MELBOURNE WATER
CLIMATE CHANGE STUDY

TECHNICAL REPORT

Case Studies:
Water Supply System, Drainage and Urban Waterways and Sewerage System

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A collaborative Project between Melbourne Water and
CSIRO Urban Water and Climate Impact Groups

Authors:
CSIRO Atmospheric Research
Roger Jones
Paul Durack
CSIRO Urban Water
Shiroma Maheepala
Carol Howe
Melbourne Water
Bruce Rhodes
Robert Yurisich
Udaya Kularathna
Simone Esler

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Disclaimer

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1 Introduction

1.1 Background

In 2002, the Water Resource Strategy Committee for the Melbourne Area released its final report *21st Century Melbourne: a Water Smart City. Final Report: Stage 3 in Developing a Water Resources Strategy for the Greater Melbourne Area*. The report summarised the increasing body of scientific evidence that gives a collective picture of a warming world and other climate changes with the potential for significant consequences on our water resource systems (Houghton et al., 2001; McCarthy et al., 2001). The Committee recommended that Melbourne Water and the metropolitan retail water companies evaluate the impacts of climate change on planned water supply and demand measures (Recommendation 17: Water Resource Strategy Committee for the Melbourne Area, 2002b).

Accordingly, Melbourne Water (MW) engaged CSIRO to investigate the implications of climate change for Melbourne Water's water supply, sewerage and drainage systems. This report covers the detailed case study undertaken to assess the implications of climate change scenarios on Melbourne's water supply system, taking account of climate change, population growth and managed changes in water demand. The analysis was undertaken before the release of the Victorian Government's White Paper *Our Water Our Future* (DSE, 2004) and contributed provisional estimates of climate change impacts to that paper (DSE, 2004). This assessment is based on water-use patterns and population projections described in the water resources strategy (Mitchell & Maheepala, 2004). It does not include adaptation to long term changes that could be anticipated from the initiatives outlined in the White Paper. Qualitative case studies undertaken by Melbourne Water into impacts of climate change on drainage and urban waterways, and on the sewerage system, are included in Appendix A and Appendix B.

1.2 Objectives of water supply case study

The key objective of the study is to assess the implications of a range of climate change and potential future development scenarios for Melbourne in maintaining reliable water supplies.

The specific objectives of the water supply case study are to assess the impact of climate change in 2020 and 2050 on:

(a) streamflow in major water harvesting catchments and subsequent changes in system yield,
(b) expected changes in system water demand due to climate and population change modified by prescribed options for demand management, and
(c) the ability to supply the changes in demand outlined in (b) given possible changes in supply in (a).

1.3 Approach

This assessment utilises a suite of modelling tools capable of simulating various aspects of the water supply system. These include rainfall-runoff and water demand models that subsequently provide inputs into the (REALM) water supply system simulation model used by Melbourne Water.

To simulate the impacts of climate change, data inputs into both rainfall-runoff and water-demand models were modified to represent plausible changes as simulated by global and regional climate models (GCMs and RCMs). Both scientific and policy-related uncertainties influencing the enhanced greenhouse effect (Jones, 2000a) were represented in these changes. The steps involved in applying climate model projections to estimate local changes in water supply and water use were:

- Determine the range of greenhouse gas emission scenarios and projections of global warming from IPCC (2001).
- Select a range of climate models from the IPCC Data Distribution Centre (ipcc-ddc.cru-uea.ac.uk) and CSIRO that provide reasonable climate simulations for Victoria (Whetton et al., 2002).
- Assess changes in local climate variables (e.g. rainfall, temperature and evaporation) for the selected climate models.
- Calibrate runoff-rainfall relationships for seven sub-catchments in the Yarra and Thomson catchments under current climate.
- Apply the local monthly mean climate changes to historical climate data to determine streamflow changes for the major reservoir and diversion sites using those rainfall-runoff models.
- Apply climate risk analysis techniques described in Jones (2000a, b) and Jones and Page (2001) to determine full range of plausible changes in streamflow from climate inputs and select low, medium and high climate change scenarios (expressed as wet, medium and dry streamflow scenarios respectively).
- Calibrate water demand under current climate using the climate variables quantifiable under climate change.
- Use local climate variables consistent with the above scenarios to estimate climate driven changes in water demand.
- Using the three climate-related scenarios described above, water demand under average climatic conditions for the three population scenarios (described in Mitchell & Maheepala, 2004), and the climate driven changes in water demand, apply REALM to assess the impact of the climate change and water demand scenarios on the water supply system, including:
    - Storage volume, and the volumes of water transferred through key paths of the water transfer network
    - Drought operations and level of service
    - Impact on water supply availability
    - Flow conditions in rivers and creeks harvested by Melbourne Water

Key inputs to the supply and demand modelling approach of Melbourne Water's REALM model are simulated streamflow volumes and climate-driven water demand. Both of these inputs are affected by climate change and impacts on this system are assessed using the methodology described above.

1.4 Report structure

This report describes the approach taken to assess the impact of climate change on Melbourne's water resources. The report structure follows the main steps undertaken in performing this assessment.

- Chapter 2 – describes the Melbourne Water supply system.
- Chapter 3 – describes the Melbourne Water supply system model REALM and identifies the components that require detailed modelling.
- Chapter 4 – describes the climate change scenarios for the Greater Melbourne Region, based on Technical Report: Climate Change in the Greater Melbourne Region (Jones et al., 2004).
- Chapter 5 – outlines the calibration of rainfall-runoff models, application of climate scenarios to those models and risk analysis undertaken for these scenarios
- Chapter 6 – outlines the selection of the three climate change scenarios and their impact on streamflow and demand in 2020 and 2050.
- Chapter 7 – assesses the combined impacts of climate and population changes on the supply system yield and behaviour.
- Chapter 8 – presents conclusions and recommendations from the study.
- Appendix A – presents a qualitative case study of impacts of climate change on drainage and urban waterways
- Appendix B – presents a qualitative case study of impacts of climate change on the sewerage system

2 Melbourne water supply system

Melbourne Water is responsible for the collection and bulk allocation of water in the Greater Melbourne Region (Figure 1). MW provides wholesale water and sewerage services to three retail water companies: City West Water Ltd, South East Water Ltd and Yarra Valley Water Ltd. Water is also supplied to Gippsland Water, Southern Rural Water and Western Water.

An extensive transfer system links Melbourne's storage reservoirs with the city's three retail water companies and their customers. The major storage reservoirs supply water via large transfer mains to the seasonal storage reservoirs and on to service reservoirs located throughout the metropolitan area. The water is then transferred to the distribution network of retail water companies, who manage reticulated supply to their customers. In 2003, the population served by the three retail water companies was approximately 3.5 million. The current average water demand from the system is around 500,000 ML/year. Melbourne's water supply system is shown in Figure 1.

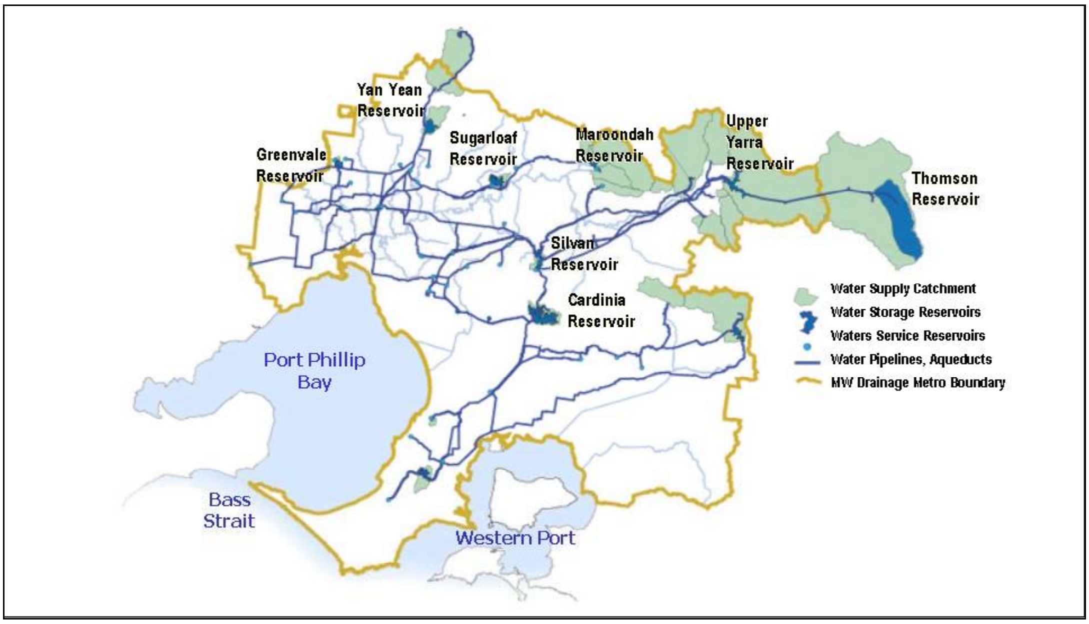

Figure 1 Schematic diagram of the Melbourne's water supply system

Approximately 90% of Melbourne's supply comes from protected areas in the upper Yarra and Thomson River catchments. Major water supply catchments in Melbourne system are listed in Table 1. Water from these catchments is stored in large reservoirs that provide a buffer against sustained variations in streamflow. Seasonal storage reservoirs, located closer to Melbourne, provide buffer storage over shorter time periods. Despite the large storage capacity of the system, prolonged low rainfall periods can cause significant drawdown of system storage levels over a number of years. Thomson Reservoir is the largest reservoir in the system and has a useable storage capacity of 1,068 GL. This accounts for 60% of the total system storage capacity.

Table 1 Major water supply catchments

Catchment	Area (km^2)	Reservoir Storage Capacity (GL)	Comment
Thomson Reservoir	487	1068	On stream storage
Upper Yarra Reservoir	337	200	On stream storage
O'Shannassy Reservoir	119	3	On stream storage
Maroondah Reservoir	147	22	On stream storage
Yarra River at Yering Gorge	2,140	96	Off stream storage
Yan Yean Reservoir	23	30	Off stream storage with minimal catchment
Tarago Reservoir (not currently in use)	78	38	On stream storage

Climate change can lead to direct and indirect impacts on catchment runoff. Direct effects expected from lower rainfall, higher temperatures and higher evaporation are likely to reduce average volumes of streamflow. Sustained periods of low streamflows into reservoirs and other harvesting sites can impact on the water supply availability and the level of service, particularly during drought periods. Indirect impacts of climate change include an increased risk of bushfires and changed vegetative growth characteristics due to the altered concentration of CO_2 in the atmosphere (e.g. Pittock, 2003). Ash forest regrowth following bushfires is implicated with reduced streamflows over a long period (Jayasuria et al., 1997; Vertessey et al., 1998, 2001). These impacts and the potential for changed regrowth characteristics have not been assessed in this case study – only the direct impacts have been assessed.

Around 10% of Melbourne's water is sourced from catchments that contain residential or agricultural land. The water from these catchments is fully treated prior to transfer to Melbourne. Changes in catchment conditions, directly or indirectly due to climate change, are likely to affect water quality.

In addition to supplying water to the retail water companies, Melbourne Water is also required to release water from harvesting sites to maintain healthy streams and rivers. Each reservoir and diversion weir has downstream environmental flow requirements. These requirements are reviewed through Government processes and could require further evaluation as our understanding of climate change develops.

3 Melbourne water supply system model

Comprehensive system modelling tools are required to assess water supply system behaviour as influenced by a variety of factors affecting that system. The factors affecting Melbourne system include the streamflow volumes, system configuration and operations, demand growth, changing expectations from the system in terms of level of service, environmental flow requirements and supplies to other water authorities.

Melbourne Water uses the REALM headworks model (Diment, 1991) to simulate the behaviour of its water supply system. REALM is a generalised tool for developing a simulation model for a specific water supply system, thus allowing the behaviour of that system (e.g., storage volumes and transfers) to be simulated for a range of operational and climatic conditions.

Melbourne Water's REALM model is used for water resource planning; including long term water-resource planning, drought planning, assessment of operating rules and, more recently, to assist the process of quantifying water volumes under bulk entitlements and environmental flow requirements. Melbourne Water uses REALM to simulate system behaviour up to 50 years into the future, in assessing the impacts due to potential changes in future streamflow and demand, and the changes to system operations or system configuration needed to manage those impacts.

The model represents the water supply system; including harvesting reservoirs and seasonal storages, diversion weirs, major transfer mains, pump stations and the water demands, aggregating retail water demands within metropolitan area into seventeen supply zones. The model uses a linear programming optimisation routine to assign water throughout the network in accordance with user-specified operating rules. Among the key aspects modelled are storage behaviour, transfer network, demand restriction rules and the environmental flow requirements. The structure of the model is summarised in Figure 2. The data inputs that may be impacted by climate change are indicated by the stippled area.

For the impact assessments, the water supply system is modelled on a monthly basis. The data used in the Melbourne Water REALM model includes:

- Historical monthly streamflow data for reservoir and diversion sites and selected key locations downstream of those sites;
- Annual demand forecasts representing population growth of various metropolitan areas;
- Reservoir and pipeline capacities and operational priorities and constraints;
- Environmental flow and other release obligations.

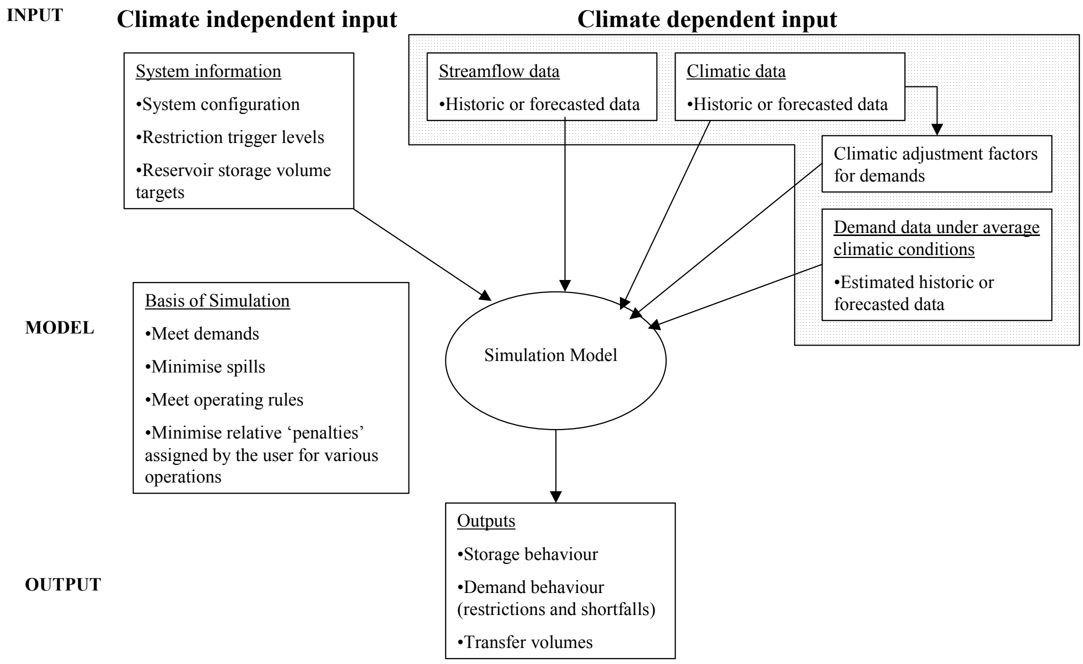

Figure 2 Structure of REALM water supply system simulation model

The REALM model uses 17 time series of monthly streamflow data representing inflows to the Melbourne Water Supply System. Seven of the 17 series represent key sites, which are the: Thomson, Upper Yarra, O'Shannassy, Maroondah, Tarago and Yan Yean Reservoirs and the Yarra River at Yering. The 17 streamflow series are composite records comprising measured streamflow data and flow data estimated from reservoir water balance or by regression against nearby catchments. Additional to these flows, climate inputs, which drive the modelled water demand and the evaporation losses from reservoirs, are also included. At the time of undertaking this study, these data covered the period 1913 to 2001.

To forecast monthly demand, the model disaggregates annual demand inputs into monthly demand by applying annual-to-monthly demand disaggregation factors. These monthly demands are subsequently adjusted to reflect the modelled climatic condition. This climatic adjustment is carried out using a factor estimated based on historical monthly demands, monthly rainfall, the number of rainy days within each month, and A-Class pan evaporation. The climate data used to simulate demand has been sourced from the Bureau of Meteorology (BOM).

It should be noted that all the simulations carried out for the Water Resource Strategy for the Melbourne Area used historical data (Water Resource Strategy Committee for the Melbourne Area, 2001, 2002a, b). Therefore, the underlying assumption was that climate will remain stationary while population-driven water demand will increase. This assumption means that climate variability remain largely within historical bounds.

3.1 Assessment framework

To assess the impacts of climate change on the water supply system, the climate-dependent inputs used to model the system (Figure 2) must be adjusted to represent plausible changes in climate. These changes are derived from models that simulate the global climate circulation patterns under greenhouse gas emission scenarios. Climate model output in the form of monthly rainfall, potential evaporation and temperature change per degree of global warming, combined with projected mean global warming in a particular year derived from the 6 illustrative SRES scenarios (IPCC, 2001, see Figure 5), provide estimates of mean monthly changes in those variables. These climatic changes provide the basis for adjusting the other climate-dependent data sets.

As shown in Figure 2, the key climate-dependent factors in the REALM model are streamflow and water demand. Changes to these two factors were estimated using the following steps:

- The potential impact of climate change on streamflow was assessed by applying historical climatic data modified by factors of mean monthly change derived from climate models to rainfall-runoff models. Similarly, assessment of the potential changes in climate-driven water demand required changing climate inputs into appropriate water-demand model in a similar way.
- Risk analytic techniques exploring selected climate change uncertainties were used to identify low, medium and high scenarios of water supply and demand in 2020 and 2050.
- The resulting streamflow and demand data from these low, medium and high scenarios provided inputs to the REALM model. The assessment of these three scenarios considered the following factors:
    - Storage volume behaviour
    - Water harvesting and transfer behaviour
    - Drought operations and level of service (eg restriction frequency, severity and duration)
    - Water supply availability or system yield
    - Flow conditions in the rivers and creeks harvested by Melbourne Water

The modelling framework developed to carry out these tasks and the impact assessment on the water supply system is shown in Figure 3.

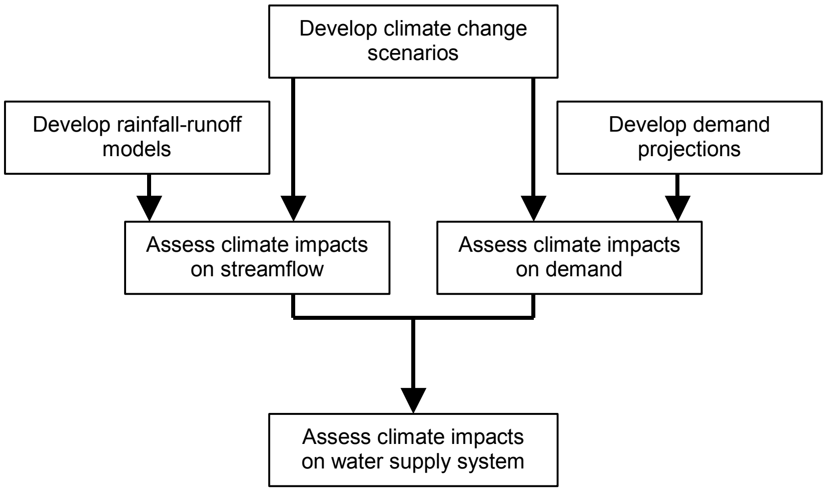

Figure 3 Flowchart illustrating the modelling process followed for assessing climate change impacts on water supply system

The next chapter provides a brief description of the climate change scenarios for the Greater Melbourne Region. A comprehensive description of the modelling work carried out for assessing the effect of climate on streamflow, water demand and the supply system behaviour is included in subsequent chapters.

4 Climate change scenarios

Climate change scenarios were developed using the latest greenhouse gas emission scenarios and climate science as described in the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (2001). Climate change scenarios for the Greater Melbourne Region have been developed by CSIRO Atmospheric Research from GCMs developed in-house and by international modelling groups and in-house RCMs. More details on climate change scenarios are available in the Technical Report titled Melbourne Climate Change Study: Climate Change in the Greater Melbourne Region (Jones et al., 2004).

4.1 Global changes

Global mean warming is the first major uncertainty that needs to be incorporated into climate scenarios. The range of global warming comes from two major input uncertainties: the range of greenhouse gas emissions and the range of climate sensitivity to radiative forcing. Other uncertainties exist, but they are less important.

For this project, the full range of warming from the six IPCC illustrative SRES (IPCC's Special Report on Emission Scenarios; Nakiçenovic and Swart, 2000) greenhouse gas scenarios in 2020 and 2050 was explored. Figure 4 illustrates projected CO_2 concentrations for each of those IPCC SRES scenarios (IPCC, 2001), i.e. A1B, A1T, A1FI, A2, B1 and B2. It should be noted that IS92a shown in Figure 4 is not a SRES scenario. IS92a is scenario stated in the IPCC's Second Assessment Report and the purpose of showing it in Figure 4 is to provide a reference point for comparing SRES scenarios with a scenario specified the IPCC's Second Assessment Report.

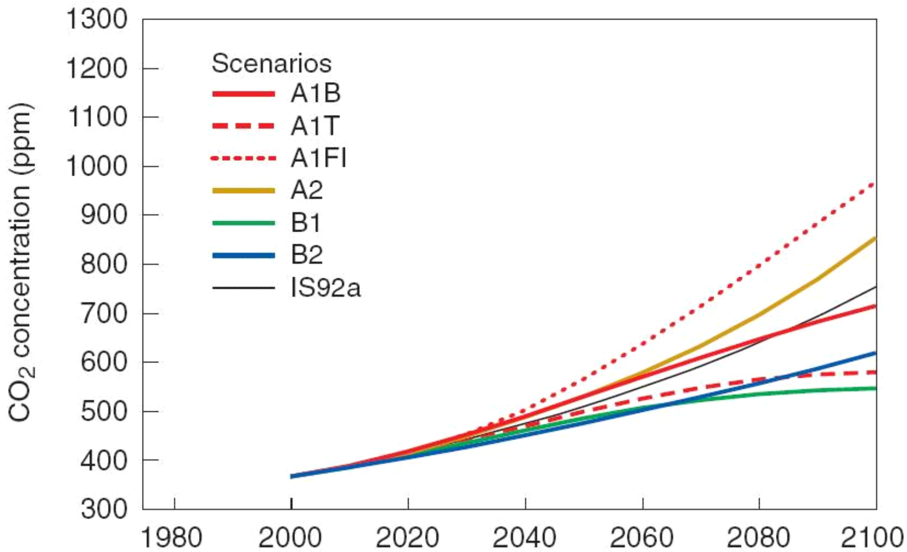

Figure 4 Atmospheric concentration of CO_2 resulting from IPCC greenhouse gas emission scenarios (source: IPCC, 2001).

GCMs apply changes in radiative balance of the atmosphere resulting from the scenarios in Figure 4 to a modelled representation of the atmosphere. Resulting changes include atmospheric warming, a more vigorous hydrological cycle and myriad changes in the regional climate. The term climate sensitivity is widely used to describe the uncertainty surrounding the rate and magnitude of global mean warming. The range of global mean warming from 1990–2100 from the IPCC (2001) is illustrated in Figure 5.

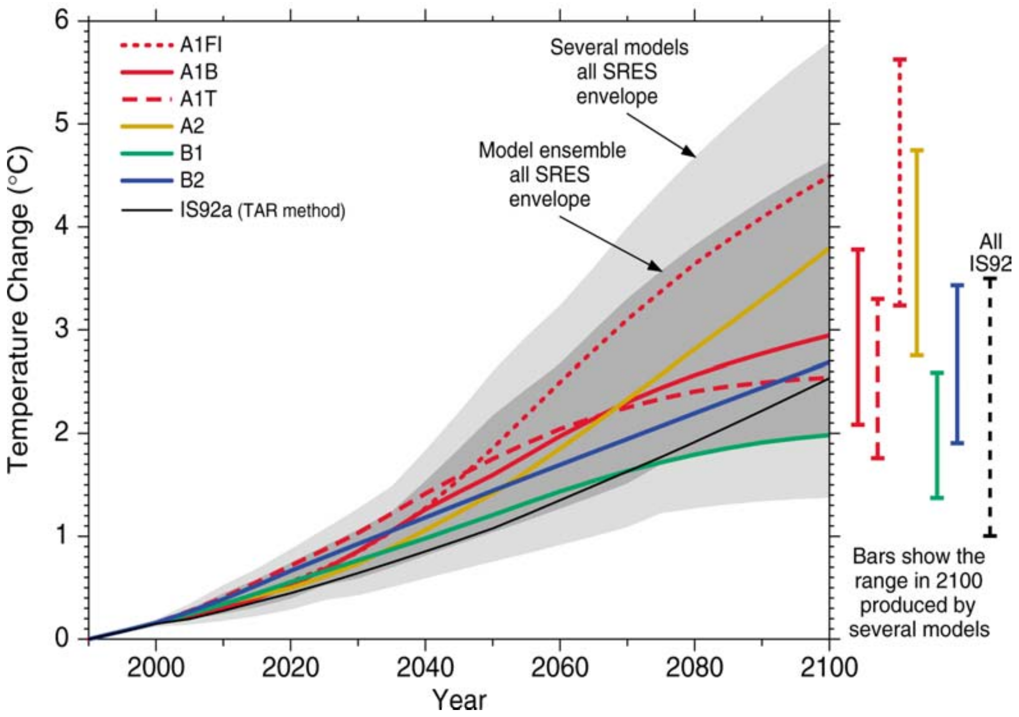

Figure 5 IPCC projections of global mean temperature. The darker shading represents the envelope of the full set of thirty-five SRES scenarios applied to seven GCMs (source IPCC, 2001).

4.2 Regional changes

The rationale guiding the production of regional changes in climate is to represent changes as wide a range of plausible changes as possible. Therefore, the emphasis was on selecting a large number of suitable climate models from those available, in an attempt to capture the entire range of uncertainty expressed by these models. Eleven climate models that had previously been evaluated for their ability to simulate current climate over Victoria (Whetton et al., 2002) were selected. The variables required from each of those models were average temperature, maximum temperature, relative humidity, shortwave solar radiation and rainfall averaged on a monthly basis. Potential evaporation was calculated from average temperature, relative humidity, shortwave solar radiation.

Regional changes produced for each of these variables are represented as local change per degree of global warming. This allows the regional changes from each climate model to be re-scaled by different scenarios of global warming (as in Figure 5) so that a wide range of uncertainty in plausible future climate can be explored. For a more detailed explanation of this technique see Jones et al. (2004), Maheepala (2003) and Maheepala et al. (2003).

The climate model simulations used were: CSIRO Mark 2, Mark 3, Cubic Conformal 50km, and DARLAM 125km models; the Canadian Climate Centre CGCM2 GHG, CGCM2 A2 and CGCM2 B2 models; the Max Planck Institute ECHAM4 model and the Hadley Centre HadCM3 GG, HadCM3 A2, and HadCM3 B2 models.

The mean monthly changes (hereafter call 'climate patterns') were created for average temperature, maximum temperature, potential evaporation and rainfall from each of the GCMs listed above. Climate patterns were calculated from a linear regression of each variable for each grid square against mean global warming. These patterns were then linearly interpolated onto a 0.05° grid (note: one degree is about 110 km, so each grid cell is about 5.5 km in size). The seasonal and annual ranges of change as a function of global warming in °C are shown in Table 2. These ranges are similar to those described in Technical Report: Climate Change in the Greater Melbourne Region (Jones et al., 2004) although they are slightly different due to the addition of several new GCMs and removal of two older GCMs from the analysis.

Table 2 Ranges of climate change expressed as change per degree of global warming for the four climate variables used to scale historical climate data

	Summer	Autumn	Winter	Spring	Annual
Precipitation (%)					
Low	5.3	4.1	1.4	-2.3	-0.5
Medium	-3.1	-0.9	-2.1	-7.9	-3.5
High	-12.9	-6.8	-4.0	-14.8	-6.1
Areal Potential evaporation (%)					
Low	2.2	2.9	0.9	2.9	2.8
Medium	3.3	3.7	4.1	4.5	3.8
High	4.8	5.1	6.8	5.3	5.1
Point Potential evaporation (%)					
Low	3.4	3.6	2.8	4.9	4.2
Medium	5.5	5.3	6.1	8.1	6.0
High	9.4	8.9	10.2	11.5	9.4
Maximum temperature (°C)					
Low	1.0	0.8	0.6	1.0	0.9
Medium	1.2	1.0	0.8	1.1	1.0
High	1.4	1.1	1.0	1.3	1.2

Simple linear interpolation of climate change patterns (derived from GCMs) is preferred to more complex methods of downscaling for a number of reasons. It may be possible to develop methods for spatial downscaling of climate patterns but the current scientific standard for generating higher resolution, regional climate change patterns is simple interpolation of coarse resolution GCM outputs.

The difficulties in developing a spatial downscaling method include the following:

- Downscaling methods usually require daily data and/or hard-to-get climate fields so obtaining the data, storing and processing is time consuming.
- Most downscaling methods are resource intensive.
- Statistical methods of downscaling usually do not change average climate change a great deal (it has more effect on downscaling daily patterns of change).
- Downscaling usually means that the output is tied to the original greenhouse gas scenario, whereas the simple interpolation provides the percentage change per degree of global warming (as in Table 2), which can be applied to the historical climatic data to produce ‘scaled patterns’. The scaled patterns represent climatic variability under different levels of global warming and can be perturbed differently to account for a range of input assumptions. The models used here were run under a limited range of greenhouse gas scenarios.
- The issue of how to link downscaled climate change data with baseline climate data is complex. For example, downscaled baseline climate data from eleven models would produce eleven different representations of current climate, whereas scaling a single data set by climate change factors is more straightforward and easily comparable.

The approach adopted in this study was to use monthly factors to scale historical daily data. This involved the implicit assumption that, in the future, patterns of daily climate variability share a similar relationship with mean climate as they do today.

The GCMs typically have grid sizes in the range of 200–400 km which produce spatially course changes. Dynamic downscaling to 50 to 60 km resolution using the CSIRO DARLAM and Cubic Conformal models show that changes are spatially more detailed but those changes also lie within the range of the entire suite of climate models. For more discussion on the implication of different climate model resolution on climate, especially rainfall, see Jones et al. (2004).

Robust patterns of change produced by the models include the possibility of higher rainfall along the southern coast of Victoria and decreases in late winter–spring rainfall. All models show increases in temperature and potential evaporation.

5 Climate impact modelling

Changes in rainfall, evaporation and temperature resulting from climate change will have an impact on streamflow in water harvesting catchments. This chapter describes the process followed to quantify the impact of climate change on streamflow and climate-driven water demand. For streamflow, these descriptions include the preparation of input climate data, calibration of rainfall-runoff models, and the application of climate scenarios to simulate altered streamflow. For climate-driven water demand, we describe the use of input data, model calibration and results. The final product is the ability to estimate changes in both streamflow and climate-driven water demand in a format that is directly applicable to the REALM model.

5.1 Modelling streamflow

5.1.1 Method and major assumptions

The first step in modelling streamflow and climate-driven demand was to create a baseline input data set for the REALM model by simulating streamflow and water demand using observed climate data. This baseline data set needed to reproduce the observations for streamflow and demand as closely as possible, so it could then provide reliable estimates of future climate change conditions.

Rainfall-runoff modelling was undertaken for seven catchments of Melbourne's water supply system. Those catchments include the Thomson, Upper Yarra, Maroondah, O'Shannassy, Tarago and Yan Yean Reservoirs and the Yarra River at Yering. The models were first used to simulate baseline streamflow, and then extended to simulate changes due to a range of climate change scenarios.

Lumped parameter conceptual rainfall-runoff models are commonly used to simulate runoff under climate change (e.g., Boorman and Sefton, 1997). Such models are used extensively under current climate with good results. The Australian Water Balance Model (AWBM), Boughton (2004), which requires daily precipitation and monthly potential evaporation as inputs, was used for this study. Melbourne Water had previously used AWBM model to simulate streamflow for the Thomson, Upper Yarra, Maroondah and O'Shannassy catchments.

The AWBM model needed to be calibrated and validated for each of the major catchments using historical data. Daily streamflow, daily precipitation and monthly average potential evaporation data were required to calibrate the AWBM model and produce a baseline time series of streamflow (i.e. the modelled time series that corresponds to the observed streamflow series).

Streamflow data was provided by Melbourne Water. Some of the streamflow data was estimated using reservoir mass balance (i.e. inflow = outflow plus increase in storage. As the data on evaporation losses from the reservoirs are not available, the estimated inflows are lower than the actual inflows, and can be assumed to implicitly account for evaporation losses from the reservoirs). The data estimated using this technique may introduce small errors into the modelled system behaviour, if the evaporation from the water surface for the modelled scenarios are different to that of the historical period used for the mass balance calculations. Such errors may accumulate if a reservoir does not overflow for some years (as has recently been the case for the Thomson Reservoir). Projected increases in open-water evaporation, due to climate change, may enhance these errors.

The AWBM model was calibrated using daily streamflow data (available from the 1940s to the 1960s onwards – see Table 3) and their performance evaluated against longer records of monthly streamflow data (1913–2001).

Climate data was sourced from official Bureau of Meteorology records and from observations made by Melbourne Water. Climate data preparation involved data identification, selection and quality control to assemble data series as free from inhomogeneities as possible. Homogeneity of data utilised in the modelling was assessed by comparing the available data series with high quality data series of rainfall and temperature constructed by the BOM using the bivariate test (Potter, 1980; Bücher and Dessens, 1991) and double-mass analysis.

Areal potential evaporation, required for rainfall-runoff modelling, was calculated from monthly temperature, humidity and sunshine duration records. This variable was preferred to A-Class pan evaporation because of record length, quality of data from the Regional Melbourne Office of the BOM and because it produced better model validation statistics for streamflow.

The system streamflows to the REALM model are currently being specified in the form of seventeen records of streamflow time series. Seven out of seventeen streamflow time series represent streamflows in major harvesting reservoirs, i.e. Thomson, Upper Yarra, Maroondah, O'Shannassy, Tarago and Yan Yean Reservoirs and the Yarra River at Yering. The AWBM model was calibrated to simulate streamflows in these seven key harvesting sites. The remaining ten records, streamflows were then calculated from these key sites using regression relationships provided by Melbourne Water. This then, provided the baseline for comparison under climate change.

Historical rainfall, potential evaporation and temperature data series were then scaled up or down using the mean monthly change factors of rainfall, evaporation and temperature variables respectively to reflect the changed climatic conditions (hereafter this process is called 'perturbation' and a 'perturbed climate series' represents a modified climate series through scaling up or down using mean monthly change factors obtained from climate models). These perturbed climatic data series were then used as an input to a calibrated rainfall-runoff model of each catchment to generate streamflow under the future climate change. This assumes that catchment conditions which underpin model calibration do not alter under climate change. This area of uncertainty was not examined in this case study.

Detailed descriptions of data preparation, model calibration and selection of climate scenarios are discussed in the following three sections.

5.1.2 Rainfall data

Composite and homogenous rainfall time series were required for each catchment. This section describes their diagnosis and construction.

The Greater Melbourne Region has a significant rainfall gradient ranging from <600 mm in the west to 1500+ mm in the east where the major supply catchments are located. The two high-quality rainfall records most suitable for use as reference stations for checking homogeneity are Toorourrong in the northwest and Labertouche to the south. Neither station is particularly close to the major supply catchments, so the principal of regional (spatial) homogeneity (see below for more details regarding the principal of regional homogeneity) was used to determine whether records were free of errors; e.g., step changes in mean rainfall caused by change in station location or splicing of individual records.

The principal of homogeneity states that any large natural change in rainfall will occur across a region, therefore statistical dislocations within single records are most likely to be caused by artificial errors. The objective of this analysis was to avoid artificial "jumps" in each record rather than individual, random errors. Continued errors in streamflow data will accumulate in simulated system storage, resulting in errors in system yield.

Most catchments had one long-running gauge record from the dam site, located at the drier end of the catchment. Rainfall data measured at these sites will therefore under-estimate catchment average rainfall. Melbourne Water provided a number of more recent recorded data obtained from gauging stations located within the catchments and, in some instances, provided average catchment rainfall data, constructed using Theissen polygons. These records contained significant inhomogeneities, because the method of averaging over the catchment did not adequately account for different record lengths and rainfall amounts. In addition, individual stations contained many gaps in their records. Therefore, the following process was used to generate a composite record of catchment average rainfall from 1913.

For each catchment, the station with the least systematic error was identified. Other records were then spliced into this record, creating a complete time series extending to 1913. The process first estimated the annual mean from the daily record based on data overlap (when daily values existed for both sites). Priorities for infilling were set using correlations established between each rainfall station (again over the period of data overlap), with the highest to lowest correlation being used until a complete record was achieved. Scaling factors (see Table 3) were determined from daily data overlap, so that the infill station values could be corrected back to the value expected over the catchment. For example, the scaling factors used for building the composite precipitation record for the Thomson catchment were 0.9542 for Jindivick station, 0.8887 for Walhalla station and 0.7419 for Woods Point station. This meant that the composite precipitation record of the Thomson catchment consisted of 95% of Jindivick precipitation record, 89% of Walhalla precipitation record and 74% of Woods Point precipitation record.

Table 3 Rainfall and streamflow data sources for Melbourne's water supply catchments with scaling factors and infill priorities

Catchment and calibration period	Precipitation		Streamflow	
	Source, infill priority and years available	Scaling factor	Monthly	Daily
Thomson 1956–2001	Jindivick 1: 1913–2001	0.9542	REALM input: 1913–1955, regression with Narrows: 1956–2001	Estimated natural streamflow at Narrows: 1954–2001
	Walhalla 2: 1913–2000	0.8887		
	Woods Point 3: 1913–1998	0.7419		
Upper Yarra 1958–2001	UY Dam Wall 1: 1958–2001	–	REALM input: 1913–1957, intake from Upper Yarra River: 1958–2001	Intake from Upper Yarra River: 1958–2001
	Jindivick 2: 1913–2001	0.9416		
	Labertouche 3: 1913–2001	1.1826		
	Walhalla 4: 1913–2000	0.8654		
Maroondah 1942–2001	Maroondah 1#: 1913–2001	0.5	Maroondah Weir flows: 1913–2001	Intake from Watts River: 1942–2001
	Black Spur 1#: 1913–2001	0.5		
O'Shannassy 1958–2001	OSH Dam Wall 1: 1958–2001	–	REALM input: 1913–1914, O'Shannassy River inflows: 1915–2001	Intake to O'Shannassy Reservoir: 1942–2001
	Woods Point 2: 1913–1998	0.9112		
	Jindivick 3: 1913–2001	1.1387		
Yering 1940–2001	MAR Dam Wall 1: 1940–2001	–	Estimated flows: 1913–1946, 1964–1974, 1984–2001, Yering recorded streamflows: 1947–1963, 1975–1983	Derived daily flows from the monthly record
	Jindivick 2: 1913–2001	0.9444		
	Labertouche 3: 1913–2001	1.1848		
	Walhalla 4: 1913–2000	0.8607		
Tarago 1964–2001	Jindivick 1: 1913–2001	–	Estimated flows: 1913–1963, composite recorded flows: 1964–2001	Derived daily flows from the monthly record
	Labertouche 2: 1913–2001	1.2323		
	Walhalla 3: 1913–2000	0.9283		
	Alberfeldy 4: 1914–1983	1.0950		
Yan Yean 1920–2001	Yan Yean 1: 1913–2001	–	Recorded flows: 1913–2001	Derived daily flows from the monthly record
	Toorourrong 2: 1913–2001	–		

The infill priority specifies the order in which station data was used to generate the composite series. If the daily value was not available for the first priority station, the second (and then third, and fourth respectively) were used. The significance of the latter priority stations contribution to the composite set is therefore very small.

[#]Catchment precipitation was derived by using a mean value from the combined Maroondah Dam Wall and Black Spur BoM sites.

For several catchments, the end result was quite straightforward. For example, Maroondah catchment rainfall stations are located at Maroondah Dam at the base of the catchment and Black Spur at the top of the catchment, so an average of the two records was used to represent the catchment average. Specific details of stations used in this methodology, and infill priorities, and scaling factors are included in Table 3.

Creating a complete rainfall record for the Thomson catchment was not as straightforward. The main rainfall station in the catchment is located at the dam wall, which is not representative of rainfall in the upper catchment. Thus, rainfall data from the dam site was not used. Instead, rainfall data obtained from BOM stations outside the catchment were scaled to represent the mean at the Thomson Dam gauge to create an homogenous record, then that record scaled up to an estimate of catchment average. This exercise significantly improved the simulation of the streamflow data at the dam site. However, since Thomson catchment contains a significant rainfall gradient, further work is needed to produce a high quality spatial and temporal record of catchment rainfall.

A summary of the rainfall and streamflow data sources for each catchment and basic scaling methods used in the model calibration are listed in Table 3.

5.1.3 Potential evaporation data

Areal potential evaporation was used as one of the climate inputs for rainfall-runoff modelling. The term evaporation refers to moisture loss to the atmosphere from soil and water surfaces, transpiration to moisture loss from vegetation and evapotranspiration to both processes combined. Potential evaporation is a measure of the latent heat within the atmosphere, which is the energy available to evaporate available moisture at the surface. Whether potential evaporation becomes actual evaporation depends on moisture availability.

Point potential evaporation is potential evaporation from an area that is too small to modify the passing air mass (Morton, 1983). A-Class pan evaporation, the evaporation from a small water surface, is commonly used as an equivalent to point potential evaporation. Areal potential evaporation takes place over larger areas (>10ha), where the air mass is modified by the underlying land-use; for example, where an air mass passes over forest transpiring water, it will moisten and cool in comparison to grassland or urban areas. Areal potential evaporation is the variable generally recommended for hydrological modelling.

The areal potential evaporation records utilised in rainfall-runoff modelling were generated using Morton's (1983) Complementary Relationship Areal Evaporation (CRAE) method, using climate inputs measured at the BOM's Melbourne Regional Office. This was preferred to utilising A-Class pan evaporation from the same station because of large errors within that record. Inputs used were monthly average temperature created from maximum and minimum daily temperature, relative humidity and sunshine hours converted to sunshine ratio (measured hours of sunshine as a proportion of total day length).

Temperature data was sourced from the BOM's high quality temperature data set (Della-Marta et al., 2003) and was used unchanged, except for a reduction of 0.5°C in minimum temperature from 1962 to account for the effects of local exposure and the urban heat island (Torok et al., 2001). Humidity was left unchanged due to a lack of high-quality data to use as a reference for homogeneity testing. Sunshine hours were adjusted to account for inhomogeneities occurring in 1916 and 1952; Hobart and Adelaide were used as references (Jones, 1995). These data were used to generate areal potential evaporation using the CRAE method.

Areal potential evaporation was used in the AWBM model for all catchments, measured as monthly average of daily potential evaporation in millimetres.

5.1.4 Rainfall-runoff model calibration

The AWBM model was calibrated for each catchment using the AWBM2002 optimisation routine (Boughton, 2004). Calibration was undertaken for the longest integration possible using available daily and monthly streamflow, precipitation and areal potential evaporation. The aim was to reproduce the streamflow records currently used in Melbourne Water's REALM model.

In most cases, the rainfall time series generated for the project represented rainfall at a point rather than catchment areal average rainfall. For the Maroondah catchment, stations from the top and base of the catchment were used, so the resulting average represented catchment average rainfall (no scaling of the composite record was required). For the other sites, the generated composite rainfall record underestimated catchment rainfall because most of the reference rainfall stations were located in the lower and drier parts of the catchment. It was then necessary to scale-up the composite time series to capture the areal average over each catchment.

In calibrating the model and obtaining a representative estimate of catchment average rainfall, we had two goals:

1. To obtain a high modelled coefficient of efficiency (COE; Nash and Sutcliffe, 1970) in streamflow, and
2. To ensure that the catchments would have a similar sensitivity to climate change (hereafter called 'hydrologic sensitivity')

A high coefficient of efficiency is the measure of how well the model reproduces observed streamflow values. For this study, the coefficient of efficiency was calculated on an annual basis.

Hydrologic sensitivity is a measure of how sensitive a particular catchment is to climate change (Jones et al., submitted). It is estimated by altering the climate inputs in regular increments across ranges of change, performing multiple runs, then reviewing the hydrological response in terms of mean annual runoff change.

Hydrologic sensitivity can be represented as:

$\partial Q = A\ \partial P + B\ \partial Eap$

where ∂Q is change in mean annual runoff, ∂P is change in mean annual precipitation in percent, ∂Eap is change in mean annual areal potential evapotranspiration in percent and A and B are constants. The larger A and B are, the more sensitive the modelled catchment response to climate change. A model with high sensitivity will produce larger changes in mean annual runoff in a given catchment compared to a model with a low sensitivity.

The purpose of examining hydrologic sensitivity was to ensure that catchments with similar biophysical characteristics such as forest-type, topography and soil depth displayed similar sensitivities to a changing climate. This will ensure that a given change in climate will produce a similar level of response in similar catchments, as would be anticipated.

For the AWBM model, the depth of soil moisture storage is the most influential parameter with regard to its hydrologic sensitivity. This is a derived parameter within the model and is not directly measured as is the case for rainfall and evaporation.

During calibration, the depth of soil moisture storage of catchments with similar characteristics was maintained at similar levels. The model contains three partitions for soil moisture storage: a shallow, medium and deep store. We manipulated the precipitation/potential evaporation ratio by increasing or decreasing precipitation until the soil moisture store for the catchment averaged between 200 and 400 mm depth. To compensate for the reduced point precipitation values (when compared to catchment scale) most rainfall time series were increased by a constant ratio across the length of data record, with this applied to each of the daily records. Scaling factors used during the model calibration are shown in Table 4**.**

Table 4 Precipitation scaling statistics for the Melbourne Water catchments.

Catchment Name	Number of stations (with BOM reference no.)	Scaling factor (% increase)
Thomson	3 (85042, 85091, 83033)	1.20
Upper Yarra	3 (85042, 85046, 85091)	1.18
Maroondah	2 (86070, 86009)	1.00
O'Shannassy	2 (83033, 85042)	1.23
Yering	3 (85042, 85046, 85091)	1.05
Tarago	4 (85042, 85046, 85091, 85000)	1.05
Yan Yean	2 (86131, 86117)	1.60

The optimisation method can be described as a 'Goldilocks' method: not too wet, or too dry, but just right. For example, if rainfall from the dry end of the catchment was used, soil moisture would be optimised at very low levels in order to supply sufficient water for streamflow (implying <0.5m average soil depth – or a 'carpark' catchment). If rainfall was over-estimated, then the soil moisture store would be unrealistically deep (implying a >5m average depth – a 'deep forest' catchment). Detailed knowledge of soil moisture depth and hydraulic conductivity is uncommon but soil depths in the Maroondah catchment are highly variable (Vertessy et al., 1998). Varied geology, slopes and aspect through the Yarra and Thomson catchments produce a diversity of soil types and depths.

Table 5 Calibration statistics for the Melbourne Water catchments.

Catchment Name	Start Year	End Year	COE	Observed Mean (GL)	Model Mean (GL)
Thomson	1956	2001	0.72	235.9	234.4
Upper Yarra	1958	2001	0.91	150.3	149.9
Maroondah	1942	2001	0.77	74.2	74.0
O'Shannassy	1958	2001	0.86	96.7	97.0
Yering	1940	2001	0.81	788.4	793.9
Tarago	1964	2001	0.61	25.8	25.9
Yan Yean	1920	2001	0.69	23.9	24.0

An average depth of 200 to 400 mm water in the soil column also produced the highest COE values for most catchments implying that this value for soil moisture is 'just right' (Table 5). This range is consistent with values for extractable soil moisture for six forest sites at Corranderk and Maroondah falling between 237 and 405 mm (Ladson et al., 2004). The reproduction of historical streamflow for the seven key supply catchments ranges from satisfactory to good (see Peel et al., 2000 for an interpretation of COE values).

Modelled baseline streamflow was then compared with current streamflow data used in Melbourne Water's REALM model for the four major catchments. Double-mass analysis was used to check for accumulating errors. Cumulative errors are important because of the multi-year carry-over storage capacity provided by the Thomson Reservoir. Double-mass analysis sums the difference between the modelled and observed records, with the annual accumulated error (deficit or surplus) expressed graphically. The double mass analysis was carried out for both the calibration period of each major catchment (Figure 6) and for 1913–2001 (Figure 7). It is useful to note, these plots do not share the same percentage error axis – chosen to highlight characteristics of each of the period comparisons, described below.

During the calibration period, accumulated flows are up to 200% of average annual flow (Figure 6). Positive errors to the mid 1970s indicate that simulations are over-estimating observations, while from the mid 1970s, simulations generally under-estimate flows. Figure 7 shows large errors from the first half of the 20th century, where simulated historical streamflow data is significantly under-estimating flows, with values of up to -800% indicated for the Upper Yarra catchment.

The break in accumulated error occurs in the 1940s, possibly due to bushfires occurred in 1939, which burnt approximately 70%, 31% and 96% of mountain ash forests (*Eucalyptus regnans*) in the O'Shannassy, Maroondah and Upper Yarra catchments, respectively. Streamflow generation characteristics generally vary after a bushfire, with short-lived increases when the trees are absent, then rapid suppression for up to 30 years followed by longer-term recovery in streamflow volumes. Most of this recovery will occur by 80 years following a fire but full recovery takes about 150 years (Vertessy et al., 1998).

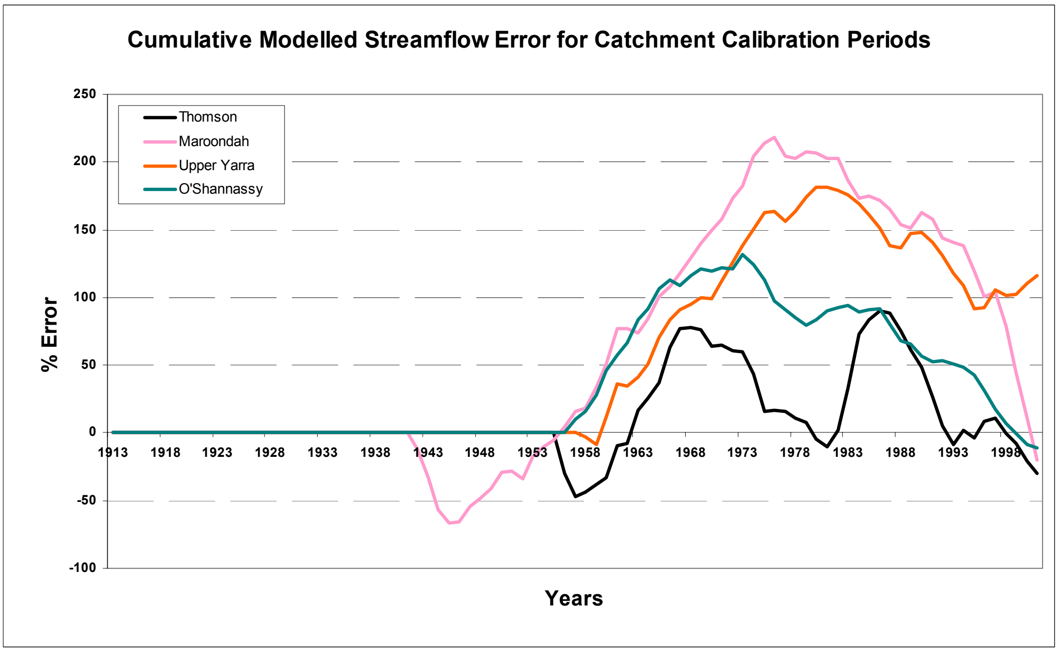

Figure 6 Double-mass plot for the calibration period

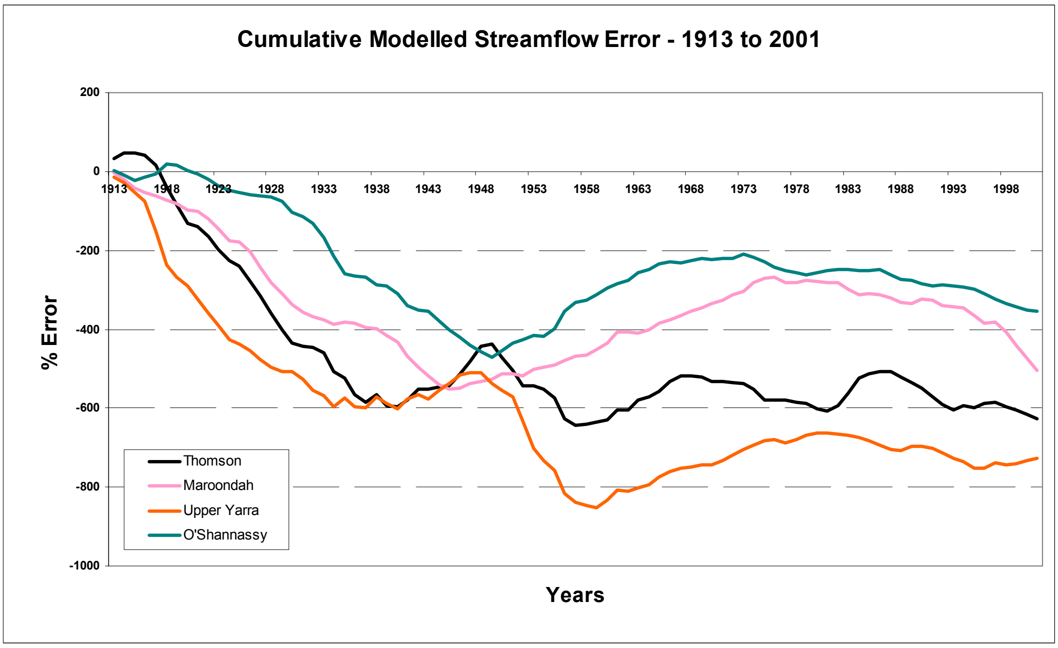

Figure 7 Double-mass plot for the entire baseline period (1913 to 2001)

Figure 8 shows simulated monthly stream flows totalled for the four largest storages and included for comparison against historical REALM values. Rainfall in southern Victoria to 1948 was lower than the period 1949–1994 but in Figure 8, observed streamflow actually shows a relative decrease over this period (save for the wettest decade of the 1950s). Such a large change in the hydrological characteristics of the catchment invalidates the use of the parameterised model before the 1939 fires and in the few years following. The rainfall-runoff model could be parameterised separately using monthly data before 1939 but it was not possible to do this within the time frame of this project. Another way to combine the effects of post-fire recovery and changing climate is to use a rainfall/runoff model such as the Macaque model, which can incorporate spatial and temporal changes in plant water use (Vertessy et al., 1998).

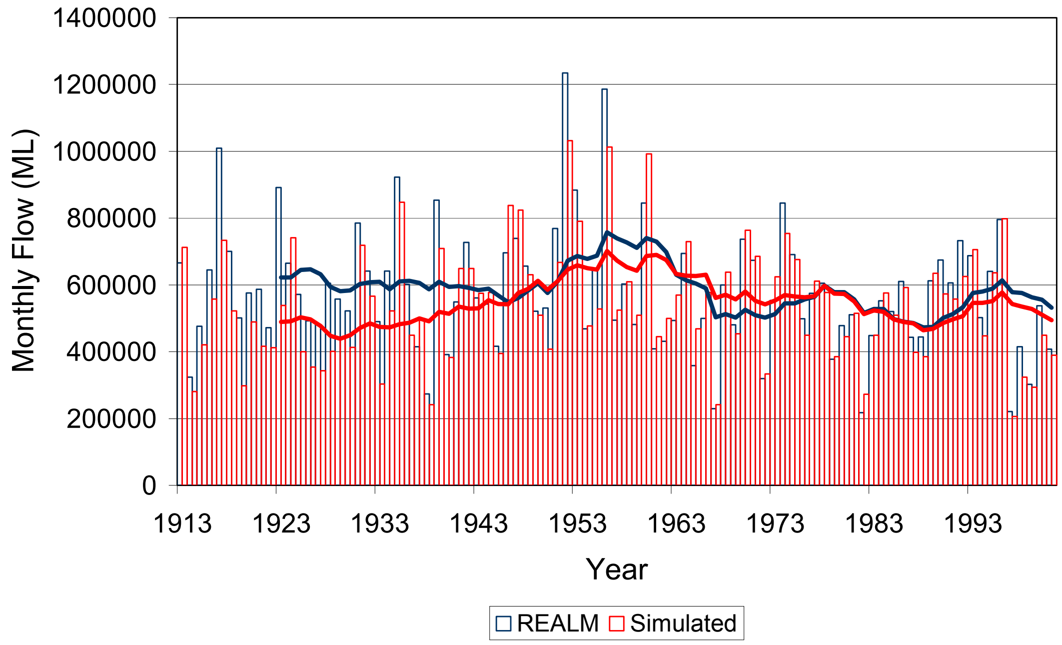

Figure 8 Observed and simulated total streamflow for the Maroondah, O'Shannassy, Upper Yarra and Thomson catchment from 1913–2001 with an 11-year running mean. Blue represents historical REALM data and red represents modelled data

Any further modelling undertaken with the aim of attributing historical streamflow changes between climate and post-fire impacts may also require investigating the homogeneity of streamflow – our testing of the rainfall-runoff models indicated that there may be some step changes in streamflow that may not be due to post-fire impacts or to climate. For example, where streamflow records have been compiled from several different sources: e.g., flow gauges, reservoir water balance and regression from nearby sites.

To account for the discontinuity in catchment hydrology between the first and second half of the 20th century, the baseline for comparison between current climate and climate change was chosen as the period 1952–2001.

5.1.5 Streamflow assessment

This section describes how multiple climate change scenarios, encompassing a broad range of climate change uncertainties, are applied to the supply system to create a relationship between climate change and change in mean annual flow. This relationship is the same as that used for measuring hydrological sensitivity, where change in mean annual runoff is related to change in mean annual precipitation and change in mean annual potential evaporation. We then used methods for quantifying the joint probabilities of global warming and regional climate changes to create a probability distribution for change in mean annual streamflow by 2020 and 2050.

That probability distribution is then used to select three scenarios: a low, medium and high climate change scenario, for further analysis.

The process followed to estimate the changes in streamflow due to influence of climate change can be described as follows:

1. Mean monthly percentage changes (per degree of global warming) for both rainfall and areal evaporation were averaged across each of the catchments from the 0.05° Victorian grid.
2. These averages were then multiplied by mean global warming to create a percentage change. The percentage change for each month was then applied to the input daily rainfall and monthly areal potential evaporation data.
3. These data were applied to the AWBM models for the seven key storage catchments for a 90-year period (1913–2001).
4. Changes for the remaining ten streamflow records were calculated using regression relationships and the climate change scenario input data for REALM was then produced.
5. This procedure was repeated for ten climate model patterns and three values of global warming by 2020 and 2050 (for low, medium and high climate change scenarios), that is for thirty climate change scenarios.
6. Changes in percent annual rainfall, potential evaporation and streamflow for the four major catchments were then used to create a regression relationship in the form $\partial Q = A\ \partial P + B\ \partial Eap$.

To quantify the regression relationship $\partial Q = A\ \partial P + B\ \partial Eap$ (described in 5.1.4), which underpins the streamflow calculation from climate variables (affected by climate change), we ran thirty climate change scenarios for 2050. This sampled the extremes of projected climate change for 2050 ensuring that the relationship would be valid for both 2020 and 2050. The method used ten climate models for the B1, A1B and A1F SRES greenhouse gas emission scenarios using low, medium and high climate sensitivity, respectively. This methodology incorporated both global and local climate uncertainties, scaling the local changes for rainfall and potential evaporation as listed in Table 2 with a range of global warming in 2050 of 0.88–2.24°C (see Figure 5). Thirty scenarios were developed, producing changes in mean annual streamflow for the Maroondah, O'Shannassy, Upper Yarra and Thomson catchments ranging between -7 to -42%.

The results show that the A constant is 1.88 and the B constant is -1.47, with an r^2 value of 0.98. Standard error as a factor of ∂Q was 1.94% of mean annual flow. Therefore, within any risk analysis using this relationship, 98% of samples will fall within ±2% of mean annual flow. The value of A is consistent with those developed for Australia using the AWBM and SIMHYD models by Jones et al. (submitted) but the value for B is a little high.

5.2 Modelling climate-driven water demand

5.2.1 Method and major assumptions

The REALM model used by MW to simulate the behaviour of the water supply system relies on a demand adjustment approach in modelling system behaviour under alternative climatic conditions. Details of this approach are given in MW Resource Management and Planning Section (2002). The demand adjustment approach can be described using the following set of equations:

$$D_{i,j} = \alpha_i \times D_j$$

$$BD_{i,j} = \beta_i \times D_j$$

$$VD_{i,j} = D_{i,j} - BD_{i,j}$$

$$CAD_{i,j} = BD_{i,j} + CLINX_{i,j} \times VD_{i,j}$$

$$CLINX_{i,j} = a + bR_{i,j} + cN_{i,j} + dT_{i,j}^{\ 2} + V_i$$

where,

i	the calendar month (1 to 12)
j	the year modelled
D_j	water demand in the j[th] year under average climatic conditions
α_i	factors indicating the monthly distribution of annual demand
$D_{i,j}$	monthly demand under average climatic conditions
β_i	factors indicating the climate-insensitive component of demand
$BD_{i,j}$	climate-insensitive monthly demand (base demand)
$VD_{i,j}$	monthly climate-sensitive demand (variable demand) under average climatic conditions
$CLINX_{i,j}$	Climatic adjustment factor to convert the climate-sensitive demand under average climatic conditions to the demand under modelled climatic conditions
$CAD_{i,j,}$	climatically adjusted total demand in month i, year j
a, b, c, d	regression parameters
$R_{i,j}$	rainfall in month i, year j
$N_{i,j}$	number of rain days in month i, year j
$T_{i,j}$	average of the maximum daily temperature in month i, year j
V_i	a constant that varies depending on the month

The above procedure can be described as follows:

1. Estimate the monthly demand under average climatic conditions based on annual demand under average climatic conditions (disaggregation from annual to monthly),
2. Estimate the climate-sensitive and climate-insensitive components of monthly demands,
3. Estimate the climatically-adjusted monthly demands by adjusting the climate-sensitive component using a factor derived from total rainfall, number of raindays and average temperature.

The climate adjustment (CLINX) factors are derived for each month in the historical dataset used to represent future hydrological scenarios, using a regression relationship with climate data. The independent variables of the regression relationship are: number of raindays, total rainfall and average maximum temperature during the month under consideration. However, because data for estimating changes in raindays were unavailable for the suite of climate models used in the study, we utilised climate variables for which change data were available. Consequently, further analysis was undertaken to examine whether the number of raindays could be replaced with monthly A-Class pan evaporation values. Other aspects of the demand estimation approach were left unchanged.

The performance of the modified regression relationship was compared with that of MW's original relationship described above. Preparation of input data for this purpose is described in the next section.

5.2.2 Input data preparation

The input data required for demand modelling include historical monthly total rainfall, monthly total A-Class pan evaporation, average monthly maximum temperature and monthly water-use for Melbourne. MW provided historical records for the maximum temperature and rainfall data from 1913 to 2001. This data was sourced from the BOM Melbourne Regional Office and is incorporated into the REALM input data, along with the CLINX factor. A-Class pan evaporation data were provided by BOM for 1913–2001. This dataset comprises A-Class pan evaporation from 1962, and sunken tank data from 1920–1961, however, the origin of data from 1913–1919 was not recorded. Water-use data representative of the current water supply area were available for 1992–2001, restricting the calibration of the model to that period.

5.2.3 Water demand-adjustment model calibration

The modified regression relationship producing the monthly CLINX factors was derived using 1992-2001 historic data for climate variables and historical monthly water demand. Parameters of the modified relationship are given in Table 6. The modified CLINX factors were then used to estimate monthly demand from 1992 to 2001. Over the calibration period, the monthly efficiency of the modified relationship was 0.93, whereas the monthly efficiency of MW's monthly demand model was 0.92, indicating that the modified demand model (with A-Class pan evaporation instead of raindays) replicated MW's original relationship.

Note, that in Section 5.1.1, Areal potential evaporation was preferred to A-Class pan evaporation data for streamflow modelling, although the latter was used here for demand modelling. To test the suitability of this dataset, point potential evaporation, calculated using Morton's CRAE model (as for areal potential evaporation), was substituted for A-Class pan evaporation in the water demand adjustment model. The monthly efficiency of this version of the model was 0.93, as for A-Class pan evaporation, indicating the suitability of either of the two variables. A brief sensitivity analysis showed that maximum temperature has the greatest impact in this model, and that potential evaporation and its precursor variable, monthly raindays, have low impacts.

Table 6 Parameters of modified CLINX relationship

Variable	Parameter Value
Intercept	2.997
Rainfall coefficient	-0.004
Pan evaporation coefficient	0.003
Temperature coefficient	0.001
V_1	-5.393
V_2	-5.556
V_3	-5.304
V_4	-5.116
V_5	-4.795
V_6	-4.309
V_7	-4.412
V_8	-4.772
V_9	-4.980
V_{10}	-5.061
V_{11}	-5.169
V_{12}	-5.077

The performance of the modelled and historical relationships is compared in Figure 9 and Figure 10 over the calibration period. Their performances are consistent, indicating the suitability of the modelled approach.

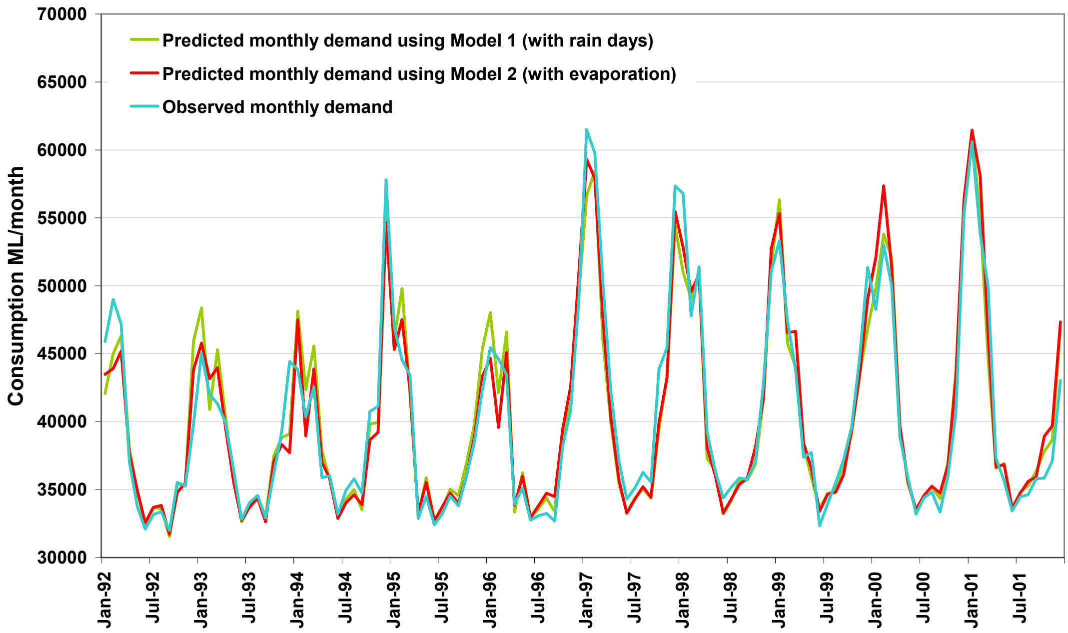

Figure 9 Monthly performance of the modified demand model compared to the original model and the recorded demand

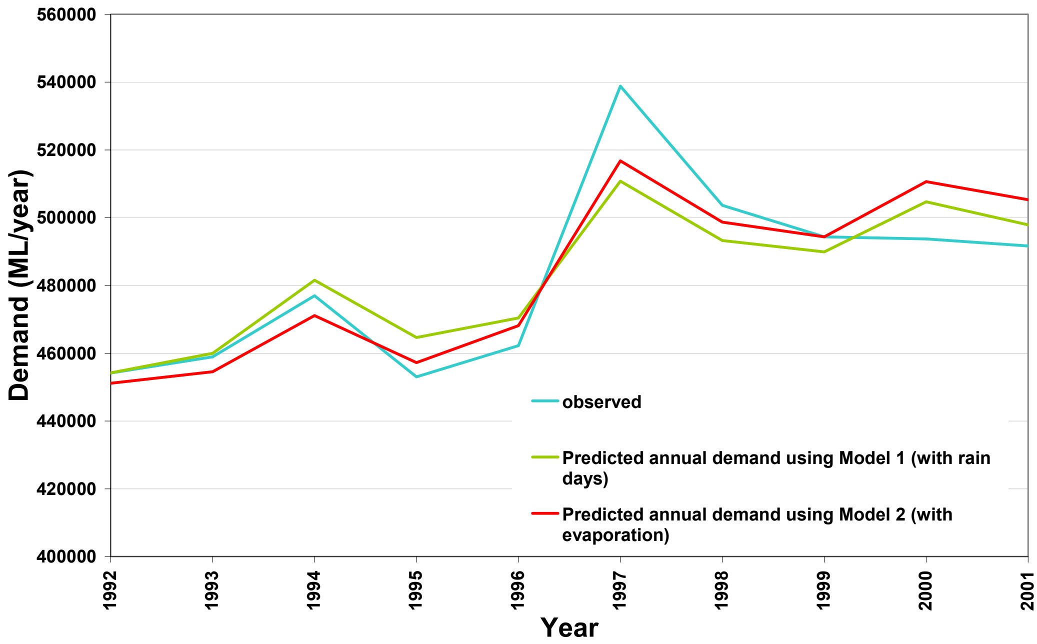

Figure 10 Annual performance of the modified demand model with pan evaporation as a variable compared to the recorded demand and simulated values obtained from the MW's monthly demand model

The above demand adjustment approach is based on a model-calibration under historic demand patterns. These demand patterns are expected to change as a result of the initiatives proposed in *Our Water Our Future* (DSE, 2004).

5.2.4 Demand assessment

The changes in water demand were assessed in the same way as for water supply (Section 5.1.5), by applying thirty climate change scenarios, then investigating changes to the CLINX climatic adjustment factor. This was undertaken to assess the relationship between water supply and demand under climate change conditions and to create some simple algorithms for the uncertainty analysis outlined in the next chapter.

Figure 11 shows the relationship between the change in mean annual system stream flow and the change in mean annual demand, which has an r^2 of 0.85. This shows that reductions in water supply due to increased potential evaporation and reduced rainfall will also increase external water demand. For every 6% decrease in mean annual system streamflow, there will be about a 1% increase in mean annual water demand.

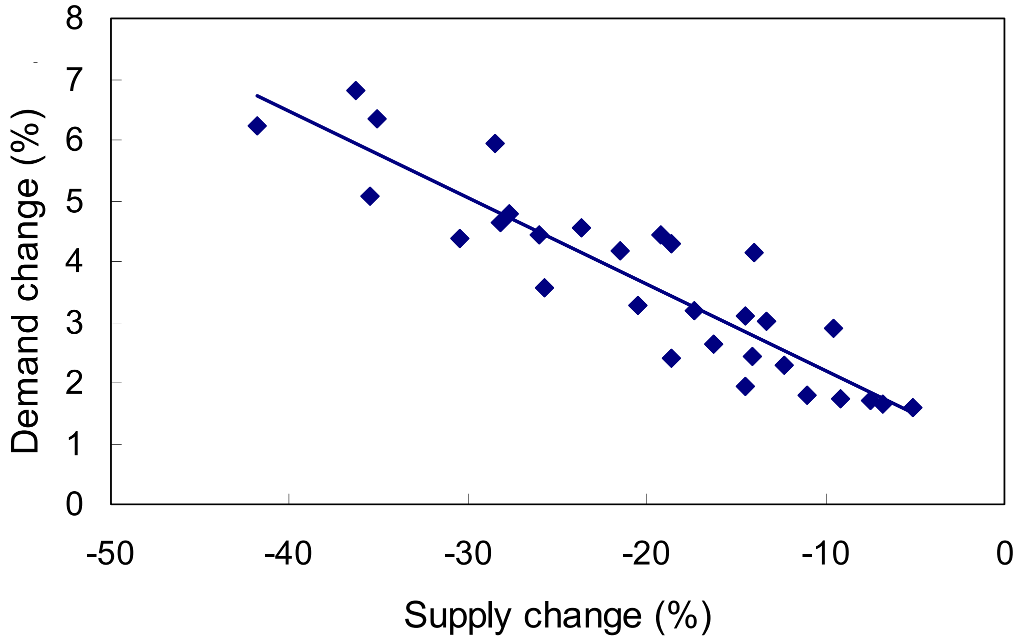

Figure 11 Relationship between change in climate-sensitive water demand and supply for thirty scenarios. Supply is averaged across the Maroondah, O'Shannassy, Upper Yarra and Thomson catchments. Demand change is represented by the variation in the CLINX factor.

6 Climate scenario selection and analysis

6.1 Uncertainty analysis

The next step was to create three climate scenarios: a low, medium and high change scenario as outlined in the terms of reference for this study. The method used is based on that described in Jones (2000b) and Jones and Page (2001). The basic rationale; if several ranges of uncertainty are combined, joint probabilities of the resulting probability distribution will tend to cluster around the average of those ranges (consistent with the central limit theorem of statistics). The results are then a product of the limits and probability density function of the precursor ranges of uncertainty and how those ranges are combined (i.e. whether they are independent, co-dependent or governed by a specific mathematical relationship).

In Section 5.1.5 we described running the hydrological models with thirty climate scenarios, but by following the method of repeated random sampling (with several simplifications based on a list of assumptions stated below), the number of climate scenarios that can be used for impact assessment can be increased in many thousands. The key simplification was the use of a simple relationship for estimating change in streamflow for the four major catchments.

Repeated random sampling was undertaken using the following assumptions (see Table 7):

1. All ranges (global warming, local rainfall and potential evaporation change) were assumed to have a uniform probability density (all points equally likely to occur) between the lower and upper limit.
2. The range of global warming in 2020 was 0.37–0.85°C with a uniform distribution. The range of change in 2050 was 0.88–2.24°C. These are changes from 1990.
3. Changes in precipitation (P) were taken from the full range of change for each quarter from the sample of ten climate models.
4. Changes in P for each quarter were assumed to be independent of each other (seasonally dependent changes between seasons could not be found).
5. The difference between samples in any consecutive quarter could not exceed the largest difference observed in the sample of ten climate models.
6. Point potential evaporation (i.e. Epp) was partially dependent on P ($\delta Epp = 5.00 - 0.21\delta P$, standard error = 1.76 per degree of global warming, $r^2 = 0.40$, randomly sampled using a Gaussian distribution, units in percent change), areal potential evaporation was less dependent.
7. Changes in point potential and areal potential evaporation (i.e. Eap)were weakly co-dependent ($\delta Eap = 0.6\delta Epp$, $r^2 = 0.35$).
8. All sampling of δP, δEap and δEpp was conducted on a quarterly basis and summed to assess annual changes in each variable. Annual changes in streamflow and the CLINX variable were then calculated.
9. One million samples were taken, but about ⅓ of the samples were rejected due to the rule in point 5.

Table 7 Ranges of uncertainty applied to Monte Carlo uncertainty analysis of changes to streamflow and climate-driven demand for 2020 and 2050.

	Global mean warming (°C)	Summer	Autumn	Winter	Spring
2020					
Precipitation (%)					
Low (wet scenario)	0.37	4.7	3.6	1.2	-2.0
High (dry scenario)	0.85	-4.8	-2.5	-1.5	-5.5
Areal potential evaporation (%)					
Low	0.37	0.8	1.1	0.3	1.1
High	0.85	4.2	4.5	6.0	4.7
Point potential evaporation (%)					
Low	0.37	1.3	1.3	1.0	1.8
High	0.85	8.3	7.8	9.0	10.1
Maximum temperature (°C)					
Low	0.37	0.4	0.3	0.2	0.4
High	0.85	1.2	1.0	0.9	1.1
2050					
Precipitation (%)					
Low (wet scenario)	0.88	11.9	9.2	3.1	-5.2
High (dry scenario)	2.24	-11.0	-5.8	-3.4	-12.6
Areal potential evaporation (%)					
Low	0.88	1.9	2.5	0.8	2.5
High	2.24	10.8	11.4	15.2	11.9
Point potential evaporation (%)					
Low	0.88	2.9	3.1	2.4	4.2
High	2.24	21.1	19.9	22.8	25.8
Maximum temperature (°C)					
Low	0.88	0.9	0.7	0.5	0.9
High	2.24	3.1	2.5	2.2	2.9

The sequence of assessment was:

1. Sample range of global warming
2. Sample quarterly rainfall for four seasons
3. Test point 5 in the assumption list above (difference between seasons, return to the beginning of the assessment (1) if false, go on to sample potential evaporation co-dependency (4) if true)
4. Sample point potential evaporation based on co-dependency with rainfall change
5. Sample areal potential evaporation as 0.6 of the point potential change
6. Add quarterly rainfall and potential evaporation to estimate annual changes
7. Calculate CLINX
8. Calculate changed streamflow

9. Repeat until step 3 has been reached 1 million iterations
10. Tally outcomes into new probability distribution for streamflow.

Because the new probability distribution is combined from several ranges of uncertainty, it resembles a normal distribution, where the central outcomes are more likely than those at the extremes. The results of the repeated random sampling can be expressed as the probability of exceeding a given change in streamflow. How sensitive are the outcomes to the underlying assumptions? Jones and Page (2001) tested a very similar relationship and found that the technique was insensitive to sampling interval (quarterly, six monthly or annual), the probability distribution of the underlying ranges of uncertainty (uniform or peaked), the range and distribution of global warming or to potential evaporation. The technique was most sensitive to the range of rainfall change.

6.2 Scenarios of streamflow and water demand

6.2.1 Selection of low, medium and high climate change scenarios

The results of the uncertainty analysis for 2020 are shown in Figure 12. This is a cumulative probability distribution that shows the likelihood of successively high levels of change. Greater than 99% of all changes show decreases in flow. Furthermore, this figure indicates that 80% of the possible outcomes for change in average annual streamflow lie between -3% and -12%. The results for 2050 are shown in Figure 13. The range of change is much larger than that of 2020. The most likely 80% of the range is between -8% and -35%.

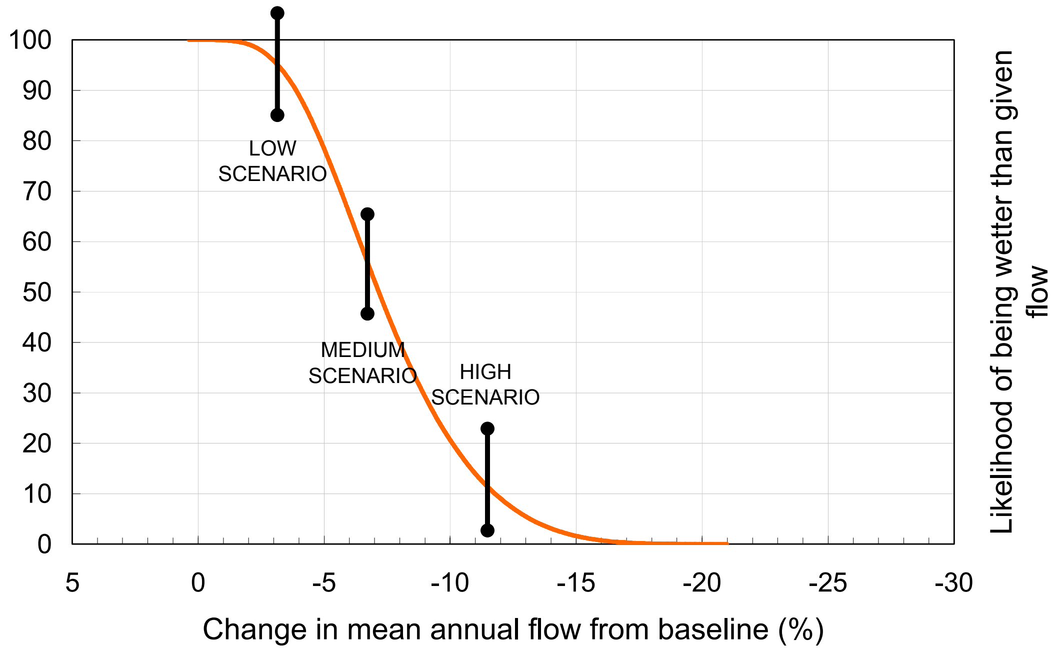

Figure 12 Exceedance probabilities for percentage change in mean annual streamflow in 2020 (vertical lines indicate the low, medium and high scenarios)

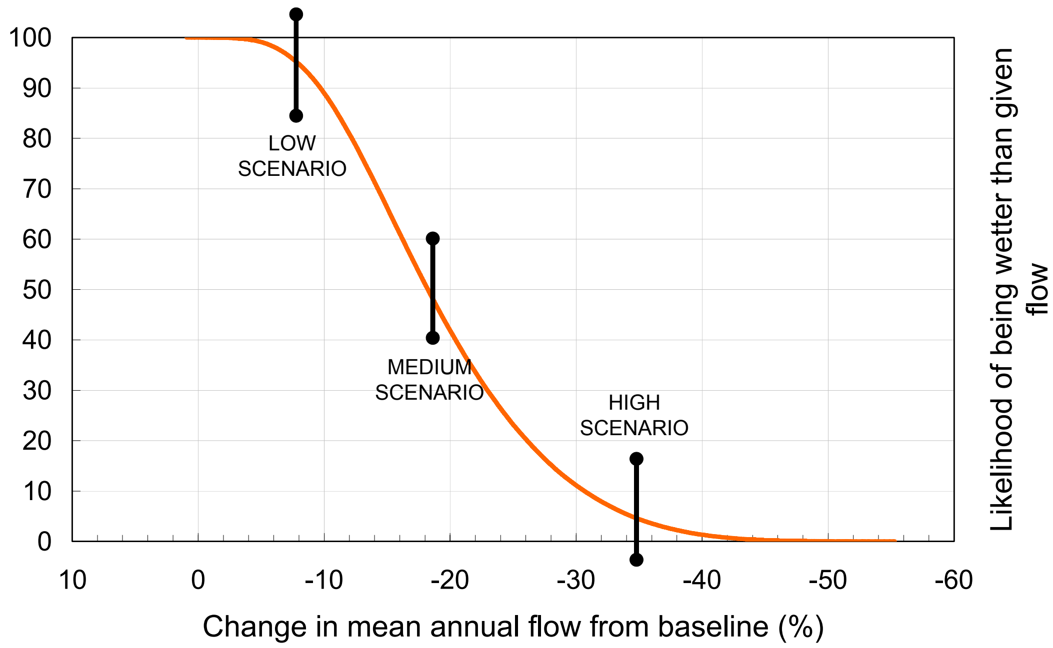

Figure 13 Exceedance probabilities for percentage change in mean annual streamflow in 2050 (vertical lines indicate the low, medium and high scenarios)

Low, medium and high climate change scenarios were wanted for the project but not the absolute lowest or highest of quantified possibilities. We used the probability distribution in 2050 (Figure 13) to select the low, medium and high climate change scenarios. They were selected at approximately the 5%, 50% and 95% probability levels. In each case we chose the closest of the thirty scenarios used in Section 5.1.5 to the given change in mean annual flow at 5%, 50% and 95%. Probability in these cases means that 95% of all outcomes are drier than the given change in flow, 50% denotes the medium and only 5% of all outcomes are drier than the high scenario.

Note that in 2020, these scenarios have drifted slightly away from these probabilities. This is due to differences in how the three global warming projections evolve (see Table 8), largely because of different loadings of sulphate aerosol emissions in the greenhouse gas emission scenarios which suppress warming in the A1F and A2 (high climate change) scenarios relative to the B1 (low climate change) scenario.

Table 8 summarises the low, medium and high scenarios for 2020 and 2050. The Canadian Climate Centre GCM II pattern combined with the B1 SRES scenario at low climate sensitivity provides the low scenario (the wettest model combined with low rates of global warming), the CSIRO Cubic Conformal Model combined with the A2 SRES marker scenario with average sensitivity provides the medium scenario (a mid-range rainfall change and global warming scenario) and the CSIRO Mark 3 combined with the A1F SRES marker scenario at high climate sensitivity provides the high scenario (a dry model with a high global warming scenario).

Table 8 Low, medium and high climate variables contributing to the supply and demand scenarios used in the water supply case study (averaged across the upper Yarra and Thomson catchments)

Warming Scenario	Low	Medium	High
Global warming scenarios	B1 with low climate sensitivity	A2 with medium climate sensitivity	A1F with high climate sensitivity
Climate model	Canadian Climate Centre Global Climate Model II	CSIRO Cubic Conformal Regional Climate Model	CSIRO Mark3 Global Climate Model
2020			
Global mean warming (°C)	0.4	0.5	0.7
Rainfall change	-0.4	-2.8	-3.2
Areal potential evaporation	1.6	2.2	1.9
Point potential evaporation	2.3	3.7	3.6
Maximum temperature	0.4	0.4	0.6
2050			
Global mean warming (°C)	0.9	1.4	2.2
Rainfall change	-0.8	-8.0	-10.6
Areal potential evaporation	3.5	6.3	6.1
Point potential evaporation	4.3	10.5	12.0
Maximum temperature	0.9	1.6	2.5

The low, medium and high scenarios can be assessed for their likelihood of occurrence in the flowing way. The low change scenario is likely to be exceeded by most scenarios of global warming; that is, most outcomes of streamflow will see greater reductions in average streamflow. The medium scenario is likely to be worse in terms of streamflow than about half of all possible scenarios and better than the other half, so it is roughly a 50:50 chance in terms of risk. The dry scenario will be exceeded by only a very small number of extreme scenarios. Therefore, it is not likely to occur, but if it did, the consequences would be the most severe of the three selected scenarios.

6.2.2 Changes in streamflow in major harvesting storages and mean annual system water demand

The projected changes in streamflow in Melbourne's four major harvesting storages under the influence of low, medium and high climate change scenarios are given in Table 9.

Table 9 Projected changes in average annual inflow to Melbourne's four major harvesting storages

Climate Change Scenario	2020	2050
Low change	- 3 %	- 7 %
Medium change	- 7 %	- 18 %
High change	- 11 %	- 35 %

When the streamflow changes shown Table 9 are (checked with the relationship described in Section 5.1.5) applied to the ∂P and ∂Eap factors in Table 8, the low and medium scenarios were within 2% of mean annual flow for the 2020 scenarios and within 3% of mean annual flow for the 2050 low and high scenarios. The medium scenario was over-estimated by 7% due to an unusually high value of Eap in the climate model. This is considered to be an acceptable result given the uncertainty involved in calculating the A and B factors.

The mean monthly changes for three scenarios in 2050 are shown for precipitation in Figure 14 and for streamflow in Figure 15. Figure 14 shows rainfall increases in some months, particularly in late summer to early winter. However, warmer and drier conditions will result in a reduction in mean monthly streamflow volumes for almost all months (Figure 15). Impacts of these reduced streamflow volumes on the system yield are examined in Chapter 7.

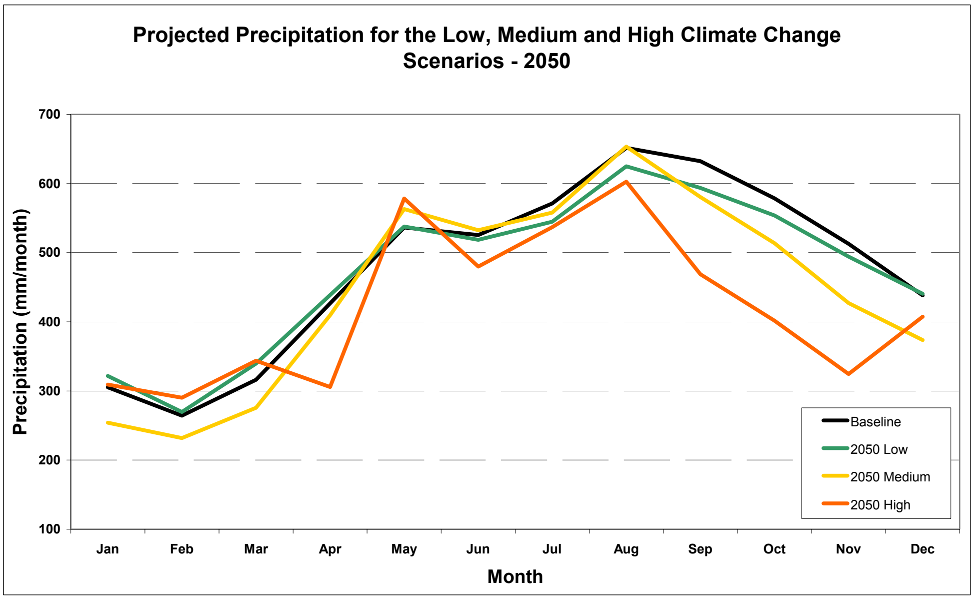

Figure 14 Projected monthly rainfall for the low, medium and high climate change scenarios in 2050, averaged across the four main supply catchments

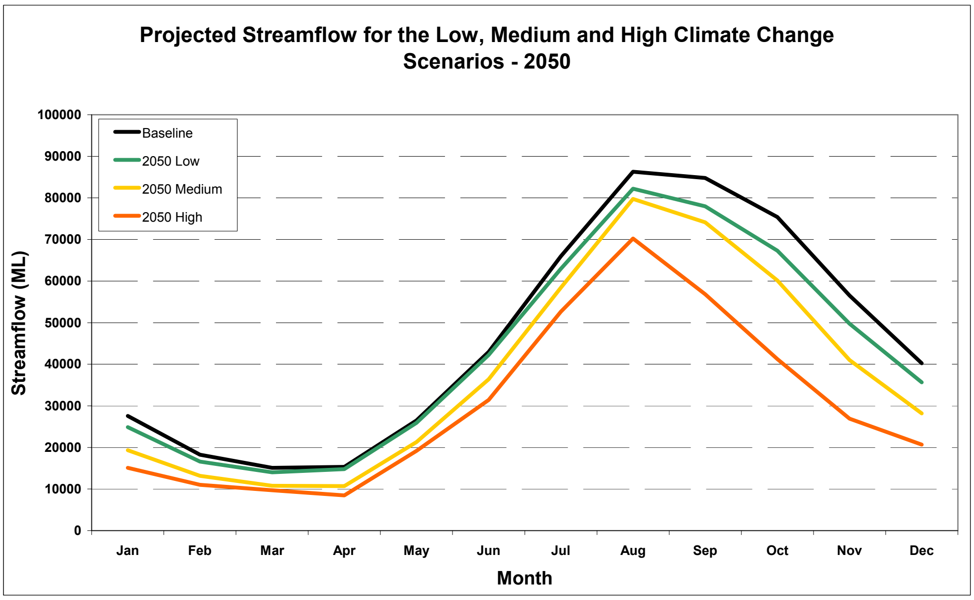

Figure 15 Projected monthly streamflow for the low, medium and high climate change scenarios in 2050 totalled from the four main supply catchments

The same scenarios were used to produce changes in monthly demand, which indicated an increases in annual water demand. Table 10 shows projected changes to the mean annual system water demand in the Greater Melbourne area in 2020 and 2050 for the low, medium and high climate change scenarios listed in Table 8.

Table 10 Projected changes in average annual demand in the Greater Melbourne area

Climate Change Scenario	2020	2050
Low change	+ 0.5 %	+ 1.3 %
Medium change	+ 1.3 %	+ 3.1 %
High change	+ 2.3 %	+ 6.2 %

The probabilistic approach described in Section 6.2.1 also produced a similar range of estimates for the change in mean annual system water demand. Figure 16 and Figure 17 show the exceedance probability distributions for the change in mean annual demand in 2020 and 2050 respectively.

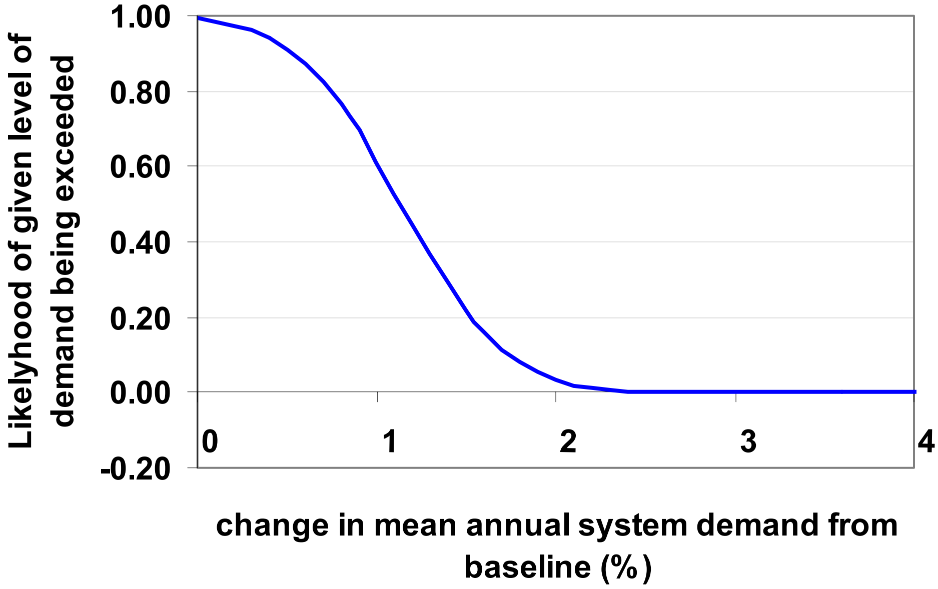

Figure 16 Exceedance probabilities for percentage change in mean annual demand in 2020

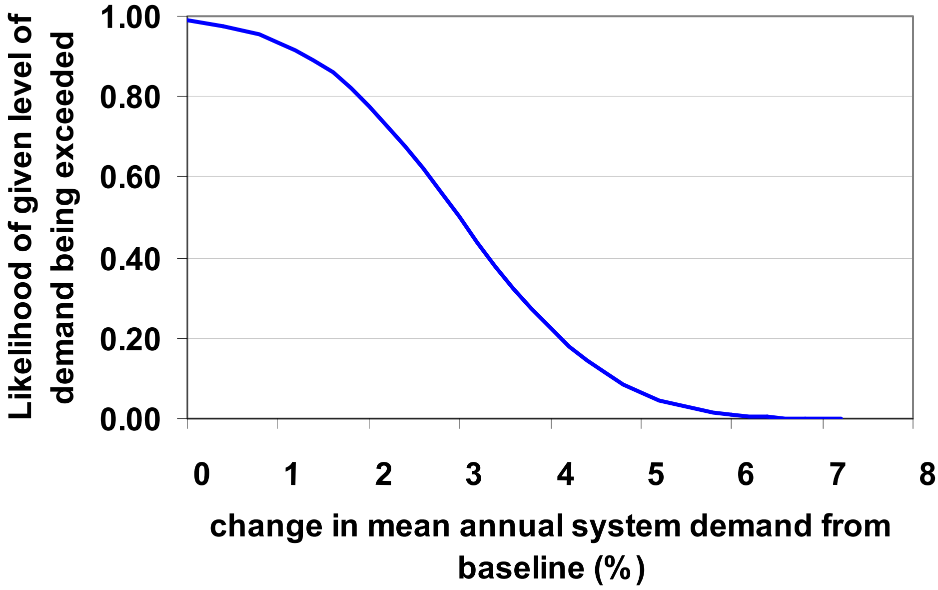

Figure 17 Exceedance probabilities for percentage change in mean annual demand in 2050

7 System yield and behaviour analysis

This chapter utilises the climate scenarios developed in the previous chapter and scenarios of population and demand management to assess the implications for water supply, demand and system behaviour in 2020 and 2050.

Water supply availability was assessed by estimating system yield at 2020 and 2050 for each of the climate change scenarios. The yield of the MW water supply system is estimated as the average annual volume that can be supplied, given the system configuration, streamflow characteristics, system operating rules, Levels of Service requirements, and the seasonal demand pattern. Reliability of supply outlines how often the design yield can be met.

The yield of the current Melbourne Water system has been estimated at 566 GL, using historic streamflow data from 1913 to 1998 (Water Resources Strategy Committee for the Melbourne Area, 2002b). The corresponding yield at full development of the system is 676 GL, with full utilisation of the Winneke treatment plant and system augmentations identified prior to the release of *Our Water Our Future* (DSE, 2004). The system at full development is assumed to include a number of augmentations including the Tarago treatment plant, O'Shannassy pipeline duplication to regain volumes foregone through decommissioning the O'Shannassy aqueduct, and East-West transfer upgrades.

System yield was estimated for three climate change scenarios in 2020 and 2050, producing six yield estimates. The yield in 2020 and 2050 under no climate change was also estimated with and without demographic changes. Streamflow and climate data from 1952–2001 were used as the baseline against which the yield estimates were compared. This shorter period was selected because of more reliable streamflow data (e.g. availability of daily data and measurements at more sites) and because the 1939 fires and subsequent regrowth mean that the catchments display different hydrological behaviour between the first and second halves of the 20th century. All changes in yield estimates are discussed as relative to the period 1952–2001, so deviations from the historical record, rather than absolute values.

7.1 System yield

System behaviour under climate change was modelled using Melbourne Water's REALM model and the alternative climate scenarios, to determine the maximum demand that could be sustained without breeching the current level of service criteria. The resulting maximum demand that could be met was identified as the system yield under the scenario being analysed. The level of service criteria used for determining system yield are:

- The likelihood of the occurrence of restrictions must not be greater than 5% of the months.
- Restrictions must not be in place for more than 12 consecutive months.

- The Stage 3 restriction level must not be exceeded.

Several other parameters affect the modelled system behaviour, particularly given the shorter baseline period (i.e. 1952 – 2001). Two key examples are:

- Initial system conditions (starting storage level for the model run): It was assumed that the initial storage level is at 80% of storage capacity. This is consistent with Melbourne Water's planning assumptions, and corresponds to the modelled average long-term system storage level.
- Water restrictions: The restriction rules and the expected savings in the current Melbourne Drought Response Plan were modelled for both 2020 and 2050.

As in the Water Resources Strategy, the modelling to estimate the yield for 2020 was based on the current system configuration, and that for 2050 was based on the fully developed system configuration, as described in the previous section.

In summary, the yield assessment modelling for each climate change scenario involved running a particular streamflow data set and a stationary (no climate change) system demand through REALM headworks model. The stationary demand was varied to determine the highest demand level that can be sustained without breaching the level of service requirements. The yield estimates obtained using this approach, are presented in Table 11.

Table 11 Yield estimates for various scenarios

Year	Scenario	Level of climate change	Yield Estimate (GL)
2020	Climate change	High	481
		Medium	510
		Low	532
	No climate change (base case)	Not applicable	556
2050	Climate change	High	404
		Medium	518
		Low	580
	No climate change (base case)	Not applicable	648

The yield estimates for 2020 and 2050 made for the Water Resources Strategy (Water Resource Strategy Committee, 2002a, b) are 566 GL and 676 GL respectively, for 2020 and 2050 assuming no climate change. These values are higher than the estimates of 556 GL and 648 GL in Table 11. These differences are due to the differences in the input streamflow data sets. The estimates of Water Resources Strategy are based on streamflow data from 1913 to 1998, compared to 1952–2001 in Table 11. Climate is obviously different over the two periods, and so is the hydrological response of the catchments due to widespread fires in 1939 as discussed earlier. This highlights the sensitivity of the yield estimates to varying patterns of streamflow and climate-driven demand. For this reason, relative shifts in yield are assessed rather than the absolute values.

7.2 System demand

Three demand projections were selected to assess the collective impact of climate change and population growth. The three demand projections are shown in Figure 18 and are based on demand management savings of 15% per capita in 2010 and 23% per capita in 2050 but used three different population scenarios based on Melbourne 2030 forecasts as shown in Table 12. The demand management savings reflect Victorian Government targets for Melbourne.

Table 12 Low, medium and high population projections for Melbourne (Mitchell & Maheepala, 2004)

Population scenarios (millions rounded up)			
Year	**Low**	**Medium**	**High**
2020	3.58	4.08	4.26
2050	3.75	4.60	5.12

The above demand projections were developed by combining the low, medium and high population projections with various per capita water use projections starting from a base level of 387 L per capita per day or about 500 GL per year in 2001 as per the Water Resources Strategy for the Melbourne area (Water Resource Strategy Committee, 2002a, b). The demand scenarios shown in Figure 18 represent:

- Low Demand Scenario: Low population growth with a 15% reduction in demand by 2010.
- Medium Demand Scenario: Medium population growth with a 15% reduction in demand by 2010.
- High Demand Scenario: High population growth with a 15% reduction in demand by 2010.

In 2020, water demand is projected to be about 530 GL under a medium population growth scenario but ranges between 490 and 554 GL depending on assumptions of population growth and the impact of demand management strategies (Figure 18). By 2050, demand becomes harder to project due to uncertainties surrounding population and water use but could range between a “best-case” of 448 GL and a “worst-case” of 630 GL.

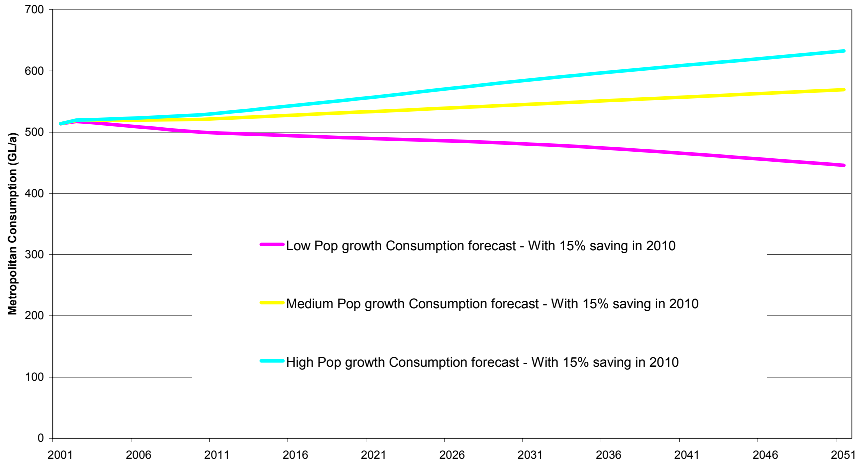

Figure 18 Demand projections used in the water supply case study

Note that the demand projections shown in Figure 18 represent stationary climatic conditions or the 'no climate change' scenario. To see the impact of changing climate on the annual system demand in 2020 and 2050 due to enhanced greenhouse gas emissions, the annual demand in 2020 and 2050 in these projections were adjusted by using the projected changes in mean annual demand (Table 10).

7.3 Collective impact of climate change and demand growth

The yield estimates in Table 11 were compared with the alternative demand scenarios presented in Figure 18 to identify the demand scenarios that can be satisfied by Melbourne's water supply system under various climate change scenarios (which also includes the no climate change scenario).

Figure 19 shows the combination of demand and climate change scenarios for 2020 and 2050 respectively, indicating those combinations under which the system is able to satisfy demands. These are also compared with estimates made for the Water Resources Strategy (based on 1913–1998 streamflow data). These estimates are shown as ranges to account for uncertainties in input streamflow data, level of service criteria, environmental flow obligations, future system operating rules and the future availability of planned system augmentations.

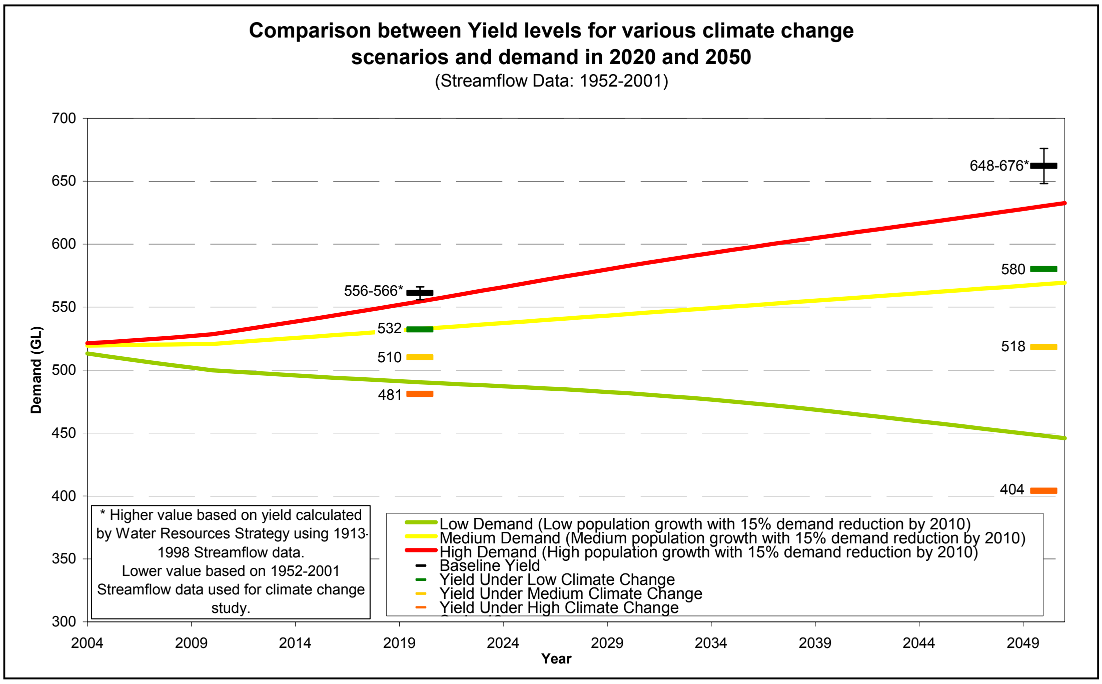

Figure 19 Comparison between yield estimates and demand scenarios. Baseline yield includes estimates made for 1952 – 2001 and 1913 – 1998 (the latter from the Water Resources Strategy, see text).

Figure 20 and Figure 21 restate the data shown in Figure 19 as buffers or shortfalls of system yield in 2020 and 2050, respectively. The yield estimates for 2020 are based on the current system configuration. Those for 2050 are based on the full utilisation of resources within water allocations used in the Water Resources Strategy. However, these options are likely to be revisited in the future, in accordance with recommendations on basin caps and following the investigations identified in DSE (2004).

The green shaded cells in Figure 20 and Figure 21 represent climate change scenarios where the projected demands could be readily met without supplementing the current water harvesting system. The yellow cells indicate scenarios where demand could be met by bringing forward enhancements to the water harvesting system as outlined in the Water Resources Strategy or by undertaking additional demand management actions. The red shaded cells represent climate change scenarios where demand cannot be readily met without harvesting additional water resources to those identified in the Water Resources Strategy and considerable review of the range of strategic options for managing supply and demand. Under these scenarios a range of contingency options would need to be activated, which may include desalination and additional recycling.

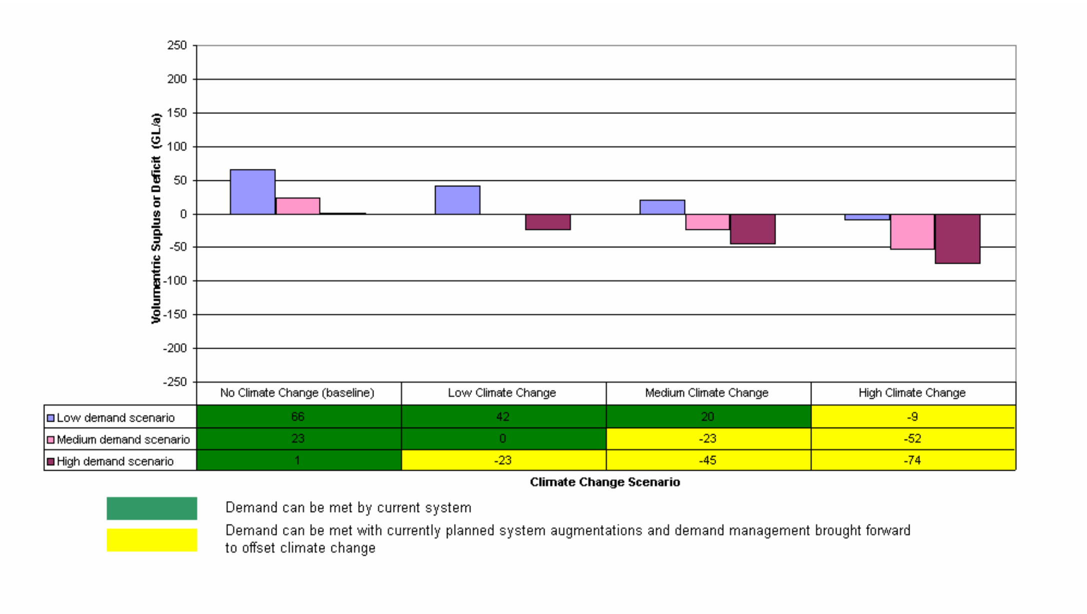

Figure 20 Potential Buffer (positive value) or shortfall (negative value) of system yield on forecast average annual demand (billion litres) in 2020

Figure 21 Potential Buffer (positive value) or shortfall (negative value) of system yield on forecast average annual demand (billion litres) in 2050

Demand management measures and water supply augmentations identified in the Water Resource Strategy for the Melbourne Area provide a sufficient buffer for climate change up to 2020. These augmentations are sufficient to manage the full range of climate change and alternative demand forecasts considered in this case study. Some of the system augmentations outlined in the Water Resources Strategy by 2050 may be required by 2020 to maintain existing levels of service, especially if anything other than low climate change should occur.

Additional measures to those outlined in the Water Resources Strategy will likely be required between 2020 and 2050 to maintain existing levels of service, especially if anything other than low climate change and growth projections occur. The monitoring of climate change and how emerging changes may affect both strategic and contingency options will also be required to ensure reliable and safe supply.

The analysis described here does not include actions or impacts arising from *Our Water Our Future* (DSE, 2004), which was released subsequent to the technical work undertaken for this study. This study recognises that further detailed assessment would be required to identify the appropriate supply enhancement and demand management actions required to manage both climatic and demographic change, including environmental assessments and ongoing monitoring of the effectiveness of demand management strategies.

7.4 System behaviour under climate change

System behaviour was analysed under the different combinations of climate change and population scenarios indicated by the green shading in Figure 20 and Figure 21. These combinations represent the scenarios in which the demand can be met without augmenting the system or lowering the demands beyond the assumptions in the Water Resources Strategy yield assessment. The same scenarios were found to be viable for both 2020 and 2050. These are listed below;

1. No Climate Change with Low Population
2. No Climate Change with Medium Population
3. No Climate Change with High Population
4. Low Climate Change with Low Population
5. Low Climate Change with Medium Population
6. Medium Climate Change with Low Population

Because the aim of this analysis was to assess the system operation characteristics under particular climate change and population scenarios in specific years (i.e., 2020 and 2050), the modelling was undertaken using stationary demand conditions. This is the same approach used above for yield estimation, the only difference being that the demand is fixed and is lower than yield. The resulting system behaviour indicates the potential range in system operation that can be expected under each specific scenario of climate change. Figure 22 and Figure 23 show the modelled total system storage levels for 2020 and 2050 respectively under a repeat of 1952–2001 streamflows with adjustment for each climate change scenario. Illustrated in these plots, is the systems sensitivity to prolonged dry periods. Overflows in effect reset the system, and prolonged dry spells lead to accumulated losses. This is especially apparent in Figure 22 during the period from the late 1970's through to mid 1980's.

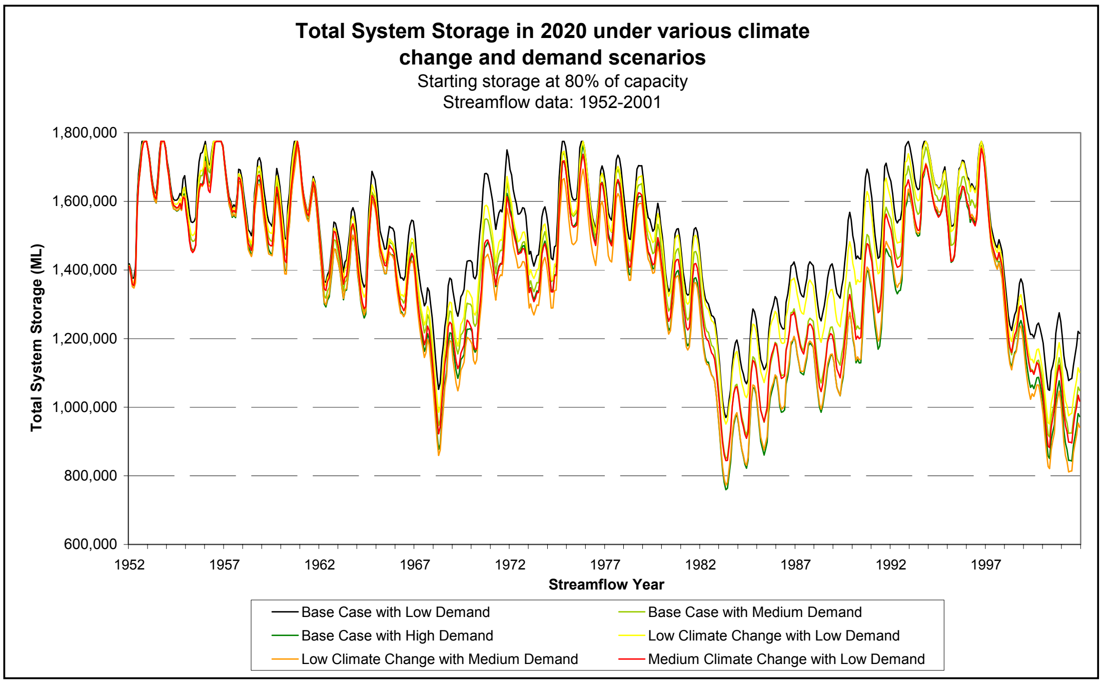

Figure 22 Potential variability of total system storage in 2020 under climate change

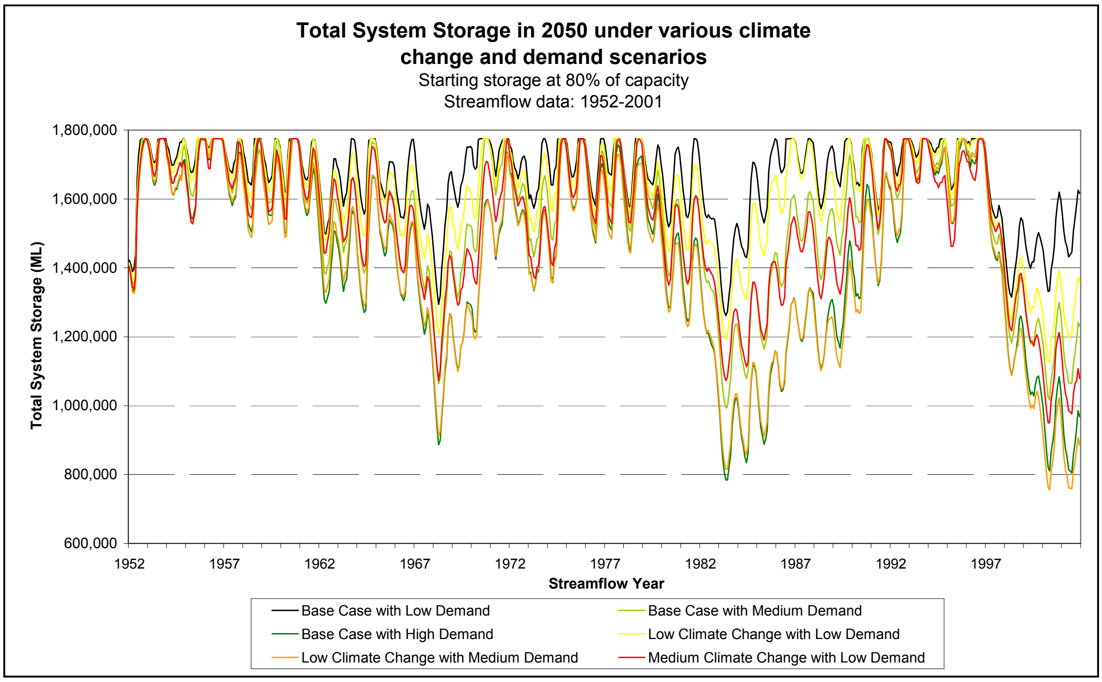

Figure 23 Potential variability of total system storage in 2050 under climate change

Table 13 summarises the total supply system storage behaviour in 2020 and 2050 for the various climate and demand scenarios. The storages are higher under all scenarios in 2050 than in 2020 because a fully augmented supply system is modelled for the year 2050. This allows the system to be operated closer to system capacities.

Table 13 Summary of total system storage behaviour in 2020 and 2050 under the various climate change and demand scenarios

	Year 2020			Year 2050		
Climate Change Scenario	Minimum Storage Level (GL)	Average Storage Level	Time Below 95% Storage	Minimum Storage Level (GL)	Average Storage Level	Time Below 95% Storage
No Climate Change with Low Demand	970	1,490	83.7%	1,260	1,660	47.0%
No Climate Change with Medium Demand	850	1,410	91.2%	990	1,550	70.7%
No Climate Change with High Demand	760	1,360	92.8%	780	1,430	81.0%
Low Climate Change with Low Demand	950	1,450	88.2%	1,130	1,610	60.0%
Low Climate Change with Medium Demand	770	1,350	94.3%	750	1,430	81.3%
Medium Climate Change with Low Demand	840	1,390	93.3%	950	1,520	75.5%

Table 14 summarises the modelled demand restrictions under the various climate and demand scenarios for 2020 and 2050.

Table 14 Summary of restrictions under the various scenarios for the years 2020 and 2050

	Year 2020			Year 2050		
Demand/Climate Change Scenario	Probability of restrictions	Highest level of Restrictions	Longest Period of Restrictions (months)	Probability of restrictions	Highest level of Restrictions	Longest Period of Restrictions (months)
No Climate Change with Low Demand	0.0%	0	0	0.0%	0	0
No Climate Change with Medium Demand	0.5%	1	3	0.0%	0	0
No Climate Change with High Demand	4.3%	2	11	2.0%	1	5
Low Climate Change with Low Demand	0.0%	0	0	0.0%	0	0
Low Climate Change with Medium Demand	5.0%	1	11	3.5%	1	10
Medium Climate Change with Low Demand	1.3%	1	5	0.0%	0	0

The above results show the sensitivity of the system behaviour to climate change and population growth. As expected, scenarios with higher levels of climate change or higher population lead to lower modelled storage volumes. Under such scenarios, the frequency and severity of modelled restrictions are higher, and the recovery from low-storage conditions is slower. The combinations of climate change and demographic changes with more severe outcomes were not assessed, as these would require one or more actions such as bringing forward of system enhancements, additional demand management or contingency options.

8 Conclusions and recommendations

This study required the translation of wide ranging outputs of climate change models into local catchment impacts through a significant research effort, a range of assumptions and a series of modelling tools. The series of modelling tools included climate models, rainfall-runoff models, demand modelling, Monte-Carlo simulations of streamflow and system demand under alternative climate scenarios and utilisation of Melbourne Water's water supply system simulation model, REALM. These tools were applied sequentially, with the output of one modelling tool providing the input to the subsequent tool.

This case study has highlighted changes expected in both mean annual streamflow volumes and mean annual system demand under the influence of various climate change scenarios by 2020 and 2050. In 2020, projected reduction in the mean annual streamflow is 3% to 11%, whereas in 2050, the projected range is 7% to 35%. The increase in mean annual demand is 0.5% to 2.3% in 2020 and 1.3% to 6.2% in 2050.

This case study has also highlighted climate change and demand scenarios where projected demands could be met: under the current system, by bringing forward planned system augmentations, or where additional measures would be needed. For example, by harvesting additional sources currently not utilised for urban demand or by reviewing strategic options for managing supply and demand and implementing subsequent recommendations. The study also highlights the potential buffers or shortfalls in yield under the combined effects of population increase and various climate change scenarios.

Demand-management measures and water-supply augmentations identified in the Water Resources Strategy for the Greater Melbourne area were found to be adequate in 2020 across the full range of climate change and alternative demand forecasts considered in this case study. However, some of the planned augmentations by 2050 may be required by 2020 to maintain existing levels of service, especially if anything other than low climate change should occur. Additional measures to those currently planned will likely be required between 2020 and 2050 to satisfy demand, especially if anything other than low climate change and growth projections occur.

The approach used in this study has had the potential for compounding model uncertainty, however, by utilising innovative methods of quantifying climate change uncertainties and identifying the likelihood of various changes in supply (with reference to the 1952–2001 baseline), this has been minimised. Climate-driven demand was included in the uncertainty assessment, but is a smaller component of system response. Demographic changes were not assessed in this way because of the influence of social and economic drivers affecting population. Furthermore, per capita demand is not a passive variable, but can be actively managed to increase system security, so should not be assessed in such a way.

Changes in the hydrological response of catchments will also affect how the catchment responds to a given climate. It can be argued that the change in hydrological response between the first and the second halves of the 20th century due to the 1939 fires has introduced non-stationarity into the data set utilised by Melbourne Water – not in climate per se – but in the time series of streamflow from affected catchments. This is shown in Figure 24 where average anomalies for rainfall and streamflow for the four major supply catchments track quite closely from the 1940s onwards but diverge before 1939. As a contrast, streamflows from the Upper Murray show the type of pattern that would be expected from 20th century rainfall from a hydrologically stable catchment, where flows in the second half of the 20th century are higher than those of the first half, as is the case for rainfall.

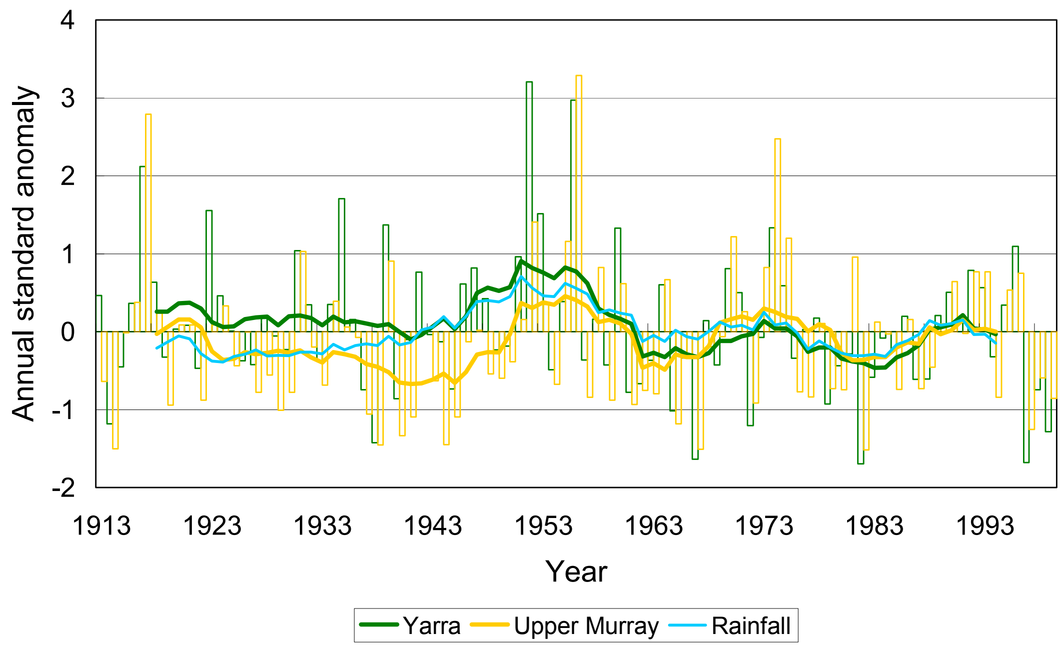

Figure 24 Annual streamflow anomalies for the four major supply catchments to Melbourne (Yarra) and Upper Murray flows into the Hume Weir (anomalies from 1952–1999) shown with 11-year running means. Also shown are the average rainfall anomalies and 11-year running means from the composite series constructed for the four main supply catchments.

The choice of baseline climate data will also have an impact on results. Here, we have compared changes to system yield from 1952–2001 data therefore, implicitly considered that the mean changes in projected climate will divert from that baseline. However, the dry run of years from 1997 reminds us that there are other influences on climate that were not explicitly considered in this study. Step changes in decadal rainfall means are possible, as has been observed in south-west Western Australia. If the dry conditions from 1997 were sustained for several decades and decreases in rainfall and increases in potential evaporation experienced on top of that, system yield would be much lower than that diagnosed for changes based on a baseline of 1952–2001.

Therefore, the results of this study need to be interpreted within the context of the uncertainties within many of the projections and modelling approaches used. Among the key uncertainties are those due to climate change, population growth, the quality of data used for modelling, modelling tools, assumptions on system configurations, system operations, restriction trigger levels, future requirements to be met by the system including environmental flows and level of service.

Recommendations of this study are:

- Maintain a watching brief on the state of the art of climate change modelling
- Assess anticipated changes in daily rainfall patterns on runoff, system yield and flood risks
- Review the quality of data used for water supply system modelling, particularly inflows to major harvesting reservoirs, and seek to improve the quality of data where possible.
- When modelling the effects of climate change on the water supply system in future, recalculate reservoir inflows to include historical evaporation losses and model reservoir evaporation losses using a separate function. This applies especially for Thomson Reservoir.
- Periodically review the "Water Resources Strategy for the Melbourne Area" to incorporate implications of climate change including cost/benefit analysis.
- Conduct on-going monitoring of climate change impacts on streamflow, water supplies and water demand along with population trends.
- Undertake risk assessment / modelling of multiple, potentially cumulative factors such as reduced streamflows coupled with increased bushfires in the catchments and increased environmental flow requirements.
- Develop and evaluate long-term contingency options to respond to severe climate change.
- Monitor effectiveness of water use reduction strategies.
- Incorporate climate change projections into the design, planning and operation of major resource management systems wherever consistent with a "no-regrets" policy, i.e. one that would generate net social benefit whether or not there is climate change.

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Appendix A
Case Study of Drainage and Urban Waterways - Flooding

Background

Melbourne Water is the drainage authority for the Greater Melbourne area and the Flood Plain Management Authority by delegation from the Minister responsible for the Water Act and is responsible for regional drainage management, including large drains, rivers and creeks, and works closely with local councils, who control local drainage systems and the Port Phillip and Westernport Catchment Management Authorities. Melbourne Water is also a referral authority in the planning process and receives applications for urban subdivisions and other developments from councils.

The Melbourne Water area of responsibility contains a range of infrastructure assets that assist in managing drainage, including 140 retarding basins, 193km of levee banks, four tidal gates and 1125km of underground stormwater drains, pumping stations and 4500km of waterways. This excludes the vast extent of local council drainage structures.

As a result of these responsibilities the implications of climate change in flooding is a key area of interest in the climate change study.

Factors affecting the frequency, depth and duration of flooding in urban areas are very complex, and may be influenced by a range of interacting influences including:

- Local climate conditions influencing storm characteristics
- Rainfall intensity, temporal patterns, and storm event rainfall totals
- Catchment shape, slope, elevation and location
- Soil types
- Catchment wetness prior to a storm event
- Drainage network and location of storms over the network
- Developments in catchment, including the amount of permeable area, open space, wetlands, paved or sealed areas
- Drain, infrastructure and waterway condition and capacities
- Flow paths and impediments to flow in a catchment area
- Flow at the time of the storm and the contribution of flow from upstream areas
- Tidal or other downstream influences, for example flood levels in downstream reaches of the waterway or drain

Local property impacts of flooding, often the most visible and costly impact of flooding, will also be influenced by local factors including:

- Local backwater influences and wave action
- Design standards used for property siting. This includes the return period for the flood event and the freeboard above the flood level to provide for local uncertainties such as backwater and wave action

- Extent of hail and rubbish in runoff and extent of flow blockage during an event
- Prior warning of storm, flood or potential flooding conditions

Melbourne's drainage system has been in place for more than 70 years. Current design standards, which have been in place in new development areas for more than twenty five years provide for a '1 in 100 year' Average Recurrence Interval (ARI) design standard for flooding. The use of the 1in 100 year design standard is a commonly used international standard and is used to define the extent of the overland flow along the drainage system or flooding from overtopping of river banks which would occur on average once in every 100 years. In other words, it means that there is a one-percent chance in any one year of such an event occurring.

In many areas of the greater Melbourne area, often in older established areas, the drainage system was built to the standards of flood protection that existed at the time, which may be less than that provided under current standards in newer areas. Melbourne Water has a capital works program to improve infrastructure, and works with councils to address flooding issues. However, there a large costs to the community in upgrading upgrade the existing drainage system in all areas. In many areas mitigation works are not cost-effective, and the most practical and equitable solution is to adapt development to suit the existing drainage system.

Flooding Desk Study

Rainfall temporal patterns and storm event rainfall totals are key factors in assessing the changes in expected flood frequency, depth, extent and duration over current estimates for a given recurrence interval flood event.

For the desk study, the CSIRO Division of Atmospheric Research climate change models suggest increases in storm event rainfall totals and intensity due to the warmer temperatures and the potential for the atmosphere to contain higher moisture levels.

Based on interpretation of these models CSIRO suggested a preliminary estimate of a 5% increase in total storm event rainfall per degree of climate warming. These estimates are preliminary and were provided solely for the purpose of assessing the sensitivity of the case study drainage system to potential rainfall changes under climate changes

While the climate change models suggest the potential for increased storm intensity, the translation of the climate change scenarios to local storm and catchment events is highly uncertain given the range of influences on catchment flooding described above.

To examine the issues and influences in converting climate change scenarios to localised flooding a case study was undertaken in a developed area to examine the impact on flooding of climate change scenarios.

The catchment used for the desk study is a small catchment in the outer eastern suburbs of Melbourne for which detailed flood studies for flood mitigation works for the 1 in 100 year Average Recurrence Interval event have been undertaken. The catchment is approximately 120 ha and comprises of a series of local drainage systems feeding to a main drain and a retarding basin for attenuating high flow events. A schematic of the catchment used for the case study is shown in Figure A1. Around 70% of the catchment area comprises of residential with block size greater than 650m^2. The remainder of the catchment consists of public parks, recreational, business and industrial areas. The catchment and drainage infrastructure is typical of that in many urban areas of Melbourne. Modelling work for the 1 in 100 year ARI event has shown that the critical duration for the event is 2 hours.

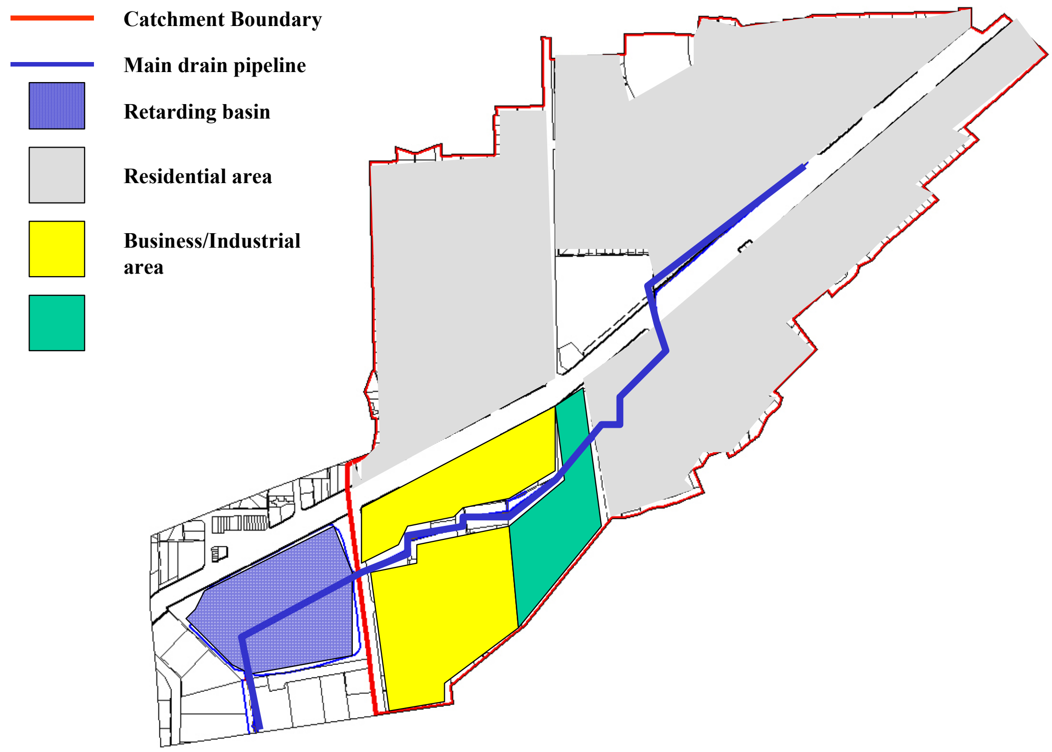

Figure A1 – Schematic of Case Study Area

The use of an area for which flood studies had been undertaken enabled quantitative assessment of the impact of climate change scenarios using calibrated catchment models on the expected flow rates associated with flooding and flood levels.

Rainfall Totals

For the purposes of the case study a preliminary estimate was provided by CSIRO of a 5% increase in total storm event rainfall per degree of climate change to apply across all recurrence interval events. As discussed above this was provided solely for sensitivity purposes for the desk study rather than an accurate assessment of expected outcomes of climate change scenarios.

Rainfall totals for the 1 in 100 year ARI, 2-hour storm event were factored in accordance with a 5% increase in totals per degree of climate change for years 2020, 2050 and 2100 and were based on a mean temperature increase for the years 2020, 2050 and 2100 of 0.6^{o}C, 1.5^{o}C and 3.1^{o}C respectively.

Flood flow rates for each scenario were obtained using the new rainfall data and running the RORB model for the catchment. The approach adopted in the case study implicitly assumes that the catchment characteristics and model parameters used not change under climate change scenarios. These parameters include the key RORB parameters associated with the non-linear storage functions and model loss rates (i.e. initial and continuing).

After flow rates were determined using RORB, flow data for the years 2020, 2050 and 2100 scenarios were then used in the hydraulic model, XP-Storm, to determine the impact on flood levels.

Table A1 shows the results of the 5% increase per degree of climate change for the case study and shows the changes in flow rates, and flood levels with a 5% increase in rainfall per degree of climate change for years 2020, 2050 and 2100.

Table A1:
Case Study Results - 5% increase in rainfall totals per degree of climate change

	5% Case Study		
	Year 2020	Year 2050	Year 2100
Total Rainfall (mm)	60	62.6	67.2
Increase in total rainfall from current (mm)	1.8	4.4	9.0
Increase in peak flow rate (cumecs)	0.5 (4%)	1.0 (8%)	2.5 (20%)
Average increase in Flood Levels (mm)	10	20	50

The table highlights for the small catchment that that there is limited incremental shifts in rainfall totals, peak flow rates and flood levels for this ARI associated with a 5% increase in rainfall total. In particular, flood level changes are well within the 300mm freeboard criteria adopted for developments in potential flood areas, and well within the expected local on-site variability from model error, backwater effects and wave action and local variability.

In order to test the sensitivity of flooding estimation for rainfall total further assessments were undertaken assuming a 10% and 20% increase in rainfall per degree temperature increase for the 1in 100 ARI event. The results are shown in Tables A2 and A3.

Table A2: 10% increase in rainfall totals per degree of climate change			
10% Case Study			
	Year 2020	Year 2050	Year 2100
Total Rainfall (mm)	61.7	66.9	76.3
Increase in total rainfall from current (mm)	3.5	8.7	18.1
Increase in flow (cumecs)	1.0 (8%)	2.3 (19%)	5.0 (42%)
Average increase in Flood Levels (mm)	30	50	110

Table A3: 20% increase in rainfall totals per degree of climate change			
20% Case Study			
	Year 2020	Year 2050	Year 2100
Total Rainfall (mm)	65.2	75.7	94.3
Increase in total rainfall from current (mm)	7	17.5	36.1
Increase in flow (cumecs)	2.0 (17%)	4.7 (40%)	10 (84%)
Average increase in Flood Levels (mm)	50	110	200

Tables A2 and A3 show that for the 10% case study Years 2020 and 2050 scenarios the average increase in the flood levels are 30 mm and 50 mm respectively, which is similar to the 5% case study for years 2050 and 2100 respectively. The Year 2100 scenario of the 10% case study has an average increase in the flood levels of 110 mm, which is the same as the 20% case study Year 2050 scenario. For the Year 2100 scenario of the 20% case study, the average increase in flood levels is 200 mm.

Although large increases in precipitable rainfall for a given ARI event in 2100 could result in potentially significant increases in flood levels of 110 mm and 200mm the increases are still within the 300 mm freeboard criteria that is used to set floor levels above the applicable flood level for a property. Even in older areas, many properties, particularly along waterways, currently have a freeboard of up to 600mm.

The average recurrence intervals for the rainfall totals for the 5%, 10% and 20% increase per degree of climate change were determined under current climate conditions as per Australian Rainfall and Runoff (1993). Table A4 shows that even with the 5% shift there are significant increases in the ARI from 1 in 130 (by 2020) to around to 1 in 250 years events (by 2100). Significant shifts in the ARI could be expected should climate change result in shifts in rainfall totals by 10% and 20% increases in rainfall per degree of climate change.

Based on the storm intensity, frequency and duration information for a nearby location to the case study, ARIs have been determined for the 5%, 10%, 20% rainfall/temperature scenarios. Table A4 highlights that the ARIs for the rainfall totals changes to the 1 in 100 ARI event to beyond 1 in 500 years. It should be noted that the results may not be accurate for ARIs greater than 100 years.

Table A4:
Results of ARI Analysis

Case Study	Scenario	Rainfall Total (mm)	Average Rainfall Intensity (mm/h)	ARI (years)
5%	Year 2020	60.0	30.00	130
	Year 2050	62.6	31.30	160
	Year 2100	67.2	33.60	250
10%	Year 2020	61.7	30.85	150
	Year 2050	66.9	33.45	240
	Year 2100	76.3	38.15	>500
20%	Year 2020	65.2	32.60	210
	Year 2050	75.7	37.85	>500
	Year 2100	94.3	47.15	>500

Rainfall Temporal Pattern

For the purpose of the desk study, and in the absence of defined local temporal patterns for storm events from climate models it was necessary to make an interpretation of the potential changes in temporal patterns. This is complex, and has highlighted an area of flood estimation practice that will require reconsideration if flood management planning is to include direct provisions for climate change.

Current Australian flood planning practice adopted in Australian Rainfall and Runoff (AR&R) (I.E.Aust 1993) separates Australia into regional zones with similar climatic conditions. Storm event temporal patterns, for a given return period event are assumed to be similar across these regions for the purposes of the design storm event. Melbourne and Sydney fall within the same zone for temporal patterns used in Australian Rainfall and Runoff.

In Australian Rainfall and Runoff, temporal patterns for storm events used for each zone and for a range of storm durations have been determined based on analysis of a range of observed storm patterns. Figure 1 shows the temporal patterns from AR&R covering the Melbourne region for 0.5, 1, 2 and 6-hour duration temporal patterns. Figure 2 highlights the change in shape of the temporal patterns for the various durations.

For the case study the critical duration flood event under current design conditions was the 2-hour event, the temporal pattern for which shows peak rainfall intensity some thirty-five minutes into the event.

As an example of the shift in temporal patterns for various locations, Figures A3 and A4 show the different temporal patterns for two severe storms in Melbourne in December 2003, and January 2004. These events were high intensity, short duration events that resulted in localised flash flooding.

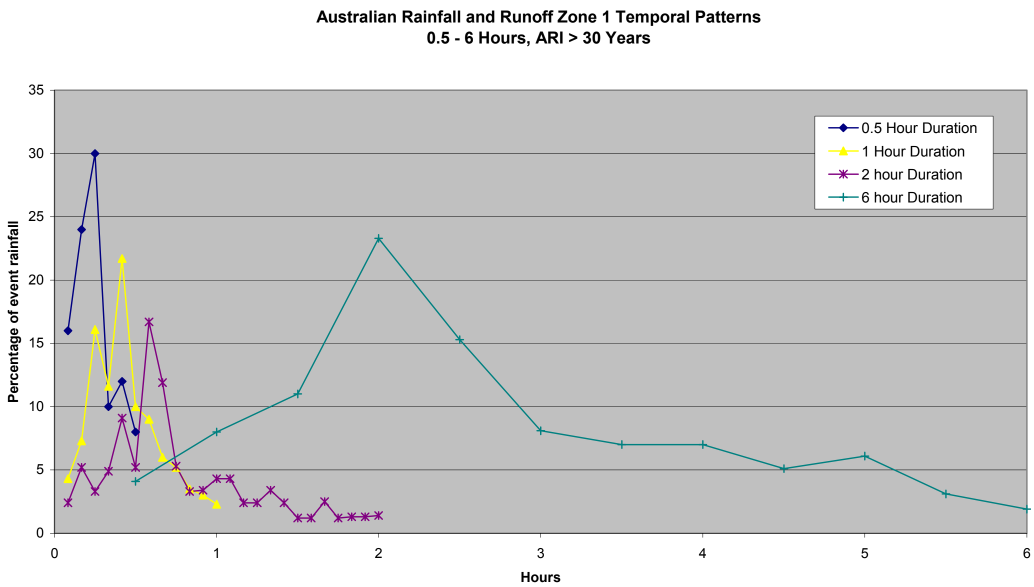

Figure A2: Zone 1 Temporal Patterns (including Melbourne) from Australian Rainfall and Runoff for 0.5 to 6 hours duration

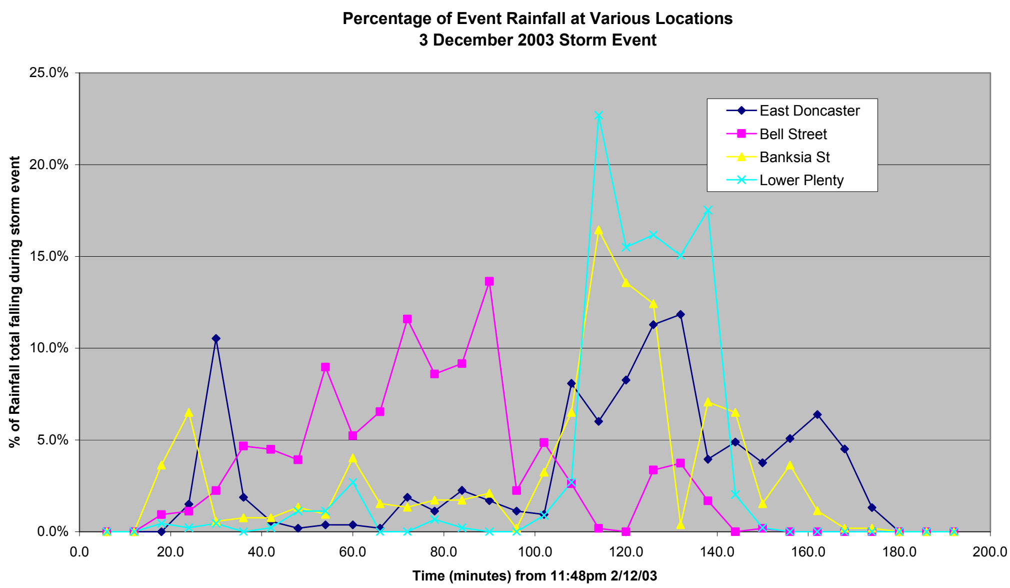

Figure A3: Temporal Patterns for 3 December 2003 Storm Event for various locations

The temporal patterns show different characteristics to design event patterns in Figure A1 for similar durations and in different locations, and highlight the variability of temporal patterns under current conditions and without the changes that might occur from climate change.

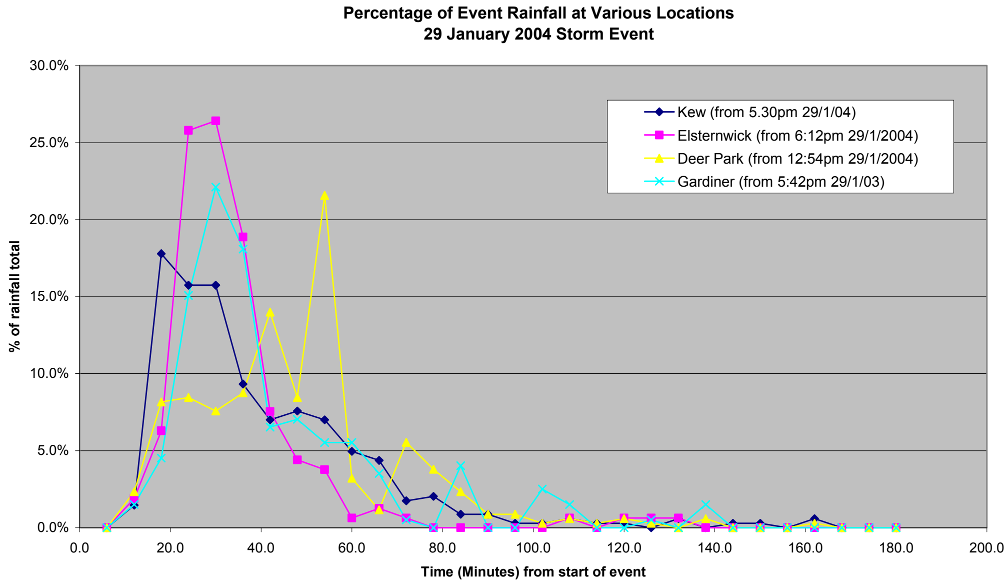

Figure A4: Temporal Patterns at various locations for 29 January 2004 storm event

The observed temporal pattern for these severe storms highlights the variability in the patterns for each event and between locations for the same event. The data also highlights the difference between design temporal patterns and observed patterns. For example, observed patterns show peak storm intensity of over 20% of the event rainfall, whereas the design rainfall for the 2-hour events shows peak rainfall of around 15% of event rainfall.

The shape of the temporal pattern for flood estimation has implications for the estimated peak flow and the timing of the peak flow for short duration extreme events a finding noted by Jordon et al, (2003) in a case study for a small catchment. However, under climate change scenarios the assumptions surrounding temporal patterns may require further review to take account of the potential for increased convection, particularly in shorter duration events. Nevertheless changes to the event temporal patterns under climate change can be expected to have implications for:

- Changes to flooding risk and extent of flooding in existing drainage infrastructure

- The design of new drainage systems to cope with specific events
- The mix and capacities of storage and conveyance capacities within a given drainage system, or sub-catchment.

The implications of temporal shifts under climate change also have implications for flood events into and downstream of the water supply system, peak inflows and overflow events in the sewerage system.

Conclusions

This preliminary investigation, based on the CSIRO data from their investigations into climate variability and change, shows that for the catchment selected for this study:

(i) The increase in flood levels will most likely be within the 300 mm freeboard criteria that is used to set floor levels above the applicable flood level for a property.

(ii) The ARI analysis indicates that three of the nine scenarios will result in rainfall that, were it to occur today, would be considered to be greater than a 1 in 500 year storm event. Another three would be equivalent to an event greater than 1 in 200. However, these figures should be considered indicative only.

(iii) The temporal patterns adopted under climate change may have implications for flood volumes and levels and flood mitigation works.

The results presented above are for a single catchment only, and may not reflect the effects of increased rainfall on other catchments as the impacts on rainfall events and flooding, but the impacts will be site dependent.

In addition freeboard allowances included in existing and proposed development provide a significant buffer for climate change. However, in areas where there is older infrastructure or where flood mitigation works do not include significant freeboard allowances there may be changes to flood risk due to climate change.

Appendix B
Case Study of Sewerage System – Sewer Overflows

System Description

Melbourne Water undertakes the wholesale function for Melbourne's sewerage systems, operating the larger main and trunk sewers and treatment plants. The three retail water companies operate the reticulation from individual properties and the branch sewers which deliver flows to Melbourne Water's transfer system, as well as some small regional treatment plants.

Approximately 95% of Melbourne's sewerage is treated at the Western Treatment Plant at Werribee and Eastern Treatment Plant at Bangholme. The inflow to these plants comes via the sewerage transfer system, an extensive pipeline system across metropolitan Melbourne collecting sewage from residential, commercial and industrial properties.

Western Treatment Plant receives approximately 54% of the flows via the Western Transfer System and Eastern Treatment Plant receives approximately 44% of the flows via the Eastern Transfer System. However limited interconnection exists to allow flexibility to transfer approximately 14 % of flows from some central areas to either treatment plant.

The transfer system incorporates underground pipelines, pumping stations, emergency relief structures and detention tanks.

The underground pipelines (sewers) generally transfer flows by gravity. However, major pumping stations to lift sewage and enable continuous transfer in the system are located at:

- Hoppers Crossing
- Brooklyn
- Kew
- North Road Caulfield

Emergency Relief Structures provide a controlled means to discharge sewer flows to waterways when the sewers become backed up or overloaded due to high rainfall infiltration or a blockage. They provide an essential means to prevent release of sewage into property fixtures. Melbourne Water maintains approximately 43 Emergency Relief Structures thorough the transfer system.

The Western Treatment Plant at Werribee is the treatment facility for the Western System and combines land filtration, grass filtration and lagoon processes for the treatment of sewage to a secondary standard. Effluent is discharged into Port Phillip Bay from four outlet points.

The Eastern Treatment Plant at Bangholme is the treatment facility for the Eastern System and uses the activated sludge process for treating sewage. Effluent is discharged to Bass Strait on the Mornington Peninsula at Boags Rocks.

All sewage discharges from the treatment plants are subject to EPA Victoria licence conditions.

Melbourne’s sewerage system, as in most Australian cities, is separate to the stormwater systems and is designed to operate independently. However, water may enter the sewerage system as infiltration into pipelines from rainfall, or through illegal property connections (mainly stormwater runoff from roofs) going directly into the sewerage system. While the amount of infiltration entering Melbourne sewers for the Melbourne is low by world standards, rainfall events do result in extra volumes of water entering the sewers. During extreme storm events high volumes of infiltration can result in increased flows in sewers and in local areas this could cause sewers to overflow from emergency relief structures to the environment.

Storm events are the key factor contributing to sewer overflows from emergency releases structures in the sewerage transfer networks. Under climate change scenarios, rainfall totals and intensity are expected to increase. However the extent of these changes and the implications for recurrence intervals for storm events is highly uncertain. Under climate change scenarios, changes to rainfall totals and intensities in storm events could increase the risk of sewer overflows both within the transfer system and local reticulated sewage collection system.

The hydraulic capacity of Melbourne’s sewerage system is designed and operated on the basis of containing all flows in the sewer for storm events with an average recurrence interval (ARI) of 1 in 5 years or less. This design criteria forms the basis of the Memorandum of Understanding with the EPA Victoria for sewer overflows to meet the requirements if the State Environment Protection Policy (SEPP) Waters of Victoria – Schedule F.7. The SEPP requires that protection agencies responsible for sewerage provision and management must ensure that losses of sewage from the sewerage system through sewer overflows, leakages and collapses are controlled and minimised and that new sewerage infrastructure is capable of containing the flows associated with at least a 1 in 5 year rainfall event and that existing infrastructure must be progressively upgraded to meet the 1 in 5 year performance benchmark.

Detailed modelling and analysis of the hydraulic behaviour of sewer flows in the main transfer system operated by Melbourne Water for the 1 in 5 year event enables assessment of the potential for sewer overflows under future development, flow and storm scenarios. A computational model of the sewer network was developed and calibrated using ‘InfoWorks’, a hydraulic modelling package developed by Wallingford Software.

The model provides information on transfer system performance, and allows:

- The assessment of the extent and severity of hydraulic capacity constraints in the system, particularly for the design criteria for wet weather flows
- Evaluation of options and timing of system augmentation
- Development of operational strategies for asset maintenance, construction and contingency planning

- Optimisation of the operation of the system to minimise expenditure and maintain standards of service
- Assessment of system performance under future growth and development scenarios for Melbourne

Figure B1 shows a schematic of the Melbourne transfer system network model. All of Melbourne Water's sewerage transfer assets, and retail water company collector sewers of 450mm diameter and above are included in the model.

The Melbourne Water Sewerage Transfer Network model uses InfoWorks CS, to simulate rainfall and runoff and hydraulic transfer in the sewerage transfer network operated by Melbourne Water. While the model takes account of the local reticulated sewerage collection system it models the main transfer systems than transfer water to the mina treatment plants. The software for the model was developed by Wallingford Software and is commonly used commonly in Australia and throughout the world for modeling sewerage systems.

The model has been developed to reflect expected system flows due to population growth and development in the year 2022/23. The network developed includes system developments, consistent with long term capital plans to ensure Melbourne Water's sewerage transfer network complies with the 1 in 5 year containment criteria in 2022/23.

Areal adjustment factors also included in the model for the 1 in 5 year and 1 in 10 year ARI events to account for the area over which the rainfall is expected. These have been determined in accordance with Derivation of Areal Reduction Factors for Design Rainfalls in Victoria (CRCCH, 1996).

Climate Change Scenarios

As for drainage and flooding, rainfall temporal patterns and storm event rainfall totals are key factors in assessing the changes in expected flow rates and the risk of sewer overflows. As noted in the flood case study, CSIRO Division of Atmospheric Research climate change models suggest increases in storm event rainfall totals and intensity due to the warmer temperatures and the potential for the atmosphere to contain higher moisture levels. Risk assessment undertaken as part of this study also identified the potential for increased risk of sewer overflows as a result of climate change.

As in the flooding desk study, CSIRO suggested a preliminary estimate of a 5% increase in total storm event rainfall per degree of climate warming. These estimates are preliminary and were provided solely for the purpose of assessing the sensitivity of the case studies.

While the climate change models suggest the potential for increased storm intensity, the translation of the climate change scenarios to local storm and catchment events is highly uncertain given the range of influences on local conditions. To examine the issues and influences in converting climate change scenarios to local conditions the transfer system model was run and system behaviour assessed for:

- Current design event behaviour
- System behaviour in around 2020 with a 5% increase in rainfall totals per degree of climate change,

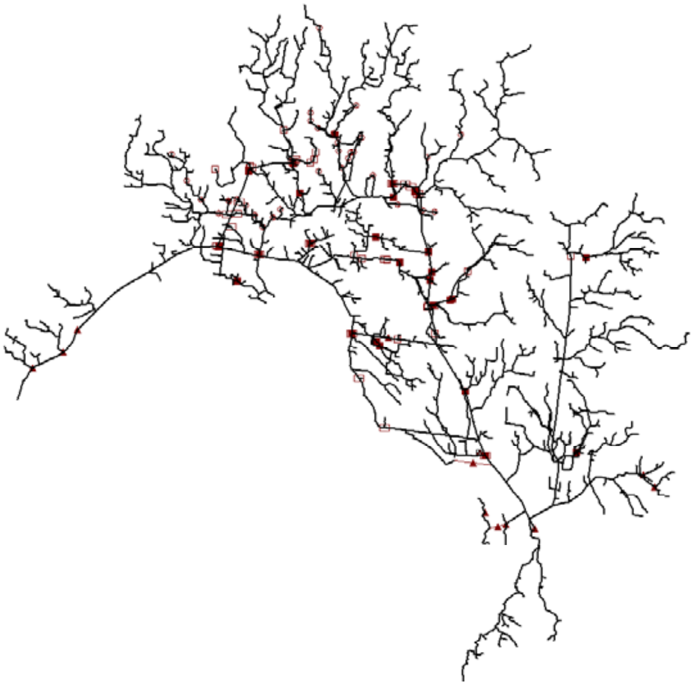

Figure B1 – Schematic of the Melbourne Sewerage Transfer System

Analysis of the transfer system has shown that for a design rainfall event of 1 in 5 ARI, the 24-hour duration event is the critical event for Melbourne Water's sewerage transfer network. That is, the event duration that results in the highest flow volumes within the network at key points. Shorter duration events are generally more critical for smaller catchments and pipes.

Modelling of the sewerage network is based on the use of Melbourne point rainfall total for a 1 in 5 year ARI, 24 hour duration design rainfall event is 73.8mm with sub-catchment area variations and areal reduction factors.

Under climate change scenarios, localised storm intensity duration, frequency and duration characteristics and temporal patterns could have implications for local system capacity constraints and local risk of overflows. Like the flooding desk study, variations in the temporal patterns were not assessed. However assessments were made of the implications of changes in rainfall totals for the design event.

As with the flooding study, the purpose of the case study was to assess the system implications of a shift in rainfall related to climate change scenarios. Event Rainfall changes were assessed on the basis of a 5% increases in rainfall total per degree of climate warming, with the assessments of climate change derived from the CSIRO estimates for the Melbourne Area.

Total rainfall increases for point rainfall the 1 in 5 year ARI were of the order of 2.2 mm for the 24-hour duration event. This represents a 3% increase in rainfall totals over current design totals. Preliminary assessment showed that this small increase in rainfall total over the 24 hour duration event will result in minimal increase in the modelled rainfall induced infiltration to the sewerage transfer network and to the risk of overflows in the sewerage network.

For comparative purposes, a 1in 10-year ARI event 24-hour event was also assessed. Melbourne point rainfall total for a 1 in 10 year ARI, 24-hour duration design rainfall event is 84.4mm. The intent of this was to show the sensitivity of the system to rainfall increases that might occur should there be a shift in the ARI under climate change. The increase in total point areal rainfall for the 24 hour, 1 in 5 year ARI event was 10.6mm, or a 14% increases in rainfall total.

Modelling Study

The modelling study showed that Melbourne Water sewerage transfer network in the year 2022/23, with current augmentation plansis compliant for the 1 in 5 event with the small shift in additional rainfall anticipated under climate change.

The modelling also shows that an increase in rainfall to the 1 in 10 year ARI event results in one emergency release structure spilling into the Yarra River in a inner Melbourne suburb.

This preliminary model result suggests if the shifts in rainfall totals were to increase for a given ARI, for example rainfall events of the 1 in 10year ARI were to become a 1 in 5 year event, there may be some limited increases in sewer overflows, above the current design standards. This increase in rainfall total from a 1 in 5 year ARI event to 1 in 10 year ARI event represents a 10.6mm or 14% increase in rainfall totals.

While the study suggests that anticipated rainfall changes of the order of 5% per degree of climate warming can be accommodated within the transfer system, the sewerage transfer system would be sensitive to larger increases in rainfall totals under potential climate change scenarios.

The preliminary result has not identified the cause of the overflows to ascertain whether it is caused by local hydraulic under-capacity or by surcharge of sewers. The results are also based only 24-hour duration events and under climate change scenarios, it may be that temporal pattern shifts and rainfall intensities may have implications for the critical duration of the design event.

The case study has been based on the Melbourne transfer system and has not assessed the implications of local sewer overflows within the local reticulated collection system (i.e. where sewers are typically less than 450mm diameter). The implications of potential climate change scenario would need to be assessed further.

Ongoing planning and review of the sewerage transfer network will provide for the ability to accommodate changes in flow due to population and developments.

Options for accommodating these changes may include reduction in inflows due to water conservation , increases in infrastructure and sewer capacities and changes to system operation. In overlaying the potential implications of climate change scenarios on expected long-term changes in population and flows, it could be expected that climate changes could be more readily adapted to with gradual climate change, than rapid shifts in climate.

Conclusions

The design of the sewerage transfer system is based on meeting the requirements of the State Environment Protection Policy (SEPP) and provides for containment of the 1 in 5 year critical duration event.

Storm events are the key factor contributing to sewer overflows from emergency releases structures in the sewerage transfer networks. Under climate change scenarios, rainfall totals and intensity are expected to increase. However the extent of these changes and the implications for recurrence intervals for storm events is highly uncertain. Under climate change scenarios, changes to rainfall totals, temporal patterns and intensities in storm events could increase the risk of sewer overflows both within the transfer system and local reticulated sewage collection system.

Assessment of the implications of the potential implications of change to rainfall totals for the sewerage transfer network suggests that small changes in rainfall totals for a given recurrence interval event may not impact on system design, but the extent of overflows is affected, indicatively, by larger shifts in rainfall totals on current events Ongoing planning and development of the sewerage system to provide for increasing flows due to population growth will assist in maintaining compliance with overflow design standards, but rapid climate changes are potentially more difficult to design for than gradual changes.

The implications of changes in temporal patterns under climate change, and the risk of overflows in local collection system networks under climate change scenarios has not been assessed. Further detailed assessment would be required to assess the direct implications of temporal patterns and climate change at specific sites within the transfer network.