fails to reach the end of its planned life.

To show lag-times in the UTR example, two further indicative demand scenarios, called flat demand and falling demand, have been added to the existing three below the final planning scenario, as shown in Table 7.2 As the demand profiles for the mid-point and baseline scenarios are above the final planning scenario, there is a shortfall in years rather than a lag-time. A further assumption is made on the supply side that the profile of the projected WAFU remains the same whatever demand scenario is used.

Table 7.2 – Planned Life, Lag-Times and Shortfalls for five scenarios

Demand Scenario	**Planned Life WITH New Reservoir**	**Assumed range of Actual Life in years WITH New Reservoir**	**Shortfall (SH) Lag-time (LT) in years WITH New Reservoir**	**Time Ratio (-SH/PL) or (LT/PL), and relative risk of UTR design with range of demand scenarios.**
Baseline	**N/A**	**30 years** (2015 – 2045)	**40 years (SH)** (2045 – 2085)	- 40 / 70 = - 0.57 More inefficient design
Midpoint	**N/A**	**50 years** (2015 – 2065)	**20 years (SH)** (2065 – 2085)	- 20 / 70 = - 0.28 Inefficient design.
Final Planning	**70 years**	**70 years** (2015 to 2085)	**Zero**	Exactly lasts for the planned life; a well designed scheme.
E.g. Flat Demand	**N/A**	**90 years** (2015 to 2105)	**20 years (LT)** (2085 to 2105)	+ 20 / 70 = + 0.28 Risk averse
E.g. Falling Demand	**N/A**	**110 years** (2015 to 2125)	**40 years (LT)** (2085 to 2125)	+ 40 / 70 = + 0.57 More risk averse

The interpretation of Table 7.2 is that as the time ratio becomes increasingly positive, the more the scheme becomes risk averse; this was the situation in Chapter 5 with the Thirlmere scheme. The opposite situation occurs when the shortfall becomes greater, and the time ratio becomes increasingly negative. If water demands are allowed to rise to the baseline profile, the greater is the risk that another scheme will be needed before the planned life is reached.

The results show that if the 100 Mm^3 UTR scheme came on stream in 2025, and the final planning demand profile was to occur, the UTR scheme would last for about 70 years, and would have a time ratio close to the full Elan scheme. If water demands were above the final planning profile, and the time ratio is used, the UTR scheme becomes more riskily inefficient than any of the Victorian schemes.

An attempt can be made in this project to assess the impact of Thames Water's "long-term risk" of 100 Ml/d. A transparent way to do this is to subtract 100 Ml/d from the UTR WAFU of 178 Ml/d. The immediate impact would be to reduce the planned life of the scheme from 70 years to 50 years. The planned life would end in 2070, and the shortfall to the baseline demand scenario would be near 40 years. The time ratio for the baseline scenario would be - 40 /50 = - 0.8, which is understandably more risky than the – 0.57 calculated for the baseline scenario without the 100 Ml/d of long-term risk. However, if the continuation of the baseline demand scenario was the company's preferred planning scenario, a larger UTR scheme and/or other schemes to boost WAFU would need to be appraised.

7.5 Comparison of Headroom for Birmingham and London

An additional comparative method has been used to help form a view of the relative risk averseness of the UTR design. It involves normalising flows by expressing headroom as a percentage of Distribution Input, and plotting this percentage over a timescale of years that starts at the beginning of the planned life of a scheme. For Birmingham, the percentages have been worked out using an annual assessment of actual headroom from 1892 when the powers to build Elan were obtained.

In Figure 7.7, the profile of percentages for Birmingham uses an estimate of actual headroom from year 1 in 1892 to year 28 in 1920, and the annual average distribution input for Birmingham. The range of the percentages is from a low at 10% (the First World War) up to 35% (in the first decade of the 20th century when the new Elan scheme had just been commissioned). For London, the constraint of 200 Ml/d of target headroom assumed in the draft WRMP (see Figure 7.3), and a distribution input of around 2000 Ml/d, produces a flat 10% from Year 12 onwards.

The finding is that using the Elan example, minimum headroom of 10% looks justifiable when considering designs for the long-term. The Birmingham numbers have been calculated up to 1984, and Figure 7.8 shows the percentage of headroom falls to near 10% again in the early 1980s.

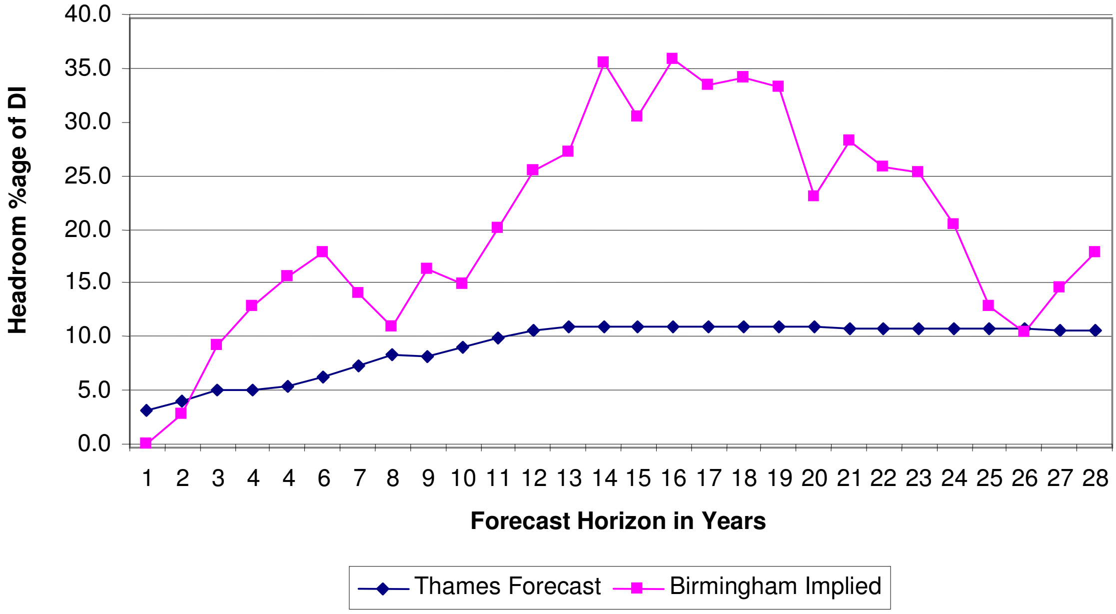

Figure 7.7 – Birmingham Implied Headroom from 1892 to 1920 using Mansergh's forecast versus London Target Headroom forecast from 2007 to 2035

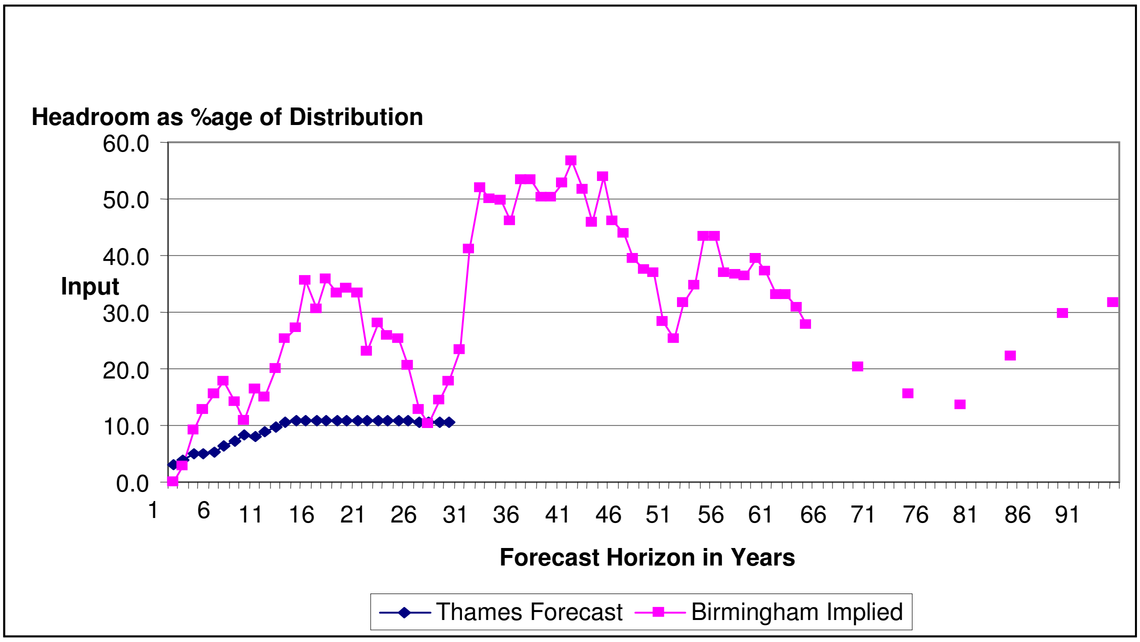

Figure 7.8 - Birmingham Implied Headroom from 1892 to 1984 using Mansergh's 1892 Demand Forecast

7.6 Summary

Chapter 7 has shown that new ways of interpreting supply demand balance diagrams can help water resource planners and engineers to draw comparisons of supply and demand related risks between historic schemes and modern scheme proposals. In this increasingly data hungry area of endeavour, new models are developed to improve our understanding, and thereby reduce uncertainty, in the quantification of detail. This is important work, but the novel approach reported in this thesis provides a counter-balance that adds historical context and value to strategic planning.

It is believed that Thames Water's argument for more storage would, on balance, be strengthened with the knowledge that all three major Victorian reservoir scheme designs studied here appear to be significantly more risk averse than the 100 Mm^3 UTR. None of the three Victorian schemes could now be called grandiose.

CHAPTER 8 DISCUSSION

This discussion synthesizes the critical analysis and observations made in this project. The research aim was to learn how the planning and design for long-term water resources and supplies schemes were undertaken in Victorian times, and whether new knowledge might help with the processes, methods and institutions of today. An "historic perspective check" of modern schemes based on the results from the novel lag time model is suggested.

8.1 Victorian engineers, target headroom and long term risk

The supply and demand diagrams in Chapter 6 that were used to estimate the planned life, and instead of a lag time, the shortfall of the 100 Mm^3 UTR design, deliberately used demand forecasts without the addition of target headroom. The premise for this approach is that the Victorians did not use any special device to account for uncertainty, and their judgement was accepted by their client Corporations. From the publications available, we can only assume that an allowance for forecasting uncertainty was not explicitly added.

We have already noted how similar the profiles of rising demand in the three Victorian Cities match the profiles of the observed data in the first half of the 20^{th} century. We can see too that in all three cases, the deviation is consistently on the risk averse side of the supply demand balance, rather than the shortfall side. We have also commented that there was no way the Victorian engineers could have predicted the impact and timing on their water demand forecasts of events like the world wars or economic recession. Perhaps the current position of Thames Water is perhaps not so different in that the company does not know the scale and timing of an event that could have a significant impact on their WRMP.

Might the Victorian engineers have implicitly included for something like Thames Water's "long term risk" in their demand forecasts? It is tempting to be drawn towards such a conclusion, but there are only three historic examples that have been evaluated in this thesis. Perhaps a reference list of schemes assessed using the principles of the lag-time model would allow "historic perspective checks" to be carried out as a standard part of any water resources scheme appraisal.

Had the comparisons of risk averseness and efficiency shortfall from this project been available to the Thames Water Public Inquiry, this "historical perspective check" on the 100 Mm^3 design size of the UTR would have prompted an interesting debate about inter-generational investment. Such a check is not for overturning all the good work that has and is being done to improve the science of understanding uncertainty, but to view proposals from a different angle. If you understand more about how water engineering history happened, the suggestion is that better, and hopefully more timely decisions can be made from knowing why things changed in the past. Now that all those have gone who lived at the end of Queen Victoria's reign, there is a growing nostalgia for all things Victorian, but the objective for the water engineer should be to understand and communicate to the outside world which were the good and the bad practices and processes that the Victorians used. In this time of environmental restlessness, there is an opportunity to replace some of the inevitable emotion with considered judgement. Mike Hulme's point about the need for scientists to become better communicators with the public of how climate change science moves forward is similar.

The work presented in this thesis answers Professor Robert Sellin's initial reflection: that from the schemes studied in this thesis, it does look that "Birmingham did get it right", but all three schemes at the time got it reasonably right. The Inspector's decision to reject the UTR might look less secure if the dry weather of the past year continues. Drought does change things, and Section 8.5 expands on this contention.

8.2 Quantifying uncertainty

With so much Victorian water infrastructure still operating, at the outset of this project, the question was asked about how and why Victorian water resources and supply assets had happened in the sizes they did. Whilst answering this question, it was thought that it would be insightful to find out for what timescales did the Victorian water engineers expect their schemes to last. The issue for this project was not the length of time that the physical assets might last, but when the reservoir yield was expected, by the Victorians, to be completely accounted for by rising water demand.

In spite of the amount of Elan and Birmingham literature, very little was found that could be isolated and called quantifying uncertainty. The exchange at the House of Commons Select Committee (HoCSC,1892) noted in Chapter 2 when James Mansergh, who understood all the detail he was presenting, was asked by how much he might have over- or under-estimated rainfall from the crucial 20 year rainfall record at the Elan site. Mansergh answered with his judgment, which he accepted might not be right. A different engineer might have refused.

We know how much contempt was held by those who objected to the Thirlmere scheme for Bateman, as indeed Bateman had for them and the Thirlmere Defence Association. Bateman did not debate his numbers, and arrogantly dismissed any challenges. From Russell's (1981) biographical paper about Bateman, we understand that it was easier to find derogatory comments rather than praise.

Bateman's behaviour when challenged says much about the way those engineers did, or rather did not, address uncertainty. Bateman's stance was that if you do not like my numbers, then you are the wrong type of client for me. However, this cannot have happened frequently as Bateman was a phenomenally busy man who designed and constructed a large number of earth dams on the sides of the Pennines.

The principal conclusion that can be reached about the Victorian water engineers' approach to quantifying uncertainty was that it did not happen explicitly. The job of Victorian consulting engineers was to suggest to the client what type of scheme was needed, and to produce a design, which would probably have factored in the engineer's own implicit uncertainty (no working papers for Bateman or Mansergh exist in the ICE's archive). It was their experience and empirically based judgments that the clients needed and valued.

The modern approach is almost diametrically opposite to that of the Victorians. The method developed by the engineering consultant Mott Macdonald in 2002 for UKWIR entitled "An improved methodology for assessing headroom" was a substantial improvement, particularly for the larger water companies. One particular problem with the method which was raised in Chapter 5 of this thesis is that the target headroom for a particular year in future is reduced as the base year of the plan moves forward. The implication is that the optimal programme of schemes for the long term, which need to be planned now, becomes sub-optimal as the years advance. Target headroom decreases, and a more short term plan becomes optimal.

As was raised at the Public Inquiry, there are big uncertainties in the amount of water needed in the environmental area. Such is the uncertainty that the EA's WRMP guideline forbids water companies to acknowledge this uncertainty in the calculations for target headroom, unless the reduction has been confirmed by EA. The maximum impact on Thames Water's water resources was suggested by the EA to be potentially 600 Ml/d. Whilst the mood at the

Public Inquiry seemed to view this as unlikely, the company would need three more Upper Thames Reservoirs to fill the gap.

There are many site specific environmental problems, such as with the EA's Restoring Sustainable Abstractions programme that need careful and expensive data collection and analysis. The EA also needs to factor in these results into its development of the River Basin Management plans, which undoubtedly will involve dealing with many other uncertainties.

There will always be uncertainty in making demand forecasts, and research is aimed at reducing the level. In the opening remarks to "Future Water" by Hilary Benn, then the Minister for the Environment, he says that he is looking for "good" (quotation mark added) water demand forecasting. The right interpretation of this remark is that uncertainty should be addressed with good science, but the Victorian engineers' response would be that experienced judgment has been applied, and the numbers provided should be accepted.

8.3 The 1892 water demand forecast for Birmingham

In the 1890s, a 50-year planning horizon for water resources and supplies was considered by engineers to be appropriate for London and Birmingham. The current planning horizon set for water companies by the Environment Agency is 25 years. To advance the case for the full Elan scheme, Mansergh extended the 50 year horizon by a further 15 years when he told the HoCSC that the world would not end in 1940. This was a foresighted move, and a key moment for achieving Birmingham Corporation's ambition in the 1892 Act.

There was massive uncertainty in taking such a long-term view; Mansergh could not, for instance, have foreseen two World Wars, or assessed their impact on water demand, but his forecast was bold and founded on experience. In developing a demand forecast that showed growth continuing throughout the 63 years, Mansergh demonstrated that he shared

Birmingham Corporation's confidence to deliver long-term economic growth, driven by its expanding manufacturing base, and the improvement in public health.

The relatively poor resourcing for opposing interests allowed Mansergh to make his case without serious technical challenge. Perhaps this contributed to the portrayal of the Corporation's attitude by Sheail (1986) as being greedy for land, and for generating resentment. However, in spite of their arrogance, there was not complete unanimity in the Corporation about the scheme, as evidenced in a letter written to a councillor in April 1892 by Birmingham politician Joseph Chamberlain. Cited by Ward (2005), Chamberlain wrote, "Pray remember that with the exhaustion of the Staffordshire Coalfields the prosperity and the further extension of Birmingham will be seriously checked". The Corporation's Water Committee had the confidence to reject this pessimistic informal demand forecast, and fortunately for the Corporation, the HoCSC were persuaded that this issue was not material.

It is interesting and constructive to consider the downward step applied by Mansergh to the growth factor in the Decremental Ratio of Increase forecasting model. For example, an arbitrary 0.5% step produces a lower forecast profile than for 0.25%. Both are shown in Figure 4.18 together with the straight-line projection based on the 15 years of actual data from 1876 to 1891.

The comparison of the three projections in Figure 4.13 for the 20 years up to 1912 shows that there is little difference between them. Thereafter, an increasing gap develops between the 0.25% and 0.5% profiles, especially after 1942 when the 0.5% profile flattens as it approaches its maximum at 190 Ml/d. The 0.25% profile at this time is growing at its maximum rate of near 5 Ml/d per annum, which is the same as the growth rate of actual demand through to 1955. Judgement was needed to select the appropriate numbers for use in the DRoI model.

Although Mansergh used a statistical device to derive and present his 63-year water demand forecast, he also demonstrated a good understanding of the main components and drivers of demand growth. However, there were two exceptions to this. The first was waste, where increases were not considered; and the second was his speculative (and not confident) population forecast for 1955 of 1.62 million, which turned out a significant over-estimate.

Even though Mansergh had advised the HoCSC that there was no preventable waste in Birmingham, this was not the case. Neither he nor the HoCSC would have known of the success that the increased water fittings testing and house-to-house waste inspection by Birmingham Corporation was to have in suppressing demand growth up to 1904. Had the amount of preventable waste been known in 1892, the argument for the full scheme would have been weakened. The population over-estimate turned out to be not as critical because by, 1955, the shortfall in unmeasured demand was compensated by the very significant increase in measured demand.

The usual response by a water undertaker at that time to the prospect of growth outstripping supply was to develop new supplies, but there were few suitable local opportunities in Birmingham, and the expenditure would have been abortive. Waste minimisation continued in Birmingham Corporation after the first phase of the Elan scheme was commissioned in 1904, and without this, the surge in demand to meet the WW1 war effort would have presented a more serious supply problem.

Elan was controversial for its size, but the passage of time has revealed that Mansergh’s scheme was neither too big, nor unaffordable, nor is it likely that the scheme will become obsolete in future. Whilst there are still arguments about whether Birmingham should have been allowed to build such a large scheme, Elan is a valuable legacy that met Birmingham Corporation's vision of a long-term sustainable water supply.

8.4 Attitude to leakage is a driver for change

For the water distribution engineer, finding and fixing leaks from water mains is a never ending process, but is an essential part of maintaining public water supplies. The amount of money and expertise that is allocated to leakage control is influenced by the cost effectiveness of the water saved, and thereby influences the scale of an excess or shortfall in the supply and demand balance for the district of interest.

A drought in 1865 showed that Liverpool Corporation had insufficient water resources, and could only provide an intermittent supply. Public health was threatened, and Liverpool was at a competitive disadvantage to Manchester, where there was a constant supply. The engineers knew that there was no prospect of providing a new water resources and supplies scheme for many years, and that leakage from water mains in Liverpool was substantial.

Necessity became the mother of invention as George Deacon, who became chief engineer at Liverpool Corporation, understood that the current method for finding leaks was slow and inefficient, and that flow measurement over time in water mains would make a big difference. By his innovative design in 1873 for a meter that could continuously and reliably record flows in a distribution main, Deacon was responsible for creating a step change improvement in leak location.

The application of Deacon's meter brought immediate results in more efficient use of manpower resources by identifying the right areas to look for leaks, and the reduction of water demand led to the restoration of constant supplies in Liverpool in 1875.

Today, Thames Water has a significant mains replacement programme that is aimed at reducing the intrinsic leakage from ageing and underperforming assets. This policy is being driven internally by the need to address the growing supply demand imbalance and thereby to reduce the risk of the company failing to deliver the company's level of service to its customers. The situation for London is less dramatic than that in Liverpool 140 years ago, but it is the same driver.

Thames Water's policy is also being driven externally by the EA, which is aware of the pressure on water resources for meeting the demand for public water supplies, and the increasing likelihood of damage to the natural environment in SE England. There was no equivalent concern for the environment in 19^{th} century Liverpool.

Today, Thames Water recognises that without a major mains replacement programme to reduce leakage in London, there would be little chance of EA seriously entertaining any proposals made by the company for new reservoir storage. A similar situation occurred in 1892, when Mansergh was probably aware that a debate in Parliament about waste and leakage could damage the case for the Elan scheme. Mansergh asserted that "there is no preventable waste in Birmingham", and successfully stopped further debate on the topic. There is political sensitivity about leakage levels from water mains and customers' supply pipes in Government and throughout the water industry. A common perception by individuals is that because domestic pipework does not leak, so neither should the pipes maintained by the water companies. The Government responded with mandatory annual leakage targets for water companies, which are now set by and enforced by Ofwat. Mansergh's assertion to Parliament would not go unchallenged today.

The powers to construct the Elan scheme were obtained, but time was to prove that in the last five years of the 19th century, there was a significant amount of preventable leakage and waste in Birmingham. Before the Elan scheme came on stream, there was a necessity to tackle leakage in Birmingham because of a deteriorating supply demand balance, just as there is now in London.

The difference in the two situations is that Birmingham Corporation knew in the 1890s that their new reservoir scheme was on its way, but for London, there is much uncertainty about how to secure the capital's water supply the future. Over the past 150 years, proposals to solve London's precarious water supply situation with remote storage schemes have been made and then been rejected with a frequency of about once in every 20 to 30 years.

8.5 Experience of drought is a driver for change

The impact of droughts that are considered in this project occurred in the years between 1890 and 2006. The discussion starts with an observation that over the past 120 years, there has been a remarkable turnaround in water suppliers' expectations of their consumers' attitude to water use. In the last years of the 19th century, consumers were being encouraged by suppliers to use more water, whilst over the past 20 years, the reverse has been true. To what extent has the experience of drought driven this change?

In the last ten years of the 19th century, there were several dry summers when water shortages in London provoked strong consumer complaint, and raised awareness of the link between a constant clean water supply and improved public health. Forward thinking water suppliers in Britain developed new schemes to provide reliable high quality supplies that could support greater legitimate water use. Taylor et al (2009) calls this the "civilising contract" made between suppliers and their consumers.

In Victorian times, the word “drought” described what a water consumer experienced when a constant water supply failed, whatever the cause. When droughts occurred, suppliers blamed consumers for their amount of waste, and consumers blamed suppliers for having inadequate supplies and poor infrastructure. During the dry summers of the 1890s, the East London Water Company simply stopped the constant supply, and forced their consumers to endure rota cuts and intermittent supplies for only a few hours per day. Taylor et al (2009) suggest that these particular shortages “reinvigorated consumer politics, and contributed to the pressure for municipalisation” that eventually occurred in 1902.

Municipal suppliers were more accountable to their consumers, and more likely to maintain constant water supplies, but municipal ownership did not guarantee a constant supply. As noted in Chapter 4, inaction by Liverpool Corporation meant that anxious consumers had to endure an intermittent supply for seven years. Birmingham Corporation was not immune from trouble; as during the First World War, an unforeseeable surge of industrial water demand to provide the vehicles and weapons of war very nearly caused a major water supply crisis. (Bradford et al. 2010).

Whilst there were notable droughts in 1921 and 1933/4, the principle of a “civilising contract” appears not to have been seriously challenged until the UK wide drought of 1959, when Taylor suggests that some suppliers believed that their difficulties were exacerbated by a “wasteful civilisation” (Taylor et al, 2009). This view was symptomatic of a perception by consumers that water supplies were cheap and infinite.

With the increasing pace of post-war population and industrial growth, the 1959 drought experience not only reflected a change of the suppliers’ mood, but also exposed a concern about the absence of water resources management and planning at both local and strategic levels. To facilitate the management of competing interests in raw water abstractions from agriculture, industry and public water supply, the Government's response was the landmark Water Resources Act of 1963. This Act empowered new catchment based River Authorities to implement abstraction licensing schemes, and also created a new Water Resources Board with the responsibility for national water resources planning. Both of these responsibilities are now vested with the EA.

Since the 1959 drought, a high proportion of the ever increasing numbers of water consumers in the UK have had the luxury of being able to take for granted their safe, constant, and relatively inexpensive constant water supply. Forecasts of burgeoning demand, and the experience of past droughts, led to the development of several schemes that enhanced water supply availability. Notable surface water schemes included the naturally filled Clywedog reservoir scheme in mid-Wales, which was completed in 1969 to support abstractions along the River Severn. New pumped storage reservoirs at Rutland Water (1976), Foremark (1977) and Carsington (1992) increased the resources available for supplies to East Anglia, and the East Midlands.

In spite of the new schemes, water use restrictions were required in the summer droughts of 1976 (widespread regional hosepipe bans, non-essential uses banned, and some localised use of standpipes and rota cuts), and in 1995 (regional hosepipe bans in the Midlands and Northern England that extended into 1996). In 2006, after three dry winters, there were regional hosepipe bans in SE England and again in 2012 from 5 April. Modern drought management relies on reductions in consumer demand, and it remains to be seen if a change in this approach will be generated by the increasing perception of water as a commodity.

Taylor (2009) confirms that consumers responded positively to the requests to save water in 1976 at the time when the providers were the nationalised Water Authorities. However, in 1995, consumers were less responsive when many consumers were still angered by the recent privatisation of water companies. Since then, improvements in river water quality through water company investment have been recognised. In the 2006 drought, consumers of Thames Water heeded media campaigns to use less water, as the focus of communication was on limiting environmental damage rather than the threat of running out of water. There appears now to be a new form of contract being forged water companies and their customers with the needs of the water environment at its heart.

After ownership of the industry was returned to private hands in 1990, (which was politically driven rather than a drought driven change), Government and regulators were aligned in wanting to see water company policies that encouraged consumers to reduce water consumption. The objectives were environmental (reduce abstractions), social (raise awareness that resources are not infinite), and fiscal (deferral of capital expenditure). Water companies began to offer water efficiency surveys to non-domestic consumers, and optional water metering to domestic consumers. The pressure on water companies was increased by a statutory requirement to promote water conservation in the 1995 Environment Act, and its importance was underlined by the supply difficulties that many water companies experienced in the drought of 1995.

With the criticism of the industry's patchy performance in the 1995 drought still in mind, the incoming Labour Government was ready in 1997 to publish an "Agenda for Action" for the industry and its regulators. Amongst a broad range of actions, water companies were required to increase the number of domestic consumers paying metered water charges, and to achieve leakage targets. These were fundamental elements of an updated "twin-track" supply and demand approach to water resources planning, which was developed by the Environment Agency for implementation by the water companies.

The touchstone today for consumer and media interest in a developing drought is when a water company announces that unless there is significant rainfall, there is likely to be a ban on the use of hosepipes. The current powers are contained in the Water Industry Act of 1991. A minimum period of 14 days elapses from when advertisements appear in the areas affected, and any material objections are dealt with, up to implementation. The objective of a hosepipe ban is not to fill the courts with the company's own consumers, but is a serious signal from the supplier for all water users to show restraint that will avoid, or delay, the time when more draconian restrictions may be needed. The ban about to be implemented on 5 April 2012 is at this stage more about reducing water use in order that more stays in the environment.

Modern water supply networks have been made more resilient to drought by the interconnection of sources. When high demand and diminishing water in storage are coincident during drought, arriving at a prognosis for future supplies is a complex process that involves many supply and demand factors. The following definition of drought by the EA starts from the premise that "Droughts are natural events" of low precipitation:-

"Droughts are natural events. A drought happens when a period of low rainfall creates a shortage of water for people, the environment, agriculture, or industry. Some droughts are short and intense, for example, a hot, dry summer, while others are long and take some time to develop. Dry winters can have the biggest impact on water resources. We rely on winter rain to top up groundwater and reservoir levels while summer rain helps to maintain reservoir levels and keep rivers flowing." (EA, 2008)

The EA definition avoids the complexity that would occur if it were widened to include man-made influences. The same was true nearly 50 years ago, when a drought was defined very generally in the 1963 Water Resources Act as "an exceptional shortage of rainfall". This latter definition implicitly recognises that it is wise not to prescribe a quantified shortage of rainfall for all areas of England and Wales that reflects the risk for a particular restriction in water use like a hosepipe ban, or possible environmental damage.

The explanation is contained in the water companies' statutory Drought Plans that are agreed with the EA. Many water companies have told their consumers that their level of service for hosepipe bans remains no more frequent than around 1 year in 20 to 30 years. Past investment in raw water storage and treated water inter-connections means that the critical time period for the shortage of rainfall is usually much longer than the three months of spring. In SE England in general, public supplies rely on abstractions from groundwater and the base flows of rivers, and successive dry winters are the critical events, as mentioned in the EA definition.

Further north and west, there is increasing reliance on surface storage, and a dry spring followed by a dry summer leads to an increased likelihood of supply restrictions. Hosepipe bans were widespread in 1995, and supply failure was only avoided in western parts of Yorkshire Water by a major tankering exercise. There are many factors to consider when the critical period is being identified for the likely start date and the length of time when a hosepipe ban needs to be in place. As shown in Chapter 5, these factors are complex and inter-related; they include the location, the time of year, and the degree of rainfall shortage, the mix of water resources, abstraction licence and raw water quality constraints on abstractions, the capacities of treatment works, trunk mains, and the flexibility of the deployment of treated water.

For vulnerabilities that lead to the loss of supply, a recent spectacular example was a "drought" caused by the River Severn flooding of Severn Trent Water's Mythe water treatment works at Tewkesbury in July 2007, which left most of the 400,000 water consumers of Gloucestershire without a piped supply for two weeks. There are now better flood defences, and new pumps and pipes that link the Mythe works to the rest of Severn Trent Water's treated water grid system. Ironically, an event caused by too much rainfall generated a response by Severn Trent Water that increases water supply resilience in future droughts.

8.5.1 "Drought is Normal"

The summer drought of 1976 was exceptionally dry and warm, and followed a series of drier than average winters. It provided a supreme test of drought management for the newly created Water Authorities, and in many parts of the UK it was a challenge that has been unequalled since then. Hydrologically, 1976 was not normal. However, this drought features significantly in Taylor et al. (2009) "Drought is normal", so what does their title infer? The researcher's interpretation is that it is a salutary reminder to the reader that it is normal from time to time to expect droughts. An interpretation can also be made at an operational planning level. This comes from the confidence that water companies and EA have in their Drought Plans being underpinned by the reliability of the water resources and supply assets provided by the Victorians. These assets help significantly to make today's drought management a "normal" part of business as usual.

The EA have identified most of SE England as an area of water stress, and wish to see the water companies significantly enhance programmes of domestic metering to reduce demand, which would require less abstraction, and thereby reduce the risk of environmental damage.

It is an easy decision for the EA to apply pressure on the water companies to enhance their demand management activities. The main reason is that the costs are borne by the water companies. Lower abstractions for public water supplies by the water companies would probably mean lower enforced licence reductions in future for environmental improvement.

The EA said at the UTR Public Inquiry, that where there is an enforced reduction, sufficient time would be allowed by the EA for the water company to replace the resource. With no responsibility for determining planning applications, the EA's stance is at best aspirational. There is also the question of whether the cost of the new resource would be adequately funded by Ofwat. Ofwat has publically stated that even if a scheme had been approved by the EA, and there was a new abstraction licence in place, this does not mean that funding for the scheme was automatic (Kiel, 2010). This comment was made with UTR in mind because Ofwat may not agree that the scheme is cost effective for a long term commitment to higher water bills for Thames Water's customers. There appears to be no room for inter-generational expenditure.

The role of water management today in maintaining good public health often overlooked. The press sees hosepipe bans as the main threat when drought strikes. Drought may be "normal", but the priority for doing something about alleviating its consequences usually has to wait until there is a problem.

8.6 Risk averseness of schemes

The similarity in the planned lives and lag-times of the revised Thirlmere scheme and the Vyrnwy and Elan schemes prompts the question; were there any common themes in their approach to planning and design which caused this similarity, or did this just happen?

There was similarity of approach at that time in the use of rainfall data to calculate the quantity of water available in a catchment. The approach was called the “three dry years”. Binnie (1981) reminds us that the concept of three dry years was understood by Parliament and laymen as the “reliable yield” of a catchment, and remained so until the 1960s. The calculation of the reliable yield of the Elan system (including the compensation water) at 464 Ml/d was derived in this way.

On the demand side, there was similarity in the over-estimation of forecasts of population, compensated by underestimating the growth in forecasts of per capita water use. For example, Hawksley’s population served with water by Liverpool Corporation was projected to double from 0.75m in 1880 up to 1.5m by 1916, but actual growth was to near 1.0m. Total demand expressed as per capita was 100 litres per day (22 gallons) in 1880, and forecast to be 133 litres (29 gallons) in1916. The 1916 actual total demand was 160 litres per head per day (35 gallons), which compares with approximately 280 litres today, of which 150 litres is the average domestic PCC.

The tone of the bold approach to scheme design was set by Bateman. He had shown in the 1840s with the Katrine scheme for Glasgow that affordable large remote upland reservoir and gravity supply schemes could be successfully engineered. Bateman researched the potential of various sites in Wales for reservoirs with gravity supplies for supplying London for the Richmond Commission, and was aware of the possibilities of using existing lakes in the Lake District for supplying either or both Manchester and Liverpool. Such schemes today would very likely be called grandiose, and the environmental damage in the short term would be seen to outweigh any long term benefit.

There was at the time similarity in outlook and ambition reflected by the Corporations long term approach to water resources planning. The availability of money, and the acceptance of debt, allowed these ambitions to be fulfilled. Thus the Corporations were able to sustain a competitive role in economic development at a time when other cities in North America and Europe were developing quickly.

Summarising, the common explanatory factors are:

1) A shared belief held at that time by the three Corporations for providing for the long term.
2) Population forecasts were over-estimated, and per capita use was underestimated in the forecasts.
3) Bateman, Hawksley and Mansergh were revered for their experience, competence and leadership in water engineering.
4) A common approach was taken that used the 3 dry years rule for estimating catchment runoff.

Whilst the work done to assess the risk averseness of the scheme designs identifies the most and least risky schemes, all the schemes were “safe” as they experienced longer planned lives than intended when designed. Were they so safe that the over-forecasting produced grandiose schemes?

1) Thirlmere would have had to have been a substantially larger scheme to produce Bateman’s planned drought yield of 227 Ml/d. A larger scheme would have been labelled as grandiose (and a Lag Time of perhaps 50 years plus), and possibly less likely to have obtained Parliamentary approval. With better rainfall data, the drought

yield was revised down around 1910, and this produces Thirlmere with a Lag Time of about 10 years.

2) At 15 to 20 years, Vyrnwy has a larger Lag Time than Elan. However, what might have been perceived as a grandiose scheme at the time has turned out not to be the case as Liverpool Corporation went on to develop additional river and reservoir sources in North Wales.

3) Elan is nearly double the capacity of Vyrnwy, and has a Lag Time of 10 years. The size of Elan was robustly challenged in 1892, but Mansergh's staged design prevailed. The full scheme was sized correctly to meet Birmingham's demands in the first three-quarters of the 20th century.

It would be interesting to look at other water resources and supply schemes that are clustered temporally or spatially, or by size or type, where there is sufficient data to gauge their relative risk averseness. Engineering historians might gain further insight to the degree of influence that common social, economic, political, and environmental factors had, or had not, on water engineers' planning and design of water schemes.

In the past two centuries in the UK, the principal drivers for water resources investment were rising demand due to the increased population served, and to support greater industrial activity. Now in the 21st century, future water demand growth in many areas of the UK is expected to be relatively flat. However it is the potential reductions in supply availability at existing sources, due primarily to environmental concerns, and the forecast impacts of rising temperatures due to climate change, which have become increasingly significant.

The lag time model applied to the forecast and actual long term supply and demand diagram has proved to be a useful concept as a guide to assess retrospectively the relative effectiveness of water resource scheme designs intended to last for at least 30 years.

8.7 Would the Elan scheme be built today?

If he was to present the case for Elan today, would Mansergh prevail? The potential environmental damage, or some might say the destruction, of a beautiful part of Mid-Wales would be likely to end any argument for the scheme, regardless of the need. There exists some deep longstanding resentment in Wales about the attitude taken by the Corporations of Birmingham and Liverpool in forcing through reservoir schemes. The politics have changed; the devolved Welsh Assembly might react emotionally and say no, or maybe the proposal might be seen as a commercial opportunity.

A new Elan scheme could be viewed as an example that fits the EA's vision to see more sharing of water resources as options for the future. Whilst it is the EA's responsibility to be the government's environmental regulator, and the champion for a sustainable environment, it is difficult to see how an objective decision could be made by the Agency. It is not unreasonable to conclude that the Planning Inspector's recommendation to reject Thames Water's UTR proposal might have been influenced in a small way by the impossibility of the EA's position.

8.8 The Implications of this thesis to future water resources planning.

The implications of this thesis are in the processes of comparing schemes, and assessing comparative uncertainty. They can be summarised as follows:

1. It is clear that the current planning approach coupled with the current regulatory requirements accentuates water resources

planning by the UK water companies for the short-term rather than the long term. The Victorian approach, which based scheme designs on longer forecast horizons than are used today, demonstrates explicitly that Victorian investment was being made for future generations.

2. An "historic perspective check" using the lag time model could help decisions to be made by water companies in scheme optimization and the priority of future schemes.

3. The existing target headroom methodology could be developed to include an historical parameter that reflected the degree of intergenerational investment. The feasibility for such an addition would require further research work.

4. Finding enough data and information concerning the original demand forecasts that were developed to justify a scheme is a key challenge. Singling out the impact a particular source within in a group of sources is a further significant challenge.

CHAPTER 9 CONCLUSIONS

9.1 Quantifying uncertainty in the forecast for water supply and demand

- Victorian water engineers did not have an explicit approach to the quantification of uncertainty when making their forecasts for future water supply and demand. Their approach was deterministic, and they were expected by their client Corporations to make empirically based judgements.

- Whilst today's water engineers have more data and knowledge, and can take a more detailed statistical approach, they have less freedom in strategic decision making than their Victorian predecessors.

- The current UKWIR methodology for quantifying uncertainty as target headroom is conceptually and statistically sound, but does not work well when large long term reservoir schemes are being considered. The method also requires many judgements to be made, and a given outcome can be forced.

- The 21st century call for environmental improvement has replaced the call made in the 19th century for the improvement of public health. There are substantial spatial and temporal uncertainties, including the impact of climate change. These are difficult to quantify and achieve reliable estimates of the amounts of water needed to deliver and maintain environmental improvements, which in themselves are difficult to specify.

9.2 Inter-generational investment

- Planning for inter-generational investment is ignored in the regulatory planning guidelines. The Victorians have taught us that a 25 year planning horizon is too short, and the 5 yearly cycle of reviewing prices prioritises a short term approach to be taken by water companies. Perhaps a more mature debate might have been had at the 2010 Public Inquiry if Thames Water had presented a plan that identified inter-generational investment, rather than being perceived as a company that wanted a particular large scheme to meet it's own somewhat arbitrary evaluation of "long term risk".

- The current regulatory guidelines make the probability of building a new reservoir in future in the UK extremely remote as water companies are not allowed to plan for surplus headroom after 25 years. Building dams in stages to meet the 25 year criterion is often not possible, or would be prohibitively expensive.

- The Environment Agency and Ofwat have much power to influence plans and the choice of schemes, but little responsibility for the outcome. The Government's approach has perhaps allowed too much of the risk of future failure to fall on the water companies and their customers.

9.3 The 1892 water demand forecast for Birmingham

- In spite of huge uncertainty, the profile of Mansergh's 63-year water demand forecast made in 1892 for the Birmingham Corporation supply area is remarkably close to the profile of actual water demands up to the forecast horizon in 1955.

- In 1892, Mansergh understood the components of demand, and this informed his judgement when making reasonable assumptions about possible future demand growth. With his use of the statistical device called the decremental ratio of increase, which accommodates the concept of a limit to growth, he demonstrated the skills to develop and present successfully to Parliament a long-term water demand forecast.

- During the 12-year construction period of the Elan scheme, the waste control initiatives introduced by Birmingham Corporation were crucial to maintaining the headroom of supply over demand that ensured continuous supplies in Birmingham. Since then, a continuing culture for waste control helped to maintain headroom. However, during the First World War, its relaxation coupled with surging demand to support the war effort, very nearly created a major water supply crisis.

- Mansergh and Birmingham Corporation were far-sighted, and they have proved using a much longer time horizon than is used now for water resources planning to have produced the valuable legacy of a sustainable water resource and supply scheme at Elan. The 1892 water demand forecast was a quantitative expression of Birmingham Corporation's confidence and belief in the long-term future of the city.

- The Victorian Corporations of provincial England raised sufficient funds, and used an ownership and accountability model that worked.

9.4 Attitude to leakage control brings about change

- An intermittent supply in Liverpool that had lasted for years during the 1860s was the catalyst of significant change in the approach to leakage control. It was the stimulus for Deacon's invention of a water meter that recorded continuous flow in distribution mains, and the measurements made using the new technology enabled a more efficient and very successful new approach to be taken to locating leaks.

- Mansergh's assertion to Parliament in 1892 that "there is no controllable leakage and waste in Birmingham" would not go unchallenged today.

- The current Government approach involves the setting of mandatory leakage targets for water companies, and demonstrates that it is serious about leakage control for political reasons, and for maintaining water supplies.

9.5 Experience of drought brings about change

- The experience of drought has been both a driver (the force), and a catalyst (the timing), for the changes to the responsibility for public water supplies, for the pressure to develop new schemes, and for prompting Government intervention leading to the updating of the approach to strategic water resources and supplies planning.

- The experience of drought, together with societal changes over the past 120 years, has redefined the original "civilising contract" between suppliers and consumers, which encouraged water use and delivered improved public health; today there is a wider contract with the environment, which is exemplified by the emphasis Government has put on all major stakeholders for efficient water use, and on water conservation.

9.6 Measuring risk averseness and efficiency in terms of supply and demand

- The relative risk averseness of the Victorian scheme designs is successfully quantified using a novel lag-time model with data derived from supply and demand balance diagrams. The least risk-averse design appears to be the full Elan scheme, and most risk averse was the original Thirlmere scheme. Vyrnwy is between Elan and Thirlmere. Thames Water's proposed 100 Mm^3 Upper Thames Reservoir has a shortfall from the intended planned life, and it could be argued that this scheme is more risky than the Victorian schemes because additional investment will be needed sooner rather than later. Caution is advised in making risk comparisons for the UTR scheme as, in this study, both the long term supply and demand profiles are relatively flat.

- Thames Water has set itself a very ambitious challenge by making the assumption of a 20 litres per head per day reduction by 2035 in the domestic PCC forecast for London. The sensitivity of this forecast and the implications are substantial. If 10 litres is saved, the forecast demand for 2035 increases by 78 Ml/d. Together with the company's estimate presented at the 2010 Public Inquiry of 100 Ml/d for "long term risk", the deployable output of 178 Ml/d for the 100 million cubic metres UTR design would appear to be completely taken up.

- The rejection by the Planning Inspector and the Secretary of State of Thames Water's plan means there is still much uncertainty about how to secure water long term public water supplies, and deliver environmental improvement in London and the SE.

- Novel concepts have been successfully developed that address the Knowledge Gap, including a new lag time model that compares the risk averseness of schemes, and opening the possibility of a new parameter of an "historic perspective check" to be included in the processes of a water company's production of a preferred plan.

CHAPTER 10 FURTHER RESEARCH

There are other types of Victorian water and sewerage assets that could be candidates for study that use the principles reported in this thesis. For example in water supply, there are many Victorian wells and boreholes that are still operational, and unveiling the reasons for the decisions taken when they were planned may show up other common features that were environmentally, technically, socially or politically significant.

Setting up a register of schemes with an "historic perspective check" could be considered as an extra piece of information in future planning. Research would be needed to establish the feasibility of a register.

A related area of study where research by engineering historians could improve our understanding is by taking a more holistic view of the Victorian legacy to demonstrate what this is worth. Today's replacement cost for each asset in financial and environmental terms is an obvious option, but the answer would be too high to be meaningful, and the programme would take a long time to deliver. The novel lag-time method revolves knowing the period of time that the engineer originally planned for an asset to last, and estimation of the lag time for that asset could be a route to valuing the legacy with more finesse.

Postscript

James Watt's three word answer to his young son's question about what makes a good engineer was "Reflection and judgment" (source, National Museum of Scotland). Today's water engineers would be likely to agree. The Victorian water engineers would be impressed with the modern armoury of computing power, good science, modelling tools, and copious data, but they would be horrified at the amount of time taken up in paralysis by analysis.

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APPENDIX A – GLOSSARY OF TERMS (EA,2008)

Abstraction	The removal of water from any source, either permanently or temporarily.
Abstraction licence	The authorisation granted by the Environment Agency to allow the removal of water from a source.
ACORN	A Classification Of Residential Neighbourhoods is a socio-demographic classification of neighbourhoods published by CACI Ltd. The system is based on the assumption that people who live in similar neighbourhoods are likely to have similar behavioural and consumption habits.
Allowable outage	The outage (calculated from legitimate unplanned and planned events) which affects the water available for use. An outage allowance may be made for such outages.
Annual average	The total demand in a year, divided by the number of days in the year.
Available headroom	The difference (in Ml/d or percent) between water available for use (including imported water) and demand at any given point in time.
Average day demand in peak week	One seventh of total demand in the peak week in any 12 month accounting period.
Average incremental social costs	The ratio of present social costs over present net value of additional water delivered or reduced demand
Baseline forecast	A demand forecast which reflects a company's current demand management policy but which should assume the swiftest possible achievement of the current agreed target for leakage during the forecast duration, as well as implementation of the company water efficiency plan, irrespective of any supply surplus.
Consumption monitor	A sample of properties whose consumption is monitored in order to provide information on the consumption and behaviour of properties served by a company.
Demand management	The implementation of policies or measures which serve to control or influence the consumption or waste of water (this definition can be applied at any point along the chain of supply).
Deployable output	The output of a commissioned source or group of sources or of bulk supply as constrained by: environment • Licence, if applicable • Pumping plant and/or well/aquifer properties • raw water mains and/or aquifers • transfer and/or output main • treatment • water quality

Distribution input	The amount of water entering the distribution system at the point of production.
Distribution losses	Made up of losses on trunk mains, service reservoirs, distribution mains and communication pipes. Distribution losses are distribution input less water taken.
Distribution system operation use (DSOU)	Water knowingly used by a company to meet its statutory obligations particularly those relating to water quality. Examples include mains flushing and air scouring.
Drought order	An authorisation granted by the Secretary of State under drought conditions, which imposes restrictions upon the use of water and/or allows for abstraction/impoundment outside the schedule of existing licences on a temporary basis.
Drought permit	An authorisation granted by the Environment Agency under drought conditions, which allows for abstraction/impoundment outside the schedule of existing licences on a temporary basis.
Dry year annual average unrestricted daily demand	The level of demand, which is just equal to the maximum annual average, which can be met at any time during the year without the introduction of demand restrictions. This should be based on a continuation of current demand management policies. The dry year demand should be expressed as the total demand in the year divided by the number of days in the year.
Final planning demand forecast	A demand forecast, which reflects a company's preferred policy for managing demand and resources through the planning period, after taking account of all options through full economic analysis.
Final planning scenario	The scenario of water available for use and final planning demand forecast which constitute the company's best estimate for planning purposes, and which is consistent with information provided to Ofwat for the Periodic Review.
Forecast/plan horizon	The end date of demand forecast or water resources plan.
Maximum Likelihood Estimation (MLE)	A statistical technique where a reconciliation item is distributed to the largest and least certain components of an estimate of the magnitude of a variable. The technique can be applied to the reconciliation of a water balance.
Meter optants	Properties in which a meter is voluntarily installed at the request of its occupants.
Meter programme	Properties, which are to be metered according to current company metering policy.
Micro-component analysis	The process of deriving estimates of future consumption based on expected changes in the individual components of customer use.
Net Present Value	The difference between the discounted sum of all of the benefits arising from a project and the discounted sum of all the costs arising from the project.

Non-households	Properties receiving potable supplies that are not occupied as domestic premises, for example, factories, offices and commercial premises.
Normal year annual average daily demand	The total demand in a year with normal or average weather patterns, divided by the number of days in the year.
Outage	A temporary loss of deployable output. (Note that an outage is temporary in the sense that it is retrievable, and therefore deployable output can be recovered. The period of time for recovery is subject to audit and agreement. If an outage lasts longer than 3 months, analysis of the cause of the problem would be required in order to satisfy the regulating authority of the legitimacy of the outage).
Point of abstraction	The top of a borehole for borehole abstraction; the river intake for a river abstraction to direct supply or bank side storage; the draw-off tower for a direct supply reservoir.
Point of consumption	The point where the supply pipe rises above ground level within the property, usually the inside stopcock or an internal meter.
Point of delivery	The point at which water is transferred from mains or pipes, which are vested in the water supplier into, pipes which are the responsibility of the customer. In practice this is usually the outside stopcock, boundary box or external meter.
Point of production	The point where treated water enters the distribution system.
Potable water produced	Raw water treatment less treatment works operational use and treatment work losses.
Potable water exported	Potable water exports from within a defined geographical area to an area outside the defined geographical area.
Potable water imported	Potable water imports from outside a defined geographical area to the defined geographical area.
Raw water abstracted	Raw water abstracted at the point where abstraction charges are levied. It is made up of raw water retained and raw water exported.
Raw water collected	Raw water retained plus raw water imported.
Raw water exported	Raw water exported from a specific geographical area.
Raw water imported	Raw water imported from outside of a specified Imported geographical area.
Raw water losses	The net loss of water to the resource system comprised of mains/aqueduct (pressure system) losses, open channel/very low pressure system losses, and losses from break-pressure tanks and small reservoirs.
Raw water operational use	Regular washing-out of mains due to sediment build-up and poor quality of source water.

Reconciliation item	The difference between the estimates of the magnitude of a variable and the sum of the estimates of the individual components of that variable.
Resource zone	The largest possible zone in which all resources, including external transfers, can be shared and hence the zone in which all customers experience the same risk of supply failure from a resource shortfall.
Risk	A measure of the probability and magnitude of an event and the consequences of its occurrence.
Source	A named input to a resource zone. A multiple well/spring source is a named place where water is abstracted from more than one operational well/spring.
Supply-demand balance	The difference between water available for use (including imported water) and demand at any given point in time (c.f. available headroom).
Supply pipe losses	The sum of underground supply pipe losses and above ground supply pipe losses.
Sustainability reduction	Reductions in deployable output required by the Environment Agency to meet statutory and/or environmental requirements.
Target headroom	The threshold of minimum acceptable headroom, which would trigger the need for water management options to increase water available for use or decrease demand.
Total leakage	The sum of distribution losses arid underground supply pipe losses.
Total water management	All water management activities from source to end use (i.e. resource management, production management, distribution management and customer-side management).
Treatment work losses	The sum of structural water loss and both continuous and intermittent over-flows.
Treatment work operational use	Treatment process water i.e. net loss, which excludes water returned to source water.
Underground supply pipe losses	Losses between the point of delivery and the point of consumption.
Unrestricted demand	The demand for water when there are no restrictions in place (this definition can be applied at any point along the chain of supply).
Void property	A property connected to the distribution network but not charged because it has no occupants.
WRP tables	Water resources plan tables used for presenting key quantitative data associated with a water resources plan.
Water available for use	The value calculated by deducting allowable outages and planning allowances from deployable output in a resource zone.
Water delivered	Water delivered to the point of delivery.

Water delivered billed Water delivered less water taken unbilled. It can be split into unmeasured household, measured household, unmeasured non-household and measured non-households water delivered.

Water taken Distribution input minus distribution losses.

APPENDIX B - CHRONOLOGY OF EVENTS IMPACTING ON WATER SUPPLIES FOR BIRMINGHAM AND LONDON FROM 1800 TO THE EARLY 1900S

Year	Birmingham	Year	London	Reference
PERIOD 1: 1800 to 1850 - BIRMINGHAM WATERWORKS COMPANY (BWCo) FORMED		**Period 1: 1800 to 1850 - THAMES WASTEWATER CRISIS STARTS**		
		1800/05	Five new water supply companies formed.	Parry, J. (1881)
		1805	150k cesspits served 1m people.	Thames Water website. (2007)
1808	70k people in 12k houses supplied from "ordinary" wells and carts.			Mathews, C.E. (1886)
1811	Parliament rejects a Bill to grant powers to form a company.			History of CBWD. (1973)
1812	Streets Commissioners become 1st public health authority.			Macmorran, J. (1973)
		1815	Connections allowed of house drains and cesspits to surface drains.	Halliday, S. (1999)
		1815	River Thames quality deteriorating "dangerously".	Hardy, A. (1984)
		1821	Anti-Water-Monopoly-Association; Bill to make dispute referees fails.	Parry, J. (1881)
1826	First Act to form BWCo, with powers to abstract from River Tame.			Short History of BWCo. (1875)
1827	Bankside reservoir storage of 30Mg started.			Short History of BWCo. (1875)

Year	Birmingham	Year	London	Reference
	(Second reservoir of 21Mg added in 1869).			
		1827	Attack on quality of Westminster supplier, Grand Junction Water Co.	Hardy, A. (1984)
		1828	Royal Commission appointed to look at quantity, quality, new sources.	Hardy, A. (1984)
		1828	9 companies, 164k tenants, 1.5m people, 200k houses.	Hardy, A. (1984)
		1830s	General development of the Public Health idea; WCs used widely.	Hardy, A. (1984)
1831	River Tame water abstracted at Aston for supply for the first time.			Short History of BWCo. (1875)
1831	Pumped from raw bankside reservoir at Aston to Monument Lane SR.			Short History of BWCo. (1875)
		1831	First Cholera outbreak, 6.5k died.	Halliday, S. (1999)
1837	Victoria becomes Queen.	1837	Victoria becomes Queen.	
		1838	Poor Law Board emphasises importance of adequate water supplies.	Hardy, A. (1984)
1842	Streets Commissioners under John Pigott-Smith embark on much needed sewerage and drainage schemes - great political apathy.	1842	Edwin Chadwick's Sanitary Report raises middle class awareness.	Ward, R. (2005)
		1844	Royal Commission on Health of Towns; more serious than imagined.	Hardy, A. (1984)
		1844	Of 900,000 people resident in New River Co district, 300,000 were "unsupplied".	Parry, J. (1881)

Year	Birmingham	Year	London	Reference
		1847	Waterworks Clauses Act, powers for Cos to provide constant supplies.	Hardy, A. (1984)
1848	Robert Rawlinson appointed inspector of Central Board of Health.			Ward, R. (2005)
		1848	General Board of Health appointed. Recommends moving intakes for water supply away from R Thames.	Hardy, A. (1984)
		1848	Metropolitan Sewers Commission; connections to sewer required.	Halliday, S. (1999)
		1848/9	Second Cholera outbreak, 14.1k died; Snow not believed.	Halliday, S. (1999)
1849	Intermittent supplies; Cholera fears; Corporation requests BWCo to clean streets.			Mathews, C.E. (1886)
PERIOD 2: 1850 to 1870 - NEW APPROACH TO SUPPLY TAKEN BY BWCo.		**PERIOD 2: 1850 to 1870 - NEW PHASE IN ENVIRONMENTAL IMPROVEMENT.**		
1851	Birmingham Improvement Act; gave Corporation the powers to purchase BWCo			Mathews, C.E. (1886)
1851	New Public Works Committee (PWC) takes over work of Streets Commissioners			Macmorran, J. (1973)
		1852	Metropolis Water Supply Act; Companies confirmed in their monopoly position	Hardy, A. (1984)
		1852	Act also recommended moving intakes above Teddington	Hardy, A. (1984)
1853	Supplies "ample and non-intermittent" in area with Parliamentary powers			Mathews, C.E. (1886)

Year	Birmingham	Year	London	Reference
		1853/4	Third Cholera outbreak, 10.7k died, link to polluted drinking water dramatically confirmed.	Halliday, S. (1999)
1854	2nd BWCo Act allowed £30k more borrowing; Corporation approved new works.			Mathews, C.E. (1886)
1854	Joseph Chamberlain first arrives in Birmingham from London aged 18.			Ward, R. (2005)
1854	Willenhall liquor spill into River Tame; domestic supplies cut; water carts used.			Mathews, C.E. (1886)
1854	Pigott-Smith takes horrified PWC members on inspection of River Tame catchment.			Macmorran, J. (1973)
1854	Rawlinson's "Proposed source of Water Supply" recommends River Blythe east of Birmingham.			Rawlinson, R. (1854)
1855	3rd BWCo Act; powers to use local sources at Hawthorn Brook, Perry Brook, R Blythe.			Mathews, C.E. (1886)
1855	General Purposes Committee recommend BWCo buyout - rejected by Council.			Ward, R. (2005)
1855	Upwards of 250k people resident in B'ham.			Mathews, C.E. (1886)
		1855	Metropolis Land Management Act; establishes Metropolitan Board of Works.	Hardy, A. (1984)
		1855	New parish based administrative network regulated drainage arrangements.	Hardy, A. (1984)
		1856	Metropolitan Board of Works takes office, Bazalgette made Chief Engineer.	Halliday, S. (1999)
		1856	London medical officers of Health serve each	Hardy, A. (1984)

Year	Birmingham	Year	London	Reference
			parish.	
		1858	The Great Stink.	Halliday, S. (1999)
1858	BWCo has "heated" correspondence with Walsall over sewage in River Tame.			Mathews, C.E. (1886)
		1860s	Monthly water reports; no supplies on Sundays until 1870s.	Hardy, A. (1984)
1861	New Edgbaston Service Reservoir built 70 feet above Monument Lane SR.			Mathews, C.E. (1886)
1862	Thomas Avery joins Council from business, and made chair of Finance Committee.			Macmorran, J. (1973)
1862	James Mansergh's first "assessment" of Elan site in Mid-Wales (initially for London?).			Mansergh, J. (1894)
1864	Thomas Hawksley report recommends groundwater and larger supply area.			Mathews, C.E. (1886)
		1865	Bazalgette's Southern system in operation.	Halliday, S. (1999)
		1865	Increasing concern for agricultural pollution of the River Thames from Oxford + Reading.	Hardy, A. (1984)
		1866	Fourth Cholera outbreak in East End confirms water-borne theory.	Halliday, S. (1999)
		1866/72	The Water Question and The Sewage Question, letters to Earl of Derby.	Bailey Denton, J. (1866)
1866	4th BWCo Act, authorises Plant's Brook abstraction, new wells, extended supply area.			Mathews, C.E. (1886)

Year	Birmingham	Year	London	Reference
1866	Act limited Aston abstraction from River Tame, and prohibited altogether from 1 Jan 1872.			Mathews, C.E. (1886)
		1868	Abbey Mills pumping station opened; Northern system in operation.	Halliday, S. (1999)
1869/72	Wells constructed at Witton (2 Mgd), Perry (2 Mgd), Kingsvale (0.5 Mgd).			Mathews, C.E. (1886)
		1869	Royal Commission on Sanitary Reform recommends public ownership of water supply.	Hardy, A. (1984)
		1869	Royal Commission about future supplies rejects Bateman's plan for remote storage in Mid-Wales.	Walters, R.C.S. (1936)
1869	Alderman Avery's resolution about public health and private enterprise.			Avery, T. (1869)
1870	5th (last) BWCo Act; authorised rivers Blythe and Bourne abstraction, Whitacre and Shustoke reservoirs.			Mathews, C.E. (1886)
1870	Council empowered to appoint Inspector to test quality.			Mathews, C.E. (1886)
1870	Richard Hassard recommends new remote storage west of Birmingham on River Teme.			Hassard, R. (1871)
1870	Sewage Enquiry Committee 300 page report.			Briggs, A. (1968)

Year	Birmingham	Year	London	Reference
PERIOD 3: 1870 to 1890 – CORPORATION TAKES OVER RESPONSIBILITY FOR WATER SUPPLY			**PERIOD 3: 1870 to 1890 - WATER SUPPLY BECOMES A POLITICAL ISSUE**	
		1871	Metropolis Water Act; secures appointment of Metropolitan Water Examiner.	Hardy, A. (1984)
		1871	Operation of Companies subject, in public interest, to Parliamentary supervision.	Hardy, A. (1984)
1871	Robert Rawlinson report to Corporation on Mid-Wales as future source of supply.			Mathews, C.E. (1886)
1871	Whitacre reservoir completed; River Blythe now used in supply for the first time.			Hassard, R. (1871)
1871	Demand 7.3 Mgd.			Mathews, C.E. (1886)
1872	Abstractions cease from River Tame for domestic use.			History of CBWD. (1973)
		1874	Royal Commission on Rivers Pollution; multitudes still at risk.	Hardy, A. (1984)
1874	Joseph Chamberlain as Mayor "knew what he had to do, and did it" by municipalising private Gas and Water companies.			Mathews, C.E. (1886)
1875	Bill became law for the Corporation to take over BWCo on 1 Jan 1876.			Mathews, C.E. (1886)
1875	Alderman Avery and George Heaton (for BWCo) brokered financial deal.			Mathews, C.E. (1886)
1875	Avery becomes first chair of new Water Committee.			Ward, R., (2005)

Year	Birmingham	Year	London	Reference
1875	A Short History of the Birmingham Waterworks Company published.			Short History of BWCo.(1875)
1875	Death rate of 25 per thousand higher than 1849, and 3 greater than national average.			Ward, R. (2005)
1875	First Health Committee formed following large scale sanitary survey.			Ward, R. (2005)
1875	Public Health Act; local authorities could combine where advantageous.			Birmingham Weekly Post, (1952)
1877	Birmingham Tame and Rea District Drainage Board formed serving 0.5m.			Birmingham Weekly Post, (1952)
		1880s	Scientific uncertainty; divergence of analytical techniques for quality.	Hardy, A. (1984)
		1881	Parry's book that opens with "We live in an age of sanitary restlessness" is published.	Parry, J. (1881)
1883	Corporation makes a profit on water supply; rates reduced for small houses.			Mathews, C.E. (1886)
1883	Consolidation Act adds Coleshill, Elmdon and Solihull to the supply area.			Mathews, C.E. (1886) History of CBWD. (1973)
1885	Demand 12Mgd; Supply 16.5Mgd; 0.5m supplied (out of 0.6m).			Mathews, C.E. (1886)
1886	Mathews believes that "It would appear that we have no anxiety for the future".			Mathews, C.E. (1886)
		1887	Discharge of sewage to the Thames ceases.	Halliday, S. (1999)

Year	Birmingham	Year	London	Reference
PERIOD 4: 1890 to 1900 - BIRMINGHAM CORPORATION PLANS AND BUILDS FOR THE LONG TERM			**PERIOD 4: 1890 to 1900 - CONSTANT SUPPLIES, AND A STRING OF DROUGHTS**	
1891	A Lecture – "The Future water supply of Birmingham" reveals Corporation's plans.			Barclay, T. (1891)
1891	James Mansergh recommends purchase of Elan and Claerwen catchments			Mansergh, J. (1894)
		1891	Storage capacity is insufficient to maintain supplies in turbid times.	Hardy, A. (1984)
		1891	New LCC pushes on to extend constant water supplies e.g. Camberwell.	Hardy, A. (1984)
1892	Objectors pamphlet "Why the Welsh water scheme is not the one for the City of Birmingham".			Double Service Committee, (1892)
		1892	Cholera on the continent gives "sanitary anxiety".	Hardy, A. (1984)
1892	First five sections of Barclay's The Future Water Supply of Birmingham is published.			Barclay, T. (1892)
1892	Royal Assent for Birmingham Corporation Water Act for Elan scheme.			Barclay, T. (1892)
1893	Chamberlain warns that the Elan scheme will over-extend City finances - advice ignored!			Ward, R., (2005)
1893	Plans for six dams and six pipelines for delivery over 60 years.			Barclay, T. (1898)
1893	Importance of keeping waste to a minimum until Elan delivered.			Barclay, T. (1898)

Year	Birmingham	Year	London	Reference
		1894	Sir Alexander Binnie proposes new storage in Mid-Wales, and again rejected.	Walters, R.C.S. (1936)
		1894/5	Severe winter and dry summer.	Hardy, A. (1984)
		1896	Summer drought.	Hardy, A. (1984)
		1898	Drought "unparalleled for 86 years".	Hardy, A. (1984)
1898	Second five sections of Barclay's book "revised and enlarged".			Barclay, T., (1898)
		1899	Constant supplies achieved in London some 40 years after the target set.	Hardy, A. (1984)
PERIOD 5: EARLY 1900s - FIRST 3 ELAN DAMS, 2 PIPELINES, + FRANKLEY WORKS DELIVERED.		**PERIOD 5: EARLY 1900s - METROPOLITAN WATER BOARD (MWB) FORMED.**		
1901	Queen Victoria dies.	1901	Queen Victoria dies.	
1904	King Edward VII inaugurates Elan scheme.			Mansergh, E.& W. (1912)
		1904	MWB takes over water companies.	Hardy, A. (1984)
1912	Earnest and Walter Mansergh’s ICE paper describes the Elan scheme.			Mansergh, E.& W. (1912)
		1921	Supply considered safe enough to abolish post of Metropolitan Water Examiner.	Hardy, A. (1984)

APPENDIX C – PARAMETERS OF WATER DEMAND FORECASTS – COMPARISON BETWEEN 1892 AND 2008

1892		2008		
Comment	**Parameters used for the forecast (M = Mansergh forecaster for 1955; see Table 4.9)**	**Parameters used for forecast**	**Example of units**	**Unmeasured or measured**
Household		**Household**		
Census data	Population total	Population total + forecast growth	Millions + thousands per year	
Birmingham evidenced growth trend data from 1871 to 1891	(M's 'not unreasonable' forecast of 1.62 million not explicitly used)	Number of new houses	Thousands/year	
		Number of meter optants	Thousands/year	
House counts for billing	Number of inhabited houses	Unmeasured households and population	Millions	
Birmingham evidenced growth trend data from 1871 to 1891	(M's implied unmeasured per capita demand forecast of 97 litres/day includes household, waste and leakage)	Measured households and population	Millions	
		Metering savings assumed	Litres/person or litres/household per day	
Comparison with other cities; London experience	Average daily domestic use in houses with and without WCs (M. assumed future growth of WCs, hot water systems, prosperity)	Water efficiency assumptions	Litres/person or litres/household per day	
		Per capita micro component domestic use per day:		
		Unmetered households	Litres/person or litres/household per day	Unmeasured
		Metered households	Litres/person or litres/household per day	Measured

1892		2008		
Non-household		**Non-household**		
Accelerated growth in manufacturing with soft water; Glasgow experience	Measured non-household use per day (M. assumed 91 litres/head per day)	Number of new non-households	Thousands/year	
	Agreements with small industrial users (M. assumed as part of non-household)			
		Non-household population	Thousands/year	
Significant use to improve public health	Street cleaning, fountains, etc. (M. assumed as part of non-household)	Measured non-household use	megalitres/day	Measured
		Unmeasured non-household use	megalitres/day	Unmeasured
		Unbilled use and operational use	megalitres/day	Unmeasured
Leakage		**Leakage**		
Fittings tested	Minimise waste (M. implied steady; part of household)	Distribution losses (based on economic level of leakage (ELoL) and mains replacement programme)	megalitres/day	Unmeasured
Household inspections	Minimise waste (M. implied steady; part of household)	Customer supply pipe losses:		
		Unmetered properties	Litres/property per day	Unmeasured
		Metered properties (also part of ELoL)	Litres/property per day	Measured
Starting with a 3% per annum growth rate observed in the 1880s, Mansergh used the DRoI method to produce a forecast up to 1955 (see Table 4.6)		Components added to produce forecast: Ml/day		

APPENDIX D - EA, DEFRA, AND THAMES WATER REPORTS, 1994 TO 2011

Year	From Government	From Thames Water	Comment
1994	Water, Nature's Precious Resource, published by National Rivers Authority		Environmentally Sustainable Water Resources Development Strategy for England and +Wales.
1996	Water Resources and Supply – Agenda for Action; report published by DoE		Post 1995 Drought Actions for Govt, EA, Ofwat, Water Cos and consumers
1998	Economically based mandatory leakage targets for Water Cos set by Ofwat		Leakage rates politically sensitive. Targets needed to deliver reductions.
1999 and 2004		Water Companies produce WRMP's to EA's specification. to align with Business Plans.	EA report to Govt that not all companies have sustainable plans.
2007	Parliamentary WRMP and Drought Plan Directions		Water company Draft and Final WRMP are made Statutory, and have public consultation
2007	EA issues Water Resources Planning Guideline report, and updates.		Guideline revised to include latest advice on Climate Change
Late 2007		Strategic Direction Statement report published	Marks the start of the 2009 Business Plan process for Water Cos.
Feb 2008	"Future Water" report, and Govt Factsheets issued by Defra.		Govt policy to reduce domestic water demand.
Feb 2008	Consultation on "Draft Statutory Social and Environmental Guidance" issued by Defra.		Govt test of policy advice to be given to Ofwat.
Mar 2008	EA public consultation on "Water for People and the Environment"		EA tests policy for their National Water Resources strategy.
Mar 2008	Managing Drought in E+W report issued by EA.		
May 2008		Draft WRM Plan made available for public	

Year	From Government	From Thames Water	Comment
		consultation	
June 2008	EA's Climate Change Adaption Strategy issued.		
Aug 2008	"Statutory Social and Environmental Guidance" issued by Defra to Ofwat.		
Sept 2008	Demand for Water in the 2050s report (EA)		One of 8 EA Module reports that support the WRMP Guideline
Nov 2008	WRM Planning Guideline revised (EA)		
Mar 2009	Water for the People and the Environment, Summary and Final Report (EA)		Water Scarcity. Restoring Sustainable Abstractions.
Mar 2009	Water is Precious, Summary and Final Report (EA Wales)		
Feb 2009		Statement of consultation Responses report to Defra	
Feb 2009		Consultants for TW report on Public Consultation	
April 2009	Water Resources Strategy – External briefing (EA)		
April 2009		Final Business Plan submitted to Ofwat	
May 2009	EA Advice report to Defra about TW's Statement of Responses.		Pivotal report that indicated the need for a Public Inquiry.
June 2009	Supplementary EA Advice to Defra. Final Advice not changed.		
3 Aug 2009	Defra letter to TW announcing Public Inquiry		
Aug 2009		TW letter to EA asking for clarification of Advice reports.	
Sep 2009	EA letter to TW identifies 21 "Outstanding Issues"		
Sept 2009		TW releases "Revised" Draft WRM Plan	TW introduces long term risk.
Dec	Independent Review of		

Year	From Government	From Thames Water	Comment
2009	Charging (the Anna Walker report) published		
Dec 2009	EA issue River Basin Management Plan, Thames		
Jan 2010		TW and EA publish "Statement of Common Ground"	Register of 49 Issues, 10 of which are unlikely to be agreed before PI
Jan 2010		Revised submission of Business Plan sections of B5 Maintaining Supply Demand Balance, and C4 Supply Demand Appraisal.	
Feb 2010		TW publishes "Statement of Case"	Many of the 49 issues resolved.
Mar 2010	EA Strategy; Water Resources Action Plan for England and Wales published		
Mar 2010	EA publish Discussion Document, Managing water resources in SE England		
Mar 2010		TW and Ofwat publish Statement of Common Ground.	
Mar 2010	Defra briefing issued for the PI Inspector.		
April 2010	Parliamentary Briefing organised by GARD, the largest NGO opponent.		Objected to the reservoir solution.
May+ June 2010		Two supplementary TW and EA SOCG reports published.	
June 2010	Entec Options Report delivered to EA.		
15 June to 18 Aug 2010	Public Inquiry into TW's Draft Water Resources Management Plan. List of Core Documents (Defra); EA Proofs of Evidence and Rebuttals.	TW's Proofs of Evidence and Rebuttals of EA and other objectors.	
13Dec 2010	PI Inspector's (Wendy Burden) report.		TW not fully compliant with Directions; no 100Mm^3 Upper Thames Reservoir.

Year	From Government	From Thames Water	Comment
Dec 2010	EA release Water Resources Action Plans by EA Region.		
1 Mar 2011	Decision Letter from Defra to TW; The SoS has accepted the Inspector's Conclusions and Recommendations.		A programme of work that covers 25 Inspector's recommendations in a further letter of 13 May 2011.
	Thesis ends here; later entries are for information.		
Apr 2011	EA revises Water Resources Management Plan Guideline		
May 2011	Letter from Defra to TW; Timetable of work.		
Dec 2011		New Draft Final WRMP issued for public consultation (to 28 Jan 12)	No UTR
Jan 2012	EA publishes "The Case for Change – Current and Future Water Availability"		
Jan 2012	EA and Ofwat jointly publish "The Case for Change – Reforming Water Abstraction Management in England"		
Jan 2012	"Water for Life" Defra White Paper		

APPENDIX E - LIVERPOOL LOSSES IN THE 19TH CENTURY – ANALYSIS OF PARRY DATA

From analysis of data published by Parry, leakage reduction in Liverpool is confirmed to have happened between 1873 and 1876.

Data used:

Parry (1881) referenced P1, and (1899) referenced P2; 1873 data from Beloe (1875). Vision of Britain website for population data: c 10k / year average growth 1861 - 1881.

Dates selected, and estimated Losses as percentages of Total Demand from analysis:

1864 - constant supply from 1858 to drought of 1865, and then an intermittent supply to 1873; losses estimated at 60% of total supply.

1873 - intermittent supply, introduction of special measures to reduce waste, losses estimated at 55% of total supply.

1876 - constant supply resumes; losses estimated at 45% of total supply

1898 - waste water meter district measurement since 1876, losses estimated at 25% of total supply.

Table of the analysis; numbers shown in bold are directly from references, non-bold numbers are interpolated from bold numbers.

Year **Population**	**Total Demand** **Mgd**	 **g/h/d**	**Losses** **Mgd**	 **g/h/d**	**Useful Demand** **Mgd**	 **g/h/d**
1864 0.52m	15.8	**30.4** **P1**	9.3	17.9	6.5	12.5
1873 **614,000 Beloe**	**17.5** **Beloe**	**28.5** **Beloe**	9.9	16.0	7.6	12.5
1876 0.66m	14.8	**22.5** **P1**	6.6	**10.0** **P2**	8.2	12.5
1880 **703,000 P1**						
1889				**Min 7.0** **P2**		
1895				**Max 11.8** **P2**		
1898 **808,000 P2**	**23.2** **P2**	**28.8** **P2**	6.0	**7.4** **P2**	17.2	21.4

Mgd – million gallons per day.

g/h/d – gallons per head per day.

Total Demand - = Losses + Useful Demand.

APPENDIX F – TABLES 8.3, 8.4 AND 8.6 FROM THAMES WATER'S REVISED DRAFT WATER RESOURCES MANAGEMENT PLAN, SEPTEMBER 2009

Table 8.3: Alternative Programme Results – London

Driver	Scenario		Demand management and leakage reduction			Supply schemes	
	Prog no.	Scenario description	Metering	Water efficiency	Leakage	Water resource schemes	Year online
Cost	1	Least cost	Compulsory targeted metering	Enhanced	1000km AMP5 500km AMP6	AR – SLARS	2018/19
						Deephams Re-use 95 Ml/d	2019/20
						Northern New River 1	2034/35
						ELRED	2034/35
Environmental and social	2	Lowest carbon	Compulsory targeted metering	Enhanced	1000km AMP5 2000km AMP6 2000km AMP7	ELRED	2027/28
						Northern New River 1	2028/29
						Southwark	2028/29
						Hogsmill B	2028/29
						ASR - Darent Valley 3	2029/30
						AR - Kidbrooke	2029/30
						East Croydon	2029/30
						AR – SLARS	2030/31
						ASR - Darent Valley 2	2033/34
						ASR - South East London	2034/35
						ASR - Thames Valley/Thames Central	2034/35
	3	Strategic environmental assessment	Compulsory targeted metering	Enhanced	1000km AMP5 2000km AMP6 2000km AMP7	ELRED	2027/28
						Northern New River 1	2028/29
						Southwark	2028/29
						Hogsmill B	2028/29
						East Croydon	2029/30
						AR - Kidbrooke	2029/30
						ASR - Darent Valley 3	2029/30
						AR - SLARS	2030/31
						ASR – Darent Valley 2	2033/34
						ASR – South East London	2034/35
						Long Reach Desalination (brackish GW)	2034/35
	4	Maximum demand management	Compulsory targeted metering	Enhanced	1000km AMP5 2000km AMP6 2000km AMP7	ELRED	2027/28
						Northern New River 1	2028/29
						Southwark	2028/29
						Hogsmill B	2028/29
						ASR - Darent Valley 3	2029/30
						AR - Kidbrooke	2029/30
						East Croydon	2029/30
						AR – SLARS	2030/31
						ASR - Darent Valley 2	2033/34
						Long Reach Desalination (brackish GW)	2034/35
Long-term risk	5	Small-scale schemes	Compulsory targeted metering	Enhanced	1000km AMP5 2000km AMP6 2000km AMP7	Northern New River 1	2020/21
						ELRED	2020/21
						AR – SLARS	2021/22
						ASR Darent Valley 2	2021/22
						ASR Darent Valley 3	2021/22
						AR - Kidbrooke	2021/22
						Deephams STW Reuse – 25Ml/d	2021/22
						Southwark	2021/22
						East Croydon	2021/22
						Hogsmill B	2021/22
						Estuary South Desalination 50Ml/d	2021/22
						ASR Darent Valley 1	2025/26
						ASR South East London	2025/26
						ASR Thames Valley/Thames Central	2025/26
						Long Reach Desalination (brackish GW)	2025/26
						Columbus (South Wales) Transfer A	2025/26

Driver	Scenario		Demand management and leakage reduction			Supply schemes	
	Prog no.	Scenario description	Metering	Water efficiency	Leakage	Water resource schemes	Year online
	6	Desalination and re-use	Compulsory targeted metering	Enhanced	1000km AMP5 2000km AMP6	Northern New River 1	2020/21
						ELRED	2020/21
						Deephams STW Reuse - 95 Ml/d	2021/22
						Estuary South Desalination 150 Ml/d	2025/26
	7	Regional transfer	Compulsory targeted metering	Enhanced	1000km AMP5 2000km AMP6	Northern New River 1	2020/21
						ELRED	2020/21
						Severn-Thames Transfer - Longdon Marsh (London)	2021/22
	8	Reservoir	Compulsory targeted metering	Enhanced	1000km AMP5 2000km AMP6	Northern New River 1	2020/21
						ELRED	2020/21
						Reservoir - Abingdon 150Mm3 (London)	2021/22
9 - Preferred programme			Compulsory targeted metering	Enhanced	1000km AMP5 2000km AMP6	Northern New River 1	2020/21
						ELRED	2020/21
						AR – SLARS	2021/22
						Reservoir - Abingdon 100Mm3 (London)	2026/27

Table 8.4: Performance Indicators for Alternative Programmes – London

Driver	Scenario		Financial costs (£m NPV)			Monetisable environmental and social costs (£m NPV)			Leakage level (Ml/d)		Surplus at 2034/35 (Ml/d)
	Prog no.	Scenario description	Capex	Opex	Total	Construction	Operation	Carbon	2020	2035	
Cost	1	Least cost	1014	281	1295	2.1	21.6	5.74	436	430	1
Environmental and social	2	Lowest carbon	1801	236	2037	2.5	-20.5	1.45	406	363	0
	3	Strategic Environmental Assessment	1801	236	2037	2.5	-20.4	1.52	406	363	11
	4	Maximum demand management	1801	236	2037	2.5	-20.4	1.49	406	363	11
Long-term risk	5	Small-scale schemes	2245	235	2480	3.9	16.8	9.18	406	363	130
	6	Desalination and re-use	1477	258	1735	2.5	20.3	9.57	406	394	173
	7	Regional transfer	1671	235	1906	6.6	-24.2	4.00	406	394	190
	8	Reservoir	1680	234	1914	12.9	-28.2	3.54	406	394	190
9 - Preferred programme			1535	234	1769	8.5	-24.3	3.35	406	394	127

NB. Because the above are expressed in terms of costs, negative values indicate an environmental and social benefit. Programme 7 costs are currently incomplete as it does not include either the environmental and social cost of increased flood risk or the financial cost of providing flood compensation storage to mitigate flood risk.

Table 8.6: Comparison of London WRZ Strategic Resources

Scheme	Financial Costs		Monetisable E&S costs			Construction period (years)	Yield (Ml/d)
	Capex (£k)	Opex (£k/yr)	Construction (£k)	Operation (£k/yr)	Carbon (£k/yr)		
Estuary South Desalination	476,921	7,580	2,020	2,079	661	6	150
Deephams STW Reuse	154,989	8,622	878	4,943	516	6	95
Northern region transfer – Opt 2	1,173,889	477	18,196	-322	159	10	267
Northern region transfer – Opt 3	2,225,558	500	14,482	362	80	10	300
Northern region transfer – Opt 4	2,406,081	2,103	2,179	1,983	342	7	300
Severn-Thames transfer – Criag Goch	776,866	479	5,666	3,547	172	12	267
Severn-Thames transfer – Longdon Marsh	867,258	405	9,240	-783	153	12	267
Reservoir – Abingdon 150Mm^3	821,572	35	20,068	-1,419	56	11	267
Reservoir – Abingdon 100Mm^3	725,522	32	14,397	-1,567	42	10	185
Reservoir – Abingdon 75Mm^3	536,584	29	11,324	-1,935	55	9	134
Reservoir – Abingdon phased 75Mm^3	632,541	29	23,877	-1,421	110	10	134
Combined – Abingdon, Marsh Gibbon, Quainton 30	1,200,862	64	17,602	-1,875	12	11	190

APPENDIX G – A REVIEW OF THE 1982 WATER DEMAND FORECAST FOR BIRMINGHAM

Please see paper enclosed in back pocket of thesis.