GOVERNMENT OF WESTERN AUSTRALIA

Climate Variability and Water Resources Workshop

Summary of outcomes

Water Resources Technical Series

Water & Rivers Commission Report WRT 5 1996

Water and Rivers Commission

CSIRO Australia

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CLIMATE VARIABILITY AND WATER RESOURCES WORKSHOP

Summary of outcomes

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Executive summary

The current low rainfall and streamflow sequence being experienced in south-west Western Australia is of major concern to the Water and Rivers Commission and the Water Corporation as the state water resource manager and provider of water services, respectively. The current water restrictions for Perth are a symptom of this sequence of low rainfall, and have considerable economic, social and environmental implications.

In response to these concerns, a Climate Variability and Water Resources in the South-West of Western Australia Seminar and Workshop were held on January 31 and February 1, 1996, respectively. The seminar and workshop brought together key international, national and local people from the University of Washington (Seattle), the Bureau of Meteorology, the CSIRO Divisions of Atmospheric Research, Oceanography and Water Resources, the Centre for Water Research, the Department of Conservation and Land Management, the Water Corporation, and the Water and Rivers Commission with knowledge of climate variability and change and their impacts on water supply for the South-West.

The objectives of the seminar and workshop were to:

- Review the current state of knowledge of climate change and variability, and their impacts on water supply, for the South-West;
- Review the current state of seasonal and interannual climate forecasting for the South-West;
- Review current water supply planning philosophies and techniques, and to recommend changes to these to manage climate change and variability (drought) impacts in the South-West; and
- Identify research needs.

Major findings of the seminar and workshop include:

- There has been a marked decrease in annual rainfall over almost all of the South-West, west of Albany. If the consequent reductions in streamflow are sustained, there will be serious implications for the reliability of water supplies.
- The current downward trend in winter rainfall over the South-West appears to be due to a general warming of the Indian Ocean over the last few decades and variations in the large-scale atmospheric circulation across southern Australia since 1971. This trend may be regarded as a part of the natural variability of the climate system.
- Studies of tree ring and coral growth data suggest that decades of very low streamflow have been experienced in other parts of the world at various times (e.g., Colorado River, USA; Burdekin River, Queensland).
- Definitive statements about the fundamental nature of climate change, its expected magnitude, and the timing and rate of the change are beyond the current limits of science.
- A prudent approach is to continue to implement water use efficiency measures and to investigate options for responding to a sustained low rainfall sequence.
- A comprehensive response by water service agencies and water resource managers to the sustained low rainfall and streamflow sequence will require a sustained and integrated program of research.
- There are bright prospects for developing new or improved methods for water resources planning and management in the South-West.

It is recommended that a liaison group involving persons and agencies involved in climate and water resources research as well as water resources management and planning be formed to:

- Determine how industry can make the best use of existing knowledge and current research efforts;
- Review opportunities for further climate variability, climate forecasting, and water resources research for the South-West;
- Prepare costed research proposals addressing the issues raised and areas addressed in this report; and
- Seek and / or provide funding for those proposals with the highest benefit in the long- and the short-term to water resource planning decision making.

1. Introduction

The current low rainfall and streamflow sequence being experienced in south-west Western Australia is of major concern to the Water and Rivers Commission as the state water resource manager and the Water Corporation as a provider of water services. The current water restrictions for Perth are a symptom of this sequence of low rainfall.

The implications of continued low rainfall and streamflow are considerable from economic, social and environmental perspectives. In response to these concerns a seminar and workshop were held on January 31, 1996 and February 1, 1996 respectively. The Climate Variability and Water Resources in the South-West of Western Australia Seminar and Workshop brought together key people with knowledge of climate variability and change and their potential impacts on water supply for the South-West.

The objectives of the seminar and workshop were to:

- Review the current state of knowledge of climate change and variability, and their impacts on water supply, for the South-West;
- Review the current state of seasonal and interannual climate forecasting for the South-West;
- Review current water supply planning philosophies andtechniques, and to recommend changes to these to manage climate change and variability (drought) impacts in the South-West; and
- Identify research needs.

The workshop consisted of three groups:

1. Climate variability and change research for the South-West
2. Forecasting of seasonal / interannual climate variability for the South-West
3. Water resources and supply planning for the South-West

The outcomes from the workshop are summarised in the following sections.

The workshop participants for the three groups are outlined in Appendix A summary from the keynote speaker, Professor Burges is provided in Appendix B. This summary outlines the research needs and priorities from Professor Burges's viewpoint. A list of seminar titles and speakers is provided in Appendix C. Appendix D is a glossary of terms used throughout this report.

2. State of understanding and knowledge gaps

2.1 Climate Variabilty

2.1.1 Long - term data sets

Correlations of tree ring data with streamflow for the Colorado River (USA) indicate that there have been periods of up to 20 years of very low streamflow. Another example of longer term climate variability is on the Burdekin River (Queensland). The Burdekin River had a period of 70-100 years when there were no significant flows. This finding was based on the presence of annual florescent bands in coral growth rings over the last 400-500 years.

Global temperatures have also varied considerably over the last thousand years, from the Medieval Warm Epoch to the "little ice age" in the 1500 to 1800s.

2.1.2 Interannual and interdecadal variability

Recent research has demonstrated not only that phenomena such as the El Niño - Southern Oscillation (ENSO) give rise to substantial interannual variability in the climate of some regions, but also that interannual fluctuations are modulated by decadal scale and longer-term variations. This interdecadal variability of the natural climate system, at least as much as interannual fluctuations, will tend to mask anthropogenic changes in climate.

Interdecadal variability can occur as a relatively smooth, long-term trend or as a 'jump'. Principal component analysis of the sea-surface temperature (SST) distribution in the Indian Ocean suggests a link between a downward trend in the winter rainfall over South-West and a general warming of the Indian Ocean over the last few decades (Drosdowsky, 1993). Further analysis by Allan and Haylock (1993) links the rainfall trend to variations in the large-scale atmospheric circulation across southern Australia.

The sea surface is considered an integrator of oceanic and atmospheric forcing.

2.1.3 Indonesian throughflow

The Indonesian throughflow is the unique feature of oceanic circulation that effects Western Australian climate. It is a system of currents flowing through the Indonesian archipelago that allows water in the upper few hundred metres to leak from the tropical Pacific Ocean into the Indian Ocean (Meyers *et al*, 1995). Indonesia is the only place in the world where warm, near equatorial waters flow between ocean-basins. The Indonesian throughflow introduces additional heat into the Indian Ocean, which is carried over large distances by currents, and ultimately released to the atmosphere (Hirst and Godfrey, 1994). This heat provides the energy that fuels the climate systems of the countries around the Indian Ocean. The Indian Ocean currents of greatest relevance to the Western Australian climate are the Leeuwin Current and the great gyre of the South Indian Ocean (made up of the South Equatorial Current, the Agulhas Current and the Circumpolar Current).

In 1983 the CSIRO established an observing system in the eastern Indian Ocean to monitor the Indonesian throughflow and its associated thermal structure. One of the important results to date is that the throughflow is influenced by ENSO which was previously thought to be primarily a phenomenon of the Pacific Ocean (Meyers, 1996). The Indian Ocean also influences Australia's climate through a mechanism that is independent of ENSO. The pattern of SST associated with these variations has a statistically significant relationship to rainfall in Australia. The warming of the Indian Ocean over the last few decades (Drosdowsky, 1993; Allan and Haylock, 1993) appears to be related to the pattern of oceanic heat transport described by Hirst and Godfrey (1994). This warming has been linked to the lower winter rainfall over the last twenty years.

2.1.4 Eastern Indian Ocean and Leeuwin Current

The oceanic circulation of the eastern Indian Ocean is dominated by the Leeuwin Current which is a shallow (< 300 m), narrow band (< 100 km) of warm, low salinity water of tropical origin that flows southward, mainly above the continental slope from Exmouth to Cape Leeuwin. At Cape Leeuwin it pivots eastward, spreads onto the continental shelf and flows towards the Great Australian Bight. Changes in the strength of the Leeuwin Current are reflected in the mean sea level changes at coastal stations. These typically show an annual amplitude of 15-20 cm, with the highest values in March (in the North-West of Western Australia) to May or June (in the South-West). This seasonal movement of the sea level maximum reflects the southward passage of the Leeuwin Current pulse.

During September to February the Leeuwin Current is weakest as it accelerates into the maximum southerly winds whereas between February and August the Current is strongest as the southerly winds are weaker. These deep surface-mixed layers may be formed due to a strong heat flux out of the ocean, which is a feature unique to the Leeuwin Current among eastern boundary currents. The west coast of Australia experiences higher mean air and sea surface temperatures as well as higher precipitation, when compared to locations at similar latitudes in Africa and South America.

There is a strong correlation between the Southern Oscillation Index (SOI, an indicator of the atmospheric component of ENSO) and west coast sea levels (a measure of the strength of the Leeuwin Current). During normal years, coastal sea levels are relatively high, indicating that the Leeuwin Current is strong. This contrasts with ENSO years in which coastal sea levels fall and the inferred transport in the Leeuwin Current is weaker.

The eastern Indian Ocean is also a region of high latent heat flux and thus evaporation rates. Results of statistical studies indicate that there is a possible relationship between Western Australian rainfall and latent heat flux in the Indian Ocean. The latent heat flux exhibits a similar seasonal variability to that observed for the Leeuwin Current and thus coastal sea levels may also be considered to be indicative of the latent heat flux and thus rainfall along the South-West.

2.1.5 Changes in climate during the 1970s

Through analysis of high quality rainfall and temperature data sets for Australia, Nicholls et al. (1996) demonstrate that during the 1970s a jump-like change occurred in the relationship between ENSO and Australian climate. In particular, annual rainfall and maximum temperature tend to be greater for a given value of the Southern Oscillation Index (SOI) now than for that value of the SOI in earlier years. Similar jumps occur in the amplitudes of the first two principal components of the SST distribution in the Indian-Pacific region. (Allan and Haylock (1993) also note a change in the large-scale winter circulation across Australia since 1971.) Using results from the Bureau of Meteorology Research Centre (BMRC) climate model, it was found that the observed changes in rainfall and temperature can be simulated when the model is forced by the observed global SST distribution. While climate models are able to simulate some changes like the jump in the 1970s, they have mixed success in simulating the observed interannual variability (Frederiksen *et al.*, 1995).

An analysis by Roger Tapp (Bureau of Meteorology), based largely on high quality rainfall records for the period 1910-1989 (see Lavery *et al.*,1992), shows a sizeable decrease in annual rainfall over almost all of the South-West, west of Albany. Strongest percentage decreases were in an area just inland from the Lower West Coast and extending south to a maximum near Walpole (see Fig. 1). Not surprisingly, the trend in May-October rainfall closely matched the annual rainfall trend. November-April trends were weaker and more varied. Within the wet season it was the later months that showed the strongest downward trend.

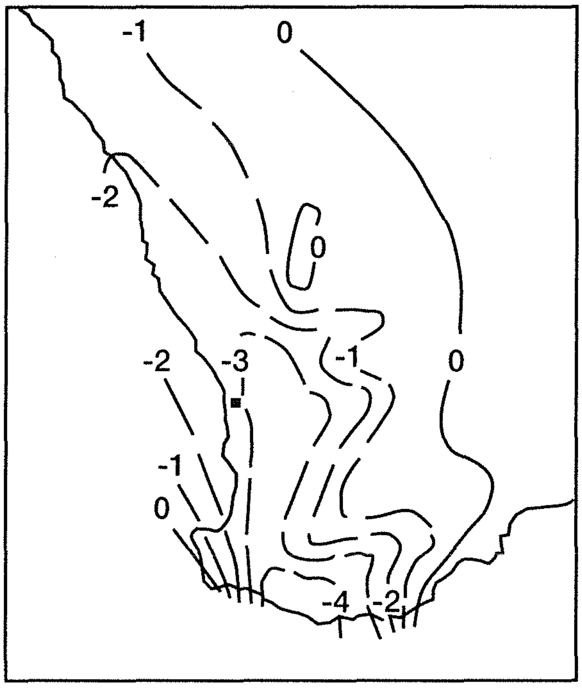
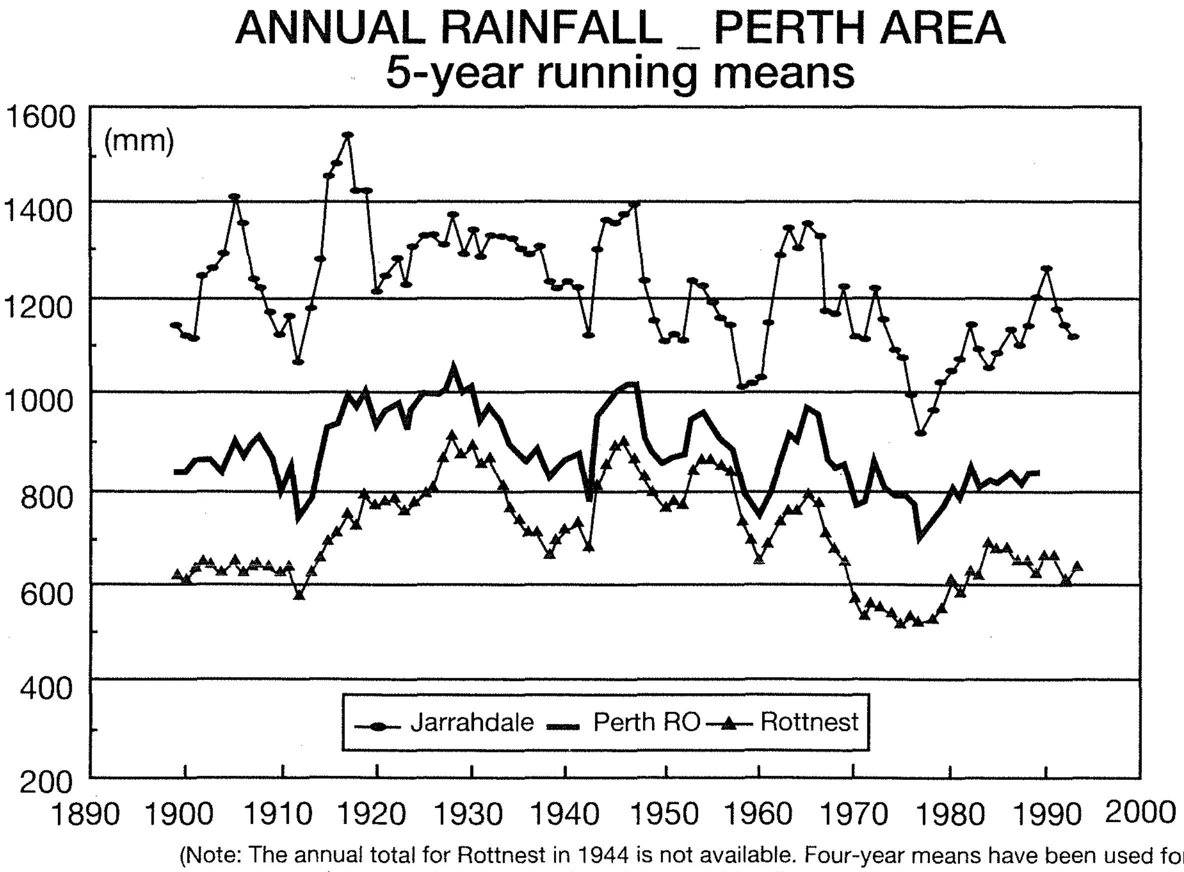


Figure 1: Trend in annual rainfall over the south-west of Western Australia, 1910-1989 (% per decade).

Such analyses obviously depend strongly on the chosen starting and finishing dates. The records for individual stations, such as those in Fig. 2, give another perspective. Many south-west stations experienced an increasing trend late last century and early in this century.

Similar upward and downward rainfall trends, on scales of decades to centuries and beyond, can be found in many other long-term rainfall records. They are regarded as part of the natural variability of the climate system and may be linked to subtle variations in atmospheric circulation patterns.



(Note: The annual total for Rottnest in 1944 is not available. Four-year means have been used for incorporating that year in order to avoid a discontinuity in the graph.)

Figure 2: Variations in the annual rainfall in the Perth area since 1897

Human activities can also affect rainfall, through changes to land surface and atmospheric composition. Any human-induced trends are usually very difficult to detect above the 'noise' of natural variability. Improved modelling should enable better definition of rainfall changes that might be expected from such processes, for comparison with records from high quality stations.

Five simulations have been undertaken using the CSIRO9 GCM forced at the surface by historically observed SSTs from 1871 to 1991. Multiple simulations have been done with slightly different initial conditions to allow for the so-called chaotic behaviour of the atmosphere, meaning that different weather sequences can occur for the same average climatic state. It is planned at present to analyse daily weather sequences from four of these simulations, from 1955 to 1990, essentially for studies over eastern Australia. With supplementary funding, the analysis could be extended to include weather over the South-West. This would see if the GCM simulations reproduced the observed behaviour during the period of rapid decline in rainfall over the region, and could help identify the cause. It would also be a guide as to whether GCM simulations could be used for seasonal forecasting in the region, given accurate forecasts of SSTs. BMRC GCM runs forced by observed SSTs for the periods 1950-1990 and 1880-1990 have reproduced trend/jump in 1970s.

2.1.6 Climate change

The most recent published outcomes of climate change scenarios for rainfall in the South-West is a change in winter rainfall of ±10%.

Limitations on these scenarios arise from several sources, including:

- The coarse resolution of the computational grids used in current GCMs;
- A number of significant assumptions are made about the forcing conditions for climate models;
- The models have known deficiencies or simplifications in their representation of particular processes, such as clouds, land-surfaces and mixing in the oceans;
- Changes in background aerosols and ozone are generally not represented in the models;
- There are external influences, like volcanoes and solar variations, that are not included in the models because they cannot be predicted; and
- The non-linearity of the climate system means that it is inherently chaotic, in the sense that simulations are very sensitive to the initial state of the system.

Assessments of climate change impacts on the surface water resources of the South-West by the CSIRO DWR and others suggest marked changes in winter streamflow regimes and that flooding may become a larger problem in many areas. However, such assessments are subject to uncertainties in:

- The level of interannual variability in our projected climate due to inadequacies in GCM simulations of precipitation at local and regional scales;
- Changes in water budgets due to changes in vegetation cover and plant water use;
- Future water demand; and
- Socio-economic and environmental impacts of adaptation and mitigation measures.

Over the next few decades, natural climate variability may mask any signals from anthropogenic climate change. It is noteworthy that GCM runs for enhanced greenhouse conditions have not produced the trend/jump in rainfall series observed in the 1970s.

Tools are being developed to improve assessments of climate change impacts (e.g., deterministic and stochastic downscaling techniques, and stochastic weather generators). These tools would be very useful in climate variability studies (see Section 3).

2.2 Seasonal forecasting

2.2.1 Current statistical techniques

A significant relationship exists in some seasons between eastern Australian rainfall and the Southern Oscillation (SO, McBride and Nicholls, 1983). This relationship provides the basis for the Seasonal Climate Outlook, (SCO) issued by the National Climate Centre (NCC) of the Australian Bureau of Meteorology. The major emphases of this service, are seasonal (three- monthly) rainfall forecasts for eastern Australia.

Since the commencement of the SCO, various forecast techniques have been employed in order to extract the maximum information from the SOI. Initially, actual seasonal rainfall was predicted using simple linear regression with the past season (three months) value of the SOI as the predictor. This predicted rainfall was then expressed as a decile value. These categorical forecasts were replaced by probabilistic forecasts in 1992, partly in response to user's requests for some error or probability estimates to be included with the forecast. The forecasts are produced using linear discriminant analysis, with the past season, or the trend in the SOI as the predictor.

In addition, a number of more subjective techniques are employed. These include two forms of phase categories of the SOI (Stone 1992, Zhang and Casey 1992) and an analogue selection technique (Drosdowsky 1994). These methods give further qualitative guidance on the probability forecast.

Smith (1994a,b) has found that NCC predictions of Australian rainfall did not exhibit any significant skill for the period 1989-1992, whereas those issued for the wheatbelt region of Western Australia by a private consulting firm for the period 1984-1992 did exhibit significant skill. These latter predictions were also noteworthy for the fact that they were issued with lead times of up to eight months.

2.2.2 Limitations of current statistical techniques

There are two major limitations in the present forecasting system. First, the forecasts are made for the monthly district average rainfall. This data set is non-homogeneous with respect to the stations used in each district, and the districts are of highly variable size with 107 covering the Australian continent. The South-West is represented by just four districts. Second, the use of a single predictor limits the areas and times for which skilful forecasts can be made. The relations between Australian rainfall and the SO are weak during the late summer and autumn period when extreme events decay, and, in particular, over the western third of the continent (including the South-West) throughout the year.

To address the first limitation, new rainfall data sets produced by interpolating all available rainfall station data onto a regular grid are being produced by the BMRC and NCC. Preliminary data sets at one degree spatial resolution and daily and monthly time scales have been developed by the BMRC.

The second limitation of the current forecast system is more restrictive, and has led in recent years to attempts to find other independent predictors. Large-scale sea surface temperature anomaly (SSTa) patterns have been shown to be related to seasonal rainfall anomalies both in Australian (e.g., Streten, 1981, 1983; Nicholls, 1984), and in other regions of the globe. Ward and Folland (1991) have linked rainfall anomalies in the Sahel and Northeast Brazil with large scale patterns of Pacific and Atlantic Ocean SSTas.

Over Australia, Nicholls (1989) and Drosdowsky (1993a, b) have documented a major mode of winter rainfall variability, consisting of a broad band running north-west to southeast from the north-west of Western Australia through central Australia to the south coast. Nicholls (1989) showed that this pattern was related to the gradient in SST between the central Indian Ocean and Indonesia. This anomaly pattern has been called the Indian Ocean Dipole. Drosdowsky (1993c) showed that the strongest precursor to this dipole pattern was found in the SSTa in the eastern Indian Ocean near the west coast of Australia during the preceding summer and autumn. From these teleconnection patterns a simple Indian Ocean Index has been produced and used as a predictor of early winter season rainfall over South Australia (Drosdowsky, 1993c).

A more systematic approach to finding potential predictors in the SST data is to determine the major modes of variability in the SSTa using techniques such as Principal Component Analysis (PCA) or Empirical Orthogonal Functions (EOFs) and then relate these to the rainfall variability. In recent years a number of high quality global SST data sets have been developed. The data used in this analysis (known as the Global Ice and Sea Surface Temperature data set or GISST), were obtained from the UK Meteorological Office and cover the period from January 1949 to December 1991. Real-time analysis of SSTs have been obtained from the Climate Analysis Center, Washington, and since mid-1993 have been produced locally in the National Meteorology Centre, Melbourne. The real-time analyses use satellite estimates of SST and have a virtually global coverage.

However historical data prior to 1982 for the Southern Ocean are limited, and since no significant relationships have been found between Australian rainfall and Atlantic SST, the PCA has been confined to the region from 60°N to 55°S and 30°E to 60°W. The first principal component is significantly correlated with the SO, and represents the mature phase of an ENSO event. The dipole pattern, which is primarily a winter-time Indian Ocean phenomenon, is not a prominent feature of the analysis, although the precursor pattern does appear.

2.2.3 Numerical forecasting

The CSIRO Divisions of Atmospheric Research and Oceanography (CSIRO DAR and CSIRO DO), and the BMRC are developing a numerical model of the coupled ocean and atmosphere to simulate and forecast climatic variations associated with the tropical Pacific and Indian Oceans on seasonal to interannual time scales. The key to improving current forecast capability lies in achieving an accurate forecast method for SST. The model development is receiving partial support from a consortium of rural research and development corporations under the auspices of the Land and Water Resources Research and Development Corporation. Data from the ocean observing system will be used to characterise the present state of the ocean (currents and thermal structure), and the numerical model used to compute the future state of the ocean and atmosphere. This project involves development of a high resolution GCM firstly with a Pacific Ocean model designed to reproduce ENSO events, and secondly with a global ocean model that has improved representation of thermal structure and circulation in the Indonesian throughflow and the Indian Ocean. This major task has a five year time frame for incorporation into the Bureau of Meteorology's operations.

2.2.4 Downscaling simulations from numerical climate models

Numerical climate models can capture large-scale circulation patterns and simulate smoothly varying fields such as sea level pressure. However, the prediction of local weather and climate conditions is always limited by the horizontal resolution of numerical climate models as well as the presence of any model-related deficiencies. This is particularly true for roughly varying fields such as precipitation at the temporal and spatial scales relevant to hydrological studies (hours to months; 10 to 100 km). Moreover, the rainfall-runoff models used in water supply operations decision making have been developed, calibrated and validated using point rainfall data. Thus there is a need to 'downscale' modelled large-scale space-time fields to the local scale.

The CSIRO DWR and the University of Washington (Seattle) are assessing the performance of a class of stochastic downscaling models in the South-West. The research has focussed on the extent to which the statistics of historical rainfall at thirty high quality sites can be reproduced by exploiting relationships between historical atmospheric circulation and gauge rainfall. Results to date for the rainfall occurrence process have been encouraging. The BMRC and CSIRO DWR have agreed to collaborate on the development of downscaling methods for Australian conditions.

2.2.5 Hindcast experiments

Hindcast experiments have been carried out for one, two or three month rainfalls, using one or two months SSTa, with a lead time of zero or one month. Regression forecasts were performed to determine which components contribute to the forecast skill. The significant components were found to vary from month to month, although all contributed at some time of the year. Overall the results show significant increase in skill of the SSTa over the SOI used alone, although this may be offset slightly if we make use of the longer time series of the SOI. In particular the SSTa show much higher skill through the so-called 'predictability barrier' in late summer to early autumn, and in some regions not significantly affected by the SO.

The CSIRO DAR plans to perform hindcasts of weather using a high resolution GCM and the predicted SSTs for the tropical Pacific provided by Cane and Zebiak for period from 1970 to 1990. This would test the skill of the method. This project is expected to take 3 years, and with the provision of supplementary funding the hindcasts would be examined to assess their applicability to the South-West.

2.3 Water resources

The hydro-climatic regime of the South-West was described by Professor Burges as being in a 'threshold' state. This means that streamflow is very sensitive to changes in rainfall because of the climate, soils and vegetation that characterise the region. This is evidenced by:

- The relatively low proportion of rainfall which becomes streamflow (typically 10 to 20%) in the wetter areas; and
- The proportionally large decrease in streamflow for a small decrease in rainfall.

Australian rainfall is the most variable in the world, and the duration and frequency of drought sequences is extreme and interspersed with sequences of above average rainfall. Sequences of above average rainfall provide most of the recharge to groundwater and when individual events are large, significant surface runoff occurs. Thus rainfall is transformed into surface runoff and groundwater recharge by a residual process. Australian streamflow shows an amplified variability, particularly in the sub-humid to semi-arid zones and the variability increases with catchment size (Fleming, 1995).

However Cramb (pers. commun.) has shown that the last twenty years have not been interspersed with sequences of above average rainfall. This amplified variability is highlighted in the South-West. A decline in annual rainfall of approximately 10% has led to a annual reduction in streamflow of approximately 30 to 40% for catchments in the jarrah forest.

2.3.1 Surface water

When the streamflow record for the last twenty years (1975 to present) is compared with either the observed record prior to 1975 (1939-1974) or the modelled and observed record prior to 1975 (1911-1974), there has been a statistically significant reduction in flow volume. This reduction appears as a sharp discontinuity in streamflow series rather than a smooth, long-term trend. Flow durations in the rivers of the northern jarrah forest are considerably smaller than before, particularly in lower rainfall areas. For example, over the last twenty years Yarragil Brook in the eastern jarrah forest flows for slightly more than 50% of the time. During the previous 25 years, Yarragil Brook flowed for about 75% of the time.

The relationship between climate variability and water quality is complex. However the annual stream salinities for catchments that are fully forested have tended to remain stable or to even decline. Higher salinities have been observed in streams that have had significant parts of their catchments cleared.

The Hurst coefficient for Serpentine Dam inflow is approximately 0.8, based on the long term record. This level of Hurst coefficient indicates strong, long-term persistence (i.e., long sequences of years in which streamflow remains higher or lower than the mean).

2.3.2 Groundwater

There is a complex interaction between land use and groundwater abstraction on the Gnangara and Jandakot mounds. However, on areas where there is native banksia woodland with no groundwater pumping, groundwater levels have declined by approximately two to three metres since 1975. Explanations for this phenomenon are not straightforward. Various reasons have been given, including lower rainfall, non-wetting soils, and leakage to the lower Leederville and Yarragadee formations.

2.3.3 Implications for management

The component of hydrologic variability due to climate can be larger than or even mask the variability due to land use change. The reduced streamflows, if they are sustained, have serious implications for water supply.

The issue of how much water should be allocated to competing users such as water supply, irrigation or the environment is made much more difficult by changes, particularly reductions in streamflow. Explicit decisions need to be made on the priority of users or on equitable reductions in water allocations. Significantly different environmental water flows or environmental water levels are derived depending on the period of record used.

2.4 Water supply planning

The current water supply system is designed and operated on the basis of needing to impose water restrictions in 10% of years (one year in ten, on average). The calculation of the nominal system yield and reliability is based on the design assumption that the climate of the last 50 years will be representative of the next 30 to 50 years.

The implications of this design assumption on the yield-reliability have been tested by adopting alternate periods from the historical record as being representative of future climate. The system yield-reliability was shown to result in a probability of water restrictions in 40% of years if the climate of the last two decades was adopted rather than the last 50 years. System yield (demand) would need to be reduced by more than 50 GL per annum to return the reliability to a probability of restrictions of 10% in any year.

Some options for increasing system yield were investigated and the financial implications of these determined. For a yield increase of 50 GL per annum, the present value increase in cost, above the current baseline cost, is about $500 million. The increase in capital cost over ten years is $200 to $400 million depending on the option selected.

The potential use of seasonal climate forecasts in operational water supply planning appears promising for assisting decision-makers during times when water restrictions may be required. However, further research and development is required.

The Water Corporation has taken a responsible position in relation to water source development to meet expected water needs. This includes the long term planning for source development (see, e.g., Stokes et al., 1995) and the approach of making incremental changes to system yield in response to new information about climate change. This approach has minimised the financial cost of water supply to customers and minimised the impacts of source development on the environment.

However, it is now the responsibility of the Corporation to review its position on climate change, climate variability and source development in view of the continuing period of historically low streamflows over the last two decades. The financial implications of adopting a 'drier climate' (e.g., the last twenty years) as the basis for water supply are significant. This issue extends to other water supply systems throughout the South-West, particularly those dependant upon surface water sources.

The guidance which climate change and variability research can provide to water supply planning in the South-West is becoming increasingly important.

Sufficient, potentially divertible water resources have been identified in the South-West to meet expected demands until at least the middle of the next century even under adverse climate change (Western Australian Water Resources Council, 1988). No evidence was presented at the workshop which suggested that this view should be changed.

The issue for water resource planning is the cost of the development of these water resources in financial and environmental terms. The Perth water supply system is designed with little excess supply capacity and source development is based on a 'just-in-time' basis. Planning for infrastructure solutions should recognise the importance of the principle of reversibility and robustness for long-term sustainability. Planning should also follow a contingent approach, with low capital solutions wherever possible.

3. Research tasks

Further research is needed to answer the questions asked by Sadler et al. (1988) in respect of climate change in the South-West:

- "What is the fundamental nature of the change? (i.e., is it a reduction of rainfall?)
- What is the expected magnitude of the change?
- When, and at approximately what rate, will the change develop?"

Two findings of the Seminar and Workshop were that definitive answers to the above questions are beyond the current limits of science and that these questions need to be expanded to include:

- What is the fundamental nature of climate variability in the South-West?
- How should water resources be managed in such a climate?
- How should water supplies be managed in such a climate?

These problems may be viewed from operational and planning perspectives under a variable and possibly changing climate. Fig. 3 illustrates the research areas that need to be addressed and their relationships. Arrows indicate when information from one area builds upon knowledge in another area. The following subsections describe the research tasks that need to be undertaken.

3.1 Climate variability (Planning mode)

3.1.1 Collation and expansion of existing knowledge

A detailed review of our current state of knowledge of rainfall trends, hydrology, and paleoclimatology of the South-West is needed. Also, the recent warming of the Indian Ocean needs to be investigated. The warming may be due to atmospheric forcing, a change in Indonesian throughflow dynamics and downstream currents in the Indian Ocean, or a combination of both.

Although a substantial body of knowledge exists, it is scattered throughout the scientific literature and within numerous organisational reports. This information needs to be brought together into a single document and expanded upon. This work would include:

- Analysis of observations and long atmospheric GCM runs (with observed SSTs) of past climate to investigate the link between synoptic patterns and multidecadal variability with regional rainfall. The CSIRO DAR fine resolution Limited Area Model (DARLAM) could be used to simulate weather patterns during the period of rainfall decline by nesting it in the GCM simulations at a resolution of 60 km or better. (Current analyses are focussing on Victoria and New South Wales due to contracts with those States. With the provision of supplementary funding, the analysis would be widened to include the South-West.) The GCM and DARLAM runs would give an understanding of the predictability of climate variations, indicating the extent to which accurate climate forecasts can be provided in the near future. (We cannot hope to forecast SST more accurately than observe SST.)
- Coupled ocean-atmosphere GCM experiments to understand the role of Indonesian throughflow in the climate system. In the spirit of the Hirst and Godfrey (1994) oceanic-GCM experiments, run the coupled model with the Indonesian passages open and closed.
- Analysis of observations and long *oceanic* GCM runs forced by surface fluxes to understand the mechanisms that control variability of SST. The Indonesian throughflow and downstream circulation in the Indian Ocean can be documented from observations during the periods before and after the climate shift that occurred during the mid-1970s (see Sections 2.1.5 and 2.1.6). A large quantity of previously unanalysed interior, oceanic data is now available due the activity of the data archaeology project at World Data Centre-A. Long oceanic GCM runs can be forced with direct observations from the Comprehensive Atmosphere Ocean Data Set (COADS) and with indirect surface fluxes from the atmospheric GCM runs mentioned above. The ocean observations and oceanic GCM experiments can be combined to improve the capability to forecast SST.

- Investigation of the strength of the link between rainfall and ocean conditions.
- A review the literature on paleoclimate analogs in the South-West. This review would look at the potential for proxy sources, such as tree rings, to provide an indication of the longer term (~500 years) variation in the climate, and the strength of the links between these sources and the variability of annual streamflow series.
- Reanalysis of rainfall variability over the last century at good quality, long-term stations in the South-West.
- An increase in the collection of oceanographic data relevant to the South-West. (The latter may be expedited with the assistance of the Royal Australian Navy.)

Atmospheric GCMs and coupled models of the ocean and atmosphere tend to give different changes in climate for enhanced greenhouse conditions. Results with these new coupled models are still being analysed. It is possible that coupled models may show more consistency than 'slab-ocean' models between the recent historical changes in rainfall over the South-West and climate changes simulated for enhanced greenhouse conditions. The accuracy of these simulations may be enhanced by improving the modelling of land surface processes for the South-West. Nevertheless, the use of coupled models will improve our understanding of seasonal variations in climate and our knowledge of the role of ocean currents and heat transport in the climate of the South-West. It may also improve the level of predicability.

3.1.2 Downscaling simulations from numerical climate models

The class of stochastic downscaling models being used by the CSIRO DWR is well-suited to the climate of the South-West in that winter rainfall is derived from frontal rather than convective systems. Further research is needed to enable modelling of rainfall amount as well as occurrence, and to investigate the coupling of the model with GCMs and limited area models. Also, there is a need to evaluate and compare alternative downscaling procedures (such as the statistical analog approach) so that the best technique for local conditions is identified.

3.1.3 Stochastic multi-site streamflow and at-site weather models

There is a need to investigate the use of 'wider' climate scenarios in supply yield and reliability assessments, including the use of different stochastic models for the simulation of streamflow and groundwater inputs to the water supply system. The use of different models will allow the study of a wider range of impacts on yield-reliability, and allow planners to 'close the gap' between these potential impacts through contingency planning.

There is a need for the development of new approaches to generating multi-site streamflow sequences similar to those observed in the South-West. One possible approach is to develop multi-site annual scale models of the 'Hurst' type and the disaggregation of annual sequences to seasonal quantities. There are two principal models available for disaggregation. The annual-scale model needs to have at least the kind of persistence structure embedded in a multi-site ARMA(1,1) model of annual streamflow volumes. The entire record should be used to determine model properties and the model should be used in conditional simulation mode. It will be crucial to compare the system vulnerability measures from such a model with the simpler low persistence model. The second model is based on the use of nonparametric disaggregation procedures (see Tarboton et al., 1996). This model does not require the a priori distributional asumptions, remains faithful to the data, and can approximate linear or nonlinear dependence.

Synthetic weather sequences are required for study of the interannual variability of groundwater recharge. The CSIRO DWR are currently investigating at-site, stochastic daily weather models for Australian conditions.

In general, stochastic models are based on the assumption that none of the probabilities which characterise the stochastic process of interest changes with time (i.e., the assumption of 'stationarity'). Therefore, agreement needs to be reached between the Water Corporation and the Regulators as to which period of the historical record should be regarded as being representative of the expected climate for the next 30 years.

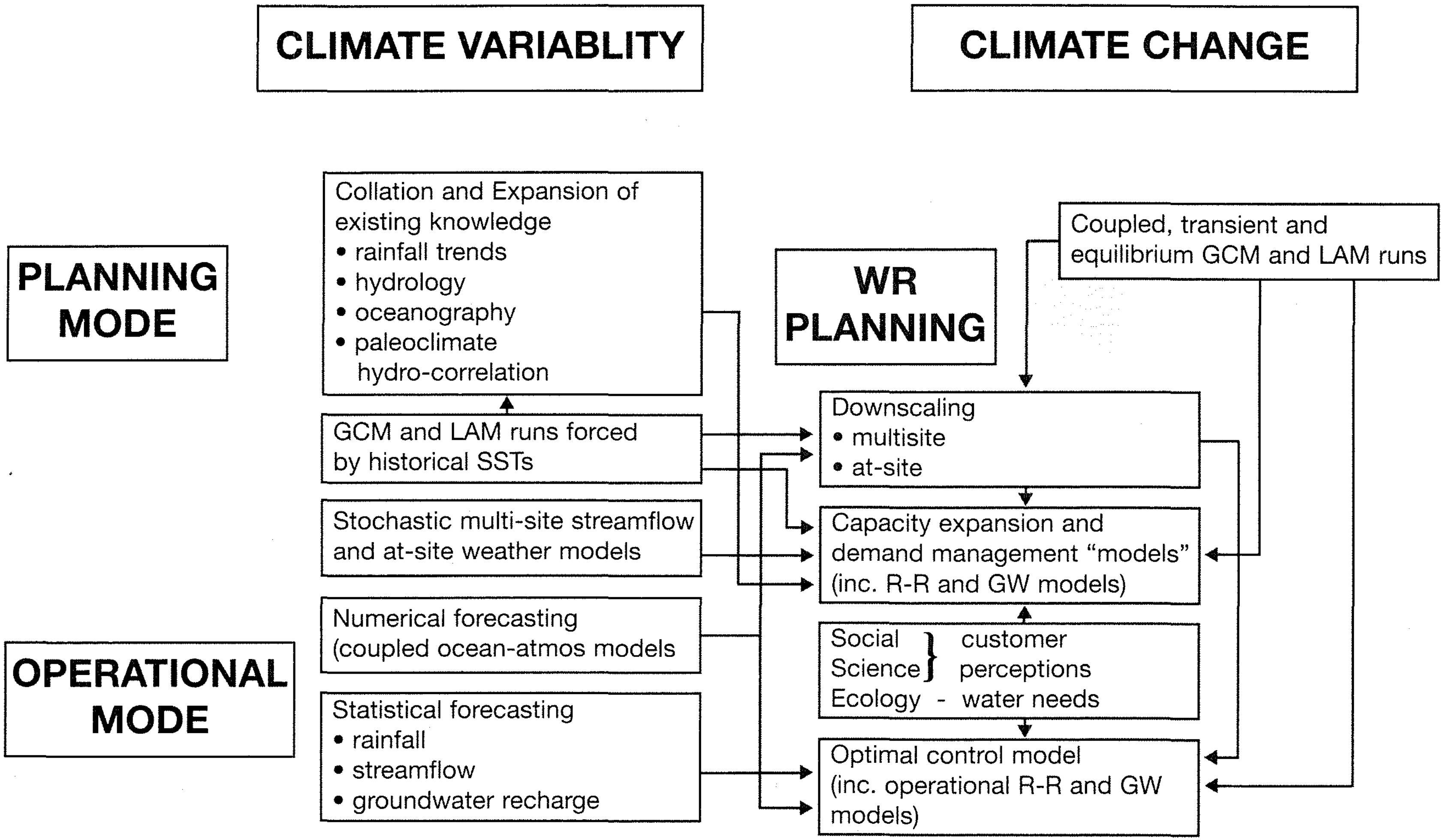


Figure 3: Research areas.

3.2 Climate variability (Operational mode)

Research and development should be undertaken to determine the feasibility of producing an operational capability for providing seasonal forecasts (to approximately 12 months ahead) of climate (principally rainfall) for the South-West. This will require a capability to forecast SSTs as accurately as possible, and exploration of a variety of forecasting methods including statistical, simple dynamical, coupled ocean-atmosphere, and statistical-dynamical models.

3.2.1 Statistical approaches to seasonal forecasting

There is a need to refine statistical methods for seasonal forecasting by further evaluation of data sets and compositing wet and dry years. A review of case studies of the most significant seasonal rainfall patterns during the past decade and their relationship to ocean conditions needs to be made (see Section 3.1.1).

Recent studies indicate that there is a relationship between mean sea level at Geraldton and Fremantle and Perth rainfall at annual and monthly time scales. Future work is required to examine the statistical and physical relationship between rainfall and sea level. Moreover, the applicability of nonparametric, nonlinear dynamical time series models (see, e.g., Lall *et al.*, 1996) to the South-West should be investigated.

3.2.2 Numerical approaches to seasonal forecasting

Unlike statistical methods, coupled numerical climate models offer a way of exploiting all of the known relationships between oceanic and atmospheric variables and propagating these relationships forward in time. While an imperfectly observed ocean, an imperfect model, and chaos in the atmosphere will cause forecasting error, there is evidence that useful information can be obtained from deterministic model forecasts on seasonal to interannual time scales. It should be noted that the results of numerical models are now used routinely for weather forecasting out to about four days ahead.

As mentioned in Section 2.2.5, the CSIRO DAR plans to perform weather hindcasts using a high resolution GCM and the predicted SSTs for the tropical Pacific. This will provide a good test the skill of numerical forecasting, and consideration should be given to the provision of supplementary funding for an assessment of the applicability of the method to the South-West.

3.2.3 Downscaling simulations from numerical climate models

See Section 3.1.3.

3.3 Climate change

Definite statements on the fundamental nature of the change in the South-West and its expected magnitude and timing may be possible when the equilibrium and transient runs from several, appropriately validated GCMs agree on the direction, size and rate of change of precipitation and other climate variables at regional scales. Considerable improvements in GCM performance have been made over the last ten years and further significant gains are expected in the near future.

Much of the work described above would provide the tools for comprehensive studies of the impact of climate change on regional water supplies. Therefore, there is much to be gained in the short-term by focussing on climate variability impacts and monitoring future developments in modelling of the general circulation of the atmosphere.

3.4 Water resources planning

Consideration of the capacity expansion problem under conditions of climate uncertainty should include:

- Adoption of a contingency approach to water resources planning.
- Investigation of the options, beyond Perth's Water Future Strategy, for responding to a sustained low rainfall sequence. This would involve a study of system yield and the feasibility, costs and benefits of using: the concept of equivalent buffer storage; confined aquifers; dual use water supply systems; seawater desalination plants; various water restriction

policies; water reuse (drainage water and wastewater); self-supply (through individual or collective wells); and water use efficiency measures to augment water supply capacity during drought or to conserve water resources.

- Assessment of customer perceptions of risk, system reliability and willingness-to-pay in relation to: increased supply capacity; water reuse; self-supply; the development of 'dual supply' infrastructure; water restrictions and changes to the water restrictions level of service policy; and the adoption of water use efficiency measures.

- Assessment of the water needs of ecological systems as well as industry and the general public. This will be a huge and ongoing activity. Understanding the important functions of wetlands and redirecting water that has been directed from them previously is likely to have significant influence on how the overall supply system will be operated.

These studies will have to:

- Consider the integration of water supply, drainage and wastewater planning to maximise opportunities to provide 'local' water supplies (e.g., shared private groundwater wells, drainage water reuse, wastewater reuse schemes) and the 'whole-of-system' costs.

- Assess the demand-supply curve implications of water use efficiency and source augmentation proposals and incorporate the uncertainty/risk in economics inherent in the financial evaluation of 'local' water supply schemes.

- Investigate the acceleration of North West Corridor Groundwater schemes as a means of dealing with the current and potentially sustained low rainfall sequence.

- Investigate the system yield, source sustainability and cost implications of different volumes (larger) and patterns of withdrawal from the confined aquifers during normal and drought years. The superficial and confined groundwater aquifers could be considered as an integrated system and draw upon as an 'immediate' measure to increase supply yield and reliability. Efforts could be made to optimise the necessary infrastructure.

- Stimulate debate and undertake public education and on the issues of climate variability and the implications for the level of service (restrictions) and the costs of changing these.

3.5 Water resources management

3.5.1 Seasonal streamflow and aquifer forecasting

There is a need to be able to translate seasonal climate forecasts to streamflow volumes and to groundwater recharge and withdrawal volumes for use in operational planning.

Models exist for simulating the response of surface water catchments in the Darling Range and for recharge to aquifers on the Gnangara Mound and the Jandakot Mound. Effort needs to be directed in these two areas to development operational rainfall-runoff models for use with seasonal climate forecasts to provide input to supply system models. The rainfall-runoff models may benefit from being recast in state-space form and using Kalman filtering to update the model parameters and state variables. Models of the major aquifer systems near Perth should also be developed and maintained in operational state for use with seasonal climate forecasts.

3.5.2 New approaches to real - time operation of Perth's water supply system

The real time operation of a conjunctive use system may be posed as an optimal control problem of a dynamical system with stochastic inputs. The most general method of solving this class of problem is stochastic dynamic programming.

The Water Corporation currently uses the REALM system yield model to simulate and optimise the harvesting and bulk distribution of water resources within the Perth water supply system. The optimisation is carried out by a linear programming algorithm. Linear programming can solve large and complex optimisation problems, but it may not be the best method for conjunctive use systems that are subject to significant constraints (e.g., finite storage and pumping capacity, operational thresholds such as the draining of wetlands), systems for which there are benefits to be gained by cautious management, and systems where the variability and uncertainty in system inputs can result in costs that are out of proportion to their deviation from system targets.

Apart from the development of new statistical and numerical models for climate, streamflow and groundwater recharge forecasting, further research directed towards the simulation and optimisation of water supply system operations should be undertaken. This work should include:

- An assessment of the utility and applicability of the REALM system yield model in assisting real-time operation of the Perth water supply system.
- The investigation of an optimal control model (based either on REALM or a stochastic dynamic programming scheme) for the operation of Perth water supply system to produce forecasts of system behaviour in response to different management decisions.

4. Conclusions and recommendations

The planning and management of water resources and supplies under climate uncertainty are complex, multidisciplinary activities. A question for the short-term is: What position should be recommended for the design and operation of a supply system in terms of the risks of under-supply and the resulting financial and social consequences?

A finding of the Seminar and Workshop is that the Water Corporation's current approach to water planning is sound.

Nevertheless, a comprehensive response to the recent downturn in rainfall and streamflow volumes will require a sustained and integrated program of research. It is recommended that a liaison group be formed to:

- Determine how industry can make the best use of existing knowledge and current research efforts;
- Review opportunities for further climate variability, climate forecasting, and water resources research for the South-West;
- Prepare costed research proposals addressing the issues raised and areas addressed in this report; and
- Seek and/or provide funding for those proposals with the highest benefit in the long- and the short-term to water resource planning decision making.

The liaison group should involve persons and agencies involved in climate and water resources research, and in the operations and management of water resources and water supplies in the South-West. This would insure that research proposals are properly integrated. It should be noted that Professor Burges has indicated a continuing interest in the problem and would welcome an opportunity for collaborative research.

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Appendix A: Workshop Participants

Group 1

Climate change and variability for the SW

Dr Bryson Bates - Chair (CSIRO)
Dr Mike Manton (BMRC)
Len Broadbridge (BoM)
Dr Ian Foster (DAWA)
Dr Rob Allan (CSIRO)
Roger Tapp (BoM)
Dr Jeff Stoneman (CALM)

Group 2

Forecasting of seasonal/inter-annual climate variability for the SW

John Ruprecht -Chair (WaRC)
John Cramb (BoM)
Wasyl Drosdowsky (BMRC)
Dr Charitha Pattiaratchi (CWR)
Dr Warrick Grace (BMRC)
Dr Garry Meyers (CSIRO)

Group 3

Water resources and supply planning for the SW

Bob Stokes - Chair (WC)
Prof Steve Burges (UW)
Robert Ng (WC)
Bob Humphries (WC)
Dr John Thomas (CSIRO)
Rob Hammond (WaRC)
Keith Cadee (WC)
Jeff Kite (WaRC)

Appendix B: Keynote speaker summary

CLIMATE VARIABILITY AND WATER RESOURCES IN THE SOUTH-WEST OF WESTERN AUSTRALIA: RESEARCH NEEDS AND PRIORITIES

by

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February 18, 1996

The research needs outlined below are based on the research recommendations presented by Bob Stokes at the Climate Variability seminar held at CSIRO Perth on January 31. I have, however, included some of my own recommendations and assigned preliminary priorities to each research task. All are listed as first priority as I think a suite of approaches and techniques need to be developed concurrently.

I would like to assist in any way that seems appropriate to members of staff of the Water Corporation and the Water and Rivers Commission in an advisory capacity or directly with colleagues who will be doing the various basic research and development. The various problems are extraordinarily interesting. Much is to be learned by studying the issues associated with the Perth region that will be of value to the water industry world wide.

With regard to the first recommendation presented by Bob, I believe that definitive statements on the fundamental nature, expected magnitude, and rate of projected climate change are beyond the current limits of science. This view was supported by Mike Manton's presentation. In the future, useful statements may be possible when the equilibrium and transient runs from several, appropriately validated, general circulation models (GCMs) agree on the direction, size, and rate of change in precipitation and other climatic variables at spatial and temporal scales of relevance to water supply systems.

The key to understanding the climatology and meteorology of South-West Western Australia is greater understanding of the influence of the Indian Ocean on the overall incoming weather patterns. Advances in such understanding will take considerable time and require extensive data collection and interpretation. While we wait for progress on that front there are many practical actions that can be taken to build resiliency into the system and to gain a sense of system vulnerability. The greatest protection against vulnerability is to build "equivalent buffer storage". This can be achieved most readily by effective "physical water demand" reduction. For the built-up areas, much can be achieved by speeding up the process of installation of an equivalent dual water supply system. In particular, encouraging home-owners or groups of home-owners to install wells (bores) to supply their supplemental irrigation water should be explored. I do not have any relevant economic data to know how feasible this option might be. The favourable hydrologic setting (ease of rain infiltration) and the timing of rain makes this a potentially attractive option. This is not a universal panacea; ecological considerations in particular locations might make this inappropriate. This might entail changes in mission statements for both the Water Corporation and the Water and Rivers Commission.

I recommend that the Water Corporation and Water and Rivers Commission focus their attention on the influence of climate variability on Perth's water supply system and plan on the basis that the relatively recent climatic history is part of natural variability. Much of the work described below would provide the tools for a study of the influence of any climate change on the regional water supply system. The only missing component is a set of climate scenarios for either transient or equilibrium conditions.

The research recommendations below are categorised as either short-term or long-term projects. Short-term projects are those that would require about one person-year. Projects designated as long-term are those that would require more than three person-years and take more than several years to complete.

A substantial research effort should be directed towards the development of rainfall and associated streamflow forecasting methods and multi-site simulation and optimisation models of the Perth water supply system which can make use of those forecasts for assisting in operational decisions. The system optimisation model should be able to deal with uncertainty in rainfall, streamflow, and demand forecasts, and incorporate appropriate stochastic optimisation so that near-optimal adjustment to reservoir releases and groundwater extraction can be made as new observations and forecasts become available.

In all activities, it is important to keep in mind the experience of long time excursions in various states of hydrologic variability. This means that any planning or operations should be couched in the context of decadal-scale variations as well as variations on the order of a few years as well as dominant seasonal variability. This hierarchy must be at the forefront of all associated activities.

Short-term research

Planning mode

1. Development of a conditional simulation program for generating synthetic streamflow sequences similar to that for the post-1975 period.(Priority 1)

The existing planning model could be used with starting streamflow values conditioned on the values at each of the inflow locations averaged over the last couple of years. The recent record (approximately 20 years) is too short to determine the correlations and marginal distributions needed by the model. At a minimum, the apparent lower annual mean and variance could be used. This will provide preliminary measures of system vulnerability.

2. Development of a coupled stochastic daily weather and groundwater recharge model for investigation of the groundwater yield implications of climate sequences similar to that for the post-1975 period. (Priority 1)

3. Explore the possibility of using relevant paleo records to get a sense of the forms of variability that has been experienced in the region. I do not know what records might be useful, but this issue should be explored to provide guidance to the forms of excursions of climatic patterns. If appropriate paleo records can be used to create surrogate streamflow volumes, this should evolve into a long-term research activity. (Priority 1)

Real-time operation mode

1. Refinement of statistical techniques for short-term rainfall forecasting based on sea surface temperatures and sea level. (E.g., Work by Bureau of Meteorology Research Centre (BMRC) and the Centre for Water Research.) (Priority 1)

2. Refinement of techniques for forecasting seasonal or annual streamflow based on sea surface temperatures (see, e.g., Simpson et al., 1993).(Priority 1)

3. Investigation of techniques for deriving weekly or monthly flows from seasonal runoff forecasts (see, e.g., Pei et al., 1987) and incorporating them in appropriate system operations models. (Priority 1)

Long-term research

Planning mode

1. Investigate system yield and cost implications of using confined aquifers, seawater desalination plants, various water restriction policies, and water use efficiency measures to augment or conserve Perth's water supply during extended drought. (Priority 1)

It seems to me that much thought has gone into this. The issues need revisiting after other activities yield new information.

2. Assessment of customer perceptions of risk, system reliability and willingness-to-pay in relation to increased supply capacity, development of "dual supply" infrastructure, water restrictions, and water use efficiency measures. (Priority 1)

3. Assessment of the water needs of ecological systems as well as industry and the general public. This will be a huge and ongoing activity. Understanding the important functions of wetlands and redirecting water that has been directed from them previously is likely to have significant influence on how the overall supply system will be operated. (Priority 1)

4. Development of a pragmatic technique for generating synthetic multi-site streamflow sequences for the entire period of record. (Priority 1)

This activity will require developing multi-site annual scale models of the 'Hurst" type and disaggregating annual sequences to seasonal quantities. There are two principal models available for disaggregation. The annual-scale model needs to have at least the kind of persistence structure embedded in a multi-site ARMA(1,1) model of annual streamflow volumes. The entire record should be used to determine model properties. The model should be used in conditional simulation mode. This model will have substantially greater persistence than in the model for topic 1 in "short-term planning". It will be crucial to compare the system vulnerability measures from such a model with the simpler low persistence model.

Real-time operation mode

1. Development of water supply system management software that can incorporate 'fuzzy' rainfall and streamflow forecasts and uncertain demand. This suggests the use of optimal control theory (see, e.g., Foufoula-Georgiou and Kitanidis, 1988; Crawley and Dandy, 1993). (Priority 1)

2. Refinement of coupled ocean and atmosphere models for short-term rainfall forecasting. (E.g., LWRRDC-funded work by BMRC and the CSIRO Divisions of Atmospheric Research and Oceanography.) (Priority 1)

3. Development of methods for down-scaling simulations from numerical climate models to relevant spatial and temporal scales. (E.g., work by CSIRO Division of Water Resources and BMRC on stochastic and statistical methods, respectively.) (Priority 1)

4. Development of catchment rainfall-runoff and groundwater models for real-time operation using seasonal (and on the order of decadal) climate forecasts. The models used for shorter-term processes may benefit from recasting the models in state-space form and using Kalman filtering for updating the model parameters and states. (Priority 1)

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Appendix C: Seminar titles and speakers

Climate

Historical rainfall trends for south-west Western Australia;
John Cramb, Bureau of Meteorology.

The global climate picture relative to south-west Western Australia;
Dr Rob Allan, CSIRO Division of Atmospheric Research.

The role of the oceans in the climate of south-west Western Australia;
Dr Gary Meyers, CSIRO Division of Oceanography.

Seasonal forecasting

Climate change prognosis for south-west Western Australia;
Dr Mike Manton, Bureau of Meteorology Research Centre.

Existing and prospective approaches to seasonal forecasting for south-west Western Australia;
Dr Wasyl Drosdowsky, Bureau of Meteorology Research Centre.

The influence of the eastern Indian Ocean on seasonal forecasting for south-west Western Australia;
Charitha Pattiaratchi, Centre for Water Research, University of WA.

Impacts of climate variability on water resources

Linking climate research and catchment hydrology;
Dr Bryson Bates, CSIRO Division of Water Resources.

Impact of climate variability on the water resources of the south west;
John Ruprecht, Water and Rivers Commission.

Impact of climate variability on water supply planning for Perth;
Bob Stokes, Water Corporation.

Appendix D: Glossary

ARMA (1,1)

ARMA is an acronym for the family of 'autoregressive-moving average' models that are widely used in time series analysis. ARMA(1,1) denotes a particular member of this family.

Atmospheric forcing

Ocean currents, surface temperature and salinity are generated by surface fluxes of heat, moisture and momentum from the atmosphere.

Climate change

A change of climate that is attributed directly or indirectly to human activity.

Climate variability

The natural year to year and season to season variation of the climate system.

Coupled ocean and atmospheric models

Numerical climate models which include three-dimensional representations of the atmosphere, ocean, cryosphere, and land surface. The cryosphere includes all global snow, ice and permafrost. See GCMs (General Circulation Models).

Deterministic models

Mathematical models in which climatic and hydrological variables are regarded as being free from random variation. In stochastic models, the variables are regarded as random variables having probability distributions.

Disaggregation

The process of deriving a time series with a smaller observation frequency form a parent series such that the new series reproduces the statistics for both observation frequencies.

Downscaling

GCMs operate at a spatial scale far coarser than that used in hydrological modelling. It is therefore necessary to downscale GCM results to the catchment scale. Downscaling techniques include: the direct use of GCM-simulated changes in climatic variables, adaptation of the parameters of point-scale stochastic daily weather models; stochastic models that simulate weather variables conditioned on large-scale atmospheric circulation patterns; and limited area models.

El Nino

A warm water current which periodically flows southwards along the coast of Ecuador and Peru in South America, replacing the usually cold northwards flowing current.

Empirical Orthogonal Functions (EOFs)

A statistical tool used by climatologists and meteorologists for the analysis of the spatial or temporal variability of data (see Principal Components Analysis).

ENSO

Collective term for El Nino and the Southern Oscillation.

GCMs (General Circulation Models)

Numerical models of the general circulation of the atmosphere that use the laws of conservation of mass (water vapour and air), momentum and heat in the atmosphere, along with state equations relating thermodynamic variables. The laws and state equations are expressed as coupled, nonlinear, partial differential equations that are solved in a rotating system of coordinates. Multiple vertical layers are used to represent the thermodynamically stratified nature of the atmosphere.

Global ocean/atmospheric model

See Coupled ocean and atmospheric models.

Hindcast experiments

Experiments designed to test a model's ability to reproduce recorded phenomena. It is a form of model validation.

Hurst coefficient (H)

An index of the degree of apparent persistence (long intervals of well below or well above 'normal' trends) in a geophysical time series. A random process has H = 0.5, whereas H is between 0.7 and 0.85 for prolonged, multiyear duration droughts

Indian Ocean dipole

A pattern of sea surface temperature anomaly related to Australian rainfall. The pattern favourable to Australian rainfall is warmer than normal temperatures in the Indonesian region and colder than normal temperatures in the central, southern tropical Indian Ocean. Less rainfall occurs when the pattern is reversed.

Indonesian throughflow

A system of ocean currents that allow water and heat to flow from the Pacific into the Indian Ocean through the Indonesian archipelago.

Large-scale circulation patterns

Results from the sun heating the surface and overlying atmosphere of the Earth unevenly. There are three main circulation patterns at the hemispherical scale. The Hadley cell circulates the warm equatorial air between the tropics and sub-tropics (0 to 30° S or N). A similar cell known as the Circumpolar trough operates at the polar regions (60 to 90° S or N) In the mid-latitudes the Ferrel cell operates where portions of the warm equatorial air from the Hadley cell and cold air from the circumpolar trough interact.

The oceans also follow large scale circulation patterns resulting from the prevailing winds in each hemisphere. This leads to waters of the ocean basins flowing in a swirl within their basins, called a gyre.

Latent heat flux

Latent heat is the quantity of heat required to change a unit mass of substance from the solid to the liquid state (latent heat of fusion) or from the liquid to the vapour state (latent heat of vaporisation) without a change in temperature. It is released when water vapour condenses into droplets and when water droplets freeze. Latent heat flux is the transfer of latent heat per unit area per unit time.

Leeuwin Current

The warm ocean current originating in the tropics that flows down the west coast of Australia

Limited area models

Limited area models have been proposed as a means of overcoming the poor performance of GCM simulations of local and regional scale precipitation for present day conditions. The models nest a fine computational grid over a limited domain within the coarse grid of a GCM. The host GCM provides the boundary conditions for the limited area model. The main advantage of limited area models is that they simulate the regional climate at a higher spatial resolution while remaining more economical to run than a GCM with a similar resolution.

Multidecadal variability

Variability that takes place over a time scale of several decades.

Multi-site streamflow sequences

Multiple time series consisting of concurrent streamflow records from several monitored sites (gauging stations).

Nonparametric nonlinear dynamical time series models

A new time series forecasting approach that is capable of modelling complex, natural systems that exhibit periodic, quasi-periodic and aperiodic behaviours.

Numerical climate models

Interconnected mathematical equations describing the laws of physics used to calculate the behaviour of the climate over time. See GCMs (General Circulation Models) and Coupled ocean and atmospheric models.

Oceanic/atmospheric-GCM

See Coupled ocean and atmospheric models.

Oceanic forcing

The capability of ocean currents or the depth of the thermocline to cause variation of sea surface temperature.

Pacific Ocean model

Limited area model of the Pacific Ocean to examine closely issues more relevant to the Pacific alone. E.g., ENSO events.

Palaeoclimate

A past climate which can be studied using traces left behind in the geologic record.

Persistence

The non-random characteristic of a hydrologic time series. See Hurst Coefficient (H).

Principal Component Analysis

A statistical tool used by meteorologists, oceanographers and hydrologists for the analysis of the spatial or temporal variability of data. Principal components are mathematically related to Empirical Orthogonal Functions, and convey more information on the underlying structure of a multidimensional data set.

Regression forecasts

Forecasts based on a statistical regression models.

Sea surface temperature anomalies (SSTa)

Deviations from the long term, mean sea surface temperature.

Southern Oscillation

A fluctuation in the atmospheric circulation, particularly over the tropical areas of the Pacific and Indian Oceans. When atmospheric pressures are high over the eastern Pacific Ocean, they tend to be low in the eastern Indian Ocean.

Southern Oscillation Index

An indicator based on the pressure gradient between the quasi-stationary low pressure region over Indonesia and the centre of the subtropical high pressure cell over the eastern Pacific Ocean. Traditionally Darwin and Tahiti are used as the sites for determining the magnitude of the Southern Oscillation. Drought conditions are experienced over Eastern Australia when the central Pacific Ocean is warm and the atmospheric pressure over Australia is relatively high.

Stationarity

A time series is stationary if its statistical properties (e.g., the mean) are essentially constant through time. Most statistical techniques rely on the assumption of stationarity.

Synoptic patterns

General circulation patterns in the atmosphere create alternating belts of low and high pressure. The belts of low pressure both create and are generated by zones of high rainfall, while those of high pressure create arid regions around the world. These combined with fronts form the synoptic pattern.

Tree rings

Annual growth layers in wood. Dendrochronology is the science of dating by means of tree rings. Dendrohydrology is the use of dated tree ring series to study hydrological issues such as the periodicity of river flow.

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