Australian Rainfall & Runoff

Revision Projects

PROJECT 5

Regional Flood Methods

STAGE 1 REPORT

P5/S1/003

NOVEMBER 2009

Australian Government

ENGINEERS AUSTRALIA
Water Engineering

AUSTRALIAN RAINFALL AND RUNOFF
REVISON PROJECT 5: REGIONAL FLOOD METHODS

STAGE 1 REPORT

DECEMBER, 2009

Project Project 5: Regional Flood Methods	**AR&R Report Number** P5/S1/003
Date 17 December 2009	**ISBN** 978-085825-9058
Contractor University of Western Sydney	**Contractor Reference Number** 20731.64125
Authors Ataur Rahman Khaled Haddad George Kuczera Erwin Weinmann	**Verified by**

ACKNOWLEDGEMENTS

This project was made possible by funding from the Federal Government through the Department of Climate Change. This report and the associated project are the result of a significant amount of in kind hours provided by Engineers Australia Members.

ENGINEERS
AUSTRALIA
Water Engineering

Contractor Details

The University of Western Sydney
School of Engineering, Building XB, Kingswood
Locked Bag 1797, Penrith South DC, NSW 1797, Australia

Tel: (02) 4736 0145
Fax: (02) 4736 0833
Email: a.rahman@uws.edu.au
Web: www.uws.edu.au

University of Western Sydney

FOREWORD

AR&R Revision Process

Since its first publication in 1958, Australian Rainfall and Runoff (AR&R) has remained one of the most influential and widely used guidelines published by Engineers Australia (EA). The current edition, published in 1987, retained the same level of national and international acclaim as its predecessors.

With nationwide applicability, balancing the varied climates of Australia, the information and the approaches presented in Australian Rainfall and Runoff are essential for policy decisions and projects involving:

- infrastructure such as roads, rail, airports, bridges, dams, stormwater and sewer systems;
- town planning;
- mining;
- developing flood management plans for urban and rural communities;
- flood warnings and flood emergency management;
- operation of regulated river systems; and
- estimation of extreme flood levels.

However, many of the practices recommended in the 1987 edition of AR&R are now becoming outdated, no longer representing the accepted views of professionals, both in terms of technique and approach to water management. This fact, coupled with greater understanding of climate and climatic influences makes the securing of current and complete rainfall and streamflow data and expansion of focus from flood events to the full spectrum of flows and rainfall events, crucial to maintaining an adequate knowledge of the processes that govern Australian rainfall and streamflow in the broadest sense, allowing better management, policy and planning decisions to be made.

One of the major responsibilities of the National Committee on Water Engineering of Engineers Australia is the periodic revision of AR&R. A recent and significant development has been that the revision of AR&R has been identified as a priority in the Council of Australian Governments endorsed National Adaptation Framework for Climate Change.

The Federal Department of Climate Change announced in June 2008 $2 million of funding to assist in updating Australian Rainfall and Runoff (AR&R). The update will be completed in three stages over four years with current funding for the first stage. Further funding is still required for Stages 2 and 3. Twenty one revision projects will be undertaken with the aim of filling knowledge gaps. The 21 projects are to be undertaken over four years with ten projects commencing in Stage 1. The outcomes of the projects will assist the AR&R editorial team compiling and writing of the chapters of AR&R. Steering and Technical Committees have been established to assist the AR&R editorial team in guiding the projects to achieve desired outcomes.

Project 5: Regional Flood Methods

The most commonly encountered hydrological problem associated with estimating flood flows is that of estimating the flood flow of a given Annual Exceedence Probability (AEP) at a location where no historical monitored information exists. Numerous alternative techniques have been developed in the different regions (primarily, the states) of Australia to provide flow estimates in ungauged catchments. The current diversity of approaches has resulted in predicted flows varying significantly at the interfaces between regions. There is a need to develop generic techniques that can be applied across the country, to test these techniques, and to develop appropriate guidance in their usage.

The aim of Project 5 is to collate techniques and guidelines for peak flow estimation at ungauged sites across Australia.

Mark Babister
Chair National Committee on Water Engineering

Dr James Ball
AR&R Editor

AR&R REVISION PROJECTS

The 21 AR&R revision projects are listed below:

ARR Project No.	Project Title	Starting Stage
1	Development of intensity-frequency-duration information across Australia	1
2	Spatial patterns of rainfall	2
3	Temporal pattern of rainfall	2
4	Continuous rainfall sequences at a point	1
5	Regional flood methods	1
6	Loss models for catchment simulation	2
7	Baseflow for catchment simulation	1
8	Use of continuous simulation for design flow determination	2
9	Urban drainage system hydraulics	1
10	Appropriate safety criteria for people	1
11	Blockage of hydraulic structures	1
12	Selection of an approach	2
13	Rational Method developments	1
14	Large to extreme floods in urban areas	3
15	Two-dimensional (2D) modelling in urban areas.	1
16	Storm patterns for use in design events	2
17	Channel loss models	2
18	Interaction of coastal processes and severe weather events	1
19	Selection of climate change boundary conditions	3
20	Risk assessment and design life	2
21	IT Delivery and Communication Strategies	2

AR&R Technical Committee:

PROJECT TEAM AND CONTRIBUTORS (INCLUDING STATE TEAMS)

Project Team Members:

- Ataur Rahman, Research Project Leader, University of Western Sydney #
- Khaled Haddad, University of Western Sydney
- George Kuczera, AR&R TC Project Manager, University of Newcastle #
- Erwin Weinmann #
- Ashish Sharma, UNSW #

Contributors:

- James Ball, AR&R Editor, University of Technology Sydney #
- Mark Babister, Chair NCWE, AR&R Technical Committee, WMAwater #
- Elias Ishak, UWS
- William Weeks, AR&R Technical Committee, Queensland Dept of Main Roads #
- Tom Micevski, University of Newcastle #
- Andre Hackelbusch, University of Newcastle #
- Luke Palmen #
- Guna Hewa, University of South Australia #
- Trevor Daniell, University of Adelaide #
- David Kemp, SAUGOV #
- Sithara Walpita Gamage, University of South Australia
- Subhashini Wella Hewage #
- Fiona Ling, Hydro Tasmania #
- Crispin Smythe #
- Chris MacGeorge#
- Bryce Graham#
- James Pirozzi, UWS#
- Gavin McPherson, UWS#
- Chris Randall, UWS#
- Robert French #
- Wilfredo Caballero, UWS#
- Khaled Rima, UWS#
- Tarik Ahmed, UWS#
- Lakshman Rajaratnam, NT Gov#
- Jerome Goh#
- Patrick Thompson#

This report was reviewed by a number of the conbritors.

LIST OF ORGANISATIONS PROVIDING DATA AND ASSISTANCE

- Victorian Department of Sustainability and Environment
- Thiess Services Victoria
- Australian Bureau of Meteorology
- Department of Natural Resources and Water (Qld)
- Hydro Tasmania
- Department of Primary Industries, Parks, Water and Environment (TAS)
- Department of Water, Land and Biodiversity Conservation (SA)
- Department of Natural Resources, Environment, the Arts and Sport (NRETAS) (NT)
- University of Western Sydney
- University of Newcastle
- Department of Main Roads (Qld)
- University of South Australia
- Department of Water and Energy (NSW)

EXECUTIVE SUMMARY

Estimation of peak flows on small to medium sized rural catchments is a common design problem in flood estimation. Design flood estimation on these catchments is required for the design of culverts, small to medium sized bridges, causeways, farm dams, soil conservation works and for many other water resources management tasks.

Australian Rainfall and Runoff (ARR) 1987 recommended various design flood estimation techniques for small to medium sized ungauged catchments for different regions of Australia (I.E. Aust., 1987, 2001). Since 1987, the methods in the ARR have not been upgraded although there have been availability of an additional 20 years of streamflow data and notable development in both at-site and regional flood frequency analyses techniques in Australia and internationally.

As a part of the current revision of the ARR (4th Edition), Project 5 Regional Flood Methods for Australia focuses on the development, testing and recommendation of new regional flood estimation methods for Australia by incorporating latest data and techniques. This report presents the initial outcome of Project 5 (Stage I) covering data preparation and exploratory data analyses.

To meet the project objective, a database has been prepared for each of the states of Victoria, NSW, Tasmania, Queensland and South Australia comprising annual maximum flood series and suitable metrics of climatic and physical catchment characteristics. The database for NT is under preparation. The database for WA is yet to be prepared. The database for Victoria, NSW, Tasmania, Queensland and South Australia contain data from 131, 96, 36, 265 and 30 stations respectively. The initial database for NT contains 130 stations.

For bulk of the selected catchments, data for up to 7 climatic and catchment characteristics variables have been abstracted. These are catchment area, design rainfall intensity (with various ARIs and durations), mean annual rainfall, mean annual areal potential evapotranspiration, main stream slope, stream density and fraction of catchment area under forest.

A number of regional flood estimation models have been developed and tested using the database. These include the Probabilistic Rational Method (PRM) and various regression based techniques: Quantile Regression Technique (QRT) based on ordinary least squares (QRT-OLS), QRT based on generalised least squares (QRT-GLS) and parameter regression technique (PRT) based on GLS regression (PRT-GLS). The methods have initially been applied to individual states based on the concept of fixed regions. The initial application of the region of influence (ROI) approach has been undertaken with the PRT-GLS method for eastern NSW. The ROI with QRT-GLS method is under development.

Based on the results of exploratory investigations, it has been found that QRT outperforms the PRM for Victoria, NSW and Qld. The QRT-GLS method has demonstrated its superiority over the QRT-OLS method. From the initial results of the application of the ROI approach with the

parameter regression technique (where prediction equations have been developed for the parameters of the LP3 distribution based on GLS regression), it has been found that the ROI GLS model exhibits superior performance to the fixed region GLS model. From the application of a simple Probabilistic Model coupled with GLS method to the combined data set of Victoria and NSW, it has been found that this method can provide design flood estimates of similar accuracy to the GLS methods for medium to large floods (ARIs of 20 to 200 years). This method has the potential to provide quite accurate design flood estimates in high ARI range (e.g. 100 to 500 years ARIs).

Long-term climate variability (and possibly climate change) has certainly affected the annual maximum flood series data at many stations. From the initial investigations, about 13% stations from Victoria, NSW, Qld and Tasmania have shown statistically significant downward trends but these initial results require further explanation from more detailed analyses.

Based on the findings of the preliminary studies presented in this report, recommended regional flood estimation methods for application and further testing have been identified.

TABLE OF CONTENTS

LIST OF FIGURES

List of Tables

1. Introduction

1.1. Background

Estimation of peak flows on small to medium sized rural catchments is probably the most common design problem in flood estimation (Pilgrim, 1987). Design flood estimation on these catchments is required for the design of culverts, small to medium sized bridges, causeways, farm dams, soil conservation works and for many other water resources management tasks. The average amount spent on these projects per year was estimated at approximately $250 million as at 1985 (Flavell, 1985; Pilgrim, 1986); this is equivalent to over $600 million per annum in 2009 (based on long term CPI series for Australian capital cities, ABS, 2009).

Australia is a large continent with numerous streams, many of which are ungauged or insufficiently gauged. As at 1993, of the 12 drainage divisions in Australia, seven did not have a stream with 20 or more years of data (Vogel et al., 1993). Australian Rainfall and Runoff (ARR) 1987 recommended various design flood estimation techniques for small to medium sized ungauged catchments for different regions of Australia (I.E. Aust., 1987, 2001). Since 1987, the methods in the ARR have not been upgraded although there have been an additional 20 years of streamflow data available and notable developments in both at-site and regional flood frequency analyses techniques in Australia and internationally (e.g. Tasker and Stedinger, 1989; Weeks, 1991; Gupta et al., 1994; Hosking and Wallis, 1993; Bates et al., 1998; Rahman et al., 1999; Kuczera and Franks, 2005; Rahman, 2005; Haddad, Rahman and Weinmann, 2006, 2008a; Griffis and Stedinger, 2007; Micevski and Kuczera, 2008; 2009; Gruber and Stedinger, 2008; and Kjeldsen and Jones, 2009).

To upgrade the regional flood estimation methods in the ARR, an informal project team was established in early 2006 with members from various states (Ataur Rahman, Khaled Haddad, Erwin Weinmann, James Ball, George Kuczera, Mark Babister, William Weeks, Robert French, Jerome Goh and David Kemp). Since then, the project team has been expanded by input from various states (e.g. Fiona Ling from Tasmania, Guna Hewa and Trevor Daniell from South Australia, Lakshman Rajaratnam from NT).

As a part of the current revision of the ARR (4th Edition), Project 5 “Regional Flood Methods for Australia” focuses on the development, testing and recommendation of new regional flood estimation methods for Australia by incorporating latest data and techniques. This report presents the initial outcome of Project 5 (Stage I) covering data preparation and exploratory data analyses.

1.2. Scope of Project 5 (Phase I)

Project 5 Regional Flood Methods for Australia sets the following deliverables:

1. A quality controlled national database of streamflow records and relevant climatic and catchment characteristics from catchments suitable for use in development of regional flood methods across Australia.
2. Development of metrics suitable for testing of climate change signals in regional flood methods.
3. Pilot testing of the selected methodologies leading to an agreed methodology. As a part of this, potential methods to be tested are Quantile Regression Technique (using ordinary least squares and generalised least squares), Probabilistic Rational Method and Region of Influence Approach.
4. A technical report detailing the above project outcomes.

1.3. Report Outline

The report contains 9 chapters as outlined below.

Chapter 1 provides a brief scope and background of the project.

Chapter 2 outlines the general criteria of catchment selection, streamflow data preparation (gap filling, rating curve error analysis, outlier test and trend analysis) and selection and abstraction of catchment characteristics data.

Chapter 3 presents the collation of streamflow and catchment characteristics data for various states. So far data from Victoria, NSW, ACT, Tasmania, Queensland and South Australia have been collated. The data from NT is still being processed. The data from Western Australia have not been received so far.

Chapter 4 describes the climate change indices and data which are relevant to regional flood estimation, which include El Niño Southern Oscillation (ENSO) phenomenon, the Interdecadal Pacific Oscillation (IPO) phenomenon, Indian Ocean

Dipole (IOD), and the Southern Annular Mode (SAM).

Chapter 5 provides a brief review of various methods relevant to regional flood estimation method namely, at-site flood frequency analysis, identification of homogeneous regions, Probabilistic Rational Method, regression techniques (ordinary least squares, generalised least squares, quantile regression and parameter regression), index flood method and fixed region vs. region of influence approach. It also presents a simplified Probabilistic Model that can be applied to the medium to high flood range.

Chapter 6 presents various exploratory regional flood frequency analyses for the states of Victoria, NSW, Tasmania, Queensland and South Australia. The results focus on comparing the Probabilistic Rational Method and various regression techniques. In most cases, independent testing has been undertaken to assess the adequacy of a particular method.

Chapter 7 discusses the issues in regional flood estimation associated with the long term climate variability and climate change. This also presents the preliminary results on trend analysis in annual maximum flood series.

Chapter 8 presents interim recommendations on suitable regional methods for further testing and for possible adoption in the ARR.

Chapter 9 presents conclusions from the data preparation and preliminary investigations undertaken in this report.

Appendices contain list of selected catchments from the different states and sample data on climate variability indices.

2. Streamflow and Catchment Data Preparation Methods

2.1. Selection of Candidate Catchments

The following factors are considered in making the initial selection of the study catchments.

Catchment area: The proposed regionalisation study aims at developing prediction equations for flood estimation in small to medium sized ungauged catchments. Since the flood frequency behaviour of large catchments has been shown to significantly differ from smaller catchments, the proposed method should be based on small to medium sized catchments. ARR (I.E Aust., 1987) suggests an upper limit of 1000 km^2 for small to medium sized catchments, which seems to be reasonable and is adopted here.

Record length: The streamflow record at a stream gauging location should be long enough to characterize the underlying flood probability distribution with reasonable accuracy. In most practical situations, streamflow records at many gauging stations in a given study area are not long enough and hence a balance is required between obtaining a sufficient number of stations (which captures greater spatial information) and a reasonably long record length (which enhances accuracy of at-site flood frequency analysis). Selection of a cut-off record length appears to be difficult as this can affect the total number of stations available in a study area. However for this study, the stations having a minimum of 10 years of annual instantaneous maximum flow records were selected initially as ‘candidate stations’.

Regulation: Ideally, the selected streams should be unregulated, since major regulation affects the rainfall-runoff relationship significantly (storage effects). Streams with minor regulation, such as small farm dams and diversion weirs, may be included because this type of regulation is unlikely to have a significant effect on annual floods. Gauging stations on streams subject to major upstream regulation were not included in this study.

Urbanisation: Urbanisation can affect flood behaviour dramatically (e.g. decreased infiltration losses and increased flow velocity). Therefore catchments with more than 10% of the area affected by urbanisation were not included in the study.

Landuse change: Major landuse changes, such as the clearing of forests or changing agricultural practices modify the flood generation mechanisms and make streamflow records heterogeneous over the period of record length. Catchments which have undergone major landuse changes over the period of streamflow records were not included in this study.

Quality of data: Most of the statistical analyses of flood data assume that the available data are essentially error free; at some stations this assumption may be grossly violated. Stations graded as ‘poor quality’ or with specific comments by the gauging authority regarding quality of the data were assessed in greater detail; if they were deemed ‘low quality’ they were excluded.

Climate variability and change: The impacts of climate variability and change on annual maximum floods were not considered in the initial selection of stations but were examined during the data analysis phase.

2.2. Streamflow Data Preparation

2.2.1. Infilling gaps in annual maximum flood series

Missing observations in streamflow records at gauging locations are very common and one of the elementary steps in any hydrological data analysis is to make decisions about dealing with these missing data points. Missing records in the annual maximum flood series were in-filled where the extra data points can be estimated with sufficient accuracy to contribute additional information rather than ‘noise’. For this project, one of the following methods was applied, as documented in Rahman (1997) and Haddad, Rahman and Weinmann (2008b).

***Method 1**:*

(a) Comparison of the monthly instantaneous maximum (IM) data with monthly maximum mean daily (MMD) data at the same station for years with data gaps. If a missing month of instantaneous maximum flow corresponds to a month of very low maximum mean daily flow, then that is taken to indicate that the annual maximum did not occur during that missing month.

Method 2:

(b) Method 2 involves a linear regression of the annual maximum mean daily flow series against the annual instantaneous maximum series of the same station. Regression equations developed were used for filling gaps in the IM record, but not to extend the overall period of record of instantaneous flow data.

For in-filling the gaps, Method 1 was preferred over Method 2, as it is more directly based on observed data for the missing month and involves fewer assumptions.

2.2.2. Trend analysis

Hydrological data for any flood frequency analysis, be it at-site or regional, should be stationary, consistent and homogeneous. The annual maximum flow series should not show any time trend to satisfy the basic assumption of stationarity with traditional flood frequency analyses methods. Thus, in this study, a trend analysis was carried out where possible to identify stations showing significant trend and the stations which did not show any trend were included in the primary data set for each Australian state. The stations showing trend were dealt separately, as discussed in Chapters 4 and 7.

Two tests were initially applied to detect time trend, the Mann–Kendall test (Kendall, 1970) and the distribution free CUSUM test (McGilchrist and Wodyer, 1975); both tests were applied at the 5% significance level. The Mann-Kendall test is concerned with testing whether there is an increase or decrease in a time series, whereas the CUSUM test concentrates on whether the mean values in two parts of a record are significantly different. As a useful guide and in addition to the trend tests, a simple time series plot and a cumulative flow graph of the station were also used to detect shifts in data.

2.2.3. Rating error analysis

The rating curve used to convert measured flood levels to flood discharge is based on periodic measurements of flow areas and velocities over a range of flow magnitudes. However, the range of observed flood levels generally exceeds the range of 'measured' flows, thus requiring different degrees of extrapolation of well established rating curves.

Any rating curve extrapolation errors are directly transferred into the largest observations in the annual maximum flood series, and use of extrapolated data in flood frequency analysis can thus result in grossly inaccurate flood frequency estimates.

To assess the degree of rating curve related error for a given station, the annual maximum flood series data point for each year (estimated flow Q_E) was divided by the maximum measured flow (Q_M) to obtain a rating ratio (RR) (see Equation 2.1). If the RR value is below or near 1, the corresponding annual maximum flow may be considered to be free of rating curve extrapolation error. However, a RR value well above 1 indicates a rating curve error that can cause notable errors in flood frequency analysis.

$$Rating\ \ Ratio(RR) = \frac{Q_E}{Q_M} \tag{2.1}$$

For any regional flood frequency analysis (RFFA), a large number of stations with reasonably long record lengths are required and hence a trade-off needs to be made between an extensive data set that includes stations with very large RR values (and thus lower accuracy) and a smaller data set with RR values restricted to what could be considered to be a "reasonable upper limit" of rating curve errors.

A working method to decide on a cut-off RR value was determined by looking at the average RR value and the maximum RR value for each station in a region/state. Based on the results from Victoria and NSW, the following cut-off values were found to represent a reasonable compromise between accuracy at individual sites and total size of the regional data set: an average RR value of 4 and a maximum RR value of 20.

2.2.4. Test for outliers

In a set of annual maximum flood series there is a possibility of outliers being present. An outlier is an observation that deviates significantly from the bulk of the data, which may be due to errors in data collection or recording, or due to natural causes.

In this study, the Grubbs and Beck (1972) method was adopted in detecting high outliers and low outliers. This method was recommended in Bulletin 17B by the US Water Resources Council after large scale testing of a wide variety of procedures.

The method is based on determining high outlier and low outlier thresholds by applying a one-sided 10% significance level test that considers the sample size. The test was developed by Grubbs and Beck (1972) for detecting single outliers from a normal distribution but (when applied to the logs of a flood data series) has been shown to be also applicable to the LP3 distribution. The method is simple to use and has been widely applied in North America (Ng et al., 2007). Its application to dealing with low outliers is straightforward. However, it should be noted here that special precaution is needed to treat any detected high outlier, given that there is a 10% chance of the null hypothesis of no outliers having been wrongly rejected. If not caused by data error, the 'outlier' data point contains very useful information regarding the frequency of large floods.

2.3. Selection and Abstraction of Catchment Characteristics Data

Catchment characteristics used in many previous regionalisation studies were summarised by Rahman (1997). He grouped the catchment characteristics under the headings of climatic characteristics, morphometric characteristics, catchment cover & land use characteristics, geological & soil characteristics, catchment storage characteristics, and location characteristics. Many catchment characteristics are highly correlated, and the inclusion of strongly correlated variables in prediction equations does not add any new information; it also causes problems in statistical analysis (e.g. multicollinearity). The following guidelines can be useful in making a reasonable selection:

- The characteristics should have a plausible role in flood generation.
- They should be unambiguously defined.
- Characteristics should be easily obtainable. When a simpler characteristic and a complex one are correlated and have similar effects then the simpler characteristic should be chosen.
- If a derived/combined characteristic is used, it should have a simple physical interpretation.
- The characteristics in the selected set should not be highly correlated, because this results in unstable parameters in multivariate analysis.

- The prediction performance of a characteristic in other regionalisation studies should be taken into account, as this can give some general idea regarding the importance of the characteristic.

Based on the hydrological significance, correlations and ease of the data abstraction, seven catchment characteristics were included in this study as listed in Table 2.1, and described below.

Catchment area: Catchment area is the main scaling factor in the flood process and directly affects the potential flood magnitude from a given storm event. The total volume of runoff (*Q*) is proportional to the area of the catchment (*A*), and of the general form:

$$Q = cA^{m} \qquad (2.2)$$

where the exponent m varies from 0.5 to 1.00.

Table 2.31 Catchment characteristics variables used in the study

Catchment Characteristics
1. *area:* Catchment area (km^2)
2. *I:* Design rainfall intensity (mm/h)
3. *rain:* Mean annual rainfall (mm)
4. *evap*: Mean annual areal potential evapotranspiration (mm)
5. *S1085:* Slope of the central 75% of mainstream (m/km)
6. *sden:* Stream density (km/km^2)
7. *forest:* Fraction of catchment area under forest.

Almost all of the reported RFFA studies have found catchment area to be very significant. One of the reasons why the area variable has been so useful in statistical hydrology is its association with other significant morphometric characteristics like slope, stream length and stream order. Area was characterised by Anderson (1957) as the ‘devil’s own variable’, because almost every watershed characteristic is correlated with it. As in the case of area, the mean annual flood is directly proportional to other morphometric characteristics, which are again directly proportional to area.

In this study, catchment area was obtained from 1:100,000 topographic maps which are readily available for large parts of Australia.

Rainfall intensity: Storm rainfall intensity ($I_{ARI,d}$), for an appropriate burst duration (d) and average recurrence interval (*ARI*), has been found to be the most significant predictor climatic characteristic in previous regionalisation studies. This is to be expected given the strong causal link between intensity and peak flow. Importantly, this intensity is simple to obtain from the published data (e.g. ARR1987 Volume 2).

The use of rainfall intensity requires the selection of an appropriate storm burst duration and ARI. It seems to be logical to use a design rainfall intensity with a duration equal to the time of concentration (t_c), as suggested in the Probabilistic Rational Method (I.E. Aust., 1987, 2001). This is because as catchment area gets bigger, t_c gets longer, which results in smaller average design rainfall intensity. However, there are different methods to estimate t_c e.g. Bransby Williams formula, Friend formula (I.E. Aust., 2001). For consistency, and ease of application, the formula recommended in ARR 1987 for Victoria and eastern NSW, given by Equation 2.3, was adopted in this study.

$$t_c = 0.76A^{0.38} \qquad (2.3)$$

where t_c is time of concentration in hours and A is catchment area in km^2.

In addition to the design rainfall intensity for a given ARI and t_c ($I_{ARI,tc}$), rainfall intensities with fixed durations and ARIs were also trialled e.g. rainfall intensities with 2 and 50 years ARIs and 1 and 12 hours durations.

The various design rainfall intensities data for the selected study catchments were obtained using the IFD Calculator on the BOM website or the design data in ARR Volume 2.

Mean annual rainfall: Mean annual rainfall has been used frequently in previous regionalisation studies. It may not have a direct link with flood peak, but it acts as a surrogate for some other characteristics (e.g. vegetation, wetness index) and is readily available. Thus, mean annual rainfall was included as a predictor variable in this study. The data for the mean annual rainfall for each catchment was extracted from the BOM Data CD of Annual Rainfall.

Mean annual evaporation: This relates to the main loss component in the rainfall-runoff process. It is readily available and thus was included in this study. The mean annual areal potential evapotranspiration data for each catchment was extracted from the BOM Data CD of Evaporation.

Slope: Slope is significant for any gravitational flow. With other catchment characteristics held constant, the steeper the slope the greater the velocity. Both overland and channel slope are important. Overland slope influences the velocity of shallow surface flow; hence, it can be expected to be of more importance for smaller catchments where the time spent in overland flow is a significant percentage of the total time needed for water to reach the catchment outlet. For larger catchments, channel slope is relatively more important than overland slope.

There are several measures of slope; the most common of these are:

Equal area slope: This is the slope of a straight line drawn on a profile of a stream such that the line passes through the outlet and has the same area under and above the stream profile.

Average slope: This is equal to the total relief of the main stream divided by its length.

S1085: This excludes the extremes of slope that can be found at either end of the mainstream. It is the ratio of the difference in elevation of the stream bed at 85% and 10% of its length from the catchment outlet, and 75% of the main stream length.

Areal slope: This involves measuring the slope at a large number of points within a catchment and then determining an average areal slope.

Taylor and Schwarz (1952) slope: This assumes that velocity in each reach of a subdivided mainstream is related via the Manning's equation to the square root of slope. This index is equivalent to the slope of a uniform channel having the same length as the longest water course and an equal time of travel.

In previous studies Strahler (1950) has shown that the overland slope and channel slope are strongly correlated. Benson (1959) found that *S*1085 gave the best prediction of the mean annual flood. The *S*1085 is closely correlated with the Taylor and Schwarz slope (NERC, 1975).

From the different measures of slope, *S*1085 was deemed adequate and the simplest to estimate from 1:100,000 topographic maps and thus was adopted in this study.

Stream density: This is directly related to drainage efficiency of a catchment, and was included in this study where possible. The definition of stream density is total stream length, which is taken as the sum of the length of all the blue lines in catchment as shown on 1:100,000 topographic maps, divided by catchment area. The length of the blue lines can be measured by opisometer/electronic distance meter or can be obtained using GIS.

Stream density is not easy to measure and also the measured value depends on the map scale used. It should be retained in the final prediction equation only if it delivers significantly improved design flood estimates. Also, if it is used in final flood prediction equations, the procedure should stress the map scale to be used in its measurement.

Forest area: The effect of vegetation on catchment response has been studied by many researchers (Flavell and Belstead, 1986; Williamson and Vand Der Wel, 1991; Flavell, 1982). Forest reduces runoff by precipitation interception and transpiration. For a surface without a canopy or leaf litter layer, the interception loss is lower and overland flow travels more rapidly with less opportunity time for infiltration. Hence, Flavell (1982) found that losses from rainfall decrease with increased clearing and that the runoff coefficient of the Rational Method increases with increased clearing. Fraction forest cover was included in this study. The fraction of catchment covered by forest was estimated on 1:100,000 topographic maps by using a planimeter to measure the areas designated as dense and medium forest, and dense and medium scrub.

3. Streamflow and Catchment Data for Various Australian States

3.1. Victoria

Based on the selection criteria presented in Section 2.1, a total of 415 stations were initially selected as candidates from Victoria each having a minimum of 10 years of streamflow record.

For in-filling the gaps in the annual maximum flood series, Method 1 was preferred over Method 2 (see Section 2.2.1 for a description of these methods). The following points summarise the results of the in-filling of the annual maximum flood series data.

- 273 data points from 187 stations were in-filled by comparing flow records (Method 1);
- 60 data points from 44 stations were in-filled by regression (Method 2);
- Regression equations used in gap filling showed high R^2 values (range 0.82 – 0.99, mean = 0.93 and SD = 0.041); and
- 10% of stations did not have any missing records.

After in-filling the gaps, the stations were then checked for possible trends, as discussed below.

Trend analysis:

Initially the Mann-Kendall test was applied to the stations. The results were rather surprising as they revealed that many stations had a decreasing trend. Given the magnitude of the number of stations showing trend, time series plots and mass curves were prepared for the stations showing trend to detect visually if significant changes in slope could be identified.

As an example, Figure 3.1.1 shows a significant overall downward trend for Station 230210, supporting the result from the Mann-Kendall test, and a noticeable decrease in annual maximum flows from the late 1980s. In order to clarify this further the CUSUM test was applied; the result was similar, with the plotted graph as seen in Figure 3.1.2 showing a downward shift in the mean from 1995 onwards.

A simple time series plot was therefore useful in addition to trend tests in detecting and confirming shifts in data. With an indication from these tests that flood data are not independently and identically distributed from year to year, there needs to be caution applied when using short records in estimating long term risks. The fact that the last 10–15 years of data (after late 1980's) show a significant downward trend for many stations makes the inclusion of stations with short records in regionalisation studies quite questionable.

It is important to incorporate these findings in the data collation for this regionalisation study. Most RFFA methods can compensate for sampling variability in many RFFA methods but we cannot compensate for the bias that will be introduced into the model due to the systematic downward trend in annual maximum flood data encountered in the short records.

One notable exception was that of Micevski et al. (2006) who presented a Bayesian hierarchal modelling approach to deal with non-homogeneity and associated bias by explicitly allowing for interdecadal variability; this certainly could be an alternative future approach. In this study, the introduction of a cut-off record length appeared to be appropriate, i.e. records shorter than 25 years and extending to near 2005 are likely to be affected by significant bias because of the persistent drought impacts since the early 1990's; they should thus be excluded from the database. Although this approach would remove more than half of the candidate stations and undermine spatial coverage, the remaining stations would be less affected by bias and thus would yield more accurate RFFA results.

Finally, 21 stations from Victoria were removed due to the presence of significant trend. The number of eligible stations remaining after the application of trend tests and the introduction of a cut off record length of 25 years, dropped to 144, which is only 35% of the initially selected 415 stations. This result shows that the effective data set for RFFA in a given region is likely to be substantially smaller than the primary data set.

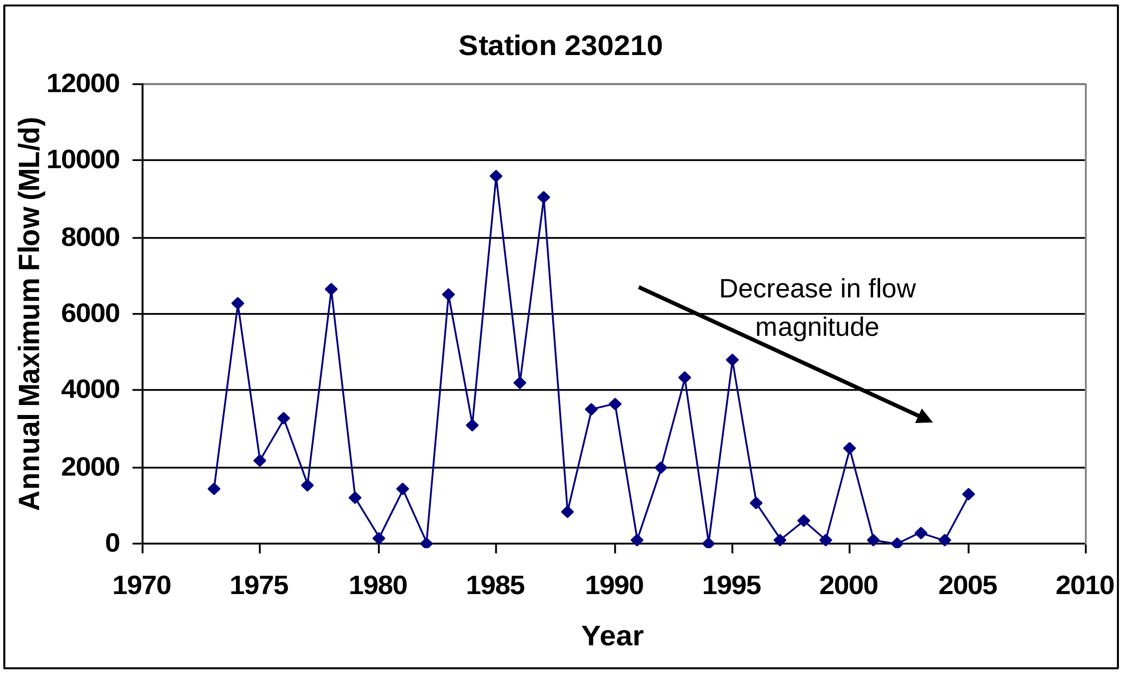


Figure 3.1.1 Time series graph showing significant trends after 1995

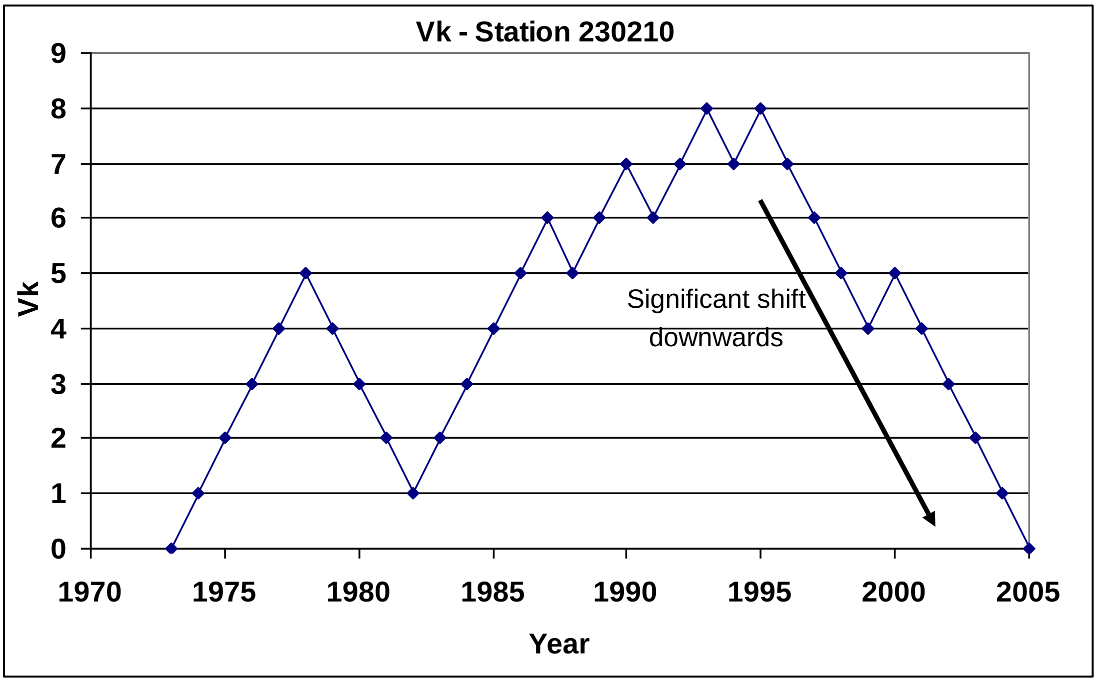


Figure 3.1.2 CUSUM test plot showing significant trends after 1995. Here V_k is CUSUM test statistic defined in McGilchrist and Wodyer (1975)

Impact of rating curve error on flood frequency analysis:

In the remaining data set of 144 stations, many had rating ratios (RR) considerably greater than 1 (RR is defined by Equation 2.1). From the histogram of RR values shown in Figure 3.1.3 it can be seen that 90% of the RR values for all the recorded annual maxima lie between 1 and 20. Thus it was decided that a cut-off RR value of 20 would be reasonable, and that any station having an average RR value greater than 4 and a maximum RR value greater than 20 would be rejected. Rating ratios significantly greater than one could magnify the errors in flood frequency quantile estimates but, on the other hand, rejecting all stations with RR values greater than one would reduce the number of stations below the minimum required for meaningful RFFA to be undertaken. Adopting the cut off values of RR, mentioned above, reduced the eligible number of stations from 144 to 131.

Impacts of rating ratio on flood frequency analysis – sensitivity analysis:

The FLIKE software, which implements the principles outlined in Kuczera and Franks (2005), was employed to fit the LP3 distribution using the Bayesian parameter fitting procedure with both the 'no rating curve error' and the 'rating curve error' cases to assess the impact of rating curve errors on flood frequency estimates. The flow that is closest to RR = 1 was used as the "anchor point" in the FLIKE rating curve error model. A log normal error probability model was also adopted. The number of error groups was taken as 2. To deal with the incremental error standard deviation a percentage difference was estimated between the anchor flow, whose rating ratio was 1, and the measured flow (Q_M), whose rating ratio could be up to RR = 20.

Station 225218 is used as an example to highlight the impact of RR on flood estimates (Figure 3.1.4). An incremental error percentage of 20% was used. The incremental error percentage represents the coefficient of variation of the ratio of the estimated flow and the anchor point flow for RR values greater than one.

The quantile estimate (100 year ARI) for the analysis ignoring the rating curve error was 99,200 ML/d; while the quantile estimate considering the rating curve error was 112, 300 ML/d (a 13% increase). From a design point of view, adopting the flood frequency estimate (without considering the rating curve error) in this example would lead to an underestimation of the 100-year flood by 13,000 ML/d. The FLIKE error model was adopted in flood frequency analyses to account for the rating curve error for all the stations, as explained above.

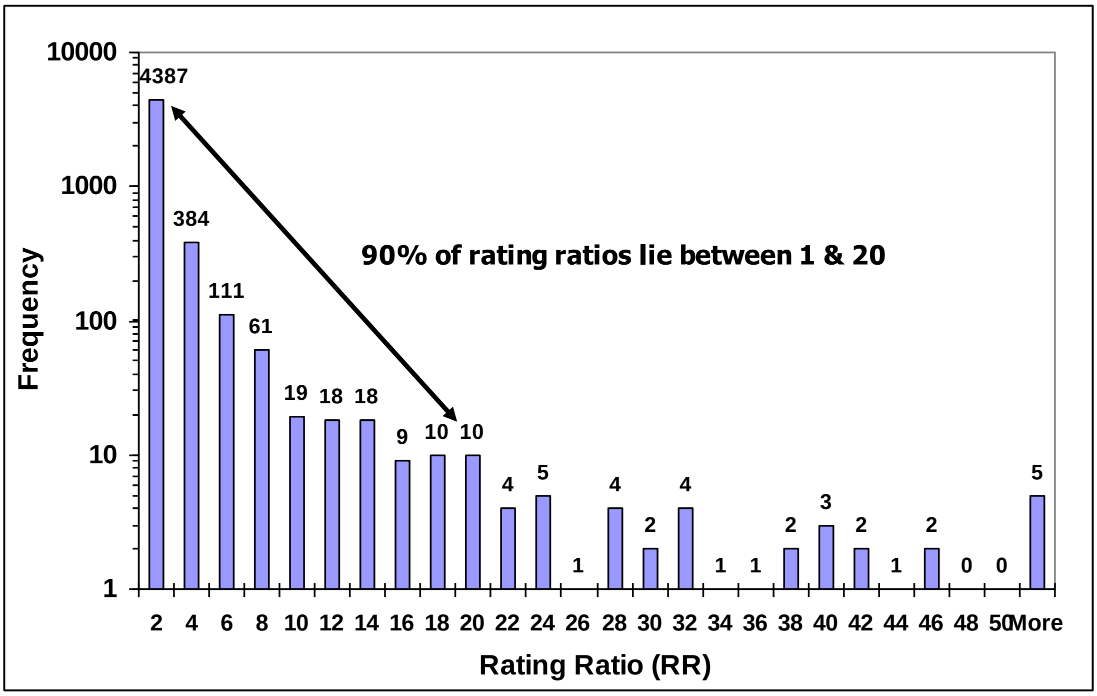


Figure 3.1.3 Histogram of rating ratios (RR) of annual maximum flood data in Victoria (stations with record lengths > 25 years)

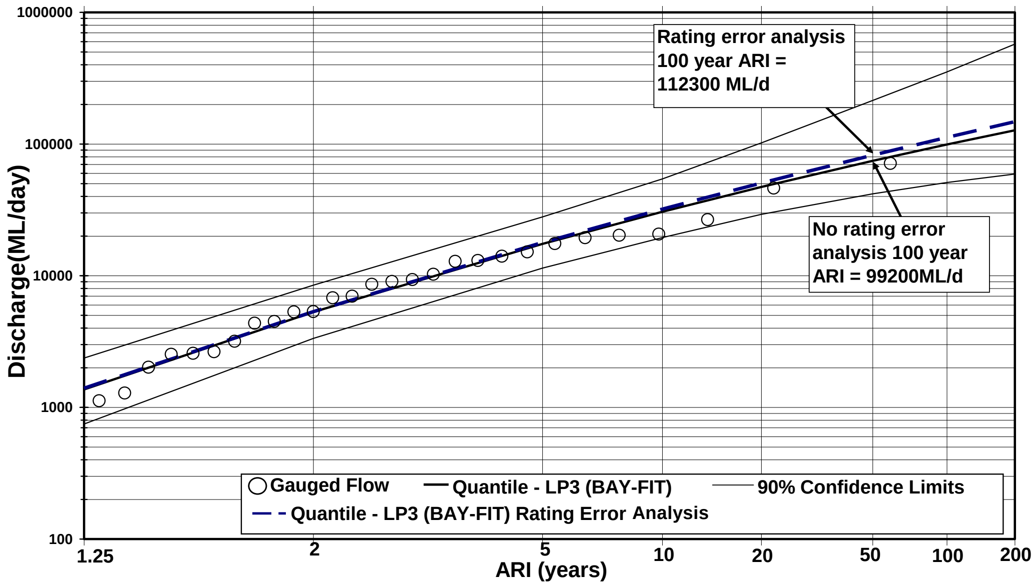


Figure 3.1.4 Impact of considering rating curve error in flood frequency analysis (Station 225218)

Outlier identification results:

The Grubbs and Beck (1972) method was adopted to check for the outliers. The results of the outlier detection procedure are summarised below:

- 43% of the stations were found to have low outliers. The maximum number of low outliers detected in a data series was 5 and never exceeded 19% of the total number of data points in a series.
- Most of the detected low outliers occurred for stations which were located in low rainfall areas, especially in the western part of Victoria.
- 31% of low outliers occurred in the years 1982 and 1967. This is not surprising as there were severe droughts during these two years; the maximum annual flows that occurred in many rivers in these years were merely base flows, and not due to flood events. Similar results were reported by Rahman (1997).
- 55% of the stations did not show any outliers. Even the values in drought years (1982 and 1967) were not low enough to be treated as low outliers. The locations of most of these stations are in the south-eastern part of Victoria.
- Only 1 station showed a high outlier, which was not removed as no data error was detected.

While the data checking revealed many 'outliers' in the flood series, these did not preclude the use of the remaining flood data in RFFA. The detected low outliers were treated as censored flows in flood frequency analysis using FLIKE (that is the information that there is no flood in that year was taken into account).

Final data set from Victoria:

As noted earlier, a total of 415 stations, each with a minimum record length of 10 years, were initially selected. After in-filling the gaps in the annual maximum flood series, trend analysis and introduction of a cut-off record length of 25 years, only 131 stations remained, which represented about one-third of the initially selected stations. The distribution of streamflow record lengths of the selected 131 stations is shown in Figure 3.1.5. The statistics of record lengths of these 131 stations are summarised below.

- Record lengths range from 25 to 52 years, mean: 32 years, median: 32 years and standard deviation: 5 years;
- 87% of the stations have record lengths in the range 25-35 years;
- 8% of the stations have record lengths in the range 35-45 years; and

- 5% of the stations have record lengths in the range 50-55 years.

The catchment areas of the selected 131 catchments range from 3 to 997 km^2 (mean: 321 km^2 and median: 289 km^2). The distribution of catchment areas is shown in Figure 3.1.6. The statistics of catchments areas of the selected 131 catchments are summarised below:

- 15 catchments (11%) are in the range of 3 to 50 km^2;
- 11 catchments (8%) are in the range of 51 to 100 km^2;
- 78 catchments (60%) are in the range of 101 to 499 km^2; and
- 27 catchments (21%) are in the range of 500 to 997 km^2.

The geographical distribution of the finally selected 131 stations is shown in Figure 3.1.7. These stations are listed in Appendix A (Table A1). There is no station in north-western Victoria that passed the selection criteria. This region is characterised by very low runoff and ephemeral streams.

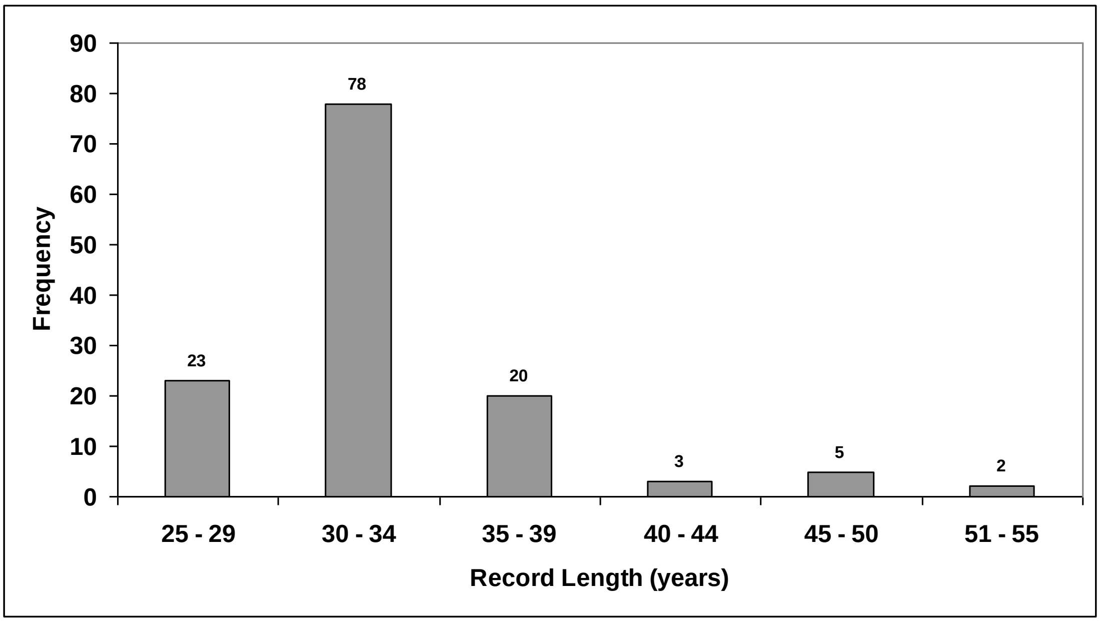


Figure 3.1.5 Distributions of streamflow record lengths of the selected 131 stations from Victoria

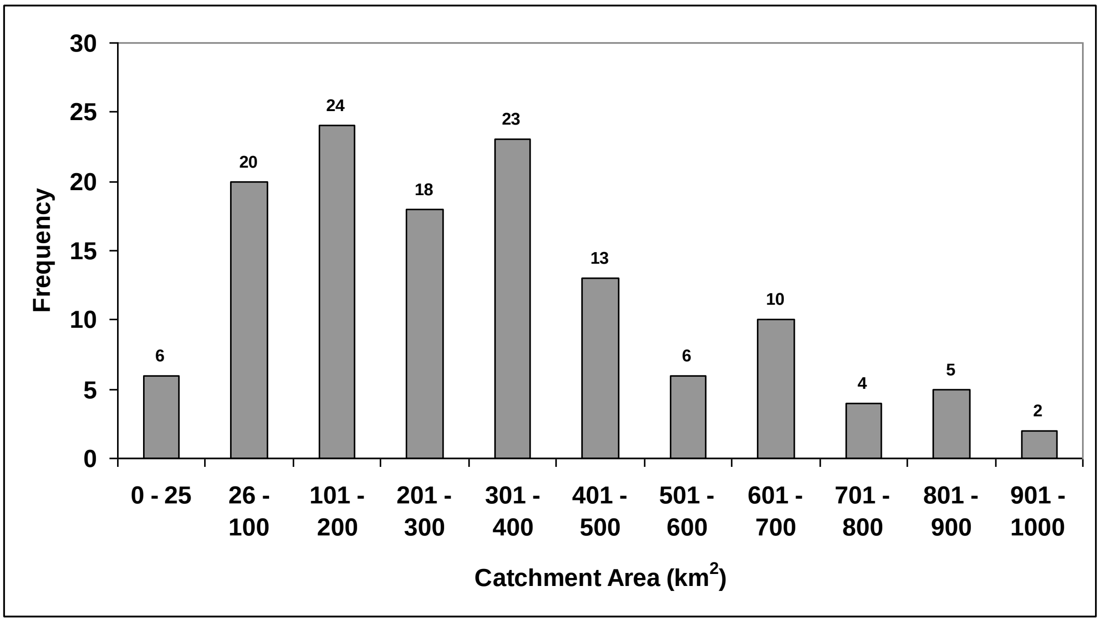


Figure 3.1.6 Distributions of catchment areas of the 131 catchments from Victoria

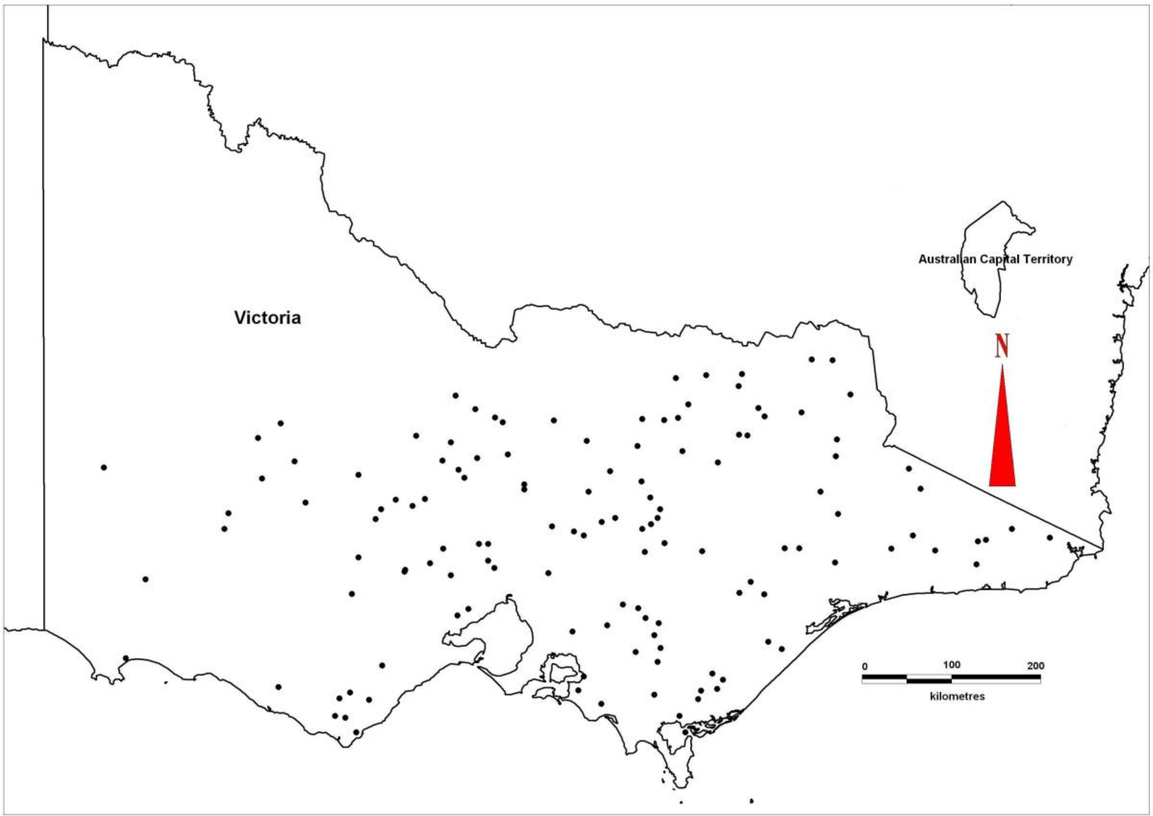


Figure 3.1.7 Geographical distributions of the selected 131 catchments from Victoria

3.2. NSW and ACT

Initially, a total of 635 stations were selected from NSW and ACT. For in-filling the gaps, Method 1 was preferred over Method 2. After in-filling the gaps and based on the selection criteria (Section 2.1), only 294 stations remained with at least 10 years of annual maximum streamflow data.

Trend analysis:

Initially the Mann-Kendall test was applied to the stations. The results show that many stations had a decreasing trend generally after 1990. Given the magnitude of the number of stations showing trend, time series plots and mass curves were prepared for the stations showing trend to detect visually if significant changes in slope could be identified. A typical plot is shown in Figures 3.2.1. A simple time series plot (Figure 3.2.2) was useful in addition to trend tests in detecting and confirming shifts in data. With an indication from these tests that flood data are not independently and identically distributed from year to year, there needs to be caution applied when using short records in estimating long term risks.

The fact that the last 10–15 years of data (after late 1980's) showed a significant downward trend for many stations makes the inclusion of stations with short record length in flood frequency analysis questionable, as this could introduce significant bias in the results. Hence, it was decided that a station should have at least 25 years of streamflow data. The number of eligible stations after the introduction of a cut off record length of 25 years dropped to 106, which is only 17% of the initially selected 635 stations.

Checking for outliers in the annual maximum flood series:

The Grubbs and Beck (1972) method was adopted to check for the outliers. The results of the outlier detection procedure are summarised below:

- 40% of the stations were found to have low outliers. The maximum number of low outliers detected in a data series was 9 and never exceeded 21% of the total number of data points in a series.
- Most of the detected low outliers occurred for stations located in low rainfall areas, especially in the western parts of New South Wales.
- 31% of low outliers occurred in the years 1982, 1967 and 1994. This is not surprising as there were severe droughts during these years; the maximum

flows that occurred in many rivers in these years were merely base flows, and not due to flood events.

- 47% of the stations did not show any outliers.
- Only 5 stations had a high outlier, which was not removed as no data error was detected.

The detected low outliers were treated as censored flows in flood frequency analysis using ARR FLIKE (Kuczera and Franks, 2005).

Rating curve error:

To assess the degree of rating curve related error for a given station, the rating ratio (RR) (see Equation 2.1) was adopted. In the remaining data set of 106 stations from NSW, many had RR values considerably greater than 1 (Figure 3.2.3). A cut-off RR value of 20 was adopted; any station having an average RR value greater than 4 and a maximum RR value greater than 20 was rejected. This reduced the eligible number of stations from 106 to 96.

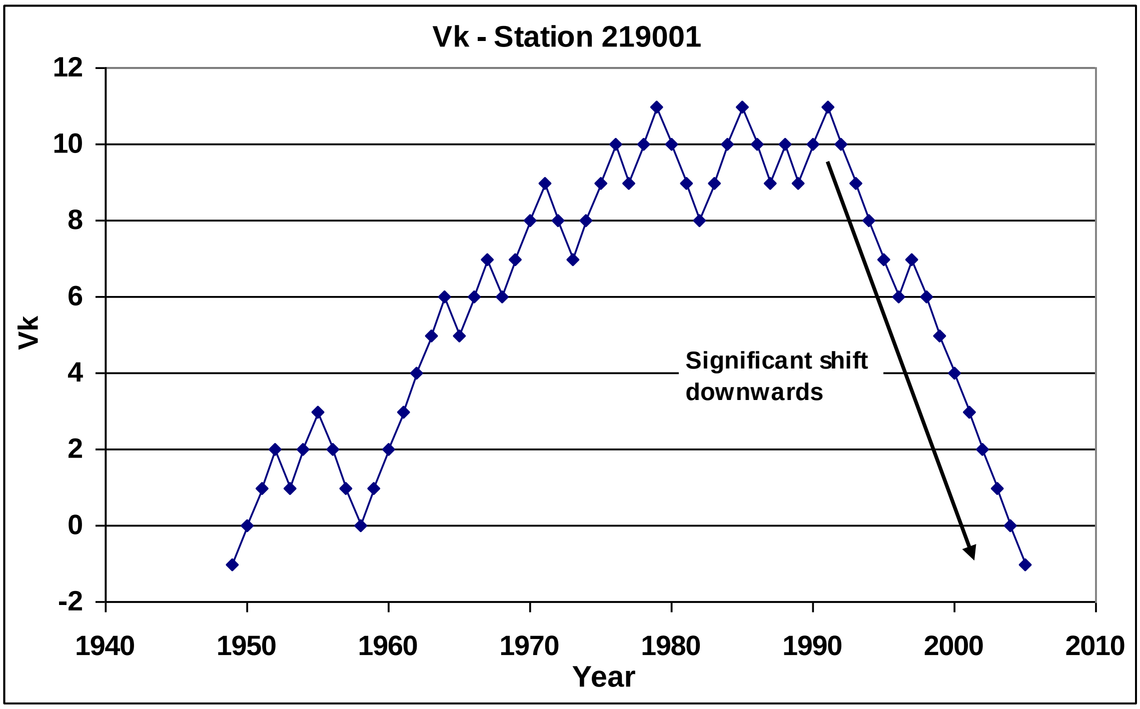


Figure 3.2.1 Result of trend analysis (Station 219001)

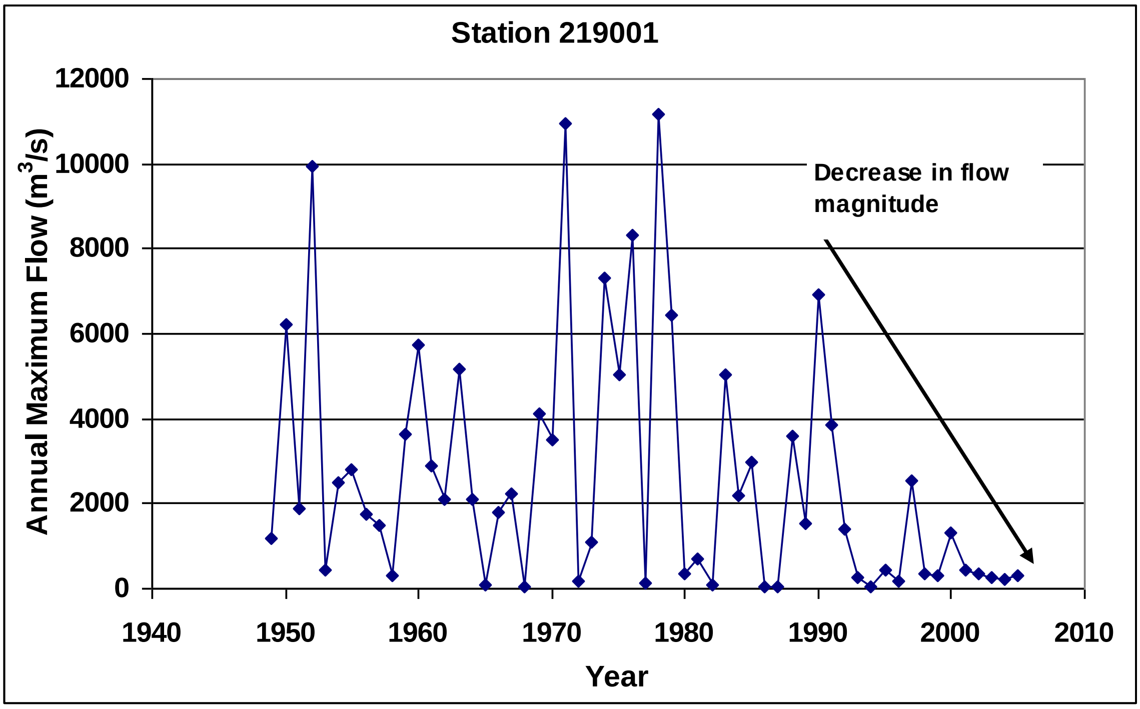


Figure 3.2.2 Result of trend analysis – time series plot (Station 219001)

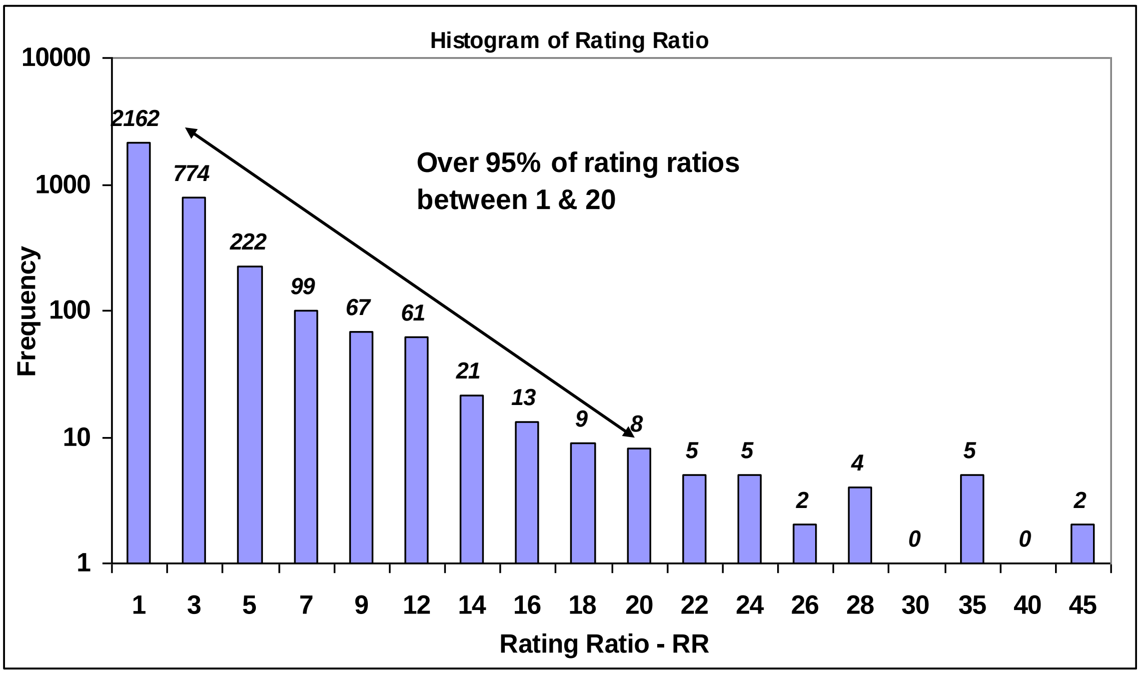


Figure 3.2.3 Histogram of rating ratios for 106 stations from NSW

Final data set from NSW:

A total of 635 stations were initially selected. After in-filling the gaps in the annual maximum flood series, trend analysis, introduction of a cut-off record length of 25 years, and consideration of rating curve errors, only 96 stations remained, which represent about 15% of the initially selected stations. The statistics of annual maximum flood series record lengths of these 96 stations are summarised below:

- Record lengths range from 25 to 74 years, mean 34 years, median 31 years and standard deviation 10 years;
- 77% of the stations have record lengths in the range 25-35 years;
- 18% of the stations have record lengths in the range 40-55 years; and
- 5% of the stations have record lengths in the range 60-75 years.

The histogram of streamflow record lengths of the 96 stations is shown in Figure 3.2.4.

The statistics of catchment areas of the selected 96 stations are summarized below:

- Catchment areas range from 8 to 1010 km^2, with an average value of 353 km^2, median of 267 km^2 and a standard deviation of 276 km^2;
- 53% of catchments have areas smaller than 300 km^2;
- 38% of stations have areas in the range of 301 km^2 to 800 km^2; and
- 10% of stations have areas in the range of 801 km^2 to 1010 km^2.

The distribution of catchment areas is shown in Figure 3.2.5.

The geographical distribution of the finally selected 96 stations is shown in Figure 3.2.6. There is no station in far western New South Wales that passed the selection criteria. The selected 96 catchments are listed in Appendix A (Table A2).

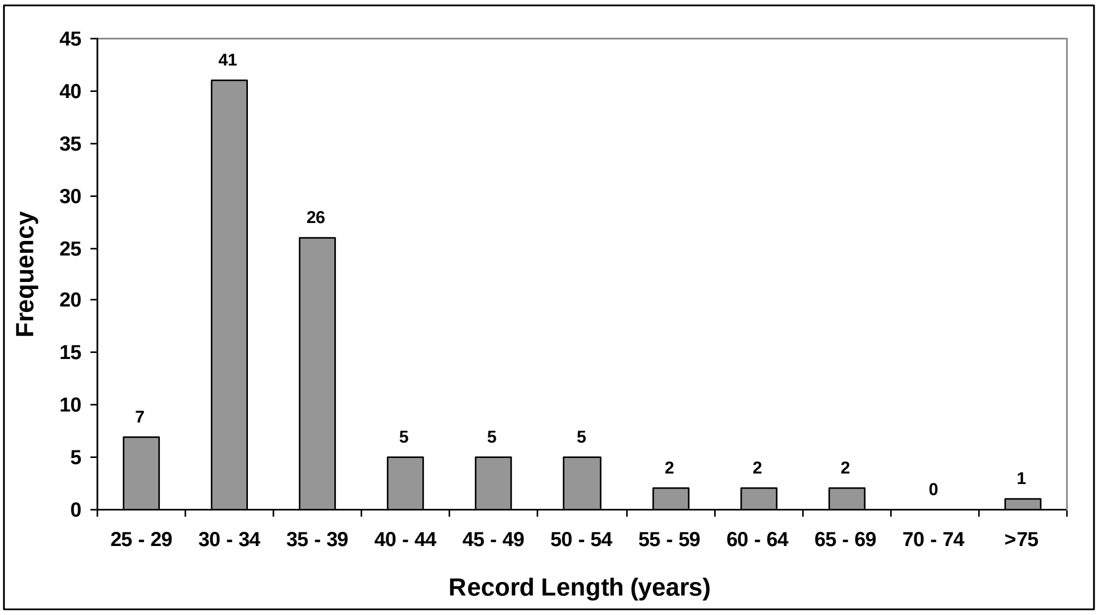


Figure 3.2.4 Distribution of streamflow record lengths of 96 stations from NSW

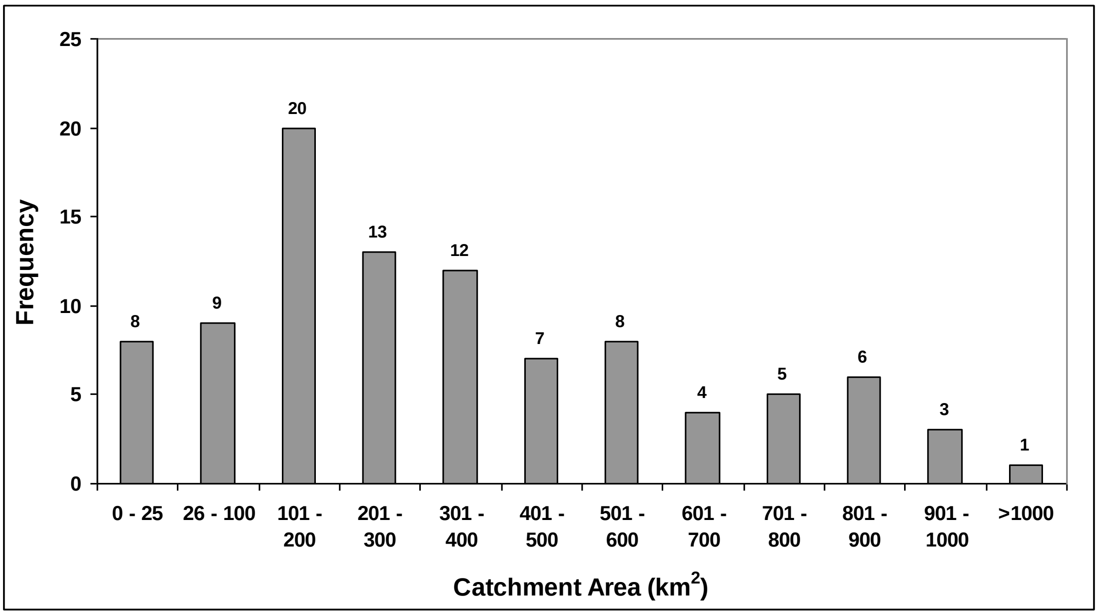


Figure 3.2.5 Distribution of catchment areas of 96 stations from NSW

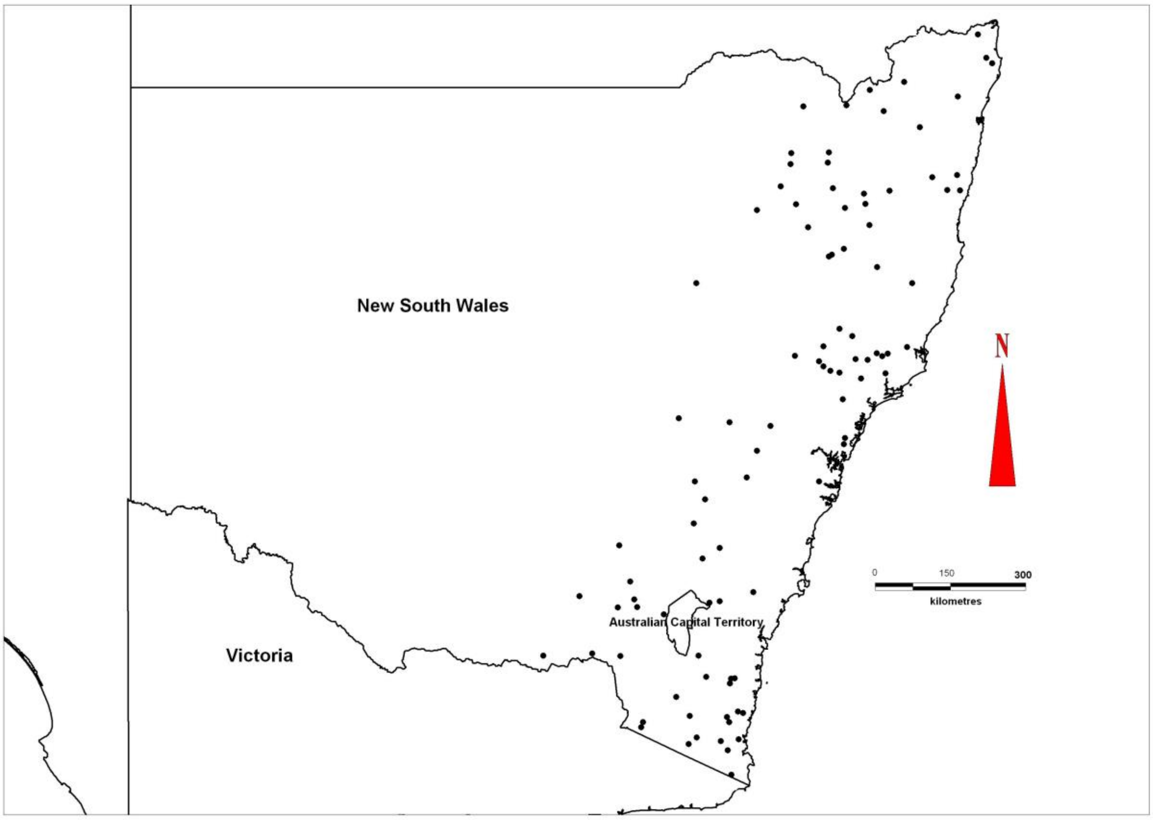


Figure 3.2.6 Geographical distributions of the selected 96 catchments from NSW

3.3. Tasmania

A total of 53 stations were selected as candidates from Tasmania each having a minimum of 10 years of streamflow record. For in-filling the gaps in the annual maximum flood series, Method 1 was preferred over Method 2 (these methods are described in Section 2.2.1). The following points summarise the results of the in-filling of the annual maximum flood series data for Tasmania:

- 18 data points from 23 stations were in-filled by comparing flow records (Method 1);
- 27 data points from 12 stations were in-filled by regression (Method 2); and
- 20% of stations did not have any missing record.

After in-filling the gaps, the stations were then checked for possible trends (Section 3.1 details the method). Only three stations showed trends. The relevant data for checking the rating ratios for Tasmania was largely unavailable, and hence no rating error analysis was undertaken. About 9% of the stations showed low outliers. The maximum number of low outliers detected in a data series was one and never exceeded 4% of the total number of data points in a series. The low outliers occurred in the years 1967, 1982 and 2001. About 75% of the stations did not show any outliers. About 14% of the stations showed high outliers, however, these data points were not removed as no data error was detected.

While obtaining catchment characteristics data, 7 stations were found to have significant proportions of lake areas, and were thus excluded; this reduced the dataset to 37 stations. From this, 3 catchments over 1590 km^2 were excluded, thus the final dataset contained 34 stations.

The streamflow record lengths of the selected stations range from 10 to 58 years (median: 21 years and mean: 24 years). The cut off record length for Tasmania was set to 10 years (which was 25 years for Victoria and NSW) as a higher cut off would make the sample size too small to develop any meaningful RFFA technique. Figure 3.3.1 shows the distribution of record lengths of the selected stations. Figure 3.3.2 presents the distribution of catchment areas of the selected catchments. The catchment areas range 4.6-1590 km^2 (median: 102 km^2 and mean: 240 km^2). Figure 3.3.3 shows the locations of the selected stations. There is a lack of station in the southern and eastern parts of the state. The finally selected catchments from Tasmania are listed in Appendix A (Table A3).

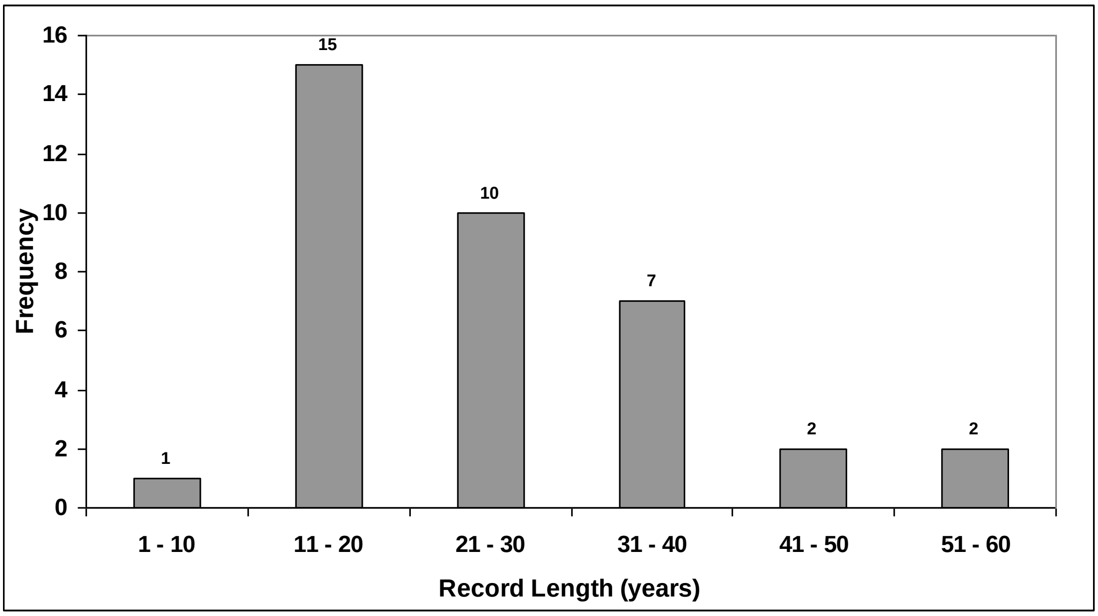


Figure 3.3.1 Distribution of streamflow record lengths of the stations from Tasmania

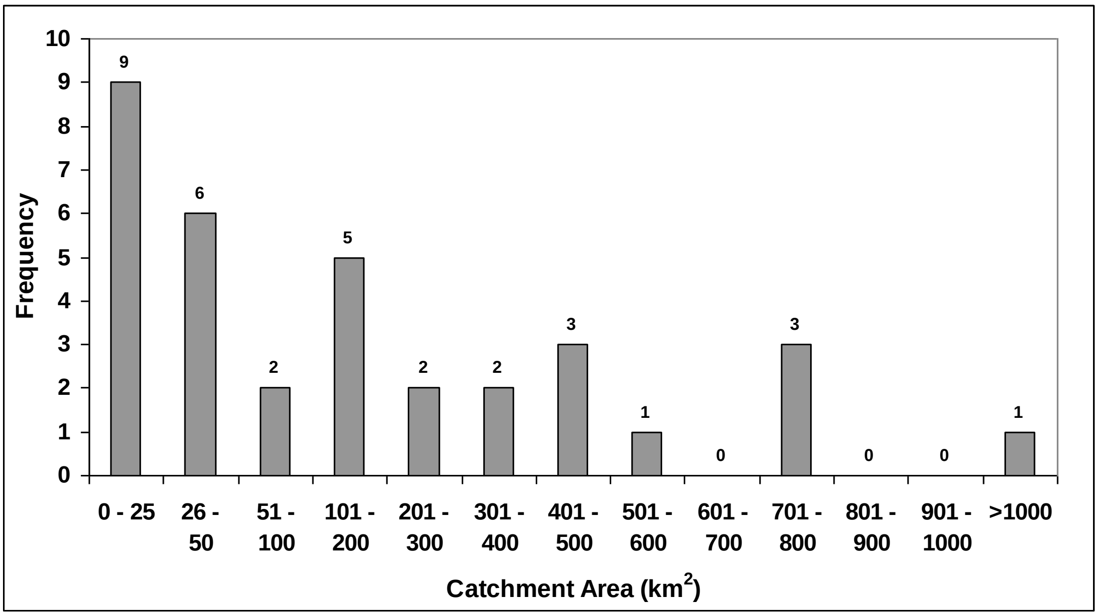


Figure 3.3.2 Distribution of catchment areas of the selected stations from Tasmania

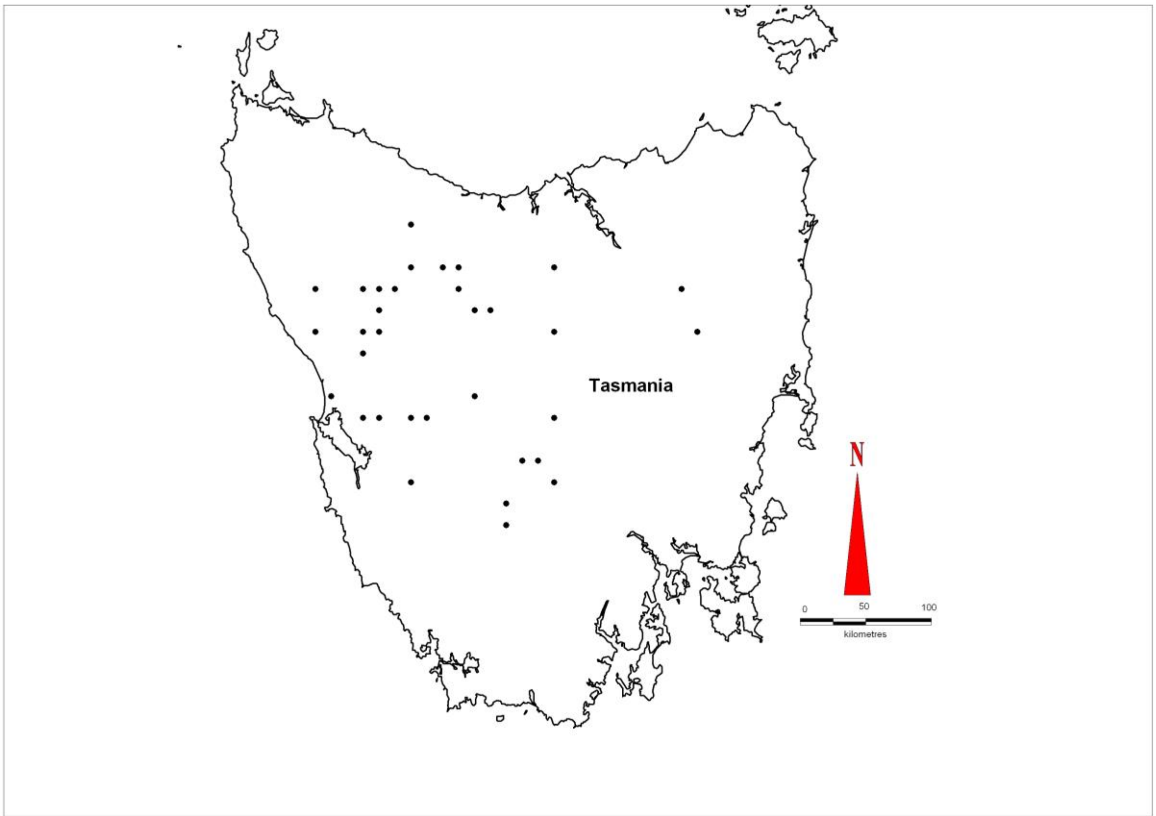


Figure 3.3.3 Locations of selected catchments from Tasmania

3.4. Queensland

The streamflow data were obtained from the Department of Natural Resources & Water (NRW). A total of 351 active and historical streamflow gauge station records were provided by NRW. Gauge station metadata, annual maximum flow records as well as the monthly and daily records were supplied by the NRW for each station. Based on the selection criteria listed in Section 2.1, the number of eligible stations reduced to 289.

The annual maximum flood series data were in-filled by comparing flow records (Method 1) and/or regression (Method 2). Method 1 was preferred over Method 2. Some years' data could not be filled due to many missing records. Some important statistics regarding the gap filling are:

- 81 data points were in-filled for 47 stations using Method 1;
- 413 data points were in-filled for 104 stations using Method 2; and
- 16 % of stations did not have missing records.

To check for outliers, the Grubbs and Beck (1972) method was used. Some important statistics about the outlier detection are:

- 39% of stations were found to have low outliers; the maximum number of outliers detected in a data series was 4 and never exceeded 10% of the total number of data points in a series.
- most of the detected low outliers occurred mainly in the midwestern and top parts of Queensland.
- The bulk of the low outliers occurred in the years 1967, 1982 and 2001; and
- 61% of stations did not have any outliers.

A total of 23 stations (7% of the stations) showed a significant trend, and were removed from the database. As a result, 265 stations were retained.

The streamflow record lengths of the initially selected 265 stations range from 10 years to 97 years (mean: 27 years, median: 26 years). (Further analysis is in progress to determine a cut off record length for the state.) The distribution of record lengths is shown in Figure 3.4.1. Some important statistics of the streamflow record lengths are provided below:

- 100 stations (37%) have record lengths in the range of 10 to 20 years;

- 27 stations (10%) have record lengths in the range of 21 to 24 years;
- 138 stations (52%) have record lengths greater than 24 years; and
- 50 stations (33%) have record lengths greater than 50 years.

The catchment areas of these 265 stations range from 7 to 963 km^2 (mean: 314 km^2, median: 258 km^2). The distribution of catchment areas of these catchments is shown in Figure 3.4.2. Some important statistics of the catchment areas are summarised below:

- 24 catchments (9%) are smaller than 50 km^2;
- 67 catchments (25%) are smaller than 100 km^2;
- 47 catchments (18%) are in the range of 101 to 200 km^2; and
- 37 catchments (14%) are larger than 600 km^2.

The locations of the selected 265 stations are shown in Figure 3.4.3. There are no suitable stations located in the south-western part of Queensland.

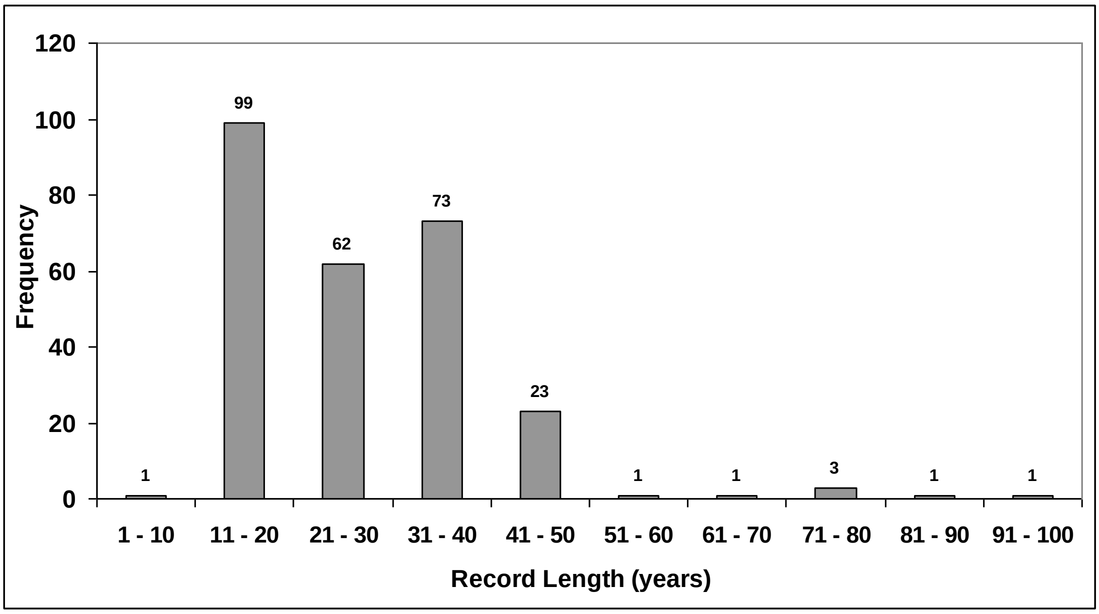


Figure 3.4.1 Distribution of streamflow record lengths of the stations from Qld

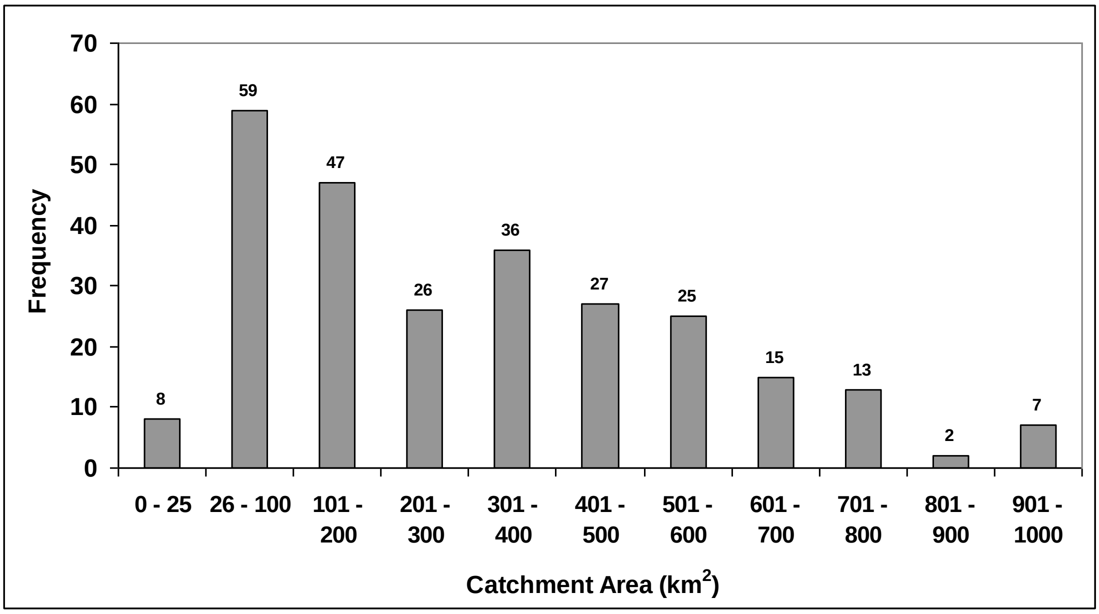


Figure 3.4.2 Distribution of catchment areas of the selected 265 stations from Qld

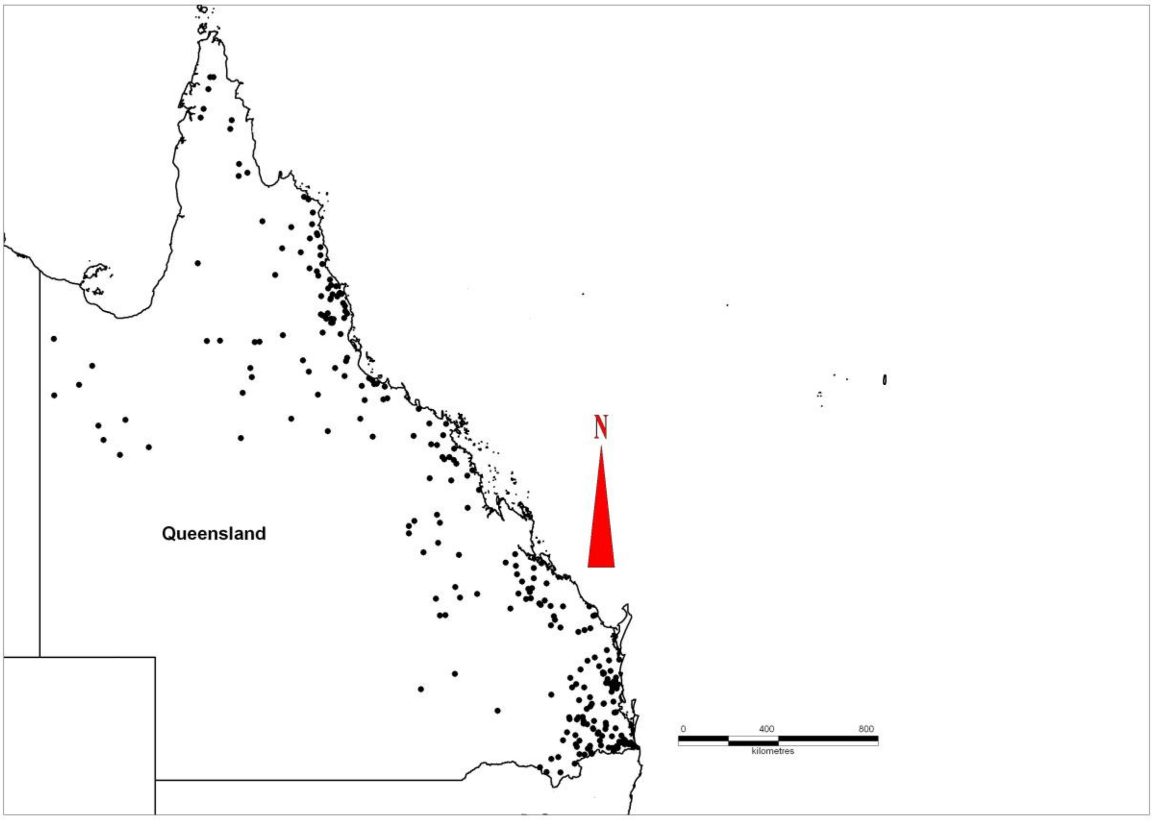


Figure 3.4.3 Locations of the selected 265 stations from Qld

3.5. South Australia

A total of 35 catchments across South Australia were initially selected based on information from the Department of Water, Land and Biodiversity Conservation (DWLBC) in South Australia that no significant impoundment or abstraction exists in the catchment contributing to the gauging station.

The areas of the candidate catchments vary from 0.4 km^2 to 6020 km^2 with a median value of 76.5 km^2. There were two catchments which exceeded the upper limit of medium catchments (1000 km^2) and were thus removed from the database.

Only unregulated streams were selected. Here unregulated refers to no significant impoundments or extraction occurring from the corresponding stream above the gauging station is occurred.

The records available at the candidate gauging stations vary from 7 to 68 years. The record lengths are typically smaller than 40 years for most of the catchments. The catchments which possess more than 10 years of streamflow records were initially selected as candidate stations.

The quality of streamflow data was assessed in greater detail and it was concluded that most of the stations had good quality data with only Stations A5090502, A4260503 and A5030525 having poor quality data. Most of the high flood peaks obtained for these stations were derived from significantly extended or extrapolated stage-discharge or rating curves.

The gaps in the flow data were filled by using a number of methods:

- Comparison of flow data with rainfall data of nearby station.
- Application of regression equations that relate mean daily flows of two nearby stations and mean daily flows and instantaneous maximum flows of a given station.

To check for rating curve extrapolation error, the RR (defined by Equation 2.1) was used. Figure 3.5.1 provides the frequency distribution of the RR values of annual peaks of the selected stations. It was found that more than 90% of the RR values were less than 3 and the average RR value was 3.3. Therefore stations having RR values higher than 3 and average RR value higher than 3.3 were removed from the database.

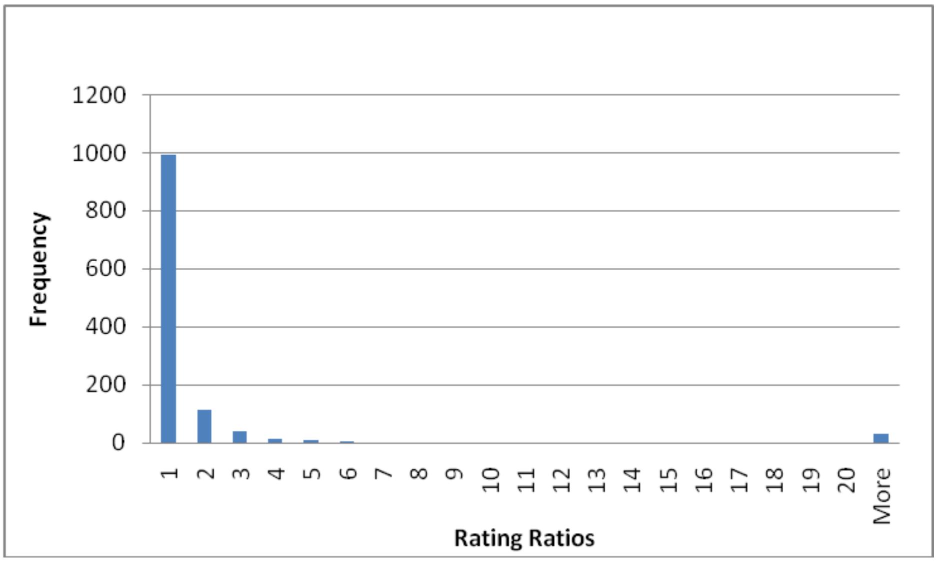


Figure 3.5.1 Distribution of Rating Ratio (RR) values for SA stations

Outliers of the annual maximum series were identified using the Grubbs and Beck (1972) method. High outliers were observed in A5030526 whereas low outliers were observed in several gauging stations such as A5030502, A4260503 and A4260533. It is decided not to remove the high outliers from the annual maximum series as no data error was detected.

As a result of the above considerations, only 30 stations were finally retained in the database. The distributions of streamflow record lengths and catchment areas of the selected 30 stations are provided in Figures 3.5.2 and 3.5.3, respectively. The selected stations are listed in Appendix A (Table A5). The locations of the selected stations are shown in Figure 3.5.4. It is evident that these stations cover only a small part of South Australia.

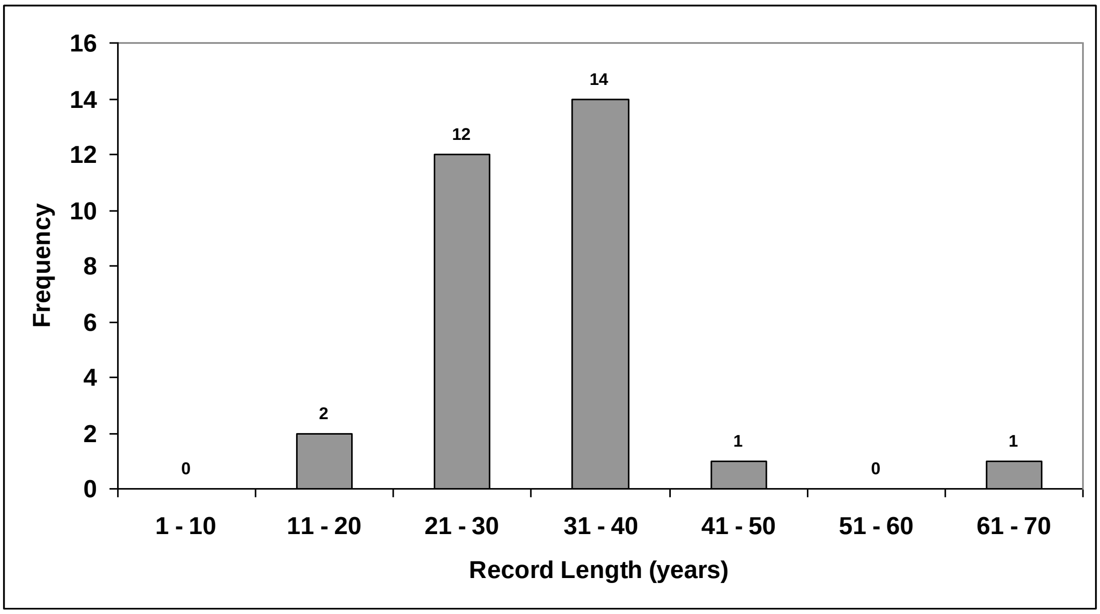


Figure 3.5.2 Distribution of streamflow record lengths of 30 stations from SA

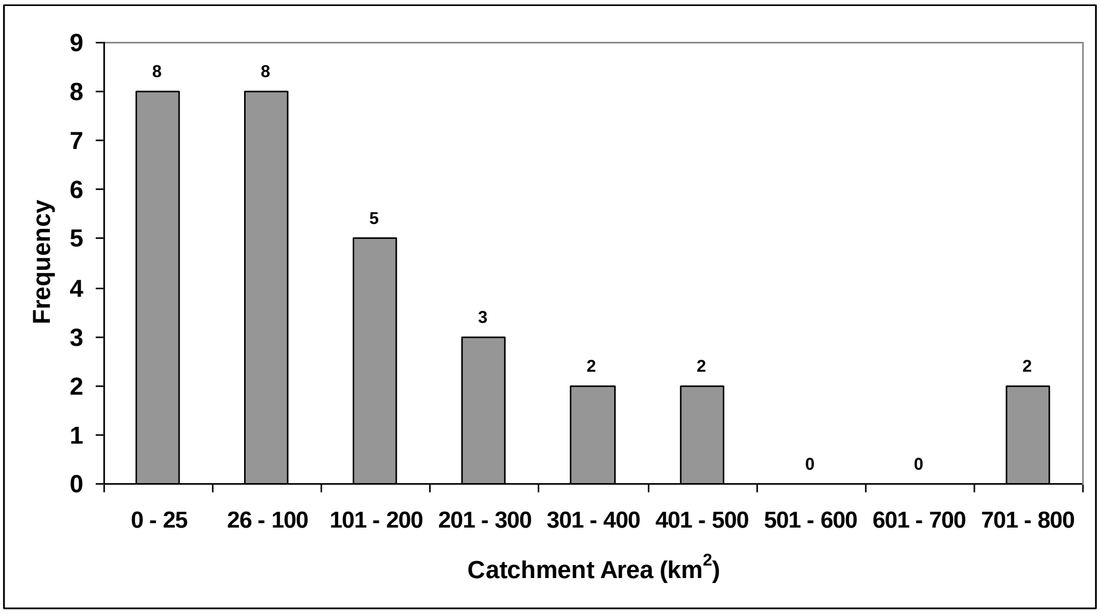


Figure 3.5.3 Distribution of catchment areas of 30 stations from SA

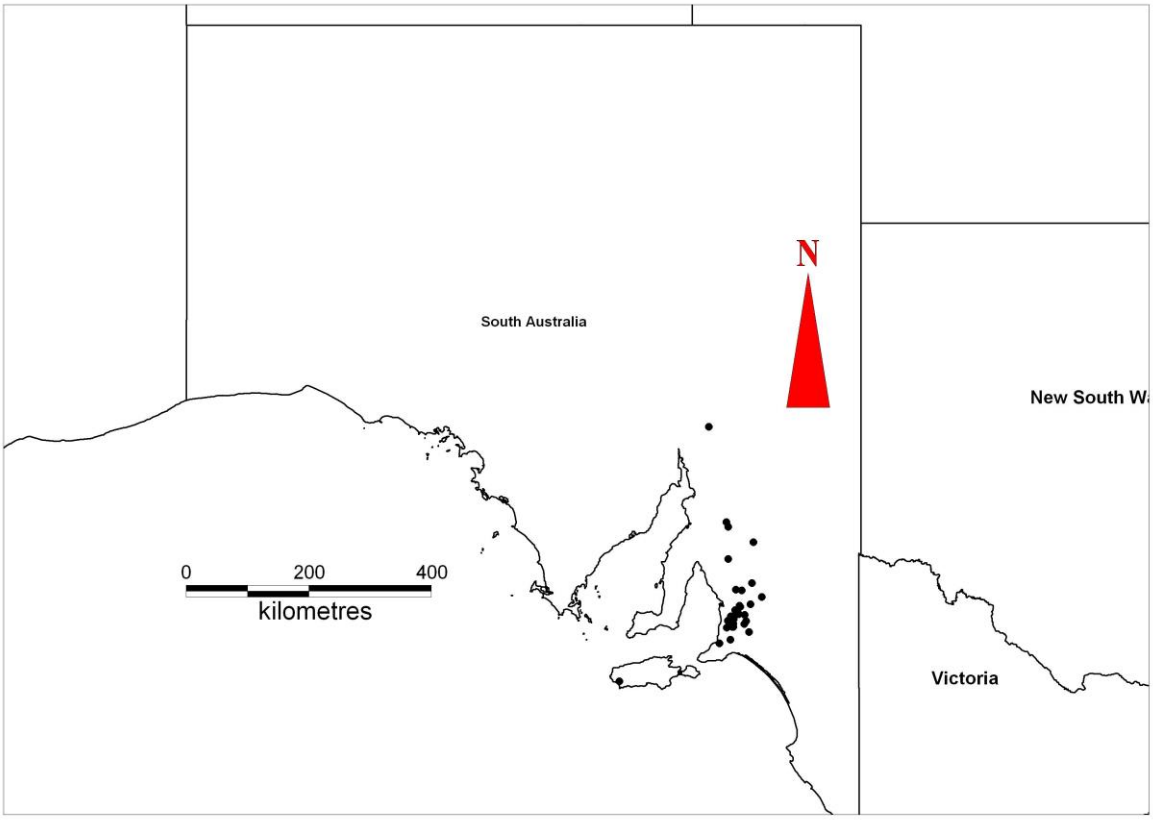


Figure 3.5.4 Locations of the selected 30 stations from South Australia

3.6. Northern Territory

The data preparation task for Northern Territory is still in progress. Initially, 130 stations have been selected as candidates based on catchment size (smaller than 1000 km^2) and streamflow data availability (at least 10 years of data). The streamflow record lengths of the candidate stations are in the range of 10 to 57 years (mean: 29 years and median 25: years). The distribution of streamflow record lengths of the 130 stations is shown in Figure 3.6.1.

The catchment areas of the candidate stations are in the range of 9 to 1015 km^2 (mean: 265 km^2 and median: 166 km^2). The distribution of catchment areas of the 130 stations is shown in Figure 3.6.2. The geographical distribution of the candidate 130 stations is shown in Figure 3.6.3. There is a lack of stations from south-western part of the state. These selected stations are listed in Appendix A (Table A6). Many of these stations were used by Weeks and Rajaratnam (2005) in developing a regional flood estimation method for ADrail project (railway from Alice Springs to Darwin).

Streamflow data preparation for the NT stations is yet to be completed. The number of eligible catchments satisfying the criteria described in Section 2.1 and passing the other tests (e.g. rating, outlier, trend, etc.) will definitely reduce from 130.

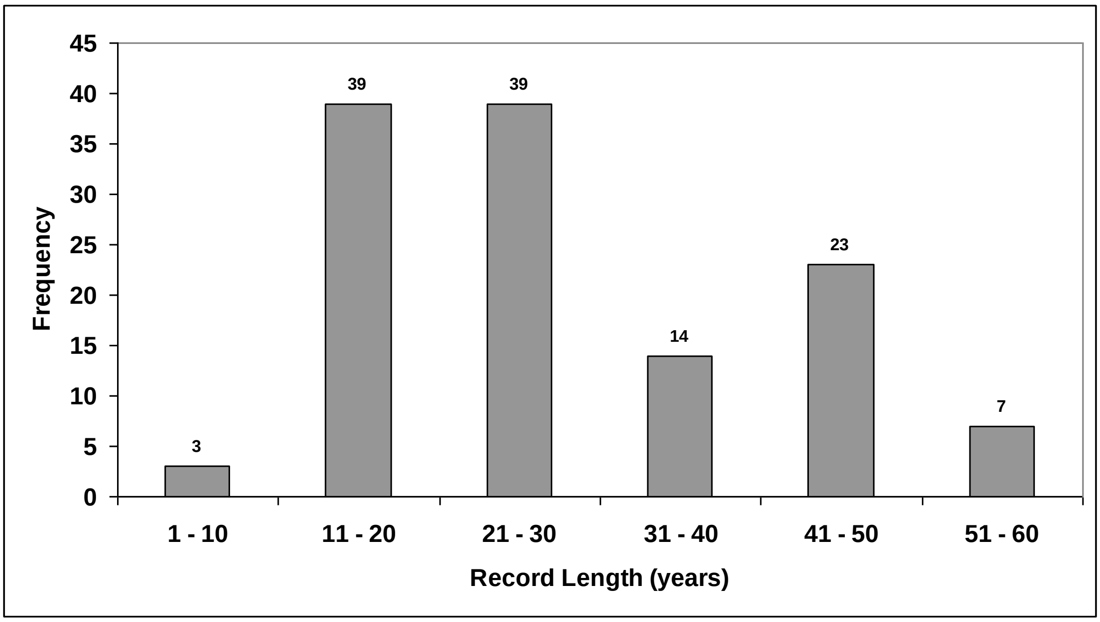


Figure 3.6.1 Distribution of streamflow record lengths of 130 stations from NT

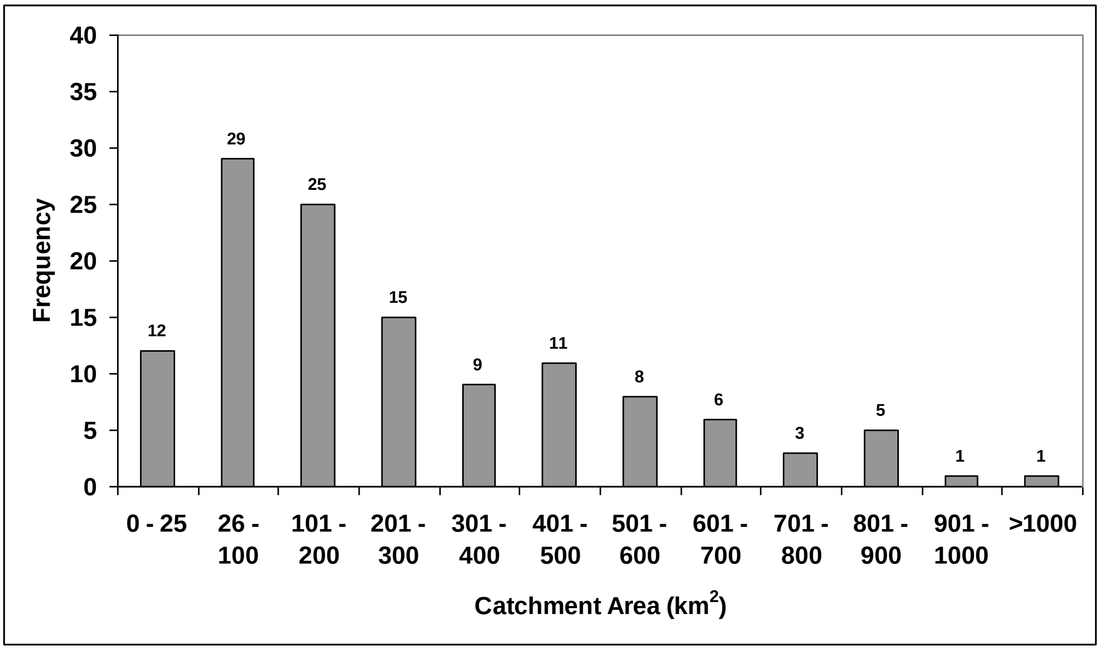


Figure 3.6.2 Distribution of catchment areas of candidate 130 stations from NT

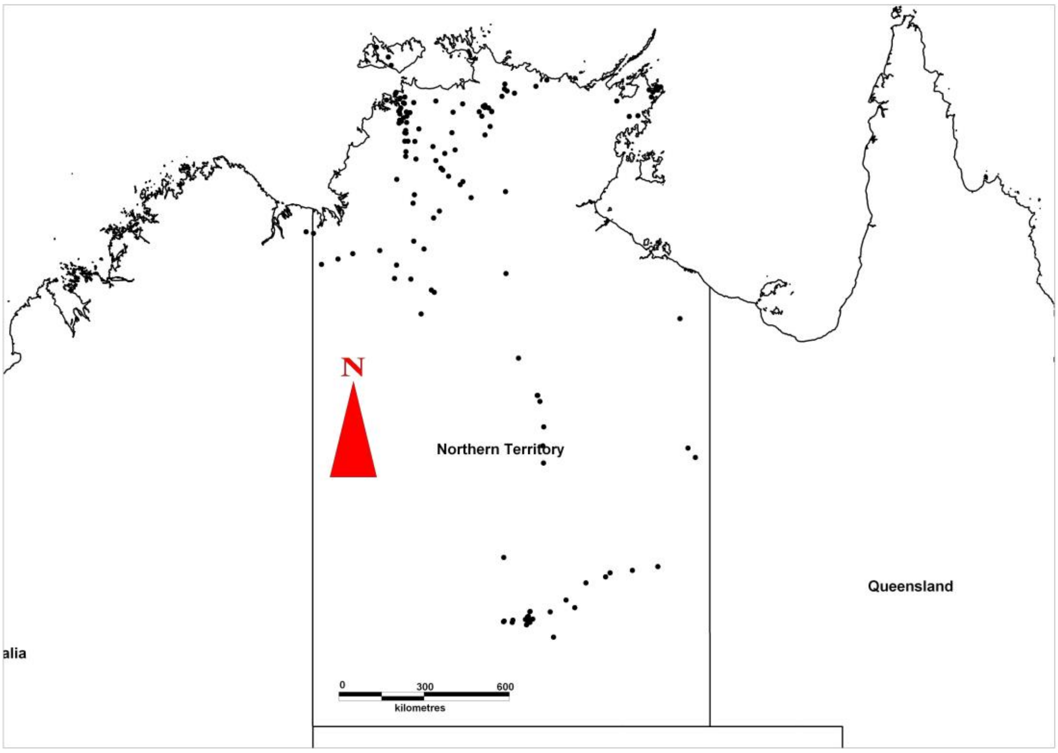


Figure 3.6.3 Locations of the candidate 130 stations from Northern NT

4. Climate Variability and Change Indices Data

The climate varies over a range of temporal scales typically associated with large-scale atmospheric and/or oceanic oscillations that have periods ranging from inter-annual to decadal or longer (Bridgman and Oliver, 2006). This notion of climate imposes an important challenge to hydrologists, since a failure to take such variability into account can lead to underestimation/overestimation of design floods, which in turn has an important implication for the environment and for the socio-economy.

Climate variability at inter-annual to inter-decadal modes may affect floods by markedly changing patterns of atmospheric moisture transport in the flood season hence changing the probabilities of flood in a given year at a particular location (Jain and Lall, 2001). If such changes are quasi-periodic, a flood record of sufficient length to sample all climate states affecting flood risk will enable a traditional analysis assuming homogeneity to adequately reflect long term flood risk. Unfortunately many flood records are relatively short and may be dominated by one climate state. Hence, it might be necessary to obtain climate data that characterize long term persistence in climate to investigate the homogeneity of flood distribution; otherwise a long term flood risk analysis based on short data may be subject to a high degree of bias.

It is found that the climate variability is typically ascribed to large-scale global or regional climatic oscillations. This chapter focuses on the climatic oscillations that have received the most research attention, and also have significant implications for engineering design and water resources management. The most well researched modes of variability are the El Niño Southern Oscillation (ENSO) phenomenon, the Interdecadal Pacific Oscillation (IPO) phenomenon, the Indian Ocean Dipole (IOD) and the Southern Annular Mode (SAM). These are discussed below and will be explored in Stage 2 of Project 5 to identify interactions between climate states and regional flood risk.

4.1. The El Nino Southern Oscillation Phenomenon

The most well researched mode of climate variability is the inter-annual El Niño Southern Oscillation (ENSO) phenomenon that generally oscillates between its two extremes of El Niño conditions (warm phase) and La Niña conditions (cold phase) with an approximate period of between 2 and 8 years (Trenberth, 1997; Rodbell et al., 1999). There are a large number of indices available for ENSO, each representing subtly different aspects of the phenomenon. However, the two main indices that have been used widely to represent the ENSO phenomenon are the Southern Oscillation Index (SOI), and the Nino set of indices (Nino 3, Nino 34 and Nino 4). The Southern Oscillation Index represents the difference in atmospheric pressure between Darwin and Tahiti, whereas the Nino set of indices represent spatially averaged sea surface temperature anomalies (SSTAs) in the eastern equatorial Pacific. The SOI monthly index data is provided in Appendix B (Table B1) and the indices representative of the NINO 3, NINO 34, and NINO 4 regions are provided in Appendix B (Table B2).

4.2. Interdecadal Pacific Oscillation

In addition to the inter-annual variability in the Pacific Ocean resulting from the ENSO phenomenon, numerous studies have described Pacific Ocean variability at decadal and inter-decadal time scales, focusing largely on the extra-tropics. The Interdecadal Pacific Oscillation (IPO) has been put forward to represent the dominant pattern of this long-term variability (Mantua et al., 1997; Mantua and Hare, 2002). It is a low frequency climate process related to the variable epochs of warming and cooling in the Pacific Ocean. IPO is described by an index derived from a low pass filtering of sea surface temperature (SST) anomalies in Pacific Ocean (Power et al., 1998, 1999); it is given in Appendix B (Table B3).

4.3. Indian Ocean Dipole Phenomenon

The Indian Ocean Dipole (IOD) is the best known aspect of Indian Ocean variability, a coupled ocean-atmosphere phenomenon characterized by anomalous cooling of SSTs in the south eastern equatorial Indian Ocean and anomalous warming of SSTs in the western equatorial Indian Ocean (Saji et al., 1999). This gradient is named as Dipole Mode Index (DMI), and when the DMI is positive, the phenomenon is referred to as the positive IOD and when it is negative, it is referred to as negative IOD. The monthly DMI dataset is provided in Appendix B (Table B4).

4.4. Antarctic Oscillation/Southern Annular Mode

The Antarctic Oscillation (AAO) is a low-frequency mode of atmospheric variability of the southern hemisphere. AAO refers to a large scale alternation of atmospheric sea level pressure between the mid and high latitudes. It is also known as the Southern Annular Mode (SAM) or Southern Hemisphere Annular Mode (SHAM), which is characterized by the normalised difference in the zonal mean sea-level pressure between 40°S and 65°S. As expected, the sea level pressure pattern associated with SAM is a nearly annular pattern with a large low pressure anomaly centred on the South Pole and a ring of high pressure anomalies at mid-latitudes. The monthly SAM dataset is shown in Appendix B (Table B5).

5. Statistical Techniques for Regionalisation

This chapter describes regional flood frequency analysis (RFFA) techniques which are most relevant to the objectives of this study. Selection of an appropriate probability distribution for at-site flood estimation is described at the beginning as this is a major step in any RFFA study. Every RFFA technique depends on the implicit or explicit assumption of 'regional homogeneity', which is described next. This follows a description of the RFFA techniques which have been identified as 'potential methods for application in Australia' e.g. Probabilistic Rational Method (PRM), Quantile Regression Technique (QRT), Generalised Least Squares (GLS) regression.

5.1. At-site Flood Frequency Analysis

The choice of an appropriate probability distribution to be used in flood frequency analysis has been a topic of interest for a long time and is of prime importance in at-site and regional flood frequency analysis (RFFA). It has received widespread attention by researchers. Benson (1968) and NERC (1975) devote considerable attention to this problem. Cunnane (1989) summarised the distributions commonly used in hydrology, mentioning 14 different distributions.

In some countries, a common distribution has been selected to achieve uniformity between different design agencies. The USA Interagency Advisory Committee on Water Data (IACWD, 1982) and the Institution of Engineers Australia (I E Aust., 1987) recommend the Log Pearson Type 3 (LP3) distribution for use in the United States and Australia, respectively. Other distributions that have received considerable attention include Extreme Value Types 1, 2, 3, Generalised Extreme Value (GEV) (NERC, 1975), Wakeby (Houghton, 1978), Generalised Pareto (GPA) (Smith, 1987), Two-component Extreme Value (Rossi et al., 1984) and the Log-Logistic distribution (Ahmad et al., 1988).

The use of a standard distribution has been criticised by Wallis & Wood (1985) and Potter & Lettenmaier (1990). They argue that a reassessment of the use of the LP3 distribution for practical flood design is overdue. Vogel et al. (1993) studied the suitability of a number of distributions (including the LP3) for Australia. They found that the Generalised Extreme Value (GEV) and Wakeby distributions provide the best approximation to flood flow data in the regions of Australia that are dominated by rainfall during the winter months; for the remainder of the continent, the Generalised

Pareto (GPA) and Wakeby distributions provide better approximations. For the same data set, the LP3 performed satisfactorily, but not as well as either the GEV or GPA distributions. The distributions that have attracted the most interest as possible alternatives to the LP3 are the GEV and Wakeby (Bates, 1994). Studies by Rahman et al. (1999) showed that GEV-LH moments method provides better results than the LP3 distribution in South–east Australia. However, the LP3 distribution, when fitted with Bayesian Maximum Likelihood Method, as implemented in ARR FLIKE by Kuczera and Franks (2005), performs equally well as the GEV-LH moments method (Haddad and Rahman, 2008). Mecevski and Kuczera (2009) presented an efficient scheme to combine at-site and regional flood data to obtain more reliable flood estimates at poorly gauged sites.

5.2. Identification of Homogeneous Regions

The identification of homogenous regions is an elementary step in RFFA (Bates et al., 1998). The development of a regional flood estimation method involves pooling of data from a number of sites in the region to extract general relationships that apply over the whole region. The practical application of the RFFA method then involves firstly allocating an ungauged catchment to an appropriate homogenous group and secondly predicting flood quantiles using developed models based on catchment characteristics (Bates et al., 1998). That is, the RFFA based on homogenous regions can transfer the information from similar gauged catchments to ungauged catchments to allow flood prediction.

The decision on what constitutes a homogeneous region for the purposes of regional flood estimation depends on the methods used, more specifically on the extent to which differences in flood characteristics can be expressed through parameters in the regionalisation method.

There have been many techniques developed which attempt to establish homogenous regions. For example the PRM uses geographical contiguity as an indication of homogeneity that is the catchments which are close to each other should have similar runoff coefficients.

Looking at homogeneity from a theoretical point of view, two catchments may be treated as homogenous with respect to flood behaviour if they both satisfy two criteria: the inputs (such as rainfall) to the hydrological systems are identical, and the climatic and physical characteristics changing the input to flood peak are the same. No two catchments can satisfy these criteria perfectly, based on the fact that each catchment has a unique physical characteristic and that each catchment has different climatic inputs. The question remains, in the search for practical "homogeneity", how one makes decisions on the degree of similarity or dissimilarity that is acceptable and on deciding a cut-off point where a region is acceptably homogenous or heterogeneous, in consideration of the practical applications of the techniques.

In defining homogenous regions for use in RFFA, a balance has to be made between including more sites for increased information and maintaining an acceptable level of homogeneity. In most situations when more sites are added to a region, certainly more information is gained about the flood regime; however sites that are hydrologically dissimilar can increase the heterogeneity in the region.

The degree of homogeneity of a proposed group is judged on the basis of a dimensionless coefficient of the annual maximum flood series, such as the coefficient of variation, coefficient of skewness or similar measures. Examples are given by Dalrymple (1960), Wiltshire (1986), Acreman & Sinclair (1986), Vogel and Kroll (1989), Chowdhury et al. (1991), Pilon and Adamowski (1992), Lu and Stedinger (1992), Hosking and Wallis (1993) and Fill and Stedinger (1995a, b).

Hosking and Wallis (1991, 1993) proposed a heterogeneity measure based on the *L* moment ratios *L CV*, *L CS* and *L* kurtosis. The advantages of this test are that it is based on *L* moments and not distribution-specific. This test has received considerable attention in recent years (e.g. Pearson, 1991; Thomas and Olsen, 1992; Alila et al., 1992; Guttman, 1993; Zrinji & Burn, 1996, Bates et al.,1998 & Rahman et al.,1999; Castellarin et al., 2008). Cunnane (1988) mentions that identification of a homogeneous region is necessarily based on statistical tests of hypothesis, the associated power of which, with currently available amounts of hydrological data, is low. Thus it is not possible to divide, with great assurance, a large number of catchments into homogeneous subgroups using flow records with limited lengths.

There has been little success in the identification of homogeneous regions in Australia. The regions based on state and geographical boundaries in Australia have often been found to be highly heterogeneous. Bates et al. (1998) examined the heterogeneity of 94 stations in Victoria, the value of H statistic (Hosking and Wallis,

1993) ranged from 3.85 to 11.79 for different groups formed based on catchment size. Haddad (2008) divided Victoria into number of zones (e.g. south-eastern, south-western, north-eastern and north-western); however, no homogeneous regions could be established. The initial investigation with the NSW data, as a part of this project, has shown that no homogeneous regions exist in NSW based on the test of Hosking and Wallis (1993).

5.3. Regionalisation Techniques for Investigation

5.3.1. PRM

In the past, the Rational Method has often been regarded as a deterministic representation of the flood generated from an individual storm. It is presented in ARR 1987 as a probabilistic or statistical method for use in estimating design floods. The peak flow for a selected ARI is estimated from an average rainfall intensity of the same ARI derived from Book II Section 1 of ARR. The central component of the method is a runoff coefficient, the use of which involves a simple linear interpolation over the geographic space between the nearest contour lines of the runoff coefficients, which assumes that geographical proximity is a surrogate for hydrological similarity.

The Rational Method was recommended in ARR1987 for application to only small catchments below some arbitrary limit such as 25 km^2. This range of validity was intended to reflect the inadequate manner in which the method considers physical factors, such as the effects of temporary storage on the catchment, and temporal and spatial variations of rainfall intensity. These physical considerations have little relevance to the probabilistic interpretation, where their effects are incorporated in the recorded floods, and hence in the flood frequency statistics and the derived parameter values. Procedures derived from observed data should be valid for catchment areas and ARIs up to and somewhat beyond the maximum areas and record lengths used in derivation (I. E. Aust., 1987).

The Probabilistic Rational Method is represented by:

Error! Objects cannot be created from editing field codes.

(5.1)

where Q_Y is the peak flow rate (m^3/s) for an ARI of Y years; C_Y is the runoff coefficient (dimensionless) for an ARI of Y years; $I_{tc,Y}$ is the average rainfall intensity (mm/h) for a design duration equal to the time of concentration t_c (hours) and an ARI of Y years; and A is the catchment area (km^2).

The runoff coefficient represents the ratio of a *peak runoff intensity*, determined from frequency analysis of flood peaks, and a *rainfall intensity* of selected duration and the same ARI, determined from frequency analysis of rainfalls (Equation 5.2). This is why Q, I and C in Equation 5.1 are subscripted by Y to represent the ARI. This probabilistic interpretation of the Rational Method and the runoff coefficient exactly fits the way in which the method is used in design practice. Even when it is not recognized, estimation of a design flood from rainfall frequency data such as those in Book II Section 1 involves use of the Rational Method as probabilistic model (I. E. Aust., 1987).

Error! Objects cannot be created from editing field codes.

(5.2)

Values for $I_{tc,Y}$ for all Australia can be obtained using information from Book II of ARR1987. For several regions with adequate streamflow data, flood frequency analyses were carried out for many small to medium sized catchments. From Q_Y values obtained by those analyses, values of C_Y were determined, and the resulting design data and methods for those regions were included in the recommended procedures in ARR1987. The catchment and rainfall characteristics and conditions affecting the relation between Q_Y and $I_{tc,Y}$ are automatically incorporated in C_Y. Derived values of C_Y have generally been found to vary in a reasonably regular or consistent manner over the range of ARI values on a given catchment, and for different catchments over a particular region (I. E. Aust., 1987).

Equation 5.2 shows that the value of C_Y depends on the duration of rainfall, and some design duration related to catchment characteristics must be specified to estimate C_Y as part of the overall procedure. A typical response time of flood runoff appears to be adequate, and the “time of concentration” is a convenient measure as far as practical application of the PRM is concerned. In this context, its accuracy regarding travel times is much less important than the consistency and reproducibility of derived C_Y values, as suggested in ARR1987. Also, values of C_Y cannot be compared unless consistent estimates of t_c are used in their derivation (I. E. Aust., 1987). However, in the deterministic interpretation of the Rational Method, the critical rainfall duration is t_c, which is considered to be the travel time from the most remote point on the catchment to the outlet, or the time taken from the start of rainfall until all of the catchment is simultaneously contributing flow to the outlet. For the PRM, these physical measures are not directly relevant. In several of the Rational Method procedures recommended in ARR1987, equations are specified for estimating t_c. The specified equation must be used with the design data given for the particular procedure and region. One commonly adopted equation is:

Error! Objects cannot be created from editing field codes.

(5.3)

where t_c is the time of concentration (hour) and A is area of catchment (km^2).

In other cases where a complete procedure based on observed data is not available, the Bransby Williams formula was recommended in ARR1987 as an arbitrary but reasonable approach. This is:

Error! Objects cannot be created from editing field codes.

(5.4)

where t_c is the time of concentration (hour); L the mainstream length measured to the catchment divide (km); A the catchment area (km^2) and S_e the equal area slope of the main stream projected to the catchment divide (m/km). This is the slope of a line drawn on a profile of a stream such that the line passes through the outlet and has the same area under and above the stream profile. In this study, Equation 5.3 has been adopted for Victoria, NSW and Tasmania.

5.3.2. Quantile Regression Technique

A flood quantile is probabilistic flood estimate for a selected average recurrence interval (ARI).

United States Geological Survey (USGS) proposed a quantile regression technique (QRT) where a large number of gauged catchments are selected from a region and flood quantiles are estimated from recorded streamflow data, which are then regressed against catchment variables that are most likely to govern the flood generation process. Studies by Benson (1962) suggested that *T*-year flood peak discharges could be estimated directly using catchment characteristics data by multiple regression analysis.

The quantile regression technique can be expressed as follows:

Error! Objects cannot be created from editing field codes. (5.5)

where *B, C, D, …* are catchment characteristics variables and Q_T is the flood magnitude with *T* year ARI (flood quantile), and *a, b, c,* … are regression coefficients. This method is not based on a constant coefficient of variation (C_v) of annual maximum flood series in the region like the index flood method. It has been noted the method can give design flood estimates that do not vary smoothly with ARI; however, hydrological judgment can be exercised in situations such as these when flood frequency curves need to be adjusted to increase smoothly with *T*.

There have been various techniques and many applications of regression models that have been adopted for hydrological regression. Most of these methods are derived from the methodology set out by the USGS as described above.

The USGS has been applying the QRT for several decades. A well known study using the QRT with an Ordinary Least Squares (OLS) procedure was carried out by Thomas and Benson (1970). The study tested four regions in the United States for design flood estimation using multiple regression techniques that related streamflow characteristics to drainage-basin characteristics. This study found that the QRT was predicting quantiles estimates quite accurately as compared to previous methods adopted by the USGS. However, there was still the point made that the equations were lacking statistically sound methodology.

The OLS estimator has traditionally been used by hydrologists to estimate the regression coefficients β in regional hydrological models. But in order for the OLS model to be statistically efficient and robust, the annual maximum flood series in the region must be uncorrelated, all the sites in the region should have equal record length and all estimates of *T* year events have equal variance. Since the annual maximum flow data in a region do not generally satisfy these criteria, the assumption that the model residual errors in OLS are homosecdastic is violated and the OLS approach can provide very distorted estimates of the model's predictive precision (model error) and the precision with which the regression coefficients are being estimated (Stedinger and Tasker, 1985).

To overcome the above problems in OLS, Stedinger and Tasker (1985) proposed the Generalised Least Squares (GLS) procedure which can result in remarkable improvements in the precision with which the parameters of regional hydrologic regression models can be estimated, in particular when the record length varies widely from site to site. In the GLS model, the assumptions of equal variance of the *T* year events and zero cross-correlation for concurrent flows are relaxed.

5.3.3. Generalised Least Squares Regression

The GLS procedure accounts for differences in streamflow record lengths at different sites and cross correlation among concurrent annual maximum flood series data. The GLS procedure as developed by Tasker and Stedinger (1989) shows improvement over the OLS regression to develop empirical relationships between streamflow statistics and catchment characteristics.

Due to the influence of the cross correlated concurrent flows across the sites, the log quantile estimates at two different sites $\hat{y}_i$ and $\hat{y}_j$ $((i \neq j)$ are correlated, and therefore the off–diagonal elements of error covariance matrix $\sum$ in the GLS regression are nonzero. Tasker and Stedinger (1989) provide the following approximation (Equation 5.6) of the components of $\sum$ which neglects the possible error in the estimated standard deviation and skew:

$$\begin{aligned} \Sigma_{ii} &= [1 + K_i\gamma_i + 0.5K_i^2(1+0.75\gamma_i^2)]\frac{\sigma_i^2}{n_i} \quad for\ i = j \\ \Sigma_{ij} &= \left[1 + 0.5K_i\gamma_i + 0.5K_j\gamma_j + 0.5K_iK_j(\rho_{ij} + 0.75\gamma_i\gamma_j\right]\rho_{ij}\frac{m_{ij}\sigma_i\sigma_j}{n_in_j} \quad for\ i \neq j \end{aligned} \tag{5.6}$$

where *K* is standard LP3 frequency factor, m_{ij} is the concurrent record length between sites *i* and *j*, ρ_{ij} is the lag zero cross correlation of flood peaks between sites *i* and *j*, and σ_i and σ_j are the population standard deviation at sites *i* and *j* respectively. To avoid correlation between the residuals and the fitted quantiles, Tasker and Stedinger (1989) recommend that (i) ρ_{ij} be estimated as a function of the distance between sites *i* and *j* (ii) the standard deviations σ_i and σ_j be estimated using a separate GLS regression analysis on catchment characteristics, and (iii) the regional skew value be used instead of the population skew γ_i.

To account for the uncertainty in the sample standard deviation and skew in Equation 5.6, a separate GLS analysis is carried out to derive prediction equations for the regional standard deviation and regional skew.

The 1-in-*T* quantile (i.e. Q_T, where *T* = 2, 5, …, 100 years) of the fitted LP3 distribution at a site with index *i* is computed as follows:

$$\hat{y}_i = \log Q = \overline{q}_i + K_i s_i \tag{5.7}$$

where K_i is the standard LP3 frequency factor for the 1-in-*T* quantile given an estimate of the skew (g_i) and at–site standard deviation of the logs of the annual maximum flood series (s_i). Therefore $\hat{y}_i$ is an estimate of the log of the desired flow quantile (i.e. $\log(Q_T) = y$):

$$\hat{y}_i = y_i + \eta_i \tag{5.8}$$

where y_i is the true value of the 1-in-*T* quantile and η_i is a random error, referred to as the time-sampling error. It is assumed that this error has a mean of zero and a variance being a function of the error in the estimated sample moments. The objective of the GLS regression procedure is to obtain the best model for estimating flood quantile for a given ARI for a given set of catchment characteristics. y_i can be expressed as a linear function of the logs of the catchment characteristics (*x*'s) and the model error δ_i:

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + ... + \beta_2 x_{i2} + \beta_k x_{ik} + \delta_i \tag{5.9}$$

The errors δ_i are assumed to be normally distributed with a zero mean and a variance of σ_δ^2. Here σ_δ^2 is the model error variance, or the residual error variance that cannot be explained by the sampling error. Combining Equations 5.8 and 5.9

one obtains:

$$\hat{y}_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + ... + \beta_2 x_{i2} + \beta_k x_{ik} + \delta_i + \eta_i \tag{5.10}$$

Equation 5.10 can also be expressed as follows:

$$\hat{\mathbf{Y}} = \mathbf{X}\beta + \boldsymbol{\varepsilon} \tag{5.11}$$

where **X** is a [*N* x (*k* +1)] matrix of **k** catchment characteristics augmented by a column of one's, $\boldsymbol{\beta}$ is a [(*k* +1) x 1] vector of regression coefficients, and $\boldsymbol{\varepsilon} = \boldsymbol{\delta} + \boldsymbol{\eta}$ is a (*N* x 1) vector of random errors, for which $E[\boldsymbol{\varepsilon}] = 0$ and $E[\boldsymbol{\varepsilon\varepsilon}^T] = \Lambda$. Due to correlation between the residuals, the OLS analysis to estimate the parameters of hydrological models is not appropriate, and a GLS analysis should be used to relate the fitted quantiles to the specified catchment characteristics and to describe the errors. The GLS estimator of $\boldsymbol{\beta}$ is:

$$\hat{\beta}_{GLS} = (\mathbf{X^T}\hat{\mathbf{\Lambda}}^{-1}\mathbf{X})^{-1}\mathbf{X^T}\hat{\mathbf{\Lambda}}^{-1}\hat{\mathbf{Y}} \tag{5.12}$$

However Λ is not known, but can be estimated from the data by:

$$\hat{\Lambda}(\sigma_\delta^2) = \sigma_\delta^2 I_N + \hat{\Sigma} \tag{5.13}$$

where I_N is a (*N* x *N*) identity matrix, and $\hat{\Sigma}$ is estimated using Equation 5.6.

The model error variance σ_δ^2 is due to an imperfect model and is a measure of the precision of the true regression model. The model error variance is assumed to be independent of the catchment characteristics. Unfortunately the model error is not known and needs to be estimated. Stedinger and Tasker (1985) proposed a method of moments estimator where σ_δ^2 can be solved iteratively by finding a non negative solution to Equation 5.14 where *N* and *k* have dimensions of *Y* and *β* is given by Equation 5.12:

$$(\hat{\mathbf{Y}} - \mathbf{X}\beta_{GLS})^T[\hat{\sigma}_\delta^2 I_N + \hat{\Sigma}]^{-1}(\hat{\mathbf{Y}} - \mathbf{X}\beta_{GLS}) = N - (k+1) \tag{5.14}$$

Equation (5.14) can yield negative estimates of model error when sampling error dominates the total error. In practice the model error estimate is set to zero, which is unrealistic. A better approach is to use Bayesian GLS method (Micevski and Kuczera, 2009) which properly handles model error and, importantly, quantifies uncertainty about it. Bayesian GLS has another advantage, namely it allows pooling of the regional estimate with any site data to produce a more accurate quantile inference.

Measures of model performance

Given a site with catchment characteristics $\boldsymbol{x_o}$, the main purpose of GLS regression is to predict the true quantile, $\mathbf{y}_{\boldsymbol{o}}$ (Tasker et al., 1986). The average variance of prediction (AVP) over the available data set is a measure of how well the GLS regression model predicts the true quantile on average where:

$$AVP_{GLS} = \hat{\sigma}_{\delta}^{2} + \frac{1}{N}\sum_{i=1}^{N} x_i (\mathbf{X}^{\mathbf{T}}\hat{\mathbf{\Lambda}}^{-1}\mathbf{X})^{-1} x_i^{T} \tag{5.15}$$

This statistic can be applied to both the estimation and validation data sets.

If the standardised residuals have an approximate normal distribution, the standard error of prediction in percent (SEP%) for the true flood quantile estimator (rather than its common logarithm) is given by

$$SEP\% = 100 \times \sqrt{10^{\ln(10)\,AVP_{GLS}} - 1} \tag{5.16}$$

To be able to determine the precision of a hydrological model, the AVP and the model error variance are preferred over the traditional R^2, which can provide distorted estimates of the models true power because it makes no distinction between model error and sampling error. Our interest in hydrological regression is to quantify the proportion of the variance among the unobserved $\hat{y}_i$, explained by the model. Let $\hat{\sigma}_{\delta}^{2}(k)$ be the estimated model error variance for the regression model with k independent variables, and $\hat{\sigma}_{\delta}^{2}(0)$ be the estimated model error variance when no independent variable is used. The pseudo $\overline{R}^{2}$ appropriate for use with the GLS regression is:

$$\bar{R}^2_{GLS} = 1 - \frac{\hat{\sigma}^2_\delta(k)}{\hat{\sigma}^2_\delta(0)} \tag{5.17}$$

The equivalent years of record, en_i (Hardison 1971), expresses the accuracy of prediction in terms of years of record required to achieve results of equal accuracy. It is calculated as:

$$en_i = \frac{\hat{\sigma}_i^2 \left[1 + K_i g_i + \frac{K_i^2}{2}(1 + 0.75 g_i^2) \right]}{\hat{\sigma}^2_\delta + (\mathbf{x_i}(\mathbf{X^T \Lambda^{-1} X})^{-1} \mathbf{x_i^T})} \tag{5.18}$$

where g_i is estimated from the regional GLS regression and $\hat{\sigma}_i^2$ is the estimated variance of the annual maximum flood series from the GLS regression and $\mathbf{x_i}(\mathbf{X^T \Lambda^{-1} X})^{-1} \mathbf{x_i^T}$ is the sampling error variance at site *i*.

The root mean squared error (RMSE) is defined by:

$$RMSE = \sqrt{\frac{\sum (Q_{obs} - Q_{pred})^2}{N}} \tag{5.19}$$

$$\mathrm{RMS} = \left(\sum \left((Q_{obs} - Q_{pred})^2 \right)^{1/2} \right) / n$$

where Q_{obs} = observed flood quantile (obtained from at-site flood frequency analysis, Q_{pred} = predicted flood quantile (obtained from the developed prediction equations) and N = number of catchments in the estimation or validation data set.

$$\text{Abs \% relative error} = \left| \left(\frac{Q_{pred} - Q_{obs}}{Q_{obs}} \right) * 100 \right|$$

5.3.4. Parameter regression technique

In the parameter regression technique (PRT), the parameters of a particular probability distribution are regressed against the catchment characteristics similar to QRT. Here, both the OLS and GLS methods can be used to develop the prediction equations for the mean, standard deviation and skewness of the annual maximum flood series. These equations are then used to predict the mean, standard deviation and skewness of annual maximum flood series for an ungauged catchment to fit a particular probability distribution. This fitted probability distribution is then used to estimate the flood quantiles for the ungauged catchment.

5.3.5. Index flood method

The key assumption in the index flood method is that the distribution of floods at different sites within a homogeneous region is the same except for a site-specific scale or index flood factor. Homogeneity with regards to the index flood relies on the concept that the standardised flood peaks from individual sites in the region follow a common probability distribution with identical parameter values. From all the method examined in this project, the Index Flood Method involves the strongest assumptions on homogeneity.

ARR1987 (I.E Aust., 1987; 2001) did not favour the index flood method as a design flood estimation technique. The index flood method had been criticised on the grounds that the coefficient of variation of the flood series C_v may vary approximately inversely with catchment area, thus resulting in flatter flood frequency curves for larger catchments. This had particularly been noticed in the case of humid catchments that differed greatly in size (Dawdy, 1961; Benson, 1962; Riggs, 1973; Smith, 1992).

There have been recent studies carried out by Bates et al. (1998) and Rahman et al. (1999) where the development of an application for design flood estimation in ungauged catchments in south-east Australia was tested using index flood method. The method involved the assignment of ungauged catchments to a particular homogenous group identified (through the use of *L*-moments) on the basis of catchment characteristics as opposed to geographical proximity. The relationships sought were carried out by statistical procedures such as canonical correlation analysis, tree based modelling and other multivariate statistical techniques. This allowed for the development of a RFFA method using up to 12 independent catchment characteristics variables.

Although the results of this method showed promise when compared to the PRM its limitations were already evident in that it needed a large number of independent variables which are very time consuming to obtain. The results of this method also depend upon the correct assignment of an ungauged catchment to a homogenous group, thus any wrong assignment would greatly increase error in quantile estimation.

5.3.6. Probabilistic Model for large to extreme flood estimation

The Probabilistic Model (Majone and Tomirotti, 2004) assumes that the maximum observed floods Q_{max} from the annual flood series of each of the sites in a region (after standardisation by the at-site average flood and a function of the coefficient of variation of annual flood series) can be pooled (similar to the station-year approach) and assumed to follow a single probability distribution. That is, the standardised Q_{max} across various sites form a homogeneous region. This is similar to the assumption of the index flood method but, by allowing for differences in the standard deviation of annual floods, it overcomes a major weakness of the index flood method.

The main focus of the Probabilistic Model is the prediction of flood quantiles of higher ARIs. To apply the Probabilistic Model to ungauged catchments, one needs to develop prediction equations for the mean and coefficient of variation of the annual flood series. Majone et al. (2007) applied the Probabilistic Model to flood data from 8500 gauging stations across the world and found that the method can provide quite reasonable design flood estimates for higher ARIs.

This study closely followed the development of the Probabilistic Model as described in Majone et al. (2007), but GLS regression was used to develop the prediction equations for the mean and coefficient of variation of the annual flood series. The Probabilistic Model is further explained in Section 6.6.

5.4. Formation of Regions

5.4.1. Fixed regions

In regional flood frequency analysis, regions have often been defined based on state/political boundaries. In ARR1987, regional flood estimation methods were developed for various Australian states based on fixed regions. The problem with this type of fixed regions is that at state/regional boundaries, two different methods can provide quite different flood estimates. To avoid this problem, regions have also been identified in catchment characteristics data space using cluster analysis (Acreman and Sinclair, 1986; Ouarda et al., 2008), Andrews curves (Nathan and McMahon, 1990) and various other multivariate statistical techniques (e.g. Ouarda et al., 2008).

One limitation with this type of region is that a correct method of assigning an ungauged catchment to a ‘homogeneous’ region needs to be formulated, which is often problematic. If the ungauged catchment is assigned to the wrong region/group, the resulting flood estimation is associated with a high degree of error.

5.4.2. Region of influence

Since hydrological characteristics do not change abruptly across state boundaries, it is desirable to avoid fixed boundaries. Regionalisation without fixed regions was performed by Acreman and Wiltshire (1987) and Acreman (1987), and based on their work the region of influence (ROI) approach was introduced by Burn (1990a, 1990b) where each site of interest (i.e. catchment where flood quantiles are to be estimated) has its own region. This way the defined regions may overlap and gauged sites can be part of more than one ROI for different sites of interest. The great advantage of the ROI approach is that it is not bounded by geographic regions often based on political boundaries such as state lines, and it thus avoids discontinuities at the boundaries of regions.

The ROI for the site of interest is formed out of stations in close proximity, with proximity measured using a weighted Euclidean distance in an M-dimensional attribute space. The distance metric is defined by

Error! Objects cannot be created from editing field codes. (5.21)

with $D_{i,j}$ as the weighted Euclidean distance between site *i* and *j*, *M* is the number of attributes included in the distance measure, and the *X* terms denote standardized values for attribute *m* at site *i* and site *j*, and W_m is a weight applied to attribute *m* reflecting the relative importance of the attribute. Standardization of attributes removes units and avoids introduction of bias due to scaling differences of the attributes. In a range of studies (Burn, 1990a; Zrinji and Burn, 1996; Tasker et al., 1996; Eng et al., 2005; Cunderlik and Burn, 2006) the attributes were standardized by the standard deviation over the entire dataset of attribute *m*. Attributes can arise from two sources, either based on physical features, such as catchment area, stream length, channel slope, stream density, or soil type, or statistical measures of climate and flow data, such as the coefficient of variation.

Since its inception many publications have dealt with the performance of the ROI approach in RFFA. Zrinji and Burn (1994) used the ROI approach for regional flood frequency analysis for ungauged sites. Dealing with ungauged sites makes it necessary to look for attributes other than flood statistics to calculate the distance measure. They used catchment characteristics as attributes instead and compared the results with results from a regression approach. They subsequently added stations to the ROI with application of a homogeneity test after each addition. If the added site resulted in heterogeneity the site was deleted and the next closest site was added and evaluated. They concluded that using the ROI approach resulted in improvements in terms of mean square errors relative to results from a regression approach. They also noted a major contribution of the ROI approach was the formation of flexible regions. Zrinji and Burn (1996) refined the method further by introducing a hierarchical ROI approach. The motivation for the hierarchical approach is that for the estimation of higher order moments (i.e. skewness) more stations are warranted. Application of the hierarchical approach yielded improved estimates of extreme flood quantiles.

6. Exploratory Regional Flood Frequency Analysis

This chapter describes development and testing of the selected RFFA methods for a number of Australian states using the database developed in Chapter 3. For each of the RFFA methods, an independent test is carried out by split-sample validation.

6.1. Victoria

For Victoria, a data set of 131 catchments was selected as described in Section 3.1. Three different regional flood estimation methods were developed and tested with this data: the Probabilistic Rational Method, QRT-OLS and QRT-GLS methods. A total of 18 test catchments were selected at random for independent testing of the developed regionalisation methods. This leaves 113 catchments for model development.

PRM for Victoria:

Flood frequency analysis was undertaken using LP3-Bayesian parameter estimation procedure using ARR-FLIKE (Kuczera and Frank, 2005) and flood quantiles for various ARIs were noted for all the 131 stations. The C10 values were estimated using Equation 5.2. The estimated C10 values were then used to create an analogue to a Digital Terrain Model (DTM) with the C10 as Z values. From the DTM the contours were derived by MapInfo by using a kriging and triangulation method based on average linear interpolation. An alternative procedure was also explored using a prediction equation (Equation 6.1.1) between C10 and catchment characteristics as independent variables, calibrated by OLS regression. The frequency factors (FF_Y) were computed as the ratio of C_Y/C_{10} and then the median value across all the model catchments was adopted as the design frequency factor for a given ARI.

Error! Objects cannot be created from editing field codes. (6.1.1)

The new C10 contour map is shown in Figure 6.1.1. In comparison to the ARR1987 contour map, the new contours generally provide better spatial coverage with greater resolution except for the north-western part of Victoria where no reliable streamflow data are available. The C10 values do not reveal any regional pattern, and low values are surrounded by higher ones in many locations similar to ARR1987, which raises a question on the method of simple linear interpolation on the contour map when estimating a value of C10 for an ungauged catchment.

The frequency factors are compared in Table 6.1.1, which shows that for ARIs of 10 to 100 years, ARR1987 and the new FF_Y values are very similar. The differences for 2 and 5 years ARIs can be partly explained by differences between the analysis of partial and annual series; ARR1987 adopted a partial series method for flood frequency analysis but this study was based on annual maximum flood series.

Table 6.1.1 Frequency factors for the new PRM for Victoria

ARI (years)	FF_Y (ARR1987)	FF_Y (New PRM 2009)
2	0.75	0.48
5	0.9	0.81
10	1	1
20	1.1	1.1
50	1.2	1.2
100	1.3	1.27

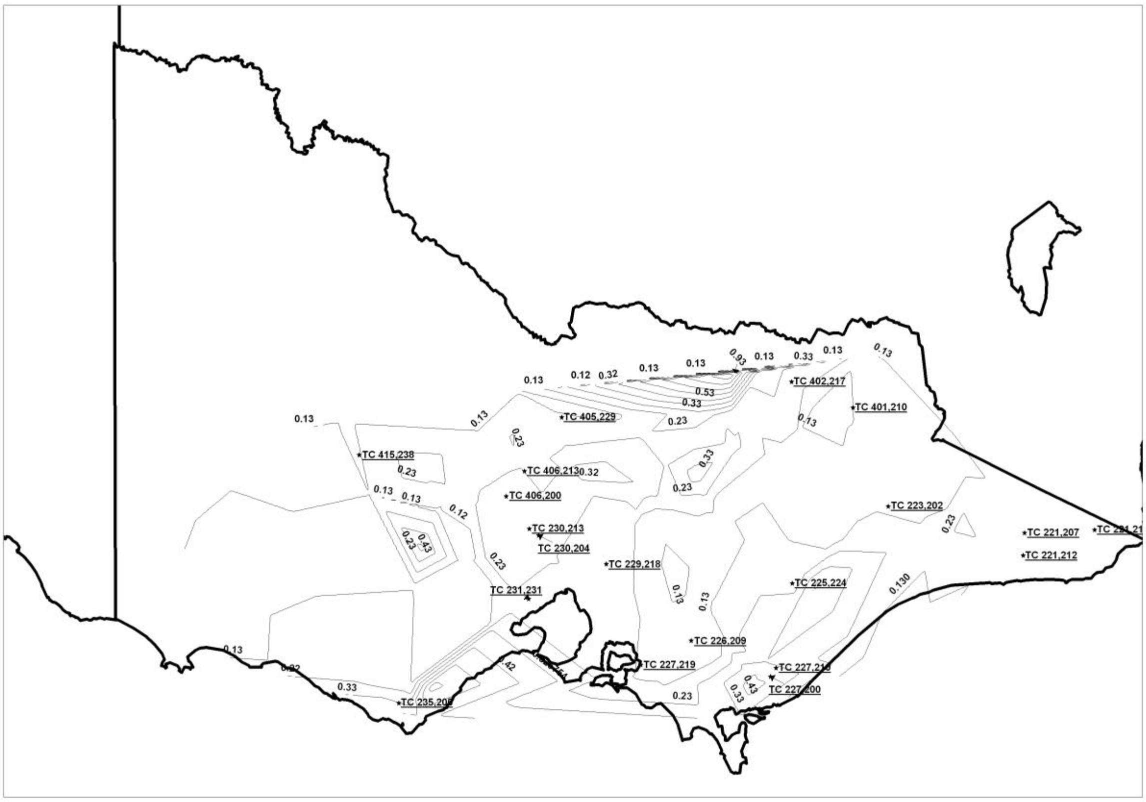


Figure 6.1.1 New C10 contour map for the PRM method in Victoria

QRT-OLS and QRT-GLS methods for Victoria:

The statistical package SPSS was used to develop prediction equations for ARI of 2 years (Q_2) to 100 years (Q_{100}) using the OLS approach. A number of alternative models were examined, e.g. variables being transformed by other than log transformations. The final models were selected based on goodness-of-fit of the model (the coefficient of determination, R^2) and various diagnostic plots. The final QRT-OLS prediction equations are given by Equation 6.1.2 and various model statistics are summarised in Table 6.1.2. All the prediction equations contain catchment area and design rainfall intensity, except for Q_2. Stream density and mean annual rainfall are present in all the equations. These equations satisfy the least squares model assumptions reasonably well. The plots of residuals do not show any notable patterns/trends. Also, the residuals are approximately normally distributed. Multicollinearity is assessed by looking at the variance inflation factors (VIF), which do not reveal any significant correlations between the predictor variables.

$$\log(Q_2) = -1.59 + 0.605\log(area) + 0.518\log(rain) + 0.711\log(sden)$$
$$\log(Q_5) = -0.159 + 0.64\log(area) + 0.587\log({}^2I_{12}) + 0.697\log(sden)$$
$$\log(Q_{10}) = 0.957 + 0.645\log(area) + 1.07\log({}^2I_{12}) - 0.438\log(rain) + 0.672\log(sden)$$
$$\log(Q_{20}) = 1.30 + 0.645\log(area) + 1.27\log({}^2I_{12}) - 0.557\log(rain) + 0.644\log(sden)$$
$$\log(Q_{50}) = 1.55 + 0.641\log(area) + 1.51\log({}^2I_{12}) - 0.649\log(rain) + 0.649\log(sden)$$
$$\log(Q_{100}) = 1.65 + 0.636\log(area) + 1.68\log({}^2I_{12}) - 0.690\log(rain) + 0.637\log(sden) \quad (6.1.2)$$

Table 6.1.2 Summary statistics of the regression equations for Victoria (‘est’ - estimation data set, ‘val’ - validation data set)

ARI (years)	Method	AVP - est	AVP - Val	SEP - est	SEP - val	R^2 (OLS/GLS)
2	OLS	0.025	0.081	16%	29%	69%
	GLS	0.016	0.070	13%	27%	75%
5	OLS	0.031	0.110	18%	34%	56%
	GLS	0.024	0.090	15%	31%	64%
10	OLS	0.040	0.100	20%	32%	53%
	GLS	0.031	0.088	17%	30%	61%
20	OLS	0.051	0.110	23%	34%	48%
	GLS	0.038	0.091	19%	31%	55%
50	OLS	0.063	0.120	26%	36%	44%
	GLS	0.046	0.100	21%	32%	51%
100	OLS	0.069	0.120	27%	34%	46%
	GLS	0.055	0.11	24%	32%	53%
Av (over ARIs)	OLS	0.047	0.111	22%	33%	53%
	GLS	0.035	0.092	19%	31%	60%

The catchment characteristics independent variables selected by the OLS approach were used in the GLS procedure. The parameters of the model error variance for the GLS models were estimated following the method described in Tasker and Stedinger (1989). The residual error covariance matrix was set up by using the regional skew value obtained from the weighted least squares (WLS) procedure as explained in Haddad, Rahman and Weinmann (2008a). In the analysis, the skewness estimators had an average variance of prediction equivalent to that which would be provided by at-site skewness estimators based upon 52 years of record. This shows that the regional skew values in the study can provide relatively more stable estimates than the at-site skew estimator. The residual error covariance matrix was then characterised by concurrent record lengths and cross correlation of concurrent flows by developing a non-linear regression relationship between correlation and distance for smoothing of cross correlation estimates. The methods adopted to develop the QRT-GLS models for Victoria are explained in Haddad, Rahman and Weinmann (2008a). The model statistics are summarised in Table 6.1.2. The final prediction equations based on QRT-GLS method are provided by Equation 6.1.3.

$$\log(Q_2) = -1.66 + 0.61\log(area) + 0.542\log(rain) + 0.704\log(sden)$$
$$\log(Q_5) = -0.160 + 0.641\log(area) + 0.569\log({}^2I_{12}) + 0.697\log(sden)$$
$$\log(Q_{10}) = 0.677 + 0.652\log(area) + 1.13\log({}^2I_{12}) - 0.362\log(rain) + 0.712\log(sden)$$
$$\log(Q_{20}) = 0.997 + 0.650\log(area) + 1.34\log({}^2I_{12}) - 0.474\log(rain) + 0.692\log(sden)$$
$$\log(Q_{50}) = 1.14 + 0.643\log(area) + 1.64\log({}^2I_{12}) - 0.539\log(rain) + 0.679\log(sden)$$
$$\log(Q_{100}) = 1.16 + 0.633\log(area) + 1.84\log({}^2I_{12}) - 0.560\log(rain) + 0.664\log(sden) \quad (6.1.3)$$

There is little difference in regression coefficients between the OLS and GLS methods as can be seen from Equations 6.1.2 and 6.1.3. This may be due to the fact that the cross correlations among concurrent annual maximum flows were quite small (average 0.30). However, Table 6.1.2 clearly indicates that the GLS method shows on average smaller average variance of prediction (AVP) and standard error of prediction (SEP) values as compared to the OLS method. Similar results were found by Stedinger and Tasker (1985) and Tasker et al. (1986). The R^2 values are also higher for the GLS method. The residuals of the GLS models are examined to check for the normality (Figure 6.1.2 shows a sample plot), which show that the standardised residuals are approximately normally distributed.

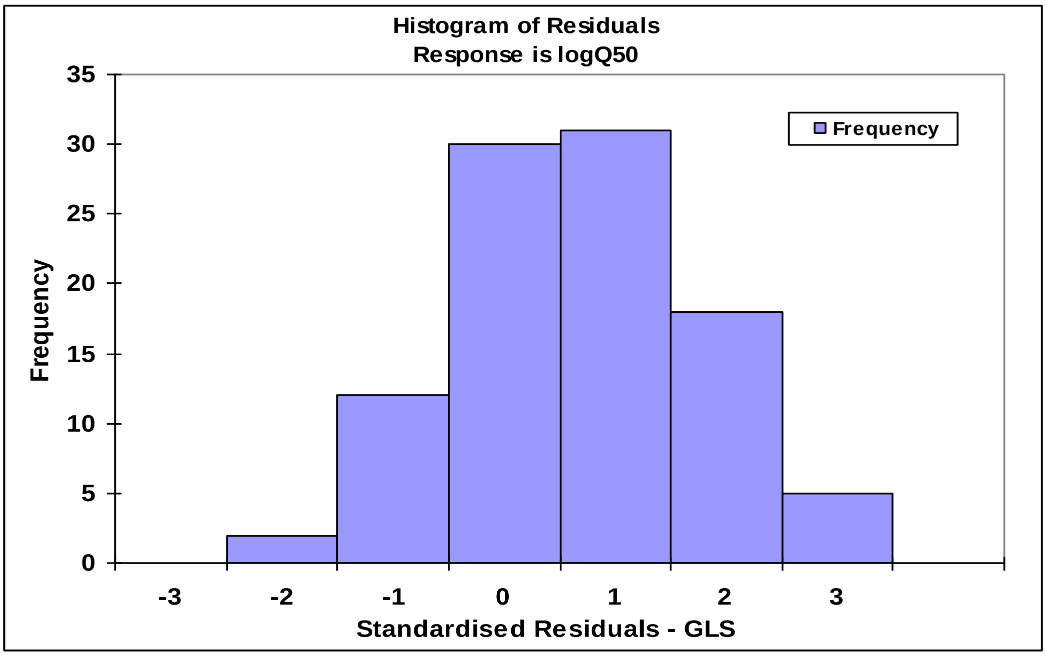


Figure 6.1.2 GLS Histogram of standardised residuals (GLS method)

Validation of QRT and PRM for Victoria:

To assess the relative accuracy of the developed techniques, a split-sample validation method was adopted. For this, 18 randomly selected catchments were set aside before the model development. Both the developed QRT and PRM were applied to these independent test catchments. The PRM based on Equation 6.1.1 was not assessed here, as it did not perform as well as the C10 map and also requires additional catchment variables, which makes the application of the method more difficult.

For each of the test catchments, the predicted flood quantiles (Q_{pred}), obtained from the developed QRT or PRM, were compared with at-site flood frequency analysis (FFA) estimates (observed quantile, Q_{obs}).

The root mean squared error (RMSE) is obtained by:

$$RMSE = \sqrt{\frac{\Sigma(Q_{obs} - Q_{pred})^2}{N}} \quad (6.1.4$$

where N = number of test catchments.

Clustered column charts are also prepared for each of the test catchments showing

Q_{pred}, Q_{obs}, and 95% CL of the at-site FFA estimates (a sample plot is shown in Figure 6.1.3). For a particular test catchment, the method which best approximates the Q_{obs} is noted (best fitting model tally). The ratio Q_{pred}/Q_{obs} is also obtained for each of the test catchments. If this ratio is smaller than 0.7, it is rated as a 'gross underestimation', if this ratio is greater than 1.4, it is rated as a 'gross overestimation' and if this ratio is between 0.7 and 1.4, it is rated as an 'acceptable estimation'.

Table 6.1.3 shows that QRT-GLS method has the smallest RMSE values except for Q_2. The RMSE values for Q_2 are very similar for the QRT-GLS method (40 m^3/s) and PRM method (39 m^3/s). In terms of best fitting model tally (Table 6.1.4), QRT-GLS gives the best result (51% cases), followed by PRM (40% cases) and QRT-OLS (only 9% cases). With respect to model tally based on Q_{pred}/Q_{obs} ratio values (Table 6.1.5), QRT-GLS method shows the best results where 48% cases fall in the category of 'acceptable estimation' 26% cases in 'gross underestimation' and 26% cases in 'gross overestimation' categories. For PRM, 45% cases fall in the category of 'acceptable estimation', 39% cases in 'gross underestimation' and 15% cases in 'gross overestimation' categories. These results show that the PRM has the highest chance of making a 'gross underestimation' (about 1 in 3 cases). This method appears to have a significant low bias in its predictions. The QRT-OLS method has the highest chance (33%, i.e. 1 in 3 cases) of making a 'gross overestimation'.

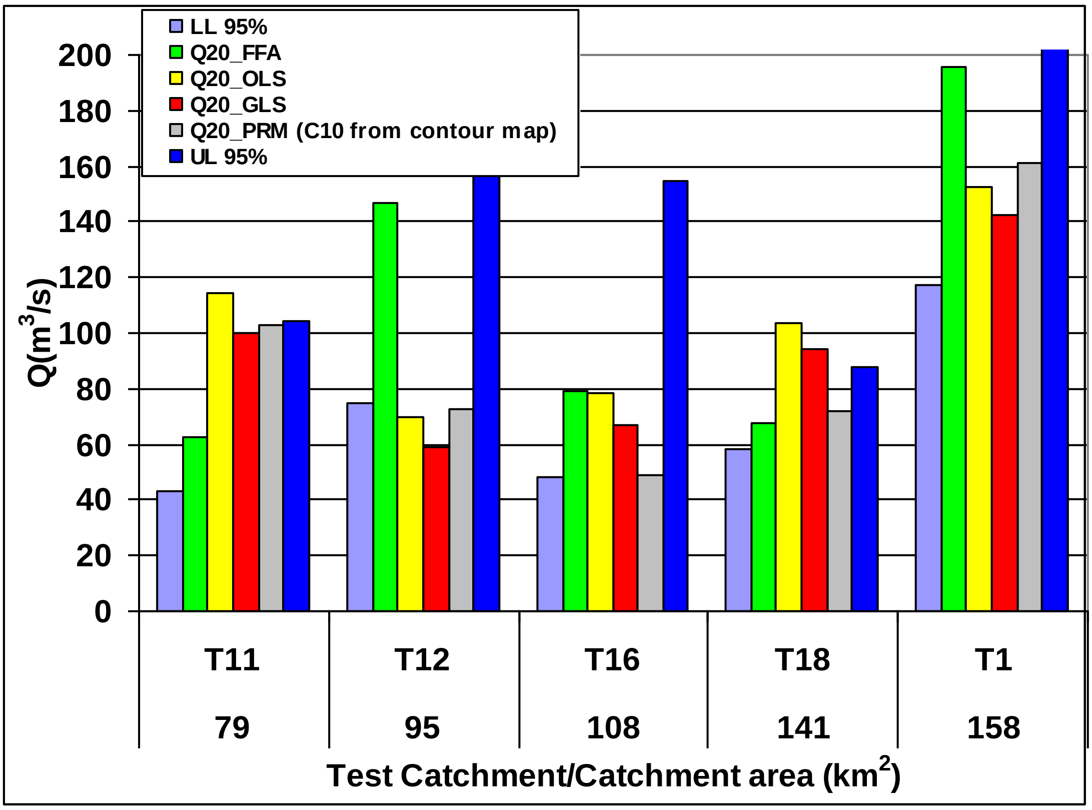


Figure 6.1.3 Comparison of flood estimates from various methods (ARI = 20 years)

Table 6.1.3 Comparison of RMSE values for Victoria

ARI (years)	RMSE (m^3/s)		
	QRT - OLS	QRT - GLS	PRM (map)
2	43	40	39
5	119	117	120
10	194	190	200
20	274	268	276
50	400	383	404
100	493	478	502

Table 6.1.4 Best fitting model tally for Victoria

ARI (years)	Best fitting cases		
	QRT - OLS	QRT - GLS	PRM (map)
2	0	14	4
5	1	8	9
10	2	8	8
20	2	8	8
50	1	9	8
100	4	8	6
Sum	10	55	43
%	9	51	40

Table 6.1.5 Summary of model tally based on Q_{pred}/Q_{obs} ratio values (Victoria)

ARI (years)	QRT - OLS			QRT - GLS			PRM (map)		
	Under	Acceptable	Over	Under	Acceptable	Over	Under	Acceptable	Over
2	8	6	4	5	9	4	6	8	4
5	5	6	7	4	9	5	5	9	4
10	5	7	6	3	10	5	5	11	1
20	4	7	7	4	10	4	7	9	2
50	5	6	7	5	7	6	10	6	2
100	6	7	5	7	7	4	9	6	3
Sum	33	39	36	28	52	28	42	49	17
%	31	36	33	26	48	26	39	45	16

Concluding remark:

From the three different RFFA methods tested for Victoria, QRT-GLS outperforms the PRM and QRT-OLS methods but still gives gross under- or overestimation in about half the cases. The PRM shows the highest degree of bias in that it is likely to give gross underestimation for 39% cases. The QRT-OLS method shows no significant bias but is likely to provide gross under- or overestimation for nearly two thirds of the cases.

6.2. NSW and ACT

In this study, NSW is divided into two regions: (a) eastern NSW (56 catchments falling on the East of the Great Dividing Range) and (b) western NSW (40 catchments falling on the West of the Great Dividing Range). Both the Probabilistic Rational Method and the Quantile Regression Technique were developed and tested for these two separate regions.

Development of QRT:

The developed prediction equations using GLS regression for eastern NSW for ARIs of 2 years (Q_2) to 100 years (Q_{100}) are provided below (Equation 6.2.1).

The summary statistics for these equations are provided in Table 6.2.1.

$$\log(Q_2) = -3.46 + 1.25\log(area) + 2.40\log(I_{2,tc})$$
$$\log(Q_5) = -2.73 + 1.15\log(area) + 2.10\log(I_{5,tc})$$
$$\log(Q_{10}) = -2.33 + 1.09\log(area) + 1.94\log(I_{10,tc})$$
$$\log(Q_{20}) = -1.99 + 1.05\log(area) + 1.78\log(I_{20,tc})$$
$$\log(Q_{50}) = -1.58 + 0.99\log(area) + 1.59\log(I_{50,tc})$$
$$\log(Q_{100}) = -1.30 + 0.94\log(area) + 1.48\log(I_{100,tc}) \quad (6.2.1)$$

Table 6.2.1 Summary statistics of the regression equations for eastern NSW ('est' - estimation data set, 'val' - validation data set, ERL - equivalent record length)

ARI (years)	AVP - est	AVP - val	SEP - est	SEP - val	RMSE - val (m^3/s)	R^2 (GLS)	Av ERL (years)
2	0.075	0.040	28%	20%	36	80%	55
5	0.063	0.044	26%	21%	59	79%	65
10	0.065	0.044	26%	21%	111	76%	74
20	0.072	0.044	27%	21%	188	72%	80
50	0.085	0.044	30%	21%	354	67%	84
100	0.097	0.042	32%	21%	577	62%	85
Av	0.076	0.043	28%	21%	220	73%	74

The developed prediction equations using the GLS regression for western NSW for Q_2 to Q_{100} are shown below (Equation 6.2.2). The summary statistics for these equations are provided in Table 6.2.2.

$\log(Q_2) = - 3.57 + 1.36\log(area) + 2.18\log(I_{2,tc})$

$\log(Q_5) = - 2.79 + 1.26\log(area) + 1.85\log(I_{5,tc})$

$\log(Q_{10}) = - 2.32 + 1.19\log(area) + 1.66\log (I_{10,tc})$

$\log(Q_{20}) = - 1.98 + 1.14\log(area) + 1.52\log((I_{20,tc})$

$\log(Q_{50}) = - 0.85 + 0.931\log(area) + 0.89\log(I_{50,tc}) + 0.44\log(sden)$

$$\log(Q_{100}) = - 0.58 + 0.88\log(area) + 0.80\log(I_{100,tc}) + 0.54\log(sden) \qquad (6.2.2)$$

Table 6.2.2 Summary statistics of the regression equations for western NSW (‘est’ - estimation data set, ‘val’ - validation data set, ERL - equivalent record length)

ARI (years)	AVP - est	AVP - val	SEP - est	SEP - val	MRE	RMSE - val (m^3/s)	R^2 (GLS)	Av ERL (years)
2	0.059	0.033	25%	18%	42%	26	86%	51
5	0.048	0.025	22%	16%	30%	99	80%	60
10	0.046	0.034	22%	19%	29%	179	78%	71
20	0.049	0.038	22%	20%	29%	272	75%	78
50	0.053	0.040	23%	20%	36%	372	73%	65
100	0.065	0.053	26%	23%	40%	477	70%	63
Av	0.053	0.037	23%	19%	34%	238	77%	65

For the developed prediction equations, it can be found that all the equations contain catchment area and design rainfall intensity as a predictor variables. These also show that design floods increase with increasing catchment area and design rainfall intensity, which is as expected. For all the equations in the eastern NSW region there are only two predictor variables, which makes the application of these equations easy in practice as these variables can be obtained very easily. For western NSW, for 50 and 100 years ARIs, an additional variable (stream density) has appeared which is not unexpected. In these equations, it is found that design floods for 50 and 100 years ARIs increase with stream density, which is as expected i.e. a higher drainage density means a quicker catchment response.

Various diagnostic plots related to the prediction equations for GLS regression are examined. The plots of standardized regression residuals and predicted flood quantiles do not show any trend (Figure 6.2.1). The Q-Q plot for the quantiles (ARI = 10 years) is shown in Figure 6.2.2 where the intercept represents the mean of the standardised residuals (which should be close to zero). The slope is approximately equal to the residuals’ standard deviation (which should be close to 1). The coefficient of determination (R^2) is reasonably high. All these indicate that the developed prediction equations satisfy the underlying model assumptions quite well.

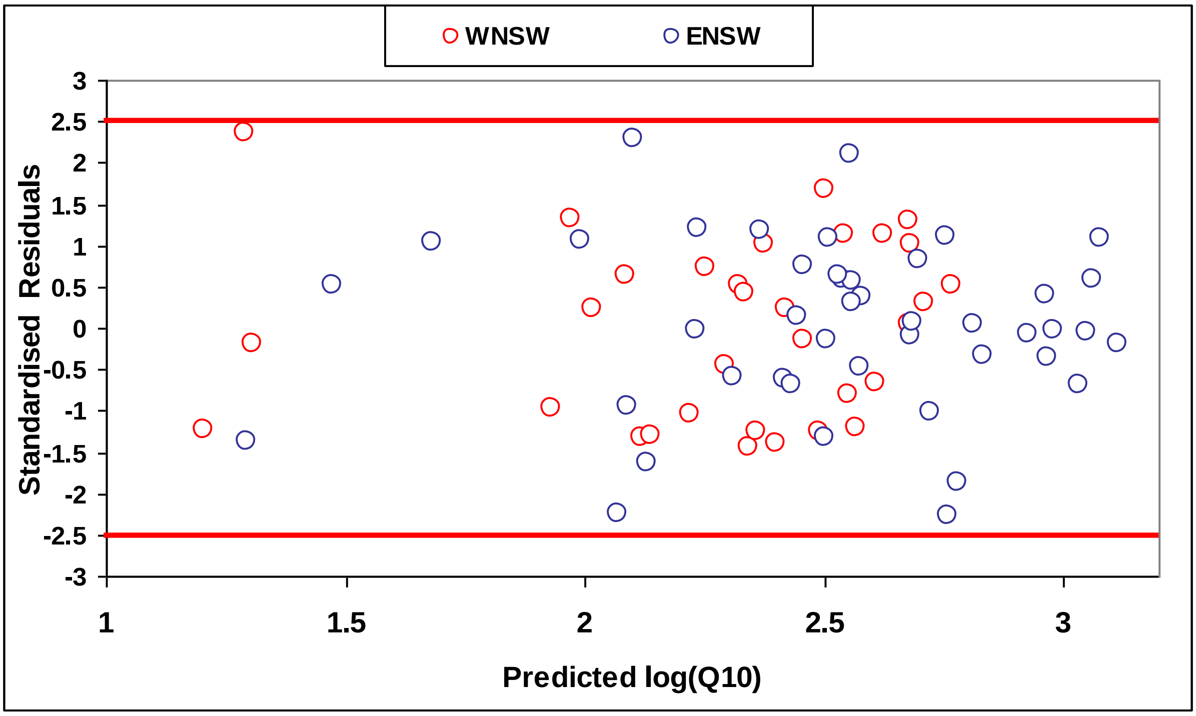


Figure 6.2.1 Standardised residuals vs predicted quantiles for ARI = 10 years (the red marks show the bound of ± 2.5×standardised residual)

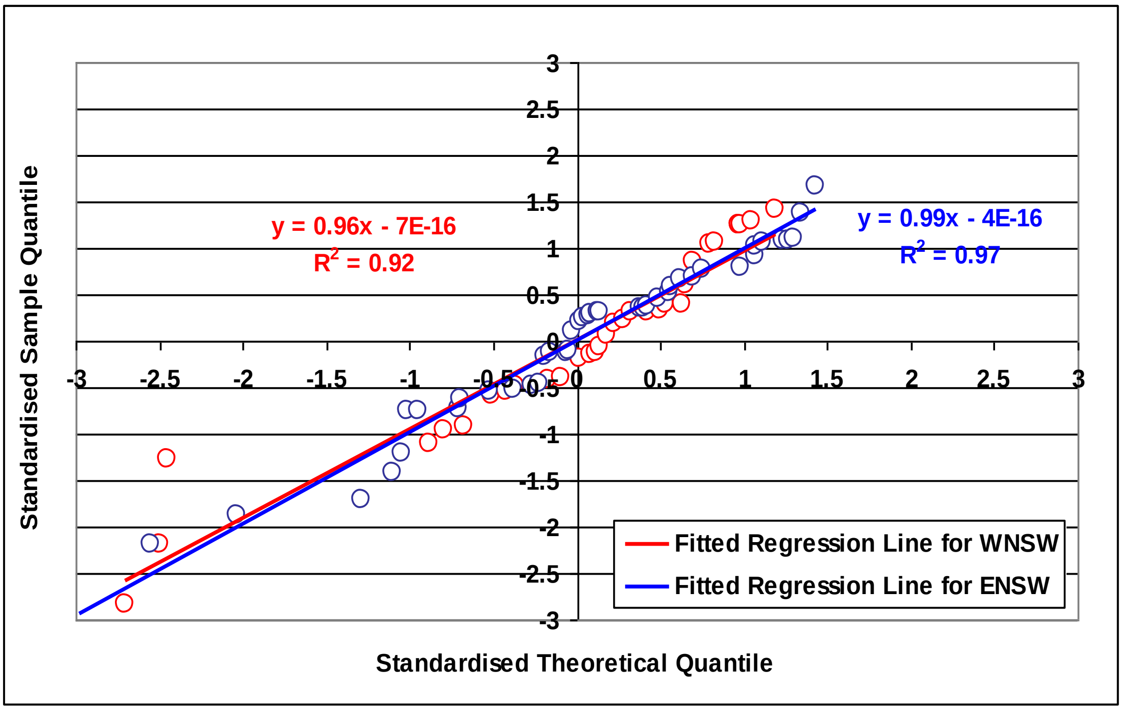


Figure 6.2.2 Standardised sample quantile vs standardised theoretical quantile for ARI = 10 years

The prediction equations show a reasonable standard error of prediction (SEP) of 27%-34% and 24-28% (Tables 6.2.1 and 6.2.2) for eastern NSW and western NSW, respectively. Also, the AVP values for the validation set are quite small giving an average value of 0.043 in log units (over all the ARIs) for eastern NSW, which equates to a standard deviation of prediction of 7.6 m^3/s on average for a test catchment. The AVP for western NSW is 0.037 in log units, which equates to a standard deviation of prediction of 6.4 m^3/s on average for a test catchment. Also it is worth noting that the root mean square error (RMSE) values are quite reasonable. The R^2(GLS) values of the developed prediction equations range from 62% to 80% for eastern NSW and 70% to 86% for western NSW. The R^2(GLS) values decrease with increasing ARIs, which is as expected since there is greater variability and associated errors with higher ARI floods. Given the high degree of variability of NSW hydrology, the levels of R^2(GLS) values obtained here appear to be reasonable. Also, the R^2(GLS) value is a better measure of model performance as compared to the traditional R^2. This is due to the fact that the OLS method makes no distinction between model error and sampling error and can thus provide distorted regression coefficients that do not represent the true model error. The QRT-GLS models on average predict a quantile with an accuracy of prediction equivalent to an average record length of 74 years for eastern NSW and 65 years for western NSW.

Development of PRM:

The Probabilistic Rational Method (PRM) recommended in ARR1987 for eastern NSW was developed based on small and medium sized catchments up to an area of 250 km^2 (Pilgrim and McDermott, 1982). The values of runoff coefficients were developed using data from 308 gauged catchments. The streamflow record lengths of some of these stations were as low as 10 years and also an ordinary product moment method was used in fitting the at-site LP3 distribution. In the present upgrading of the PRM (presented here), the accuracy has been enhanced by increasing the streamflow record lengths of the study catchments (minimum 25 years) and by adopting improved at-site flood frequency analysis (e.g. LP3-Bayesian method). The PRM for Victoria was developed and recommended for use up to an area of 1000 km^2 (I.E. Aust., 1987, 2001). In the current investigation of the PRM for eastern NSW (presented here), the validity of the method for catchments up to 1000 km^2 (similar to Victoria) is examined. The eastern NSW region was divided into 6 zones in ARR1987 as shown in Figure 6.2.3. In this study, Zones A, B, C and eastern part of Zone F (i.e. NSW stations from Drainage Division II) are regarded as eastern NSW and Zones D, E and western part of F (i.e. NSW stations from Drainage Division IV) are regarded as western NSW.

To develop the PRM, C_{10} values were estimated using Equation 5.2 for each of the model catchments. The GIS program Mapinfo's Vertical Mapper add-on is then used to develop the C_{10} contour map. A spreadsheet containing the latitude, longitude and C_{10} values for each model catchment is produced and entered into the mapping program with the C_{10} value represented in the z axis. The program used triangulation methods to create a digital terrain model, from which isopleths were developed. The isopleths are labelled and the test catchments are located on the map. Linear interpolation is then used to estimate the C_{10} values for the test catchments from the contour map.

Figure 6.2.3 ARR1987 designated zones for FF_Y (I.E. Aust., 1987, 2001)

The developed C10 contour map for eastern NSW is presented in Figure 6.2.4. The values of the runoff coefficients tend to decrease from east to west (similar to C_{10} contour map in ARR1987). The developed frequency factors for eastern NSW are presented in Table 6.2.3, which are the average values obtained from the model catchments falling in the respective zones. Also, no relationship between C10 values and catchment elevation (as reported in ARR1987) is found.

Table 6.2.3 Frequency factors for eastern NSW

ARI (years)	ARR Designated Zones			
	Zone A	Zone B	Zone C	Zone F*
2	0.429	0.382	0.322	0.370
5	0.764	0.723	0.706	0.725
20	1.177	1.242	1.235	1.230
50	1.402	1.576	1.507	1.528
100	1.575	1.884	1.688	1.751

* eastern part of Zone F falling in Drainage Division II

Figure 6.2.4 C10 contour map for eastern NSW

The frequency factors for western NSW are shown in Table 6.2.4 and the new C10 contour map is shown in Figure 6.2.5. The frequency factors for the three zones in western NSW are very similar and hence the same values are adopted for all the three zones. Also, no relationship between C10 values and catchment elevation (as reported in ARR1987) was found.

Table 6.2.4 Frequency factors for western NSW

ARI (years)	ARR designated zones		
	Zone D	Zone E	Zone F*
2	0.35	0.35	0.35
5	0.71	0.71	0.71
20	1.25	1.25	1.25
50	1.58	1.58	1.58
100	1.84	1.84	1.84

*western part of Zone F falling in Drainage Division IV

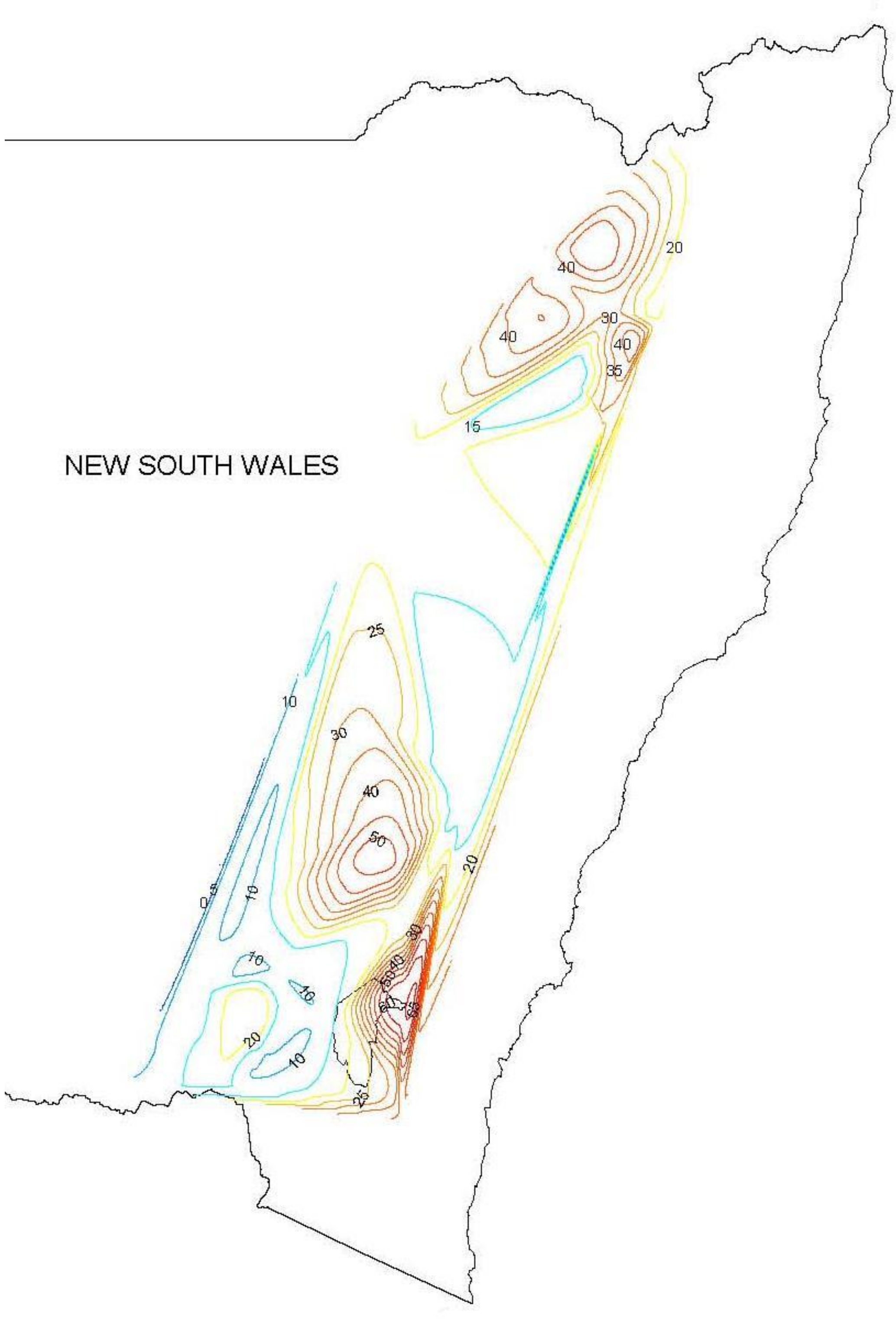


Figure 6.2.5 C10 contour map for western NSW

Validation of QRT and PRM for NSW:

To assess the relative accuracy of the developed techniques, a split-sample validation method was adopted. For this, twelve and eight randomly selected catchments were set aside before the model development for eastern New South Wales and western New South Wales, respectively. Both the developed QRT and PRM were applied to these independent test catchments.

Clustered column charts are prepared for each of the test catchments showing Q_{pred}, Q_{obs}, and 95% CL of the at-site FFA estimates. For a particular test catchment, the method which best approximates the Q_{obs} is noted. The ratio Q_{pred}/Q_{obs} is also obtained for each of the test catchments. If this ratio is smaller than 0.7, it is rated as a 'gross underestimation', if this ratio is greater than 1.4, it is rated as a 'gross overestimation' and if this ratio is in between 0.7 and 1.4, it is rated as an 'acceptable estimation'.

Table 6.2.5 presents a comparison between the RMSE values for the three selected models (QRT-OLS, QRT-GLS and PRM). It can be seen that for each of the flood quantiles except for Q_2, the QRT-GLS method produces smallest RMSE values than the two other methods. For Q_2, RMSE values for PRM and QRT-GLS methods are very similar.

Table 6.2.5 Comparison of RMSE values for eastern NSW

ARI (years)	RMSE (m^3/s)		
	QRT-OLS	QRT-GLS	PRM
2	39	36	35
5	63	59	65
10	115	111	120
20	193	188	197
50	370	354	385
100	585	577	596

Table 6.2.6 Comparison of median relative error values for eastern NSW

ARI (years)	Median relative error (%)		
	QRT-OLS	QRT-GLS	PRM
2	23	23	21
5	19	17	34
10	17	17	38
20	13	13	32
50	26	27	30
100	28	28	38

The plots of the predicted and observed flood quantiles are prepared for each of the test catchments. Figure 6.2.6 shows the plot for Q_{20}. This shows that the QRT-GLS method provides 'very reasonable' estimates (as compared to Q_{obs} values) for 9 out of the 12 test catchments. It can be seen from these plots that all the three methods provide model prediction within the 95% confidence limits of the at-site FFA estimates. A summary of the model tally (visual inspection) is provided in Table 6.2.7, which shows that QRT-GLS method provides the best fitting for 31 cases out of 72 (6 ARIs and 12 test catchments) i.e. for 43% of the cases QRT-GLS method provides the best matches.

The summary of the Q_{pred}/Q_{obs} ratio values for all the 6 ARIs and 12 test catchments are summarized in Table 6.2.8. Out of the 72 cases (6 ARIs and 12 test catchments), the QRT-OLS, QRT-GLS and PRM shows 49, 52 and 38 cases within 'acceptable estimation', which is equivalent to 68%, 72% and 53% cases. That is, QRT-GLS method provides 'acceptable estimation' for 72% of the cases, which seems to be excellent result. The QRT-OLS, QRT-GLS and PRM, respectively show 7%, 11% and 30% 'gross underestimation', which indicates that the PRM has the highest chance of making an underestimation (about 1 in 3 cases). The QRT-OLS, QRT-GLS and PRM, respectively show 25%, 17% and 16% 'gross overestimation', which indicates that QRT-OLS has the highest chance of making an overestimation (about 1 in 4 cases). These results clearly demonstrate that on average QRT-GLS method is likely to provide the best flood quantile estimate in eastern NSW.

Table 6.2.9 compares the RMSE values for the three methods based on the 8 test catchments for western NSW. Among the three methods, QRT-GLS method generally shows the smallest RMSE values.

Table 6.2.7 Best fitting model tally (eastern NSW)

ARI (years)	Best fitting cases		
	QRT-OLS	QRT-GLS	PRM
2	3	4	5
5	3	5	4
10	3	7	2
20	4	5	3
50	5	5	2
100	5	5	2
Sum	23	31	18
%	32	43	25

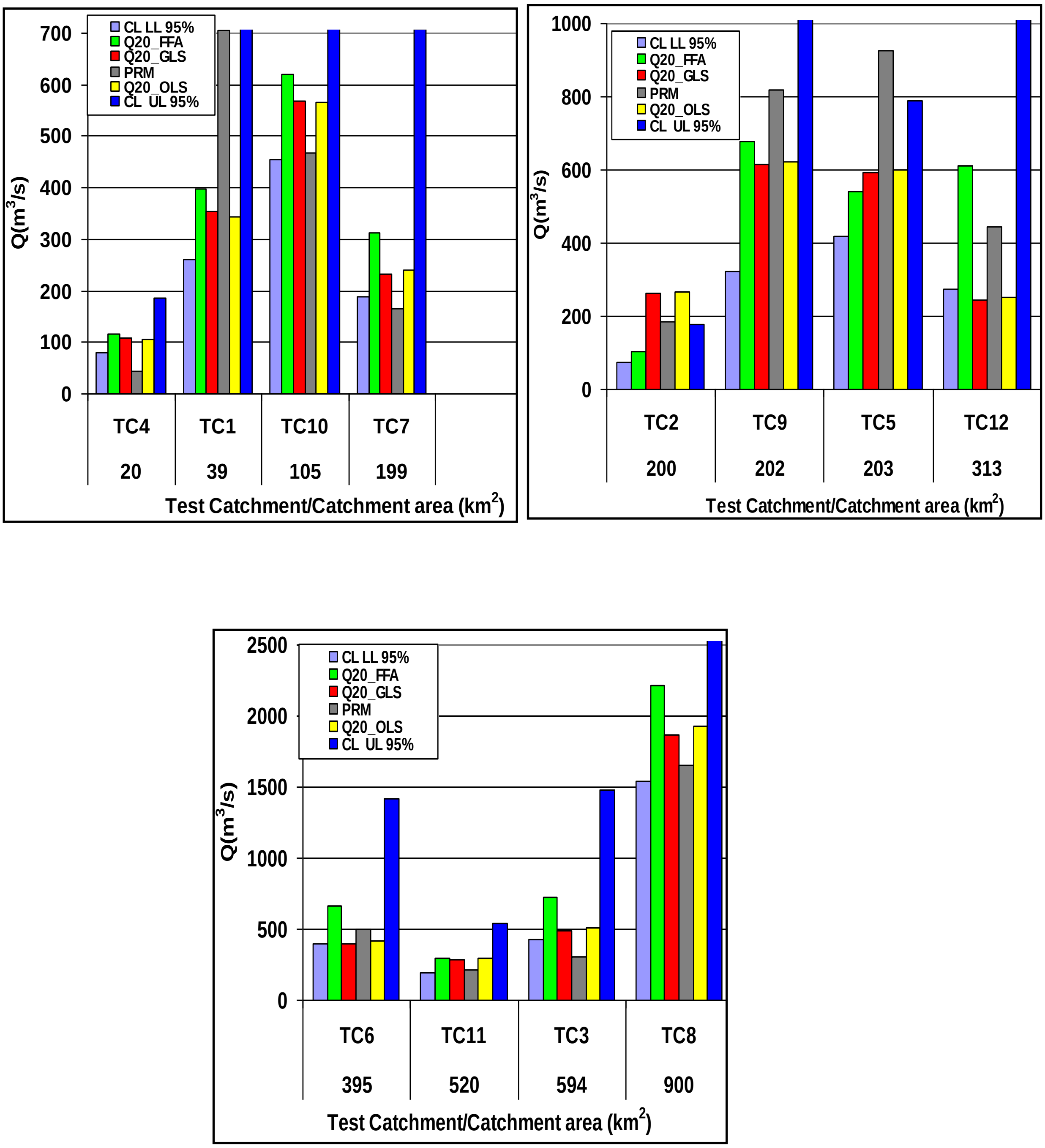


Figure 6.2.6 Comparison of flood quantiles for Q_{20} (eastern NSW)

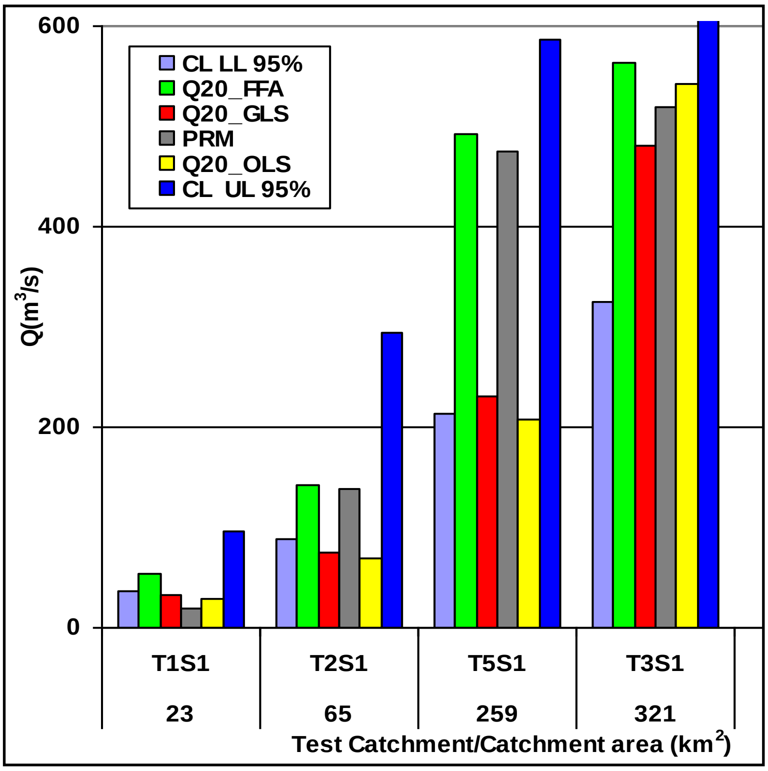
Table 6.2.8 Summary of model tally based on Q_{pred}/Q_{obs} ratio values (eastern NSW)

ARI (years)	QRT-OLS			QRT-GLS			PRM		
	Under	Acceptable	Over	Under	Acceptable	Over	Under	Acceptable	Over
2	1	6	5	3	7	2	2	8	2
5	0	8	4	0	8	4	4	6	2
10	0	10	2	0	11	1	4	6	2
20	0	10	2	0	10	1	4	6	2
50	2	8	2	2	9	1	4	6	2
100	2	7	3	3	7	3	4	6	2
Sum	5	49	18	8	52	12	22	38	12
%	7	68	25	11	72	17	30.5	53	16.5

Table 6.2.9 Comparison of RMSE values for western NSW

ARI (years)	RMSE (m^3/s)		
	QRT-OLS	QRT-GLS	PRM
2	27	26	96
5	103	99	145
10	185	179	247
20	282	272	362
50	383	372	527
100	494	477	654

The plots of the predicted and observed flood quantiles were prepared for each of the 8 test catchments from western NSW. Figure 6.2.7 shows the plot for Q_{20}. This shows that the QRT-GLS method provides 'very reasonable' results (as compared to Q_{obs} values) for 5 out of the 8 test catchments. It can be seen from these plots that at these sites all the three methods provide model prediction within the 95% confidence limits of the at-site FFA estimates. A summary of the model tally (visual inspection) is provided in Table 6.2.10, which shows that the PRM provides the best fitting for 24 cases out of 48 (6 ARIs and 8 test catchments) i.e. for 50% of the cases PRM method provides the best matches. The QRT-GLS method provides the best fitting for 20 cases (42%). The QRT-OLS method provides the best fitting for only 4 cases (8%).



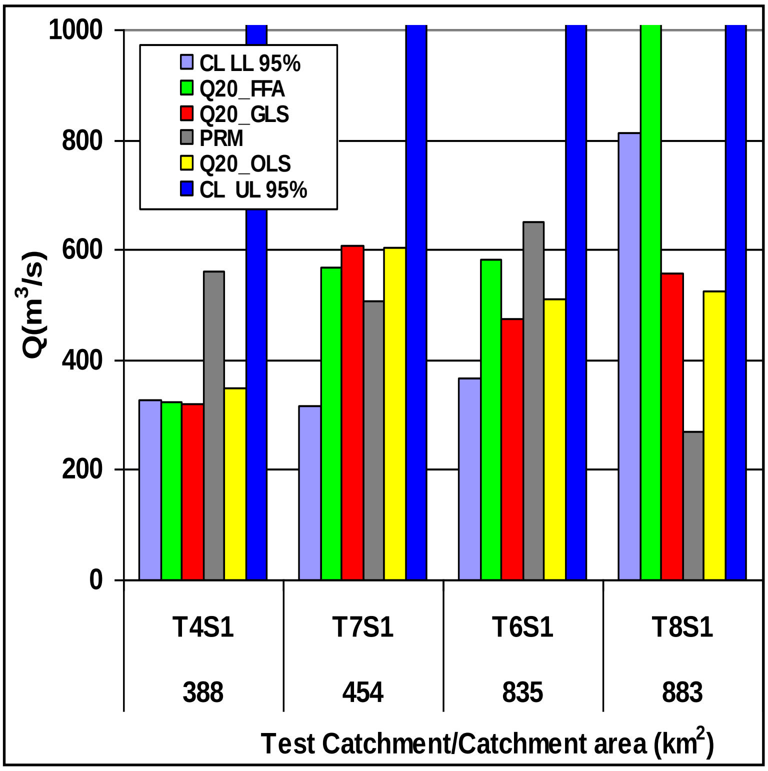


Figure 6.2.7 Comparison of flood quantiles for Q_{20} (western NSW)

The summary of the Q_{pred}/Q_{obs} ratio values for all the 6 ARIs and 8 test catchments are summarized in Table 6.2.11. Out of the 48 cases (6 ARIs and 8 test catchments), the QRT-OLS, QRT-GLS and PRM show 16, 22 and 20 cases within 'acceptable estimation', which is equivalent to 33%, 46% and 42% cases. That is, the QRT-GLS method provides 'acceptable estimation' for the highest number of cases.

Table 6.2.10 Best fitting model tally (western NSW)

ARI (years)	Best fitting cases		
	QRT-OLS	QRT-GLS	PRM
2	0	5	3
5	1	4	3
10	1	4	3
20	0	3	5
50	1	1	6
100	1	3	4
Sum	4	20	24
%	8%	42%	50%

Table 6.2.11 Summary of model tally based on Q_{pred}/Q_{obs} ratio values (western NSW)

ARI (years)	QRT-OLS			QRT-GLS			PRM		
	Under	Acceptable	Over	Under	Acceptable	Over	Under	Acceptable	Over
2	3	4	1	2	5	1	1	2	5
5	4	2	2	3	4	1	3	2	3
10	4	2	2	3	4	1	3	2	3
20	5	3	0	5	3	0	2	5	1
50	5	3	0	5	3	0	2	5	1
100	5	2	1	4	3	1	3	4	1
Sum	26	16	6	22	22	4	14	20	14
%	54	33	13	46	46	8	29	42	29

Concluding remarks:

Three different regional flood estimation methods are developed and tested for eastern NSW (east of the Great Dividing Range) and western NSW (West of the Great Dividing Range). These are Quantile Regression Technique (QRT) based on ordinary least squares (OLS), Quantile Regression Technique (QRT) based on generalized least squares (GLS) and Probabilistic Rational Method (PRM). For the

QRT, a set of flood prediction equations are developed and for the PRM, new C10 contour map is developed for eastern and western NSW. A split-sample validation approach is adopted to compare the performances of the developed regional flood estimation methods. The following conclusions are drawn from this study:

- The developed prediction equations based on QRT-GLS method for eastern NSW outperforms the PRM and QRT-OLS methods. These prediction equations satisfy the underlying model assumption very well and demonstrate quite reasonable goodness-of-fit measures.
- For western NSW (west of the Great Dividing Range), the PRM and QRT-GLS methods perform very similarly. Since QRT-GLS method is founded on superior statistical properties, it is preferable to the PRM.

The best performing QRT-GLS estimates for NSW are compared with at-site FFA estimates for 20 years ARI in Figure 6.2.8a,b and 6.2.9 (other estimates i.e. confidence limits, PRM and QRT-OLS are removed from these plots for better visual comparison). These plots show the QRT-GLS estimates are quite satisfactory for most of the test catchments.

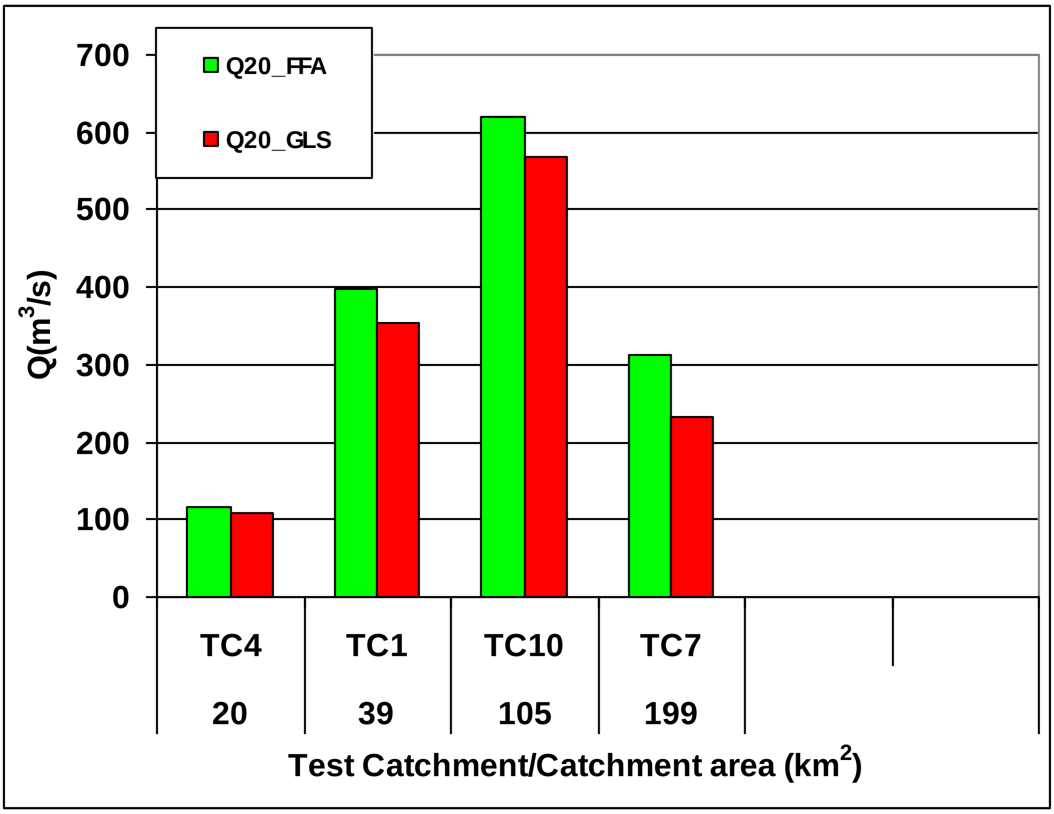
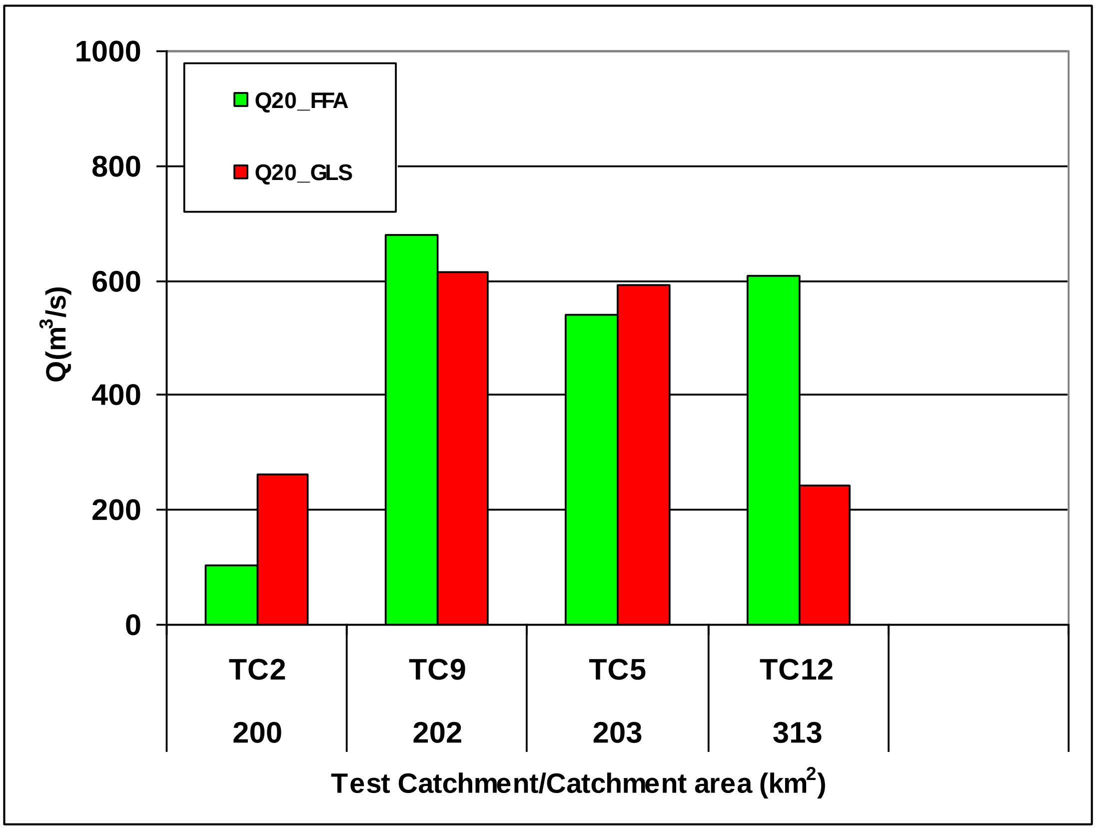


Figure 6.2.8a Comparison of flood quantiles for Q_{20} (eastern NSW): QRT-GLS and at-site FFA estimates shown



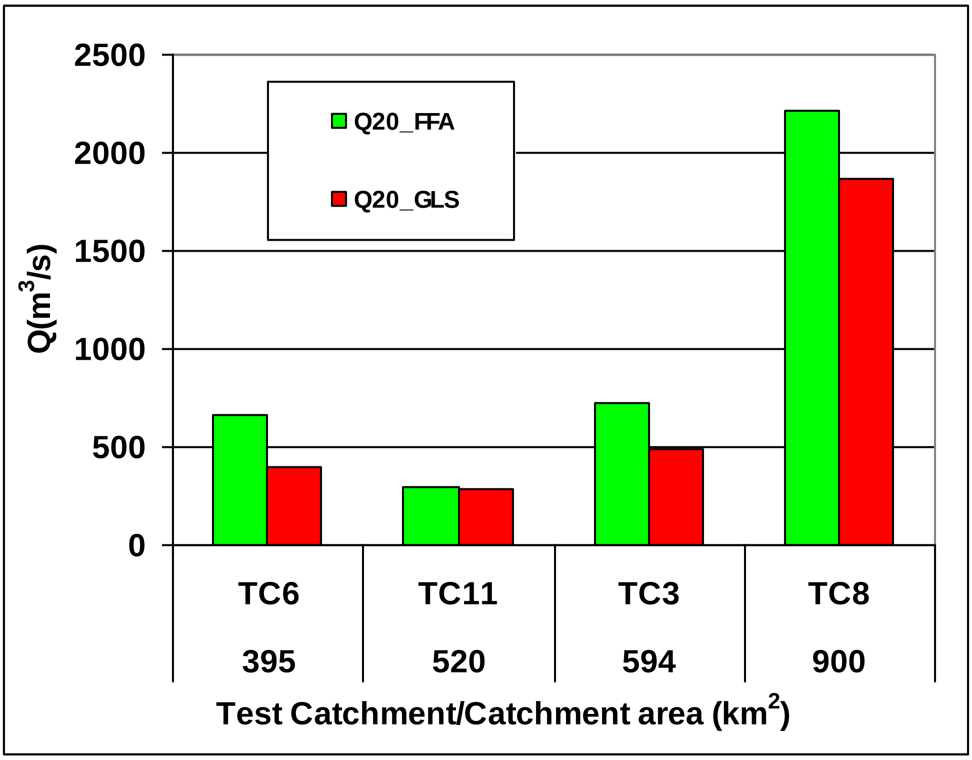


Figure 6.2.8b Comparison of flood quantiles for Q_{20} (eastern NSW): QRT-GLS and at-site FFA estimates shown

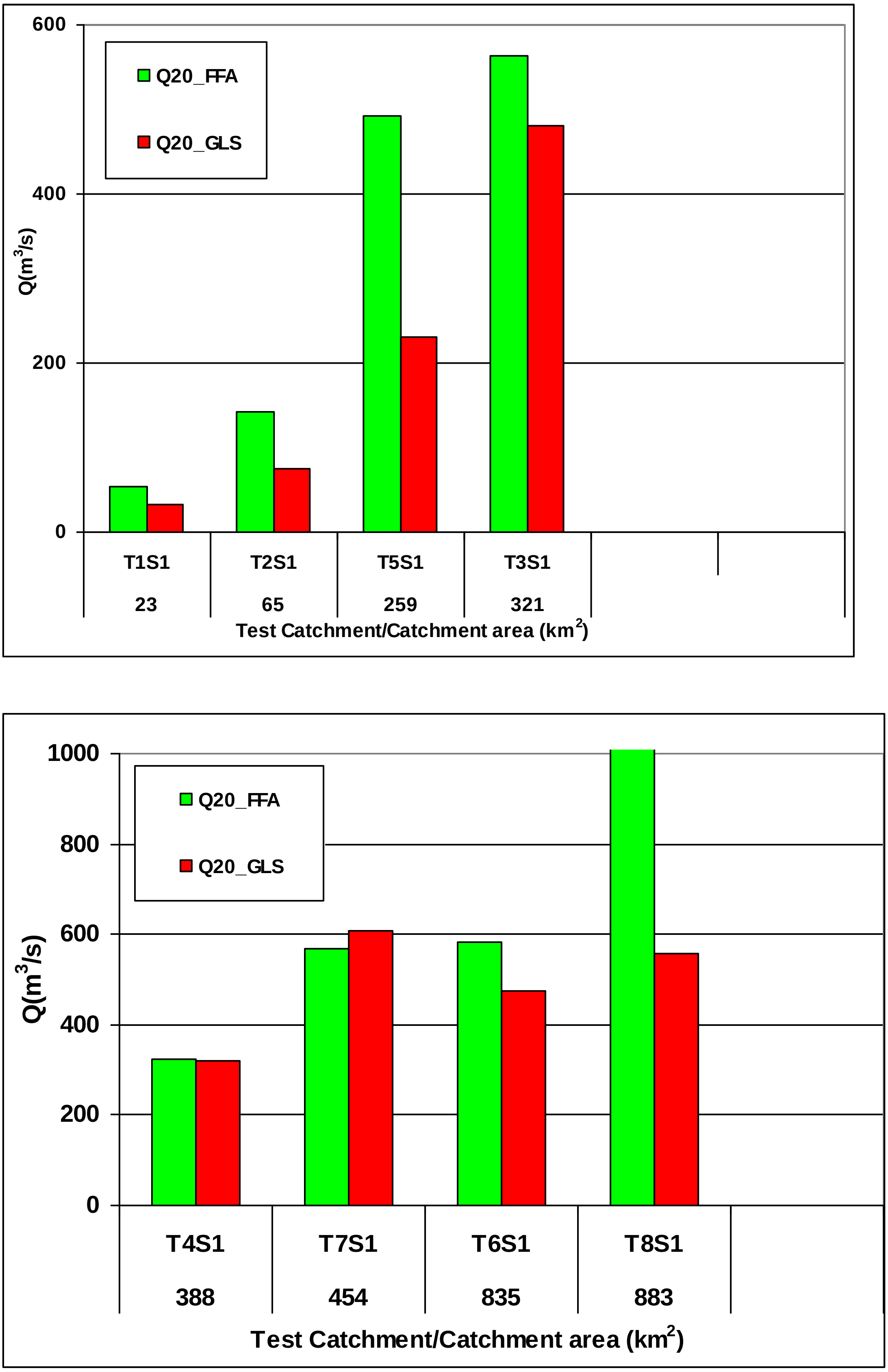


Figure 6.2.9 Comparison of flood quantiles for Q_{20} (eastern NSW): QRT-GLS and at-site FFA estimates shown

6.3. Tasmania

For at-site flood frequency analysis, seven different probability distributions (including LP3 and GEV) were tested and it is found that the log-normal is the best performing distribution for Tasmania. The FLIKE software was used to fit the log-normal distribution to the site's annual flood maximum series using the Bayesian inference method.

A Bayesian generalised least squares (GLS) regression method was adopted to develop the prediction equations for Tasmania. Initially, to construct the error covariance matrix of residual errors, the relationship between the inter-station correlation and inter-station distance was expressed by a smooth function. There is no automatic technique of variable selection in the GLS regression. Here, a method similar to stepwise regression was used as shown by Hackelbush et al. (2009). A total of 23 GLS models with different combinations of catchment characteristics were developed. For each run/iteration, the model error variance and its standard deviation are recorded along with its pseudo R^2, Bayesian Information Criteria (BIC), Akaike Information Criteria (AIC) and Average Variance of Prediction (AVP) values (Figure 6.3.1 presents sample results for ARI of 20 years). The set of predictor variables giving the smallest model error variance, BIC, AIC and AVP values and the highest pseudo R^2 value is finally adopted in the prediction equations.

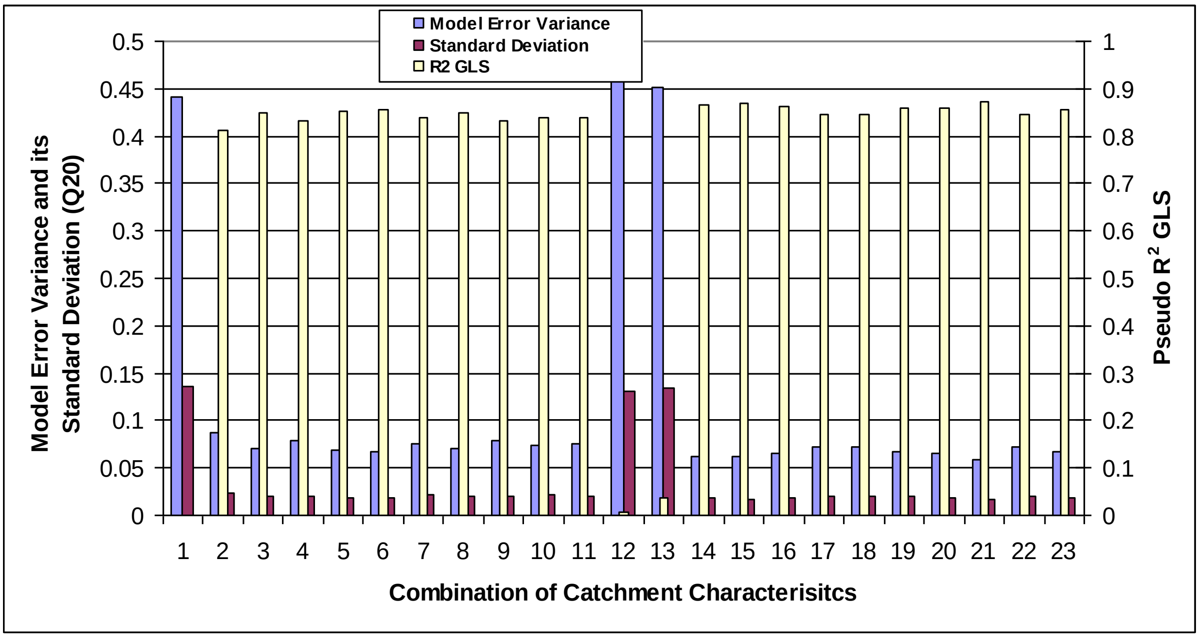


Figure 6.3.1 Selection of predictor variables for flood quantile model (ARI = 20 years)

The developed prediction equations for various ARIs for Tasmania are shown below (Equation 6.3.1). The prediction equations show reasonable standard error of prediction values (26%-31%) (Table 6.3.1). Also, the AVP values are quite small (0.067 to 0.076 in log units). The R^2(GLS) values of the developed prediction equations range from 83% to 85%, which are higher than those of Vic and NSW. The QRT-GLS models on average predict a quantile with an accuracy of prediction equivalent to an average record length of 71 years.

$$\log(Q_2) = 1.84 + 1.26\log(area) + 1.40\log(I_{2,tc})$$
$$\log(Q_5) = 1.98 + 1.30\log(area) + 2.17\log(I_{5,tc})$$
$$\log(Q_{10}) = 2.06 + 1.26\log(area) + 1.92\log(I_{10,tc})$$
$$\log(Q_{20}) = 2.12 + 1.22\log(area) + 1.69\log(I_{20,tc})$$
$$\log(Q_{50}) = 2.19 + 1.16\log(area) + 1.42\log(I_{50,tc})$$
$$\log(Q_{100}) = 2.24 + 1.12\log(area) + 1.23\log(I_{100,tc}) \quad (6.3.1)$$

Table 6.3.1 Summary statistics of the regression equations for Tasmania ('est' - estimation data set, 'val' - validation data set, ERL - equivalent record length)

ARI (years)	AVP	SEP - est	SEP - val	R^2 (GLS)	Av ERL (years)
2	0.076	31%	28%	83%	28
5	0.064	28%	26%	85%	45
10	0.064	28%	26%	85%	60
20	0.065	28%	26%	85%	77
50	0.067	28%	26%	85%	100
100	0.068	29%	27%	84%	117
Av	0.067	29%	26%	85%	71.2

The major assumptions in the OLS regression are that the standardised residuals are normally distributed with zero mean and the variance is constant across all the sites. These assumptions are hardly satisfied in practice and the residuals are often heterosecdastic. The GLS regression accounts for the heterosecdastic structure of the residuals. If the underlying assumptions are satisfied, the standardised residuals should be within ± 2, and the QQ-plot should follow a straight line with slope equal to one and intercept equal to zero. Figures 6.3.2 and 6.3.3 show that these assumptions have been well satisfied.

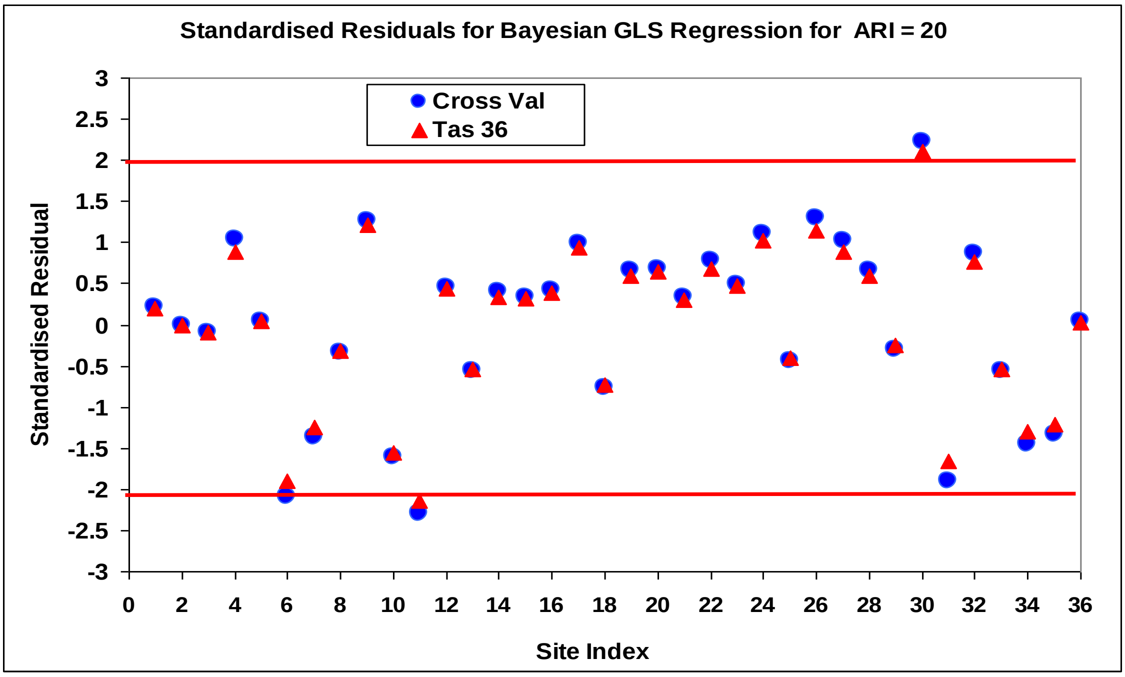


Figure 6.3.2 Standardised residuals for ARI of 20 years

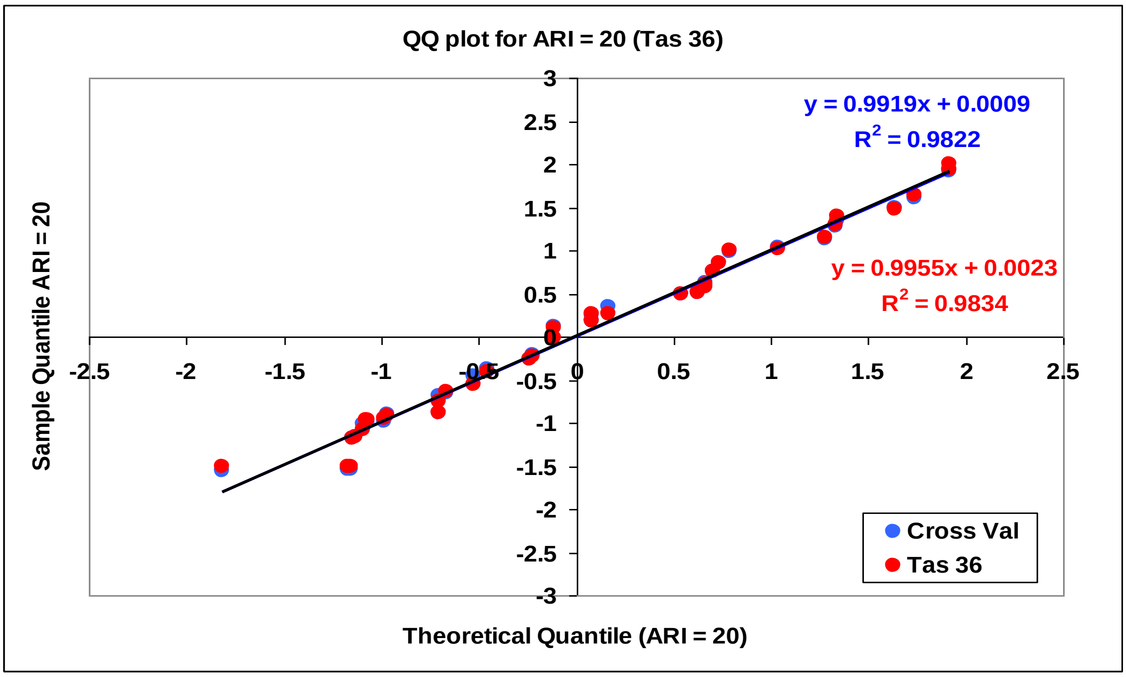


Figure 6.3.3 QQ-plot for ARI of 20 years

To assess the performance, the developed predictions equations are applied to 17 catchments that have streamflow record lengths of 25 years or greater. Here, 'one-at-a-time cross validation method' is adopted where all but one catchments are used to develop the prediction equation and then the developed prediction equation is applied to the catchment that was left out. The procedure is repeated for all the catchments so that the developed prediction equations are tested independently on all the model catchments. The flood quantiles estimated from the prediction equations are compared with at-site flood frequency analysis estimates. Figure 6.3.4 shows the results for 20 years ARIs; the results may be rated as 'excellent' for 11 out of the 17 catchments (315074, 308799, 315450, 318350, 308446, 318065, 310149, 310148, 308145, 318017 and 310154), 'fair' for 4 out of 17 catchments (308819, 316624, 310472 and 304040) and 'poor' for two catchments (304597 and 304125).

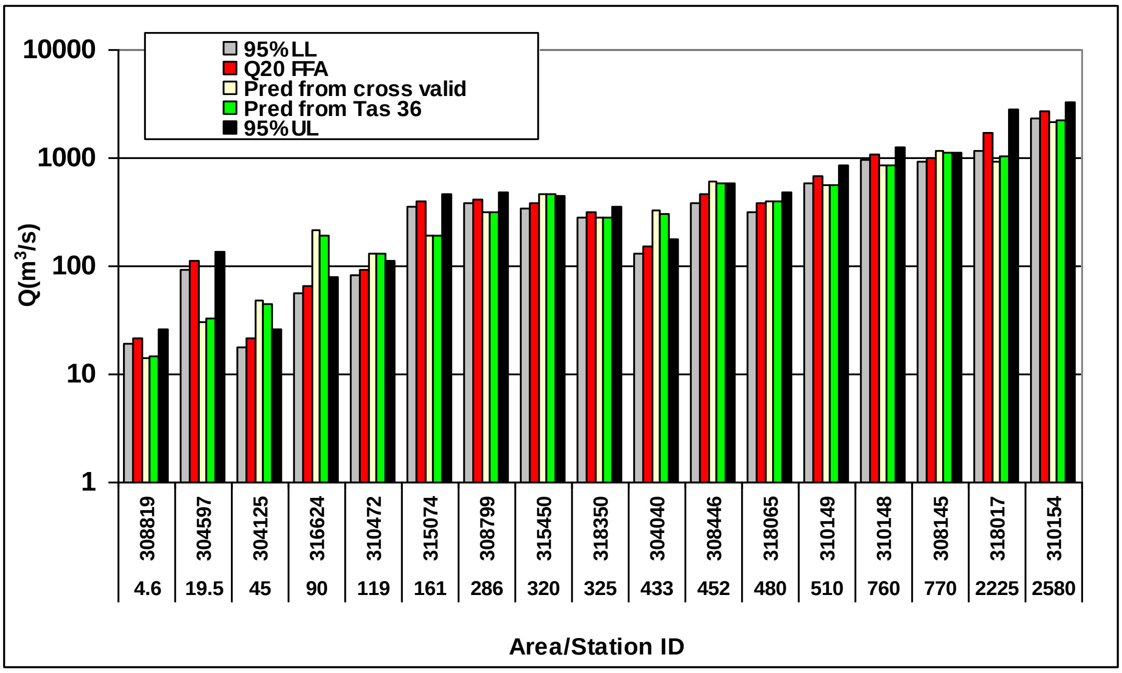


Figure 6.3.4 Comparison of predicted flood quantiles with at-site FFA estimates (ARI = 20 years) (CL refers to at-site FFA confidence limits, where LL refers to lower 95% CL and UL refers to upper 95% CL)

Concluding remark:

A set of regional flood prediction equations are developed for Tasmania based on GLS regression. The developed prediction equations satisfy the underlying model assumptions very well. These equations contain only two predictor variables, which are easy to obtain. The developed models on average predict quantiles with an accuracy of prediction equivalent to an average record length of 71 years.

6.4. Queensland

Palmen and Weeks (2009) developed a QRT-OLS method for Queensland as summarized below. This study used a LP3 distribution for at-site flood frequency analysis. The quantiles were calculated for each station for the range of ARI up to 100 years.

The QRT-OLS regression was adopted to develop the prediction equations. The analysis shows that catchment area is the most significant variable, with the rainfall intensity for the 72 hour duration, 50 year ARI being the second most significant. After these two variables are included, no other variables are consistently significant throughout the range of ARIs.

The developed prediction equations are given by Equation 6.4.1.

$$
\begin{aligned}
\log(Q_2) &= -0.909 + 0.752\log(area) + 1.587\log(i_{50,72}) \\
\log(Q_5) &= -0.168 + 0.707\log(area) + 1.293\log(i_{50,72}) \\
\log(Q_{10}) &= 0.159 + 0.688\log(area) + 1.164\log(i_{50,72}) \\
\log(Q_{20}) &= 0.412 + 0.674\log(area) + 1.064\log(i_{50,72}) \\
\log(Q_{50}) &= 0.681 + 0.657\log(area) + 0.957\log(i_{50,72}) \\
\log(Q_{100}) &= 0.855 + 0.645\log(area) + 0.888\log(i_{50,72}) \qquad (6.4.1)
\end{aligned}
$$

The prediction equations were then used to calculate the estimated design discharges for each station. The estimates were then compared to the at-site FFA results. Three methods were used to evaluate the accuracy of the prediction equations:

- The adjusted R^2 value.
- The root mean squared error (RMSE).
- The percentage of stations that have estimated values within ± 20% of the at-site FFA values.

The results of the validation of the prediction equations are summarised in Table 6.4.1.

Table 6.4.1 Validation results for Queensland (based on all the catchments)

ARI (years)	Adjusted R^2	RMSE	Catchments within ± 20% of at-site FFA results (%)
2	0.577	± 76%	26%
5	0.630	± 54%	29%
10	0.638	± 49%	33%
20	0.627	± 50%	35%
50	0.584	± 50%	32%
100	0.537	± 53%	34%

For an independent testing, 15 test catchments were randomly selected. These catchments are located throughout the state, so the group represents a range of different conditions. Each independent test catchment was individually removed from the model and tested, with the process repeated for all the 15 test catchments. In addition to testing the performance of the QRT-OLS procedure, the test was also carried out to compare the performance with the Main Roads Rational Method (MRRM) (I.E. Aust., 1987; 2001). The results of the independent testing are summarised in Table 6.4.2.

This test indicates that the QRT-OLS method outperforms the Main Roads Rational Method for 11 out of the 15 test catchments. There are four of the fifteen test catchments where the Rational Method is found to be superior to the QRT-OLS method, but only one (Station 137003A) where there is a significant benefit. However on this catchment, neither method performs well.

Concluding remark:

A set of regional flood estimation equations were developed for Queensland based on QRT-OLS method. The equations contain only two predictor variables, which are easy to obtain. Independent testing shows that the developed prediction equations generally outperform the Queensland Main Roads Rational Method. For Queensland data set, the QRT-GLS method will be applied in Stage II of Project 5.

Table 6.4.2 Model evaluation using independent test catchments

Independent Test Station	Standard Error of Prediction		Superior Model	
	MRRM	QRT	MRRM	QRT
104001A	15%	17%	✓	
108002A	48%	9%		✓
111007A	55%	36%		✓
113007A	72%	42%		✓
118003A	41%	16%		✓
120308A	63%	66%	✓	
129001A	41%	38%		✓
130207A	28%	30%	✓	
133003A	35%	6%		✓
137003A	185%	348%	✓	
138120A	47%	19%		✓
143033A	180%	102%		✓
422302A	147%	98%		✓
912113A	34%	21%		✓
915006A	63%	32%		✓

6.5. South Australia

The RFFA study for South Australia is still in progress. At this stage, at-site flood frequency analysis has been completed for the selected 30 stations using GEV-LH moments method. The catchment characteristics data set is being prepared and initial RFFA study is expected to commence in Aug 2009.

6.6. Probabilistic Model: Application to NSW and Victorian Data

To test the validity of the Probabilistic Model, the data set from Victoria and NSW is combined to give 227 stations (as shown in Figure 6.6.1). The catchment area ranges from 3 to 1010 km^2 with a median value of 289 km^2. The streamflow record lengths (n_i) are in the range of 25 to 74 years, with a mean value of 33 years and 75th percentile of 37 years. From the 227 catchments, 18 were selected at random and put aside for independent testing of the developed model. The remaining 209 catchments were used to develop the Probabilistic Model and the prediction equations for the parameters of the model using the GLS regression.

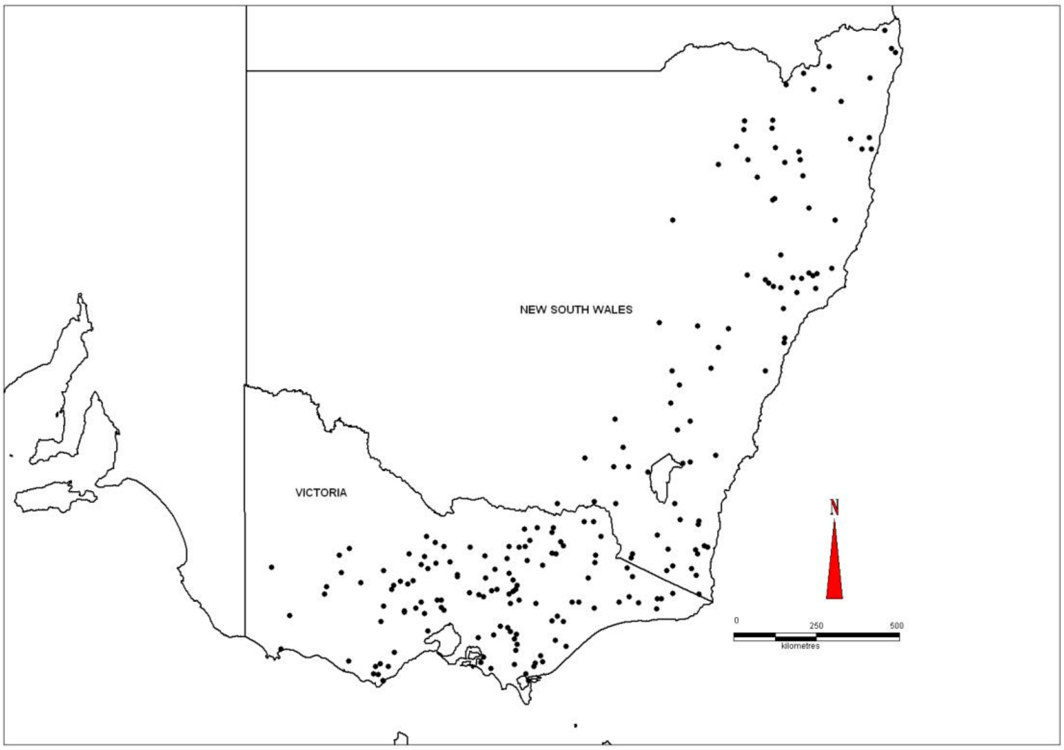


Figure 6.6.1 Locations of the 227 catchments used to develop Probabilistic Model

Development of Probabilistic Model:

The Probabilistic Model, presented here, considers only the maximum observed flood (Q_{max}) at each station in the region. The selected $Q_{\max}$ values are initially standardised with respect to the at–site average of the annual maximum flood series (μ) and are then plotted in the (CV, $Q_{\max}/\mu$) plane. In the following graphs $Q_{\max}$ is replaced by Q for simplicity. Figure 6.6.2 shows such a plot for the study data set consisting of 209 data points from 209 sites, which suggests the following relationship:

Error! Objects cannot be created from editing field codes. (6.6.1)

Here the exponent λ is considerably greater than 1 (as would be the case for an EV1 distribution). For the given data set, the parameters of Equation 6.6.1 were estimated to be α = 3.21 and λ = 1.42 by the maximum likelihood approach, the R^2 for the model was 81% indicating a reasonably good fit.

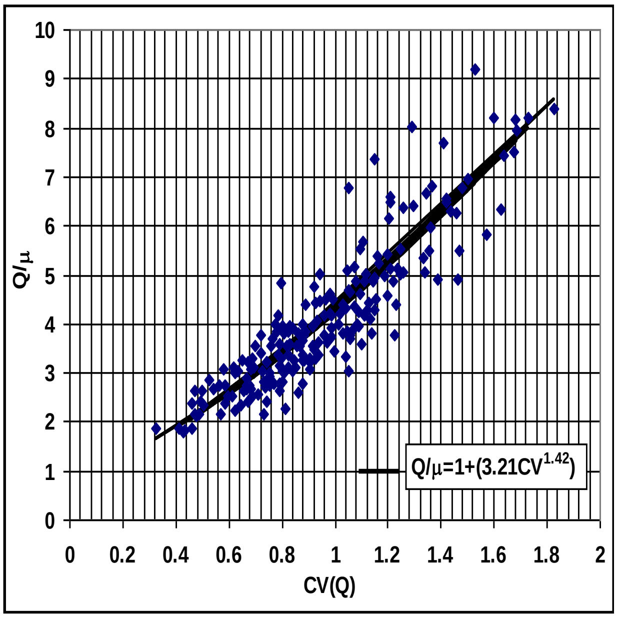


Figure 6.6.2 Scatter of Q_{max}/μ data in the ($CV(Q)$, Q/μ) plane and non linear interpolating function.

A large part of the observed scatter in Figure 6.6.2 is due to the fact that the standardised maxima from individual sites correspond to different ARIs. Based on Figure 6.6.2, the best way to model this scatter is to search for a Probabilistic Model in the form of

Error! Objects cannot be created from editing field codes. (6.6.2)

where it is assumed that *f(ARI)* is a function of the average recurrence interval (ARI) only. From Equation 6.6.2, a standardised variable can be defined by:

Error! Objects cannot be created from editing field codes. (6.6.3)

where *s* represents the at-site standard deviation of annual maximum flows.

This form of standardisation takes account not only of differences in the mean values but also of the coefficient of variation, raised to the power appropriate for the specific regional data set.

The following plotting position formula was applied, as used by Majone & Tomirotti

(2004), to estimate the ARIs of the N = 209 values of Y in the pooled data set:

$$\text{ARI} = \frac{1}{1-\left(1-\frac{m}{N}\right)^{\frac{1}{n}}} \qquad (6.6.4)$$

where m is the rank of the observation, n is the average site sample size and N the number of sites (assumed to be independent in terms of maximum observed floods). The plot of Y vs. ARI is shown Figure 6.6.3, which reveals that the experimental data can be interpolated by a curve whose central part can be approximated by a linear function of ARI:

Error! Objects cannot be created from editing field codes. (6.6.5)

which in terms of Q/μ becomes:

Error! Objects cannot be created from editing field codes. (6.6.6)

Equations 6.6.3 & 6.6.6 yield the analytical expression of the Probabilistic Model for the study data set.

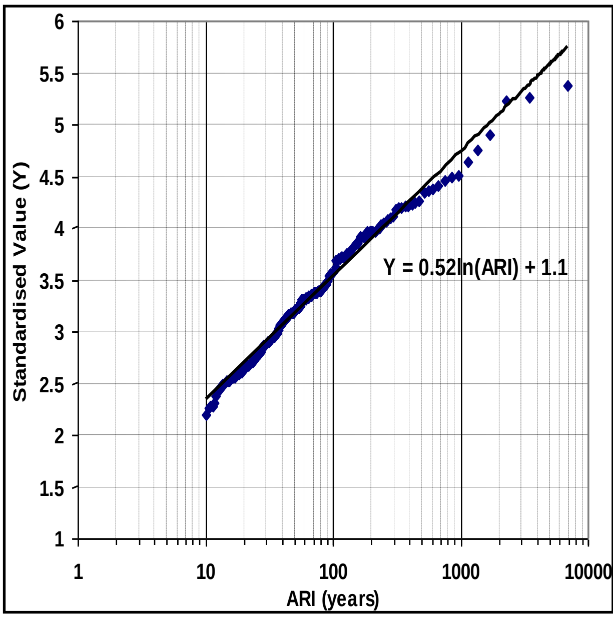


Figure 6.6.3 Frequency distribution of the standardised values (*Y*) and linear interpolating function

It can be seen from Figure 6.6.3 that the range of *Y* values for which the fitted model might be considered reliable is from about 2.5 to 4.2. Therefore, in the case of south-east Australia, given the existing data set, the Probabilistic Model can be applied for ARIs in the range of 20 to 400 years. Figure 6.6.4 shows the behaviour of the dimensionless quantiles derived from Equation 6.6.6 for ARIs 10, 20, 100 and 400 years. Figure 6.6.4 shows that the Probabilistic Model can provide reasonably good estimations for these ARIs, as the set of curves capture most of the points in the pooled data set.

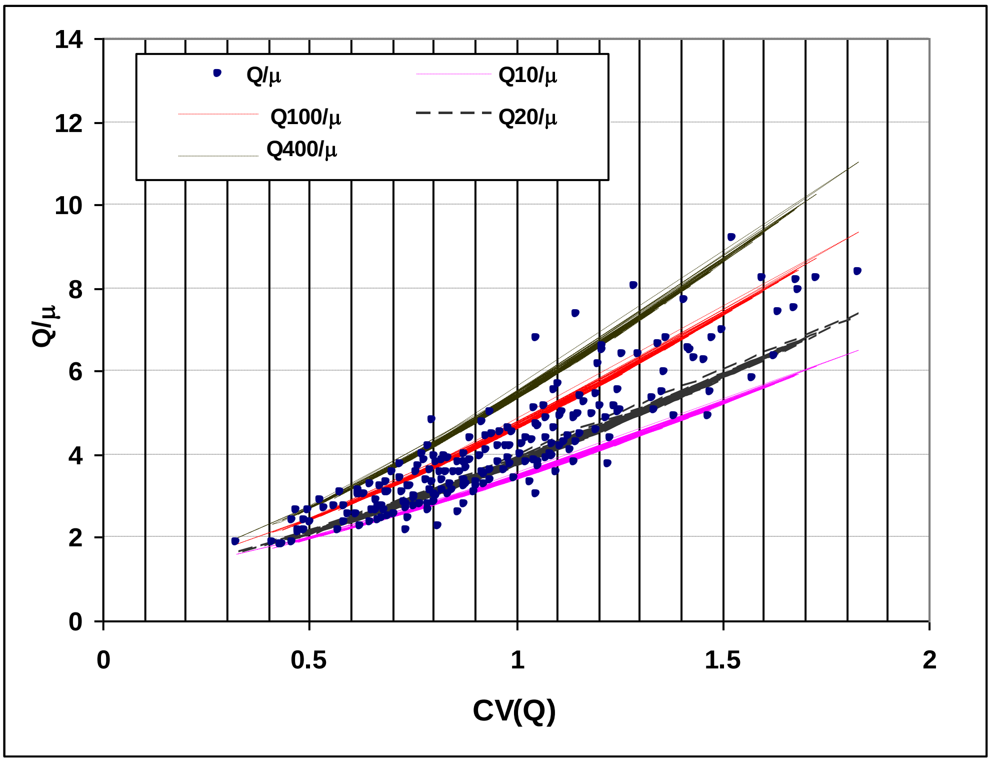


Figure 6.6.4 Various Q/μ quantiles derived from the Probabilistic Model

Table 6.6.1 lists the CV values for the Victorian and NSW stations along with catchment areas and Y_{max} values. Figure 6.6.5 shows how the Probabilistic Model fits the at-site data for a range of CV values. As can be seen from Figure 6.6.5, with reference to different ranges of CV values considered in this analysis, the Probabilistic Model can provide quite accurate growth curve estimation. Further assessment of the Probabilistic Model reveals quite good results for the ARI range of 10 to 400 years and for CV values in the ranges 0.30 - 0.74, 0.75 - 0.90 and 0.91 -

1.10. The Probabilistic Model performs best in the CV range of 0.75 - 1.10 (approximately 50% of the study catchments fall in this range), however for CV values ranging from 1.11 to 2.00, the Probabilistic Model performs quite poorly for ARIs of 10 to 50 years, while still providing relatively stable estimates for ARIs of 100 to 400 years.

Table 6.6.1 CV values for study catchments from Victoria and NSW

State	Number of stations	Average record length (years)	CV_{min}	CV_{av}	CV_{max}	A_{min} (km^2)	A_{av} (km^2)	A_{max} (km^2)	Y_{max}
VIC	121	33	0.32	0.86	1.69	3	320	997	5.26
NSW	88	34	0.58	1.08	1.83	8	352	1010	5.37

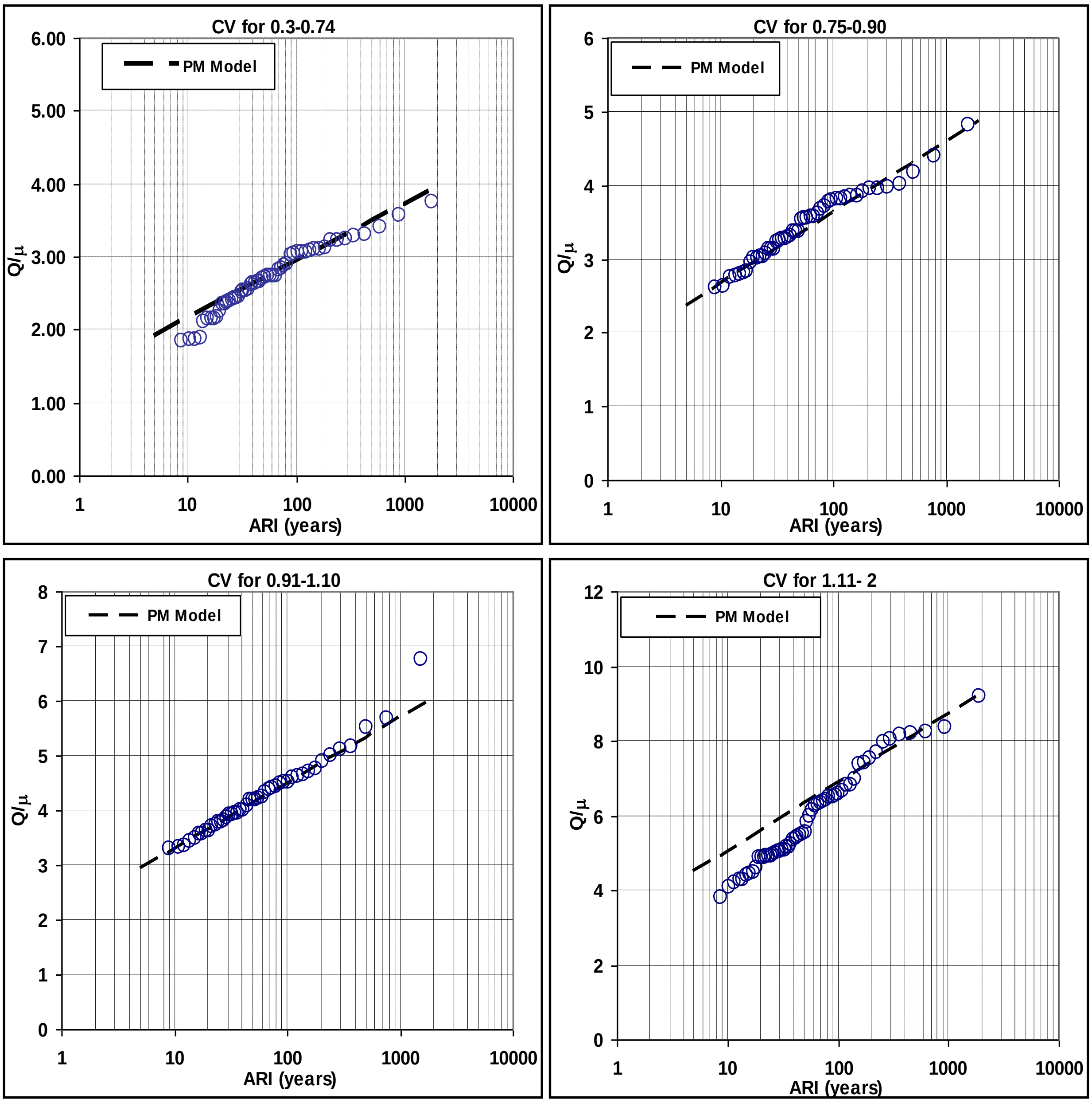


Figure 6.6.5 Empirical frequency distributions of Q/μ quantiles for different values of CV and Q/μ derived from the Probabilistic Model

Application of the Probabilistic Model for ungauged catchments:

To apply Equation 6.6.6 to ungauged catchments, one requires the estimation of $\mu(Q)$ and $CV(Q)$ for the ungauged catchment in question. The GLS regression is used to develop the prediction equations for $\mu(Q)$ and $CV(Q)$ as a function of catchment characteristics. Figure 6.6.6 shows a poor relationship between *CV(Q)* and catchment area. However, in the GLS regression, other catchment characteristics are found to be useful in predicting *CV(Q)*. Table 6.6.2 shows the GLS regression equations for $\mu(Q)$ and *CV(Q)* along with some summary statistics. These equations show a plausible set of explanatory variables and reasonable R^2 values.

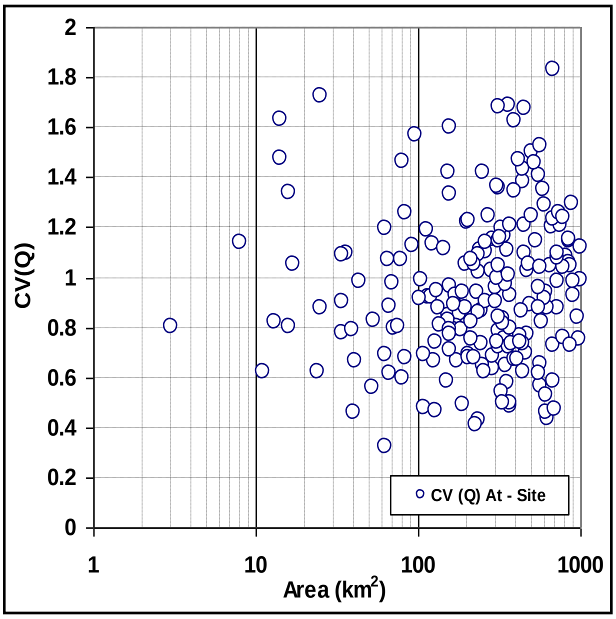


Figure 6.6.6 Relationship between *CV(Q)* and catchment area

Table 6.6.2 Summary of model for $\mu(Q)$ and CV(*Q*) (*Sep* is standard error of prediction)

Equation	Model statistics
$\mu((Q))$ = 10^[- 2.99 + 1.13log(*area*) + 2.00log($^{50}I_{12}$) + 0.35log*(sden)*]	R^2 = 74%, Sep% = 31%
CV(Q) = 1.07 + 0.63log($^{2}I_{12}$)-1.26log*(rain)*+1.05log*(evap)*	R^2 = 64%, Sep% = 26%

Split-sample validation:

The developed prediction equations in Table 6.6.2 and Equation 6.6.6 are applied to the 18 test catchments, which were not used in developing Equation 6.6.6 and the equations in Table 6.6.2. The validation analysis is undertaken for ARIs up to 200 years only, this is because at site flood frequency estimates for larger ARIs are subject to extreme extrapolation errors and any validation results obtained is of little significance. Validation for larger ARIs should be checked against results from rainfall-runoff modelling. To assess how well the developed prediction equations approximate the observed flood quantiles, a number of statistical measures are applied, as described below.

Firstly, the standard error (SE) of estimated values is estimated by Equation 6.6.7 for both the estimation and validation set:

$$SE = \sqrt{\frac{1}{N-1}\sum_{k=1}^{N}(PM - FFA)^2} \tag{6.6.7}$$

where *n* is the number of stations used in the analysis and *FFA is* the at-site flood frequency estimate (based on LP3-Baysian procedure) and *PM* is the estimate from the Probabilistic Model.

Bias is used to measure over-estimation and under-estimation of the observed quantile, as defined below.

Error! Objects cannot be created from editing field codes. (6.6.8)

A positive bias would imply that the PM gives overestimation with respect to the at-site FFA estimate.

The root mean square error (RMSE) is calculated as shown by Equation 6.6.9:

Error! Objects cannot be created from editing field codes. (6.6.9)

Table 6.6.3 summarises various error statistics for ARIs of 10 to 200 years with the Probabilistic Model. This shows that the standard error of prediction with the method for the validation data set is 25 to 30%, which is quite reasonable for this type of regional flood estimation method. For ARIs of 50 to 200 years, the Probabilistic Model gives slight underestimation. The root mean square error (RMSE) values in Table 6.6.3 show good results with the 20 years ARI showing the lowest RMSE. The predicted flood quantiles are plotted against the at-site flood frequency estimates for ARIs of 10 to 200 years (Figure 6.6.7 shows the plot for 100 years ARI), which generally show a good match. For 100 years ARI, the results can be regarded as 'very good' for 14 out of the 18 test catchments and 'reasonably good' for the remaining 4 test catchments. It is found that the Probabilistic Model overestimates both the 2 and 5 years ARI flood quantiles (with median relative error values in the range of 73% to 258%), which is as expected, as these ARIs are outside the proposed range of application of the Probabilistic Model considered here.

Table 6.6.3 Summary of error statistics with Probabilistic Model (Here 'est' means estimation data set, 'val' means validation data set, SE is standard error, MRE is median relative error as compared to at-site FFA estimate, RMSE is the root mean square error)

ARI (years)	Probabilistic Model	SE m^3/s 'est'	SE m^3/s 'val'	Ave Bias - m^3/s	MRE – FFA (%) 'val'	RMSE – m^3/s 'val'
10	$Q/\mu = 1 + (1.1 + 0.52\ln(10))CV^{1.42}$	387	325	41	29%	35
20	$Q/\mu = 1 + (1.1 + 0.52\ln(20))CV^{1.42}$	429	392	20	10%	47
50	$Q/\mu = 1 + (1.1 + 0.52\ln(50))CV^{1.42}$	486	425	-1.5	21%	60
100	$Q/\mu = 1 + (1.1 + 0.52\ln(100))CV^{1.42}$	529	481	-2.1	30%	72
200	$Q/\mu = 1 + (1.1 + 0.52\ln(200))CV^{1.42}$	571	540	-3.3	35%	86

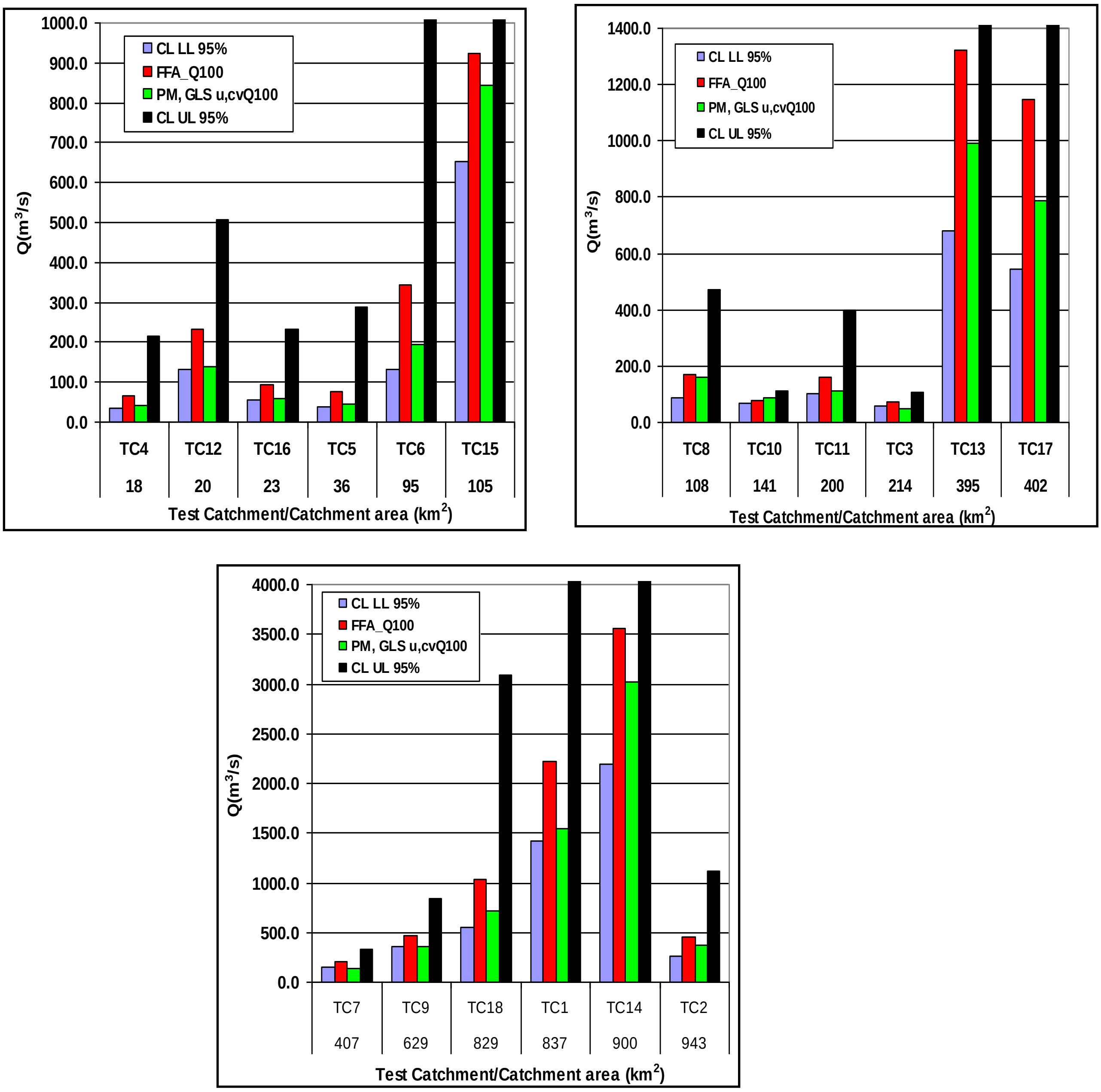


Figure 6.6.7 Comparison of predicted flood quantiles with at-site FFA estimates (ARI = 100 years) (CL refers to at-site FFA confidence limits, where LL refers to lower 95% CL and UL refers to upper 95% CL)

Concluding remark:

The following concluding remarks can be made from the application of the Probabilistic Model to the combined data set of Victoria and NSW:

- The Probabilistic Model coupled with GLS regression offers a powerful method of regional flood estimation for medium to high ARIs. The application of the method to a data set of 209 catchments in south-east Australia shows that this can provide quite accurate flood estimation with standard error of prediction of about 29% for the validation data set over the ARIs considered.

- The proposed regionalisation method offers an alternative to more commonly used regional flood estimation methods such as the Index Flood Method, the Quantile Regression Technique and the Probabilistic Rational Method. Its distinguishing feature is that, when pooling data from different sites in a region, it takes account of the often large differences in the coefficient of variation of annual floods at different sites. This allows pooling of data from larger regions.
- Further work is proposed to examine the following potential improvements of the method in terms of its range of application and its accuracy of prediction:
    - Apply the method to a larger data set comprising flood data from all Australian states.
    - Extend the range of application to lower ARIs by using say 3 to 5 largest annual floods at each site rather than only the largest one.
    - Reduce potential bias introduced by inter-site dependence of observed maximum floods by applying the concept of the ‘effective number of independent sites’ rather than the total number of sites used in the station-year approach.

6.7. Application of region of influence approach

Hackelbush et al. (2009) examine the region of influence (ROI) approach using data of 55 catchments located in eastern NSW in conjunction with a Bayesian generalised least squares (GLS) regional flood frequency regression. The approach is based on the Bayesian GLS approach of Micevski and Kuczera (2009). Here the GLS procedure regionalises the mean, standard deviation and skewness of the LP3 distribution with simultaneous consideration of model and sampling error. The ROI approach starts with the 15 nearest sites to the site of interest. The regional model is calibrated to this site data and the model error variance is noted. Then the ROI is expanded to include the 20 nearest sites. This process is repeated until the region producing the smallest model error variance is identified.

One-at-a-time cross-validation is used to validate the regional models. The method of cross-validation leaves the site of interest out and develops regional equations for the mean μ, standard deviation σ, and skewness γ using the remaining sites. This is repeated for all stations considered in this study. This ensures the validation is always an independent test of the model performance. In the ROI regional model, the site of interest is always excluded.

The mean, standard deviation and skewness equations for each site are based on the ROI with the lowest model error variance. Figure 6.7.1 summarises the number of sites selected in the ROI for each site and each LP3 parameter. For the GLS regression model for the mean, the ROIs typically have fewer sites than the ROIs for the standard deviation and skewness. On average, ROIs for the mean have 22 sites, 30 sites for ROIs for the standard deviation, and 40 sites for ROIs for the skewness. This suggests that the LP3 mean experiences the greatest heterogeneity of the LP3 parameters. It highlights the inherent weakness of a fixed region regionalisation, which, if made too big, will have a model error inflated by the heterogeneity unaccounted for by the catchment characteristics.

Figure 6.7.2 presents Q-Q plots for the ROI validation of the LP3 mean, standard deviation and skewness. The Q-Q plot plots the standardized residuals against the standardized normal variate with the same exceedance probability. If the plot follows a straight line, then the standardized residuals behave as if they were sampled from a normal distribution. Of particular significance is that for all LP3 parameters there are no genuine outliers in the Q-Q plots. This suggests the regional equations can be used with considerable confidence with the knowledge that heterogeneity has been adequately accounted for with the consequence that there should be no gross errors.

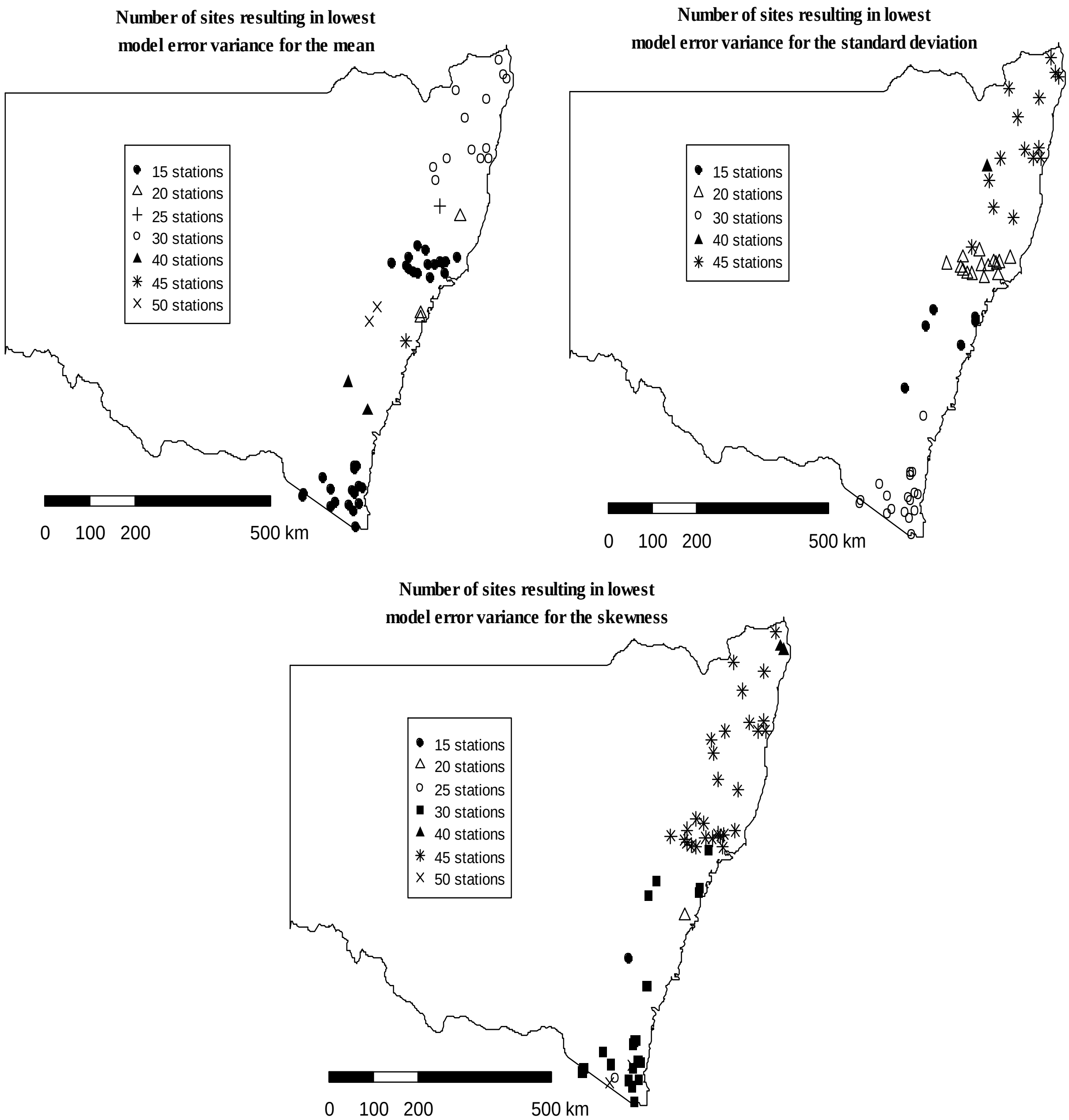


Figure 6.7.1 Number of site for the GLS regression model for the mean, standard deviation and skewness which resulted in a ROI for the site of interest with lowest model error variance

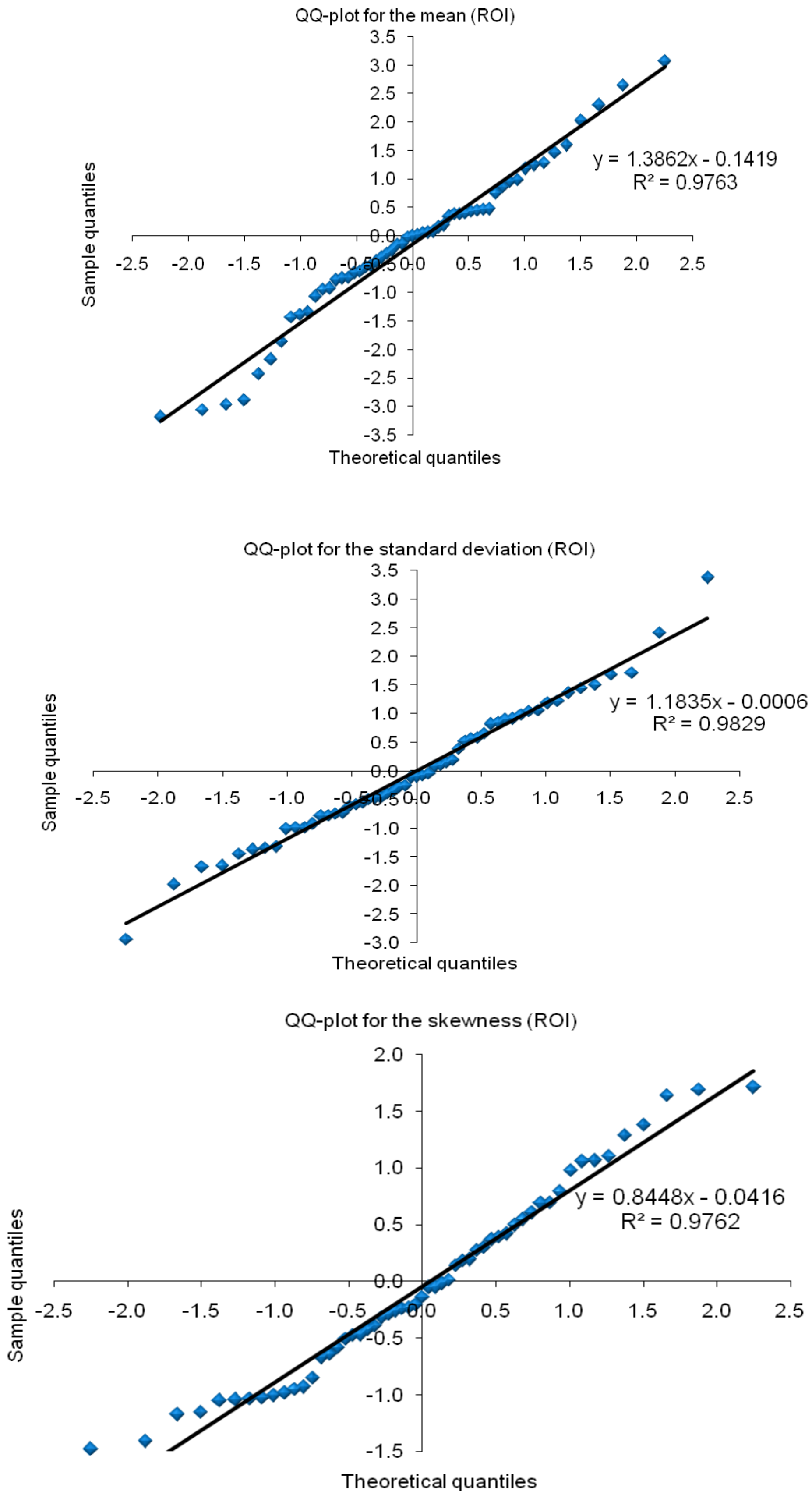


Figure 6.7.2 Q-Q plots for the mean, standard deviation and skewness of the standardized residuals

The regional equations for the LP3 parameters represent an intermediate goal. The ultimate objective is to infer quantiles at an ungauged site. Figure 6.7.3 presents Q-Q plots for Z scores and the standardized normal distribution for 10 and 100 years ARI quantiles. The black diamonds represent quantiles estimated by ROI GLS regression, while the red diamonds represent quantiles estimated by fixed region GLS regression.

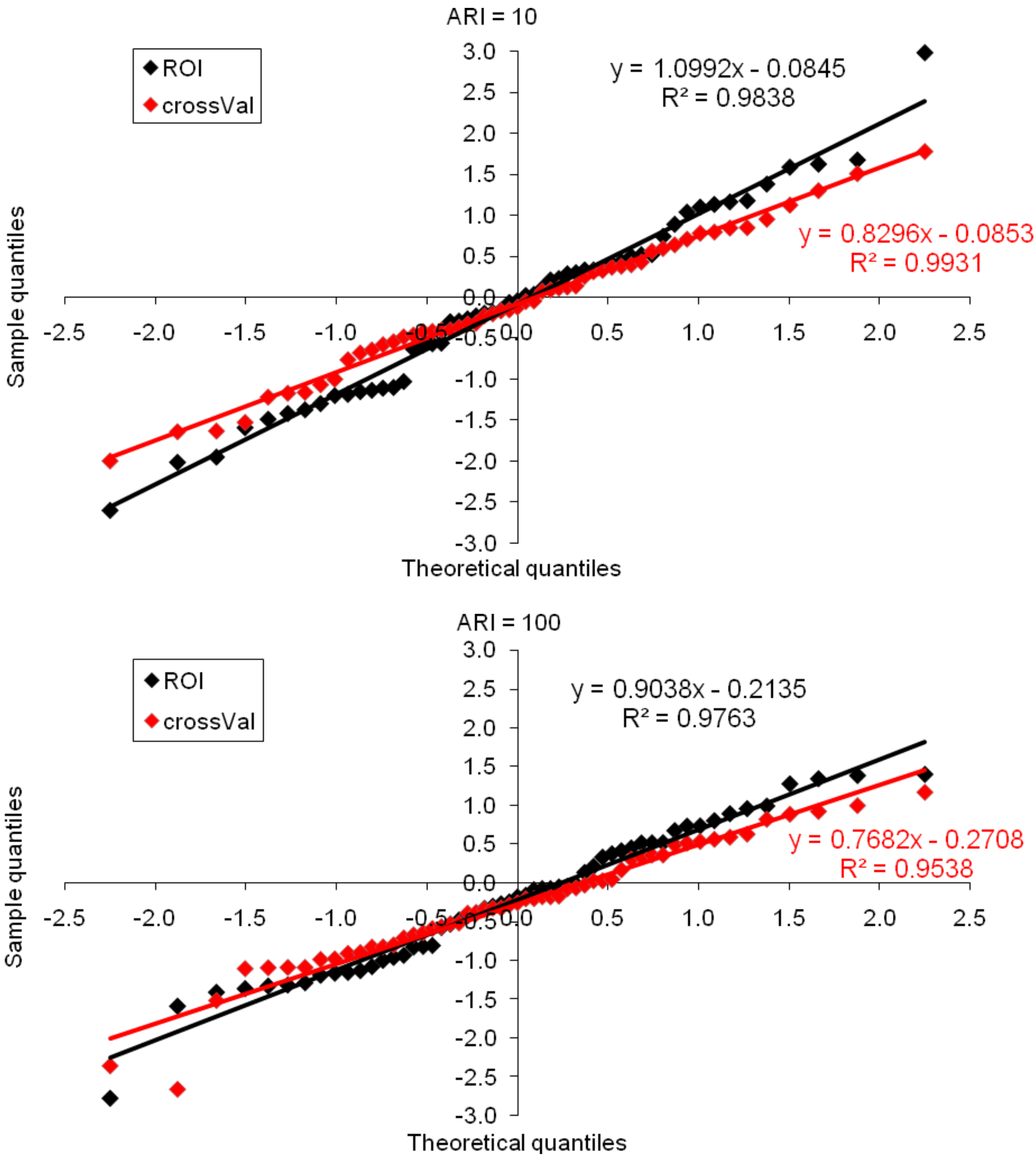


Figure 6.7.3 Q-Q plots of Z scores for 10 and 100 years quantiles (black diamonds represent ROI GLS, while red diamonds fixed region GLS)

The Q-Q plots show that the assumption of normality for the Z scores is well satisfied with all but one point closely following a straight line. If the Z scores were indeed normally and independently distributed with mean 0 and variance 1, then the slope of the Q-Q plot, which can be interpreted as the standard deviation of the sample, should approach 1 and the intercept, which is the mean of the sample, should approach 0 as the number of sites increases. For 55 sites, a χ^2 test shows that there is a 2.5% chance that the sample standard deviation of the Z scores will exceed 1.177 and a 2.5% chance that it will be less than 0.804. For the 100 years ARI quantiles the fixed region GLS appears inconsistent with the assumptions made in the regional analysis at the 5% significance level. Likewise, for 55 sites, there is a 2.5% chance that the sample mean of the Z scores will exceed 0.264 and a 2.5% chance that it will be less than -0.264. Again for 100 years quantile the fixed region GLS results were found to be inconsistent with the hypotheses made in the regional model at the 5% significance level.

These results indicate that the fixed region GLS model overestimates the uncertainty in the 100 years quantiles. This is most likely because site heterogeneity was not accounted for adequately by the fixed region regression model resulting in an inflated model error variance. It was noted that in case of the LP3 mean, the ROI only used 22 sites, on average, to identify the model with minimum error variance. This is an important finding as it strengthens the case for a ROI approach in preference to a method based on a fixed region.

In Figure 6.7.4, flood quantiles for ARIs of 10 and 100 years are compared for four sites. For each ARI, 5, 50 and 95% posterior percentiles of the quantile are presented for the site data (labelled as FLIKE), fixed region GLS (labelled as crossVal) and ROI GLS (labelled as ROI). Site 203030 had the largest absolute Z-score and illustrates the worst case in the cross validation. As expected flood quantiles using site data have the lowest uncertainty (i.e. the width of the 90% probability limits is the smallest). Estimates for the posterior median for all sites, except site 203030, are of the same magnitude. However, if the fixed region and ROI GLS are compared, ROI predicts flood quantiles with lower uncertainty than does fixed region GLS for all four sites considered here.

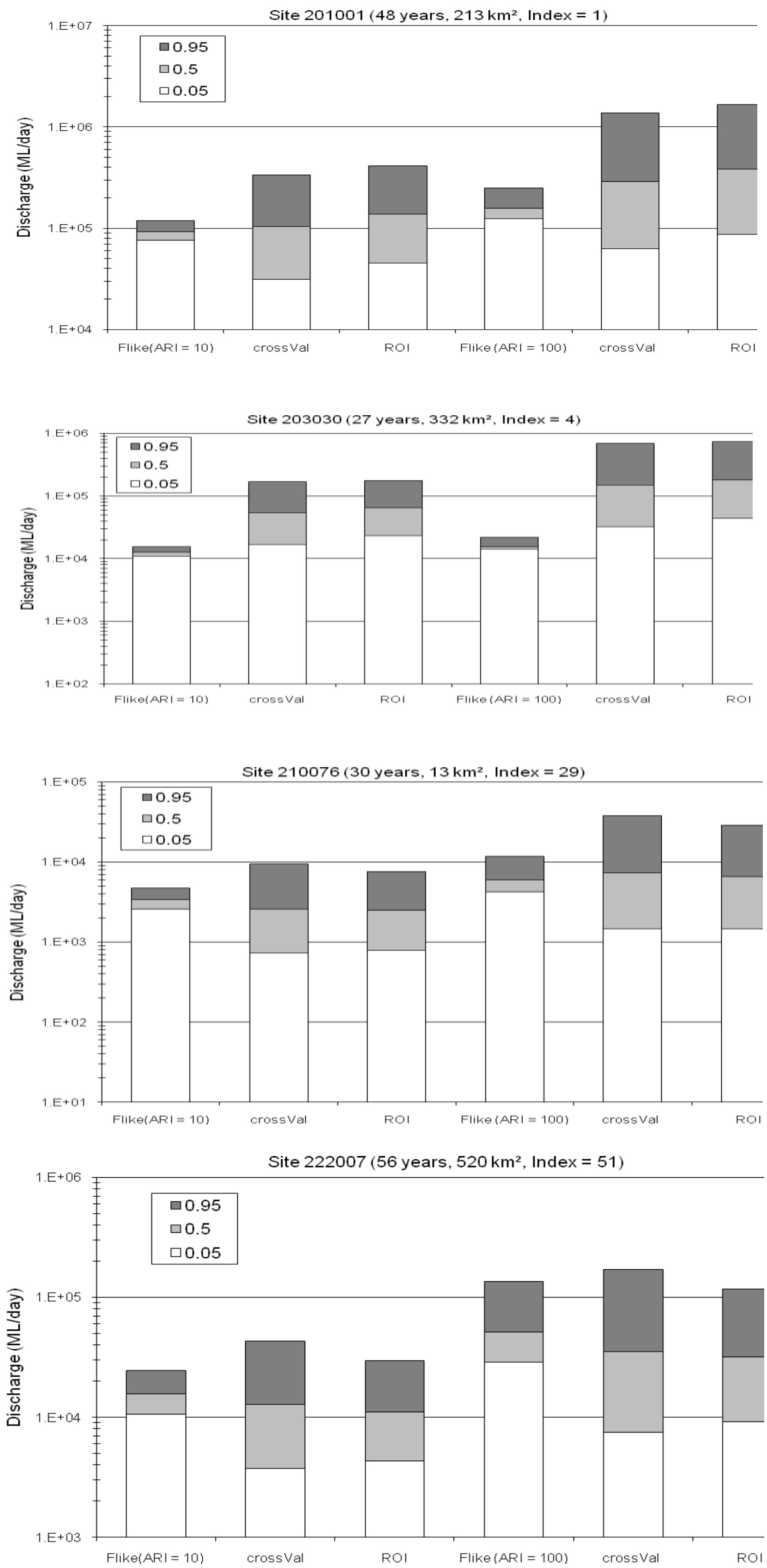


Figure 6.7.4 Posterior distribution of 10 and 100 years flood quantiles for four sites - 5, 50 and 95% posterior percentiles of the quantile are presented for the site data (labelled as FLIKE), fixed region GLS (labelled as crossVal) and ROI GLS (labelled as ROI)

Concluding remark:

A Bayesian GLS regression was used to regionalise the first three moments of the LP3 distribution for 55 sites located in eastern New South Wales with the aim of providing flood quantile estimates at ungauged catchments.

Estimation of the regional mean was performed using a regression equation consisting of two explanatory variables, the catchment area and the 12-hour, 50-year rainfall intensity. The regression equations for the standard deviation and skewness only had a constant term.

The ROI experiment for the mean resulted in ROIs which averaged 22 sites, for the standard deviation 30 sites, and for the skewness 40. This suggested that the greatest regional heterogeneity is in the mean of the LP3 parameters. The Q-Q plots of the standardized residuals showed that the residuals behaved normally with no evidence of gross outliers.

Finally, flood quantiles for average recurrence intervals for 10 and 100 years were studied. Q-Q plots showed that Z-scores closely follow a straight line indicating that the assumption of normality is met. Slopes and intercepts were consistent with the assumptions made in the regional model. One is drawn to the conclusion that the ROI approach using minimum model error variance as the criterion to select a region is preferred to an approach based on a fixed region. The ROI approach has the intrinsic advantage of avoiding boundary inconsistency which plagues methods based on fixed regions.

A detailed comparison of predictive uncertainty was conducted for four sites, one of which had the worst Z-score. It showed, as expected, that the use of at-site data produced the most accurate quantiles. The worst-case site highlights the fact that the 90% prediction limits of the regional quantile estimates may not overlap with the at-site 90% prediction limits. That said, such variability is to be expected and the mismatch is not gross. The ROI prediction limits were consistently more compact than those of the fixed region model. Overall the ROI GLS model exhibits superior performance to the fixed region GLS model primarily because it better deals with heterogeneity that explanatory variables cannot capture.

7. Exploratory Analysis on Climate Change Issues

Climate change is the change in the state of the climate that can be identified by changes in the mean, and that persists for an extended period, typically decades or longer. For instance, Australian average surface temperature has increased over the past 98 years as shown in Figure 7.1. The last two decades have been particularly warm, with the warmest year on record occurring during 2005. This annual average temperature increase is consistent with the global average warming trend reported by the Intergovernmental Panel on Climate Change (IPCC, 2001). According to the fourth IPCC assessment report (IPCC, 2007), the observed increase in global average temperature since the mid-20th century is likely to be due to human emissions of greenhouse gases. Moreover, the climate is expected to continue to warm up over the 21st century due to the historical and projected future emissions, potentially affecting all aspects of the hydrological cycle (IPCC, 2007). The implications for flood hydrology are expected to be significant, with projections of increased rainfall intensities and mean temperature specifically.

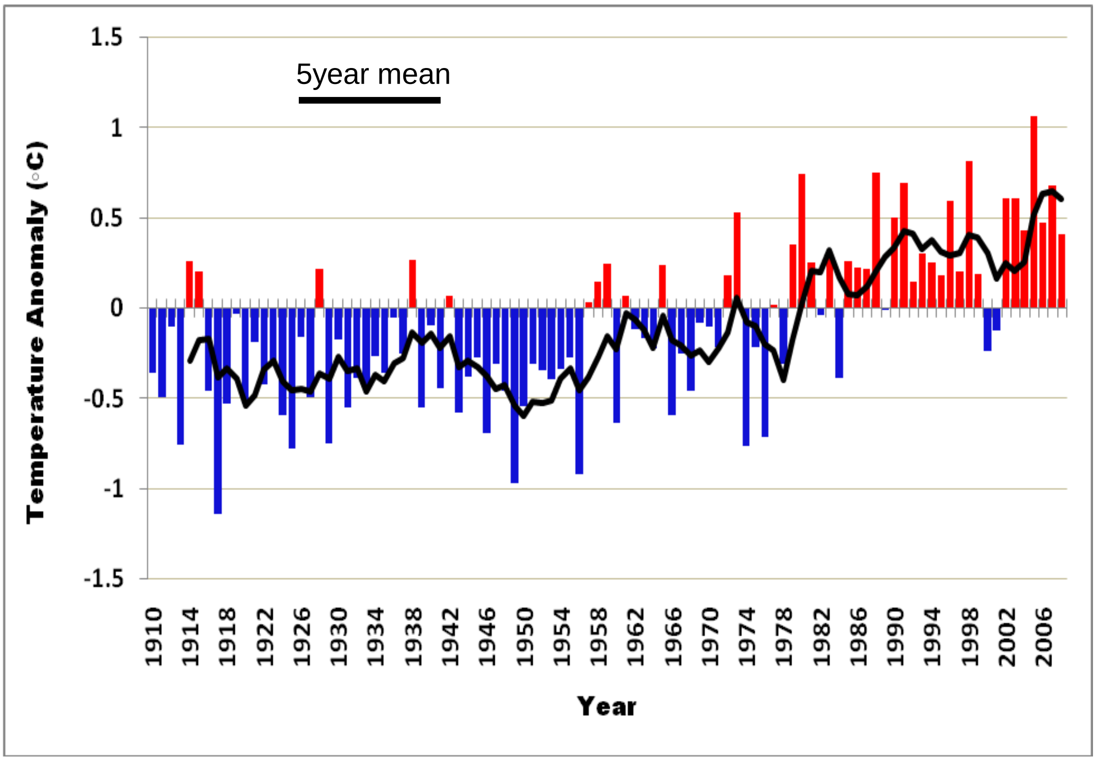


Figure 7.1 Annual mean temperature anomalies for Australia based on 1961-2008.
Source: Australian Bureau of Meteorology

For instance, investigations of future climate projections point out that the intensity of the 20 years ARI daily rainfall event is likely to increase by up to 10% in parts of South Australia by the year 2030 (McInnes et al., 2002), 5 to 70% by the year 2050 in Victoria (Whetton et al., 2002), 5 to 15% by 2070 in NSW (Hennessy et al., 2004), up to 25% in Northern Queensland by 2050 (Walsh et al., 2002). Where, future temperature projections reveal a rise by about 1C over Australia by 2030, and between 1C to 2.5C under low emissions, or between 2.5C to 5C under high emissions by 2070 (CSIRO, 2007). Most of these studies used the Atmosphere-ocean Global Climate Models (GCMs), to simulate future time series of climate variables for the area of interest, accounting for the effects of the concentration of greenhouse gases in the atmosphere (IPCC, 2007).

Despite the confidence associated with large scale global climate projections, there remains significant uncertainty associated with small-scale regional responses of short duration extreme events due to the uncertainty of future greenhouse gases emissions and their effect on future climate (Westra et al., 2008). GCMs outputs are generally not considered of sufficient resolution to be applied directly in hydrological impact studies, and there is a need to derive scenarios with more appropriate scale. This led to the development of downscaling, with techniques varying from simple algorithms to sophisticated physically based methods (Ashbolt and Maheepala, 2008). Prudhomme et al. (2003) investigated the uncertainty and climate change impact on the flood regime by randomly generating 25,000 climate scenarios using several GCMs, SRES-98 emission scenarios (IPCC, 2001) and climate sensitivities. They found that the largest uncertainty can be attributed to the GCM used, with the magnitude of changes varying by up to a factor of 9 in the study area.

Furthermore, recent studies have shown evidence of the existence of inter-annual to inter-decadal natural climate variability that impact on long-term flood risk by markedly changing patterns of atmospheric moisture transport in the flood season, hence changing the probabilities of flood in a given year at a particular location (Jain and Lall, 2001). For instance, Kiem et al. (2003) and Kiem and Franks (2004) assessed the role of ENSO processes and their multidecadal modulation, in indicating flood/drought risk across NSW. They found that La Niña events dominated the long term flood risk, and the multidecadal modulation of ENSO processes resulted in extended periods of enhanced/reduced flood risk across NSW. Franks and Kuczera (2002) split the NSW flood data time series into pre- and post-1945 samples and the outcomes of their study revealed that the post-1945 20-year flood estimate exceeds the pre-1945 20-year flood estimate for most of the analysed sites.

Micevski et al. (2006) demonstrated that floods in NSW which occurred in the negative phase of the IPO had peak discharges 1.8 and 1.7 times greater than floods of the same frequency which occurred during IPO positive phase respectively. Moreover, Verdon et al. (2004) found that rainfall and streamflow considerably enhanced during the La Niña phase of ENSO, after they examined the influence of ENSO and IPO on these parameters in eastern Australia using seasonal totals. On multidecadal scales, the negative IPO phase was more associated with “wetter” conditions than the positive phase. Importantly, the magnitude of La Niña events was found to be further enhanced during the negative phase of the IPO.

Only few studies in the hydrological literature have dealt with the two basic assumptions (non-stationarity & non-homogeneity) in regional flood frequency analysis. Most of these investigations used the regional index flood method with the assumption of non-stationarity in the first two moments of the time series (Cunderlik and Burn, 2003; Cunderlik and Ouarda, 2006; Leclerc and Ouarda, 2007). While others investigated the non-homogeneity in the time series due to interdecadal climate variability such as Micevski et al. (2006a).

In summary, climate change and long-term natural variability have challenged the traditional assumptions of stationarity and homogeneity of flood peaks adopted in the current flood estimation techniques. All earlier studies acknowledge the vital considerations of non-stationarity and climate change in any flood risk assessment, as ignoring them can lead to significant biased estimates of flood risk. The ongoing global climate change debate and identification of inter-annual and decadal ocean-atmosphere oscillations (e.g., ENSO and IPO), and their teleconnections to continental hydroclimate, have led to increased awareness of this issue.

Trends in flood data:

Review of hydrological records conducted in different parts of the world provided evidence of regime-like or quasi-periodic climate behaviour and of systematic trends in key climate variables due to climate variability (Gallant et al., 2007; Fu et al., 2008). Zhang et al. (2001) have investigated trends in Canadian streamflow for the past 30 to 50 years; they found that overall Canadian streamflows experienced negative trends. Moreover, significant upward trends were observed in several gauge records by Jeong et al. (2008) after they have investigated trends in the peak flood data for the major Korean river basins. Zhang et al. (2007) have reported that the eastern part of Yangtze River basin in China is dominated by decreasing extreme precipitation trends, and the western part at the upper Yangtze River basin, and middle and lower Yangtze River basin are dominated by increasing extreme precipitation trend. However, caution is advised in interpreting these results as flooding is a complex phenomenon, caused by a number of factors that can be associated with local, regional, and hemispheric climatic processes. Moreover, river flow has strong natural variability and exhibits long-term persistence which can confound the results of trend and significance tests based on relatively short data series.

Most of the above studies used the Mann-Kendall test to evaluate the trend in the hydrological variables. The Mann-Kendall test is a non-parametric test that compares the relative magnitudes of sample data. One benefit of this test is that the data need not to conform to any particular distribution.

Trend in Annual Maximum Flood Series Data in Australia - Preliminary Results:

To test the trend in the annual maximum flood series data, two trend tests have been applied, the Mann–Kendall test (Kendall, 1970) and the distribution free CUSUM test (McGilchrist and Wodyer, 1975). The Mann-Kendall test is concerned with testing whether there is an increase or decrease in a time series, whereas the CUSUM test concentrates on whether the means in two parts of a record are significantly different. As a useful guide and in addition to the trend tests, a simple time series plot and a cumulative flow graph of the station have also been used to detect shifts in data.

From initial trend analysis (conducted at 5% level of significance), 21 stations from Victoria (13% of the stations), 31 stations from NSW (24% of the stations), 23 stations from Qld (7% of the stations) and 3 stations from Tasmania (8% of the stations) have shown decreasing trend in annual maximum flood series. Considering Victoria, NSW, Qld and Tasmania together, some 13% stations show downward trend. The locations of these stations are shown in Figure 7.2. These stations are listed in Appendix B (Tables B6 to B9). These initial results need to be further investigated since south-eastern and eastern Australia were affected by severe drought in 1990s and hence low floods dominated the post 1990 annual maximum flood series data (as indicated by Figure 3.1.1) for many stations in this region. It is yet to be confirmed whether the detected decreasing trend in annual maximum flood series data for these stations (described above) is a part of long-term climate variability or it is due to climate change. As such, the trend analyses should be repeated using the data from the stations having longer period of record say at least 50 years.

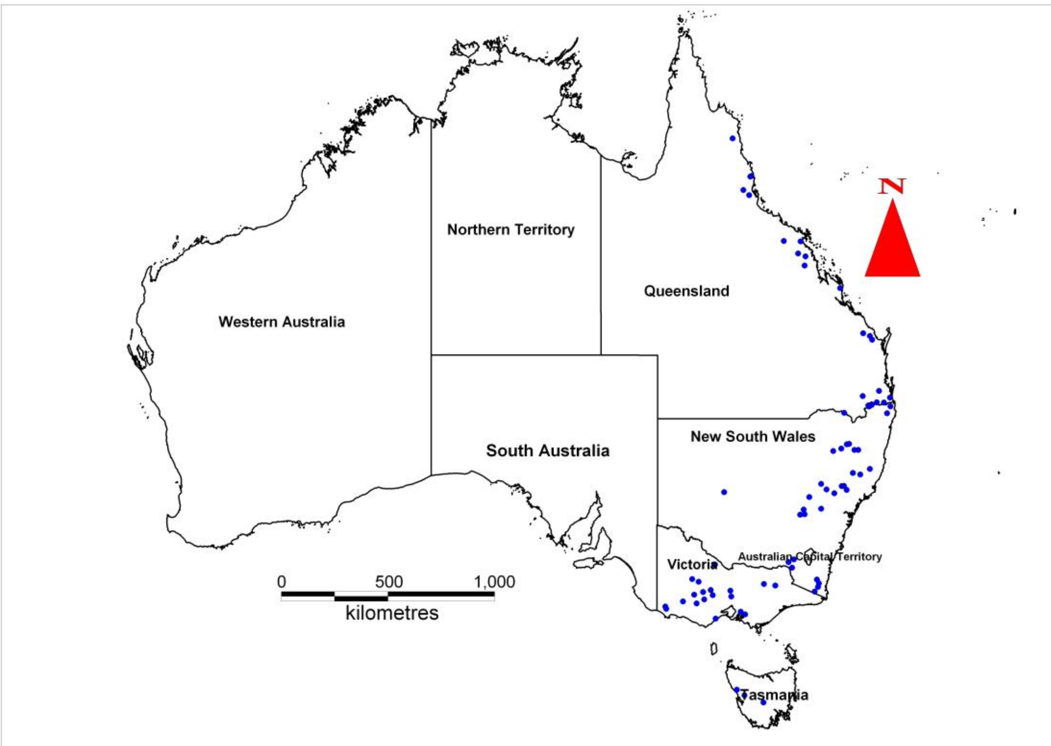


Figure 7.2 Stations showing trends in annual maximum flood series (Vic, NSW, Qld and Tasmania)

8. Recommended Regional Methods for Application and Further Testing

The preliminary investigations, reported here, have focused on the Probabilistic Rational Method (PRM) and various regression based techniques: Quantile Regression Technique (QRT) based on ordinary least squares (QRT-OLS), QRT based on generalised least squares (QRT-GLS) and parameter regression technique (PRT) based on GLS regression. The methods have initially been applied to a number of Australian states based on the concept of fixed regions. The preliminary application of the region of influence (ROI) approach has been undertaken with the PRT-GLS method for eastern NSW. The ROI with QRT-GLS method is under development.

Based on the results of preliminary investigations, it has been found that QRT outperforms the PRM for Victoria, NSW and Qld. The QRT models have been developed using the same predictor variables as the PRM for NSW and Tasmania; results show that two predictor variables (catchment area and design rainfall intensity with duration equal to time of concentration and ARI equal to that of the prediction equation) can provide quite accurate design flood estimates. The particular advantage of the QRT over the PRM is that QRT does not require a map of the runoff coefficient which assumes that hydrologic similarity depends directly on geographic proximity.

The QRT-GLS method has demonstrated its superiority over the QRT-OLS method. Unlike the OLS estimators, the GLS estimators account for differences in the variance of streamflows from site to site due to different record lengths, correlation between concurrent flows, correlation between the residuals and the fitted quantiles, and the model error in the regional model.

From the initial results of the application of the ROI with the parameter regression technique (where prediction equations are developed for the parameters of the LP3 distribution based on GLS regression), it has been found that the ROI-GLS model exhibits superior performance to the fixed region GLS model. It is expected that the QRT-ROI-GLS model would perform quite well.

From the application of the Probabilistic Model coupled with the GLS method to the combined data set of Victoria and NSW, it has been found that this method can provide quite accurate design flood estimates for medium to large floods (ARIs of 20 to 200 years). The Probabilistic Model shows a similar degree of accuracy in flood estimation as the QRT-GLS method in the range of 10 to 100 years ARIs. The real advantage of the Probabilistic Model may be in the 100 to 500 years flood range (using data from greater number of stations) where the degree of uncertainty with other methods is very high.

Preliminary trend analysis results show that about 13% stations from Victoria, New South Wales, Queensland and Tasmania show downward trend in annual maximum flood series. These initial results need to be further investigated since these parts of Australia were affected by severe drought in the 1990s, and hence low floods dominated the post 1990 annual maximum flood series data for many stations in this region. It is yet to be confirmed whether the detected decreasing trend in annual maximum flood series data for these stations is a part of long-term climate variability or it is due to climate change.

Based on the preliminary investigations described in this report, the following methods should be considered and further tested for inclusion in Australian Rainfall and Runoff:

1. The ROI-QRT-GLS and ROI-PRT-GLS methods should be further tested for the combined data set of the states of Victoria, NSW and Queensland (possibly SA and Tasmania, subject to investigation). Provided they are demonstrated to be superior or at least as good as fixed region GLS, they should be adopted because ROI methods avoid discontinuities at region boundaries.
2. The QRT-GLS and PRT-GLS methods (based on fixed regions) should be applied to develop final prediction equations for states having smaller data set such as Tasmania and South Australia. The possibility of combining the western Victorian and South Australian data should be examined in the framework of the ROI approach.
3. Where a GLS approach is adopted, the Bayesian GLS method should be used to properly account for uncertainty in the model error variance and in the quantiles.
4. Where a PRT approach is judged equal to or superior to a QRT approach it should be adopted. This is because the PRT approach can be applied to all

quantiles and can be updated with any site information to produce more accurate quantile estimates.

5. The applicability of the finally adopted regional flood estimation methods to catchments smaller than 10 km^2 should be assessed.
6. A detailed error analysis should be undertaken for the finally adopted regional flood estimation methods.
7. Suitable computer-based application tools should be developed to apply the recommended regional flood estimation methods.
8. The Probabilistic Model coupled with the GLS regression approach should be applied to the combined data set of all the Australian states to develop models to estimate large floods (e.g. ARIs of 100 to 500 years).
9. For arid and semi-arid parts of Australia (e.g. western NSW, north-western Victoria, southern South Australia, western Qld and northern NT), a simple index type regional flood estimation technique should be developed and tested with appropriate regional growth factors and simple prediction equation to estimate mean flood. This model may be calibrated using the Probabilistic Model.
10. The impact of climate variability and climate change on regional flood estimates should be investigated. In this regard, non-stationary flood frequency analysis should be undertaken for the stations that have shown decreasing trend in the annual maximum flood series. The relationship between various climate variability and climate change indices and flood quantiles should be investigated to develop appropriate adjustment factors to account for the impact of climate change on regional flood estimates.
11. The sensitivity of the finally adopted regional flood estimation methods to data needs (i.e. the ability for the data to be replicated) should be investigated.
12. The finally adopted regional flood estimation methods should be calibrated using the newly derived design rainfall data when available.

9. Summary and Conclusions

A database has been prepared for each of the states of Victoria, NSW, Tasmania, Queensland and South Australia comprising annual maximum flood series and suitable metrics of climatic and physical catchment characteristics. The database for NT is under preparation. The database for WA is yet to be prepared.

1. For Victoria, a total of 415 stations, each with a minimum record length of 10 years, were initially selected. After in-filling the gaps in the annual maximum flood series, trend analysis, consideration of rating curve error and introduction of a cut-off record length of 25 years, 131 stations were finally selected in the database of Victoria. The streamflow record lengths of these stations range from 25 to 52 years (average 32 years).

2. For NSW, initially 635 stations were selected. After in-filling the gaps in the annual maximum flood series, trend analysis, consideration of rating curve error and introduction of a cut-off record length of 25 years, 96 stations were finally selected in the database of NSW. The streamflow record lengths of these stations range from 25 to 74 years (average 34 years).

3. For Tasmania, initially 53 stations were selected. After infilling the gaps in the annual maximum flood series, consideration of rating curve error and regulation, a total of 34 stations were retained. The final dataset of Tasmania contained 34 stations with flow record lengths in the range of 10 to 58 years (average 24 years).

4. For Queensland, a total of 351 stations were considered initially. After infilling the gaps in the annual maximum flood series and consideration of the quality of the data and other relevant criteria, a total of 265 stations were retained in the database. The streamflow record lengths of these stations range from 10 to 97 years (average 27 years). Further analysis is in progress to determine a suitable cut-off record length for Queensland, which will reduce the size of the database.

5. For South Australia, a total of 35 stations were initially selected. After infilling the gaps in the annual maximum flood series, consideration of data quality, rating curve error and degree of regulation, a total of 30 stations were retained

in the database. The streamflow record lengths of these stations range from 17 to 66 years (average 33 years).

6. A total of 130 candidate stations have been selected from NT. The streamflow record lengths of these stations range from 10 to 57 years. The number of eligible catchments satisfying the criteria described in Section 2.1 and passing the other tests (e.g. rating, outlier, trend, etc.) will be smaller than 130.

The selected catchments from the states of Victoria, NSW, Tasmania, Queensland, South Australia and Northern Territory are shown in Figure 9.1.

For bulk of the selected catchments, data for up to 7 climatic and catchment characteristics variables were abstracted. These are catchment area (*area*), design rainfall intensity with various ARIs and durations (*I*), mean annual rainfall (*rain*), mean annual areal potential evapotranspiration (*evap*), main stream slope (*S1085*), stream density (*sden*) and fraction of catchment area under forest (*forest*).

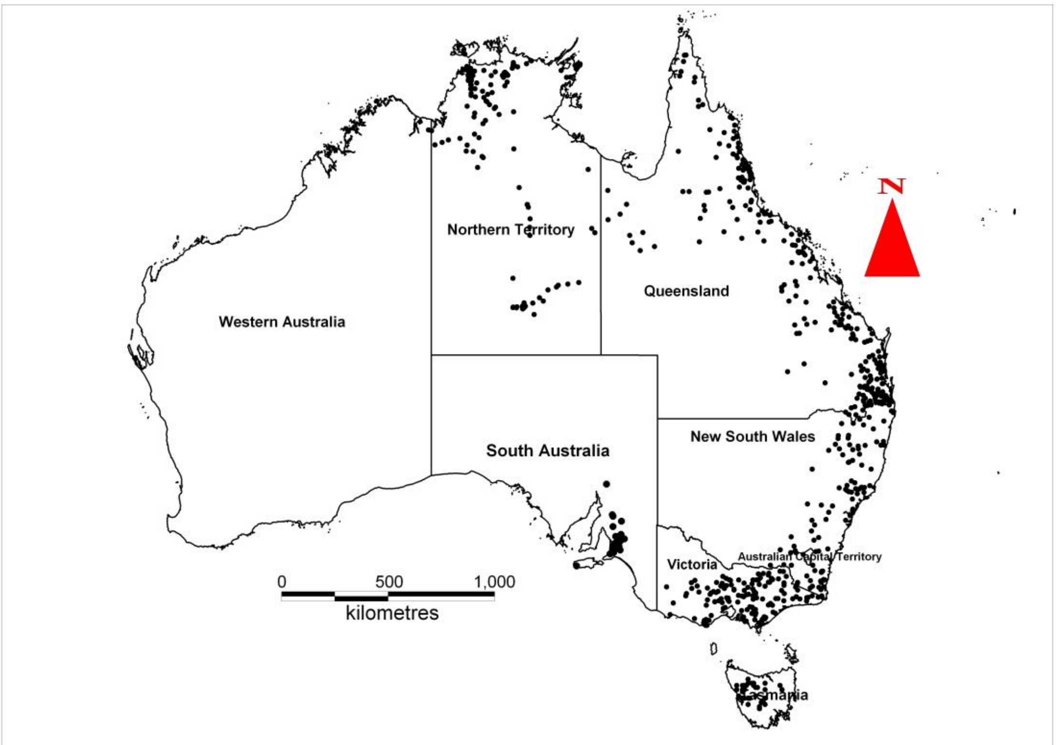


Figure 9.1 Selected catchments from Australia as in July 2009

The following important lessons can be learnt from the data preparation phase of this study:

- In a regionalisation study, a large primary data set, even if selected using a fairly stringent set of criteria, cannot guarantee a similarly large final data set, as streamflow data are affected by many sources of uncertainties and errors (such as gaps in the data series, trend in the data and rating curve error).

- Any hydrological data preparation exercise for a regionalisation study is a compromise between quantity & quality of data, spatial coverage & record length, and noise & useful information with respect to the intended purpose of the regionalisation study. For example, if the selected regionalisation study is expected to exploit spatial interpolation (such as the Probabilistic Rational Method), too great a reduction in station numbers would be undesirable as this would perhaps increase the error in spatial interpolation at a greater rate than the increase in accuracy achieved by having a longer streamflow record length at individual stations (which reduces the error in at-site flood estimates). In contrast, for the quantile regression technique, a reasonable number of stations with moderate spatial coverage would suffice if they capture the expected variability and interactions in flood and catchment data, and hence increased streamflow record lengths at individual stations would be more desirable.

- The rating curve errors present in the flood data for many of the largest observed events may affect the design flood estimates significantly. An empirical procedure was developed that computes a rating ratio between the estimated flow and the maximum measured flow and then selects a cut off value of this ratio to discard stations that are likely to be affected by excessive rating curve errors.

- Despite the best efforts in the data preparation phase, the final adopted data set may still contain undetected errors in some of the annual maximum floods. These may show up in later stages of a regional flood estimation study as discordant observations and will require further checking as to the most likely source of the apparent discordancy.

A number of regional flood estimation models have been developed and tested using the developed database. These include the Probabilistic Rational Method (PRM) and various regression based techniques: Quantile Regression Technique (QRT) based on ordinary least squares (QRT-OLS), QRT based on generalised least squares (QRT-GLS) and parameter regression technique (PRT) based on GLS regression (PRT-GLS). The methods have initially been applied to individual states based on the concept of fixed regions. The preliminary application of the region of influence (ROI) approach has been undertaken with the PRT-GLS method for eastern NSW. The ROI with QRT-GLS method is under development. Based on the preliminary investigations presented in this report, the following conclusions can be drawn:

- The QRT outperforms the PRM for Victoria, NSW and Qld dataset. The QRT models have been developed using the same predictor variables as the PRM for NSW and Tasmania; results shows that two predictor variables (catchment area and design rainfall intensity with duration equal to time of concentration and ARI equal to that of the prediction equation) can provide quite accurate design flood estimates. The particular advantage of the QRT over the PRM is that QRT does not require a map of the runoff coefficient which assumes that hydrologic similarity depends directly on geographic proximity.
- The QRT-GLS method outperforms the QRT-OLS method. Unlike the OLS estimators, the GLS estimators account for differences in the variance of streamflows from site to site due to different record lengths, correlation between concurrent flows, correlation between the residuals and the fitted quantiles, and the model error in the regional model.
- From the initial results of the application of the ROI with the parameter regression technique (where prediction equations are developed for the parameters of the LP3 distribution based on GLS regression), it has been found that ROI GLS model exhibits superior performance to the fixed region GLS model. It is expected that QRT-ROI-GLS model would perform quite well, which is under development.
- From the application of Probabilistic Model coupled with GLS method to the combined data set of Victoria and NSW, it has been found that this method can provide quite accurate design flood estimates for medium to large floods (ARIs of 20 to 200 years). The Probabilistic Model shows a similar degree of accuracy in flood estimation as the QRT-GLS method in the range of 10 to 100 years ARIs. The real advantage of the Probabilistic Model might be in the

100 to 500 years flood range (using data from greater number of stations) where the degree of uncertainty with other methods is very high. This needs further investigation.

- Preliminary trend analysis results show that about 13% stations from Victoria, New South Wales, Queensland and Tasmania exhibit downward trend in annual maximum flood series. These initial results need to be further investigated since these parts of Australia were affected by severe drought in the 1990s, and hence low floods dominated the post 1990 annual maximum flood series data for many stations in this region. It is yet to be confirmed whether the detected decreasing trend in annual maximum flood series data for these stations is a part of long-term climate variability or it is due to climate change.

Based on the findings of the preliminary studies presented in this report, recommended regional flood estimation methods for application and further testing have been identified.

References

Acreman, M.C. (1987). Regional flood frequency analysis in the UK: Recent research-new ideas. Rep. Inst. of Hydro., Wallingford, UK.

Acreman, M.C. and Sinclair, C.D. (1986). Classification of drainage basins according to their physical characteristics: an application for flood frequency analysis in Scotland. J. Hydrol., 84:365-380.

Acreman, M.C. and Wiltshire, S.E. (1987). Identification of regions for regional flood frequency analysis. EOS, 68(44), 1262(Abstract).

Ahmad, M.I., Sinclair, C.D. and Werrity, A. (1988). Log-logistic flood frequency analysis. J. Hydrol., 98: 205-224.

Anderson, H.W. (1957). Relating sediment yield to watershed variables. Trans. Am. Geophys. Union, 38: 921-924.

Ashbolt, S.C., and Maheepala, S. (2008). Assessing the impact of climate change on urban water systems: overview of methods. Hydrology and Water Resources Symposium, Adelaide.

Bates, B.C. (1994). Regionalisation of Hydrological Data: A review. Report 94/5. CRC for Catchment Hydrology, Monash University, Australia; pp61.

Bates, B.C., Rahman, A., Mein, R.G. and Weinmann, P.E. (1998). Climatic and physical factors that influence the homogeneity of regional floods in south-eastern Australia. Water Resour. Res., 34(12), 3369-3382.

Benson, M.A. (1959). Channel slope factor in flood frequency analysis. J. of the Hydraul. Div., ASCE., 85 (HY4), 1-19.

Benson, M.A. (1962). Evolution of methods for evaluating the occurrence of floods. U.S. Geol Surv. Water Supply Paper, 1580-A, 30pp.

Benson, M.A. (1968). Uniform flood frequency estimating methods for federal agencies. Water Resour. Res., 4(5): 891-908.

Bridgman, H. A., and Oliver, J. E., (2006). The Global Climate System - Patterns, Processes and Teleconnections, Cambridge University Press, Cambridge.

Burn, D.H. (1990a). An apprisal of region of influence approach to flood frequency analysis. J.Hydrol., 35(2):149-165.

Burn, D.H. (1990b). Evaluation of regional flood frequency analysis with a region of influence approach. Water Resour. Res., 26(10): 2257-2265.

Castellarin, A., Burn, D.H. and Brath, A. (2008). Homogeneity testing: How homogeneous do heterogeneous cross-correlated regions seem? J. Hydrol., 360, 67-76.

Chowdhury, J.U., Stedinger, J.R. and Lu, L.H. (1991): Goodness of fit tests for regional flood distributions. Water Resour. Res., 27(7): 1765-1776.

CSIRO (2007). Climate Change in Australia, Technical Report 2007.

Cunderlik, J. M. and Burn, D. H. (2003) Non-stationary pooled flood frequency analysis. J. Hydrol., 276, 210-223.

Cunderlik, J. M. and Burn, D. H. (2003) Non-stationary pooled flood frequency analysis. J. Hydrol., 276, 210-223.

Cunderlik, J.M. and Burn, D.H. (2006). Site-focused nonparametric test of regional homogeneity based on flood regime. J. Hydrol., 318, 301-315.

Cunderlik, J. M. and Ouarda, T.B. (2006). Regional flood-duration-frequency modeling in the changing environment. J. Hydrol., 318, 276–291.

Cunnane, C. (1988). Methods and merits of regional flood frequency analysis. J. Hydrol., 100: 269-290.

Cunnane, C. (1989). Statistical Distributions for Flood Frequency Analysis. World Meteorological Organisation, Operational Hydrology Report. No 33.

Dalrymple, T. (1960). Flood frequency analyses. U.S. Geol. Surv. Water Supply, pap 1543-A,80 pp

Dawdy, D.R. (1961). Variation of flood ratios with size of drainage area. U. S. Geol. Surv. Prof. Pap. 424-C, Paper C36.

Eng, K., Tasker, G.D. and Milly, P.C.D. (2005). An analysis of Region-of-Influence methods for Flood Frequency Regionalization in the Gulf-Atlantic rolling plains. Journal of the American Water Resources Association, 41(1), 135-143.

Fill, D.H. and Stedinger J.R. (1995a). L moment and PPCC goodness-of-fit tests for the Gumbel distribution and effect of autocorrelation. Water Resour. Res., 31(1) 225-229.

Fill, D.H. and Stedinger J.R. (1995b). Homogeneity tests based upon Gumbel distribution and a critical appraisal of Darymple's test. J. Hydrol., 166:81-105.

Flavell, D.J. (1982). The rational method applied to small rural catchments in the south west of Western Australia, Hydrology and Water Resources Symposium, p49-53.

Flavell, D.J. (1985). Australian Rainfall and Runoff revision. Civil College Tech. Report, Engineers Australia, 6 Sep 1985, pp. 1-4.

Flavell, D.J. and Belstead, B.S. (1986). Losses for design flood estimation in Western Australia, Hydrology and Water Resour. Symp.

Franks, S.W. and Kuczera, G., (2002). Flood frequency analysis: evidence and implications of secular climate variability, New South Wales. Water Resour. Res. 38 (5), 1062. doi:10.1029/2001WR000232.

Fu, G., Viney, N.R., and Charles, S.P. (2008). Temporal variation of extreme precipitation events in Australia; 1910-2006. Hydrology and Water Symposium, Adelaide.

Gallant, A.J.E., Hennessy, K.J. and Risbey, J. (2007). Trends in rainfall indices for six Australian regions: 1910-2005. Aust. Meteorol. Mag. 56, 223-239.

Griffis, V.W. and Stedinger, J.R. (2007). The use of GLS regression in regional hydrologic analyses. J. Hydrol.., 344:82-95.

Gruber, A.M. and Stedinger, J.R. (2008). Models of LP3 regional skew, data selection and Bayesian GLS regression. World Environmental and Water Resources Congress, ASCE, Ahupua'a.

Grubbs, F.E. and Beck, G. (1972). Extension of sample sizes and percentage points for significance tests of outlying observations, Technometrics 4 (14), pp. 847–853.

Gupta, V.K., Mesa, O.J. and Dawdy, D.R. (1994). Multiscaling theory of flood peaks: regional quantile analysis. Water Resour. Res., 30, 12, 3405-3421.

Guttman, N.B. (1993). The use of L moments in the determination of regional precipitation climates. J. Climate, 6:2309-2325.

Hackelbusch, A., Micevski, M., Kuczera., G, Rahman, A. and Haddad, K. (2009). Regional flood frequency analysis for eastern NSW: A region of influence approach using generalised least squares log-Pearson 3 parameter regression. 32nd Hydrology and Water resources Symp, Newcastle, 30th Nov to 3rd Dec 2009 (under review)

Haddad, K. (2008). Design flood estimation in ungauged catchments using a quantile regression technique: ordinary and generalised least squares methods compared for Victoria, Masters (Honours) thesis, School of Engineering, University of Western Sydney, New South Wales.

Haddad, K. and Rahman, A. (2008). Investigation on at-site flood frequency analysis in south-east Australia, 69, 3, 59-64, Journal of the Institution of Engineers, Malaysia.

Haddad, K., Rahman, A. and Weinmann, P.E. (2008a). Development of a generalised least squares based quantile regression technique for design flood estimation in Victoria, 31st Hydrology and Water Resources Symp., Adelaide, 15-17 April 2008, 2546-2557.

Haddad, K., Rahman, A. and Weinmann, P.E. (2008b). Streamflow data preparation for regional flood frequency analysis: important lessons from a case study. 31st Hydrology and Water Resources Symp., Adelaide, 15-17 April 2008, 2558-2569.

Haddad, K., Rahman, A. and Weinmann, P.E. (2006). Design flood estimation in ungauged catchments by quantile regression technique: ordinary least squares and generalised least squares compared. 30th Hydrology and Water Resources Symp., The Institution of Engineers Australia, 4-7 Dec 2006, Launceston, 6pp.

Hardison, C.H. (1971). Prediction error of regression estimates of streamflow characteristics at ungauged sites. U.S. Geol. Pap., 750-C, C228-C236.

Hennessy, K., McInness, K., abbs, D., Jones, R., Bathols, J., Suppiah, R., Ricketts, J., Rafter, T., Collins, D., and Jones, D. (2004). Climate change in New South Wales -Part 2: Projected changes in climate extremes. Consultancy Report for the New South Wales Greenhouse Office, CSIRO.

Hosking, J.R.M. and Wallis, J.R. (1991). Some statistics useful in regional frequency analysis. IMB Math. Res. Rep. RC 17096, IMB T.J. Watson Research Center, Yorktown Heights, N.Y., 23 pp.

Hosking, J.R.M. and Wallis, J.R. (1993). Some statistics useful in regional frequency analysis. Water Resour. Res., 29(2), 271-281.

Houghton, J.C. (1978). Birth of a parent: The Wakeby distribution for modelling flood flows. Water Resour. Res., 14(6): 1105-1115.

Institution of Engineers Australia (I. E. Aust.) (1987, 2001). Australian Rainfall and Runoff: A Guide to Flood Estimation. Editor: D.H. Pilgrim, Vol.1, I. E. Aust., Canberra.

Interagency Advisory Committee on Water Data. (1982). Guidelines for Determining Flood Flow Frequency. Bulletin #17B of the Hydrology Subcommittee, US Geological Survey, Reston, VA.

IPCC (2007). Climate Change The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, UK.

IPCC (2001). In: Houghten, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linder, P.J., Dai, X., Maskell, K., Johnson, C.A. (Eds.), Climate Change 2001: The Scientific Basis. Cambridge University Press, Cambridge, 881 pp.

Jain, S., Lall, U., (2001). Floods in a changing climate: does the past represent the future? Water Resour. Res. 37/12, 3193–3205.

Jeong, D.I., Stedinger, J.R., Kim, Y., Sung, J.H. and Yoon, S.Y. (2008). Reflecting a Climate Change Factor in Flood Frequency Analysis for Korean River Basins. Water Down Under, Adelaide, Australia, 14-17 April.

Kendall, M.G. (1970). Rank Correlation Methods. 4th Edition, Griffen, London, 202 pp.

Kiem, A.S. and Franks, S.W., (2004). Multi-decadal variability of drought risk, eastern Australia. Hydrol. Proc. 18 (11), 2039–2050.

Kiem, A.S., Franks, S.W. and Kuczera, G., (2003). Multi-decadal variability of flood risk. Geophys. Res. Lett. 30 (2), 1035. doi:10.1029/2002GL015992.

Kjeldsen, T.R. and Jones, D. (2009). An exploratory analysis of error components in hydrological regression modelling. Water Resour. Res., 45, W02407, doi:10.1029/2007WR006283.

Kuczera, G. and Franks, S. (2005). At-site flood frequency analysis. Australian Rainfall and Runoff, Book IV, Draft Chapter 2.

Leclerc, M. and Ouarda T.B. (2007). Non-stationary regional flood frequency analysis at ungauged sites. J. Hydrol., 343, 254–265.

Lu, LH and Stedinger, J.R (1992). Sampling of variance of normalized GEV/PWM quantile estimators and a regional homogeneity test. J. Hydrol., vol 138, pp 223-245.

Majone, U. and Tomirotti, M. (2004). A trans-national regional frequency analysis of peak flood flows. L'Aqua, 2/2004, 9-17.

Majone, U., Tomirotti, M. and Galimberti, G. (2007). A probabilistic model for the estimation of peak flood flows. Special Session 10, 32nd Congress of IAHR, Venice, Italy, July 1-6.

Mantua, N. J., Hare, S. R., (2002). The Pacific Decadal Oscillation. J. Oceanogr., 58 (1), 35–44.

Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M. and Francis, R. C., (1997). A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society, 78, 1069-1079.

McGilchrist, C.A. and Woodyer, K.D. (1975). Note on a distribution free CUSUM technique. Technometrics, 17(3), 321-325.

McInness, K.L., Suppiah., R., Whetton, P.H., Hennessy, K.J., and Jones, R.N. (2002). Climate Change in South Australia, Report for the South Australian Government by the Climate Impact Group, CSIRO Atmospheric Research.

Micevski, T. and Kuczera, G. (2009) Combining site and regional flood information using a Bayesian Monte Carlo approach, Water Resour. Res., doi:10.1029/2008WR007173

Micevski, T. and Kuczera, G.A. (2008), A general and practical Bayesian procedure for regional and at-site flood frequency analysis, Proceedings of Water Down Under 2008, Adelaide, SA.

Micevski, T., Kuczera, G., and Franks, S.W. (2006a). A Bayesian hierarchical regional flood model. 30th Hydrology and Water Resources Symp., The Institution of Engineers Australia, 4-7 Dec 2006, Launceston, 6pp.

Micevski, T., Franks, S.W. and Kuczera, G., (2006b). Multidecadal variability in coastal eastern Australian flood data. J. Hydrol., 327, 219-225.

Micevski, T. and Kuczera, G. (2009). Combining site and regional flood information using a Bayesian Monte Carlo approach. Water Resour. Res., 45, W04405, doi:10.1029/2008WR007173.

Nathan, R.J. and McMahon, T.A. (1990). Identification of homogeneous regions for the purpose of regionalisation. J.Hydrol., 121(4):217-238.

Natural Environment Research Council (NERC) (1975). Flood Studies Report, NERC, London.

Ng, W.W., Panu, U.S. and Lennox, W.C. (2007). Chaos based analytical techniques for daily extreme hydrological observations. J. Hydrol., 342, 17-41.

Ouarda, T.B.M.J., Ba, K.M., Diaz-Delgado et al. (2008). Intercomparison of regional flood frequency estimation methods at ungauged sites for a Mexican case study. J. Hydrol., 348, 40-58.

Palmen, L.B, and Weeks, W.D, (2009). Regional flood frequency for Queensland using the Quantile Regression Technique. 32nd Hydrology and Water resources Symp, Newcastle, 30th Nov to 3rd Dec 2009 (under review)

Pearson, C.P. (1991). New Zealand regional flood frequency analysis using L moments. J. Hydrol., New Zealand, Vol. 30(2): 53-64.

Pilgrim, D.H. (1987). Estimation of peak flows for small to medium sized rural catchments. Book 4, Section 1, Australian Rainfall and Runoff, The Institution of Engineers Australia.

Pilgrim, D.H. and McDermott, G. (1982). Design Floods for Small Rural Catchments in Eastern New South Wales, The Institution of Engineers Australia.

Pilgrim, D.H. (1986). Bridging the gap between flood research and design practice. Water Resour. Res., Vol. 22, Supplement, No. 9, pp 165S-176S.

Pillon, P.J, and Adamowski, K. (1992). The value of regional information to flood frequency analysis using the method of L-moments. Can. J. Civ. Eng., 19(1): 137-147.

Potter, K.W. and Lettenmaier, D.P. (1990). A comparison of regional flood frequency estimation methods using a resampling method. Water Resour. Res., 26(3): 415-424.

Power, S., Casey, T., Folland, C., Colman, A. and Mehta, V., (1999). Inter-decadal modulation of the impact of ENSO on Australia. Clim. Dynamics, **15**, 319–324.

Power, S., Tseitkin, F., Torok, S., Lavery, B., Dahni, R., McAveney, B., (1998). Australian temperature, Australian rainfall and the Southern Oscillation, 1910–1992: Coherent variability and recent changes. Aust. Meteorol. Mag. 47 (2), 85–101.

Prudhomme, C., Jakob, D., and Svensson, C. (2003). Uncertainty and climate change impact on the flood regime of small UK catchments. J. Hydrol., 277,1-23, doi:10.1016/s0022-1694(03)00065-9.

Rahman, A. (1997). Flood Estimation for ungauged catchments: A regional approach using flood and catchment characteristics, PhD thesis, Department of Civil Engineering, Monash University.

Rahman, A. (2005). A quantile regression technique to estimate design floods for ungauged catchments in south-east Australia. Aust. Jour. of Water Resour. 9(1), 81-89.

Rahman, A., Bates, B.C., Mein, R.G. and Weinmann, P.E. (1999). Regional flood frequency analysis for ungauged basins in south – eastern Australia. Aust. J. Water Resour. 3(2): 199:207.

Riggs, H.C. (1973). Regional analyses of streamflow techniques. Techniques of Water Resources Investigations of the U.S. Geol. Surv., Book 4, Chapter B3, U.S. Geol. Surv., Washington D.C.

Rodbell, D.T., Anderson, D.M., Abbott, M.B. and Newman, J.H. (1999). An approximately 15,000-Year Record of El Nino- Driven Alluviation in Southwestern Ecuador, Science, 283, 516-520.

Rossi, F., Fiorentino, M. and Versace, P. (1984). Two-component extreme value distribution for flood frequency analysis. Water Resour. Res., 20(7): 847-856.

Saji, N. H., et al. (1999). A dipole mode in the tropical Indian Ocean. Nature, 401, 360-363.

Smith, J.A. (1992). Representation of basin scale in flood peak distributions. Water Resour. Res., 28(11): 2993-2999.

Stedinger, J.R. and Tasker, G.D. (1985). Regional Hydrologic Analysis, 1.Ordinary, Weighted, and Generalised Least Squares Compared, Water Resour. Res. 2209/1421:1432.

Strahler, A.N. (1950). Equilibrium theory of erosional slopes approached by frequency distribution analysis. Amer. J. Sci. 248: 673- 696, 800- 814.

Tasker, G.D. and Stedinger, J.R. (1989). An Operational GLS model for Hydrologic Regression, J. Hydrol. 111/361:375.

Tasker, G.D., Eychaner, J.H. and Stedinger, J.R. (1986). Application of Generalised Least Squares in Regional Hydrologic Regression Analysis, U.S. Geological Survey Water Supply Paper 2310/107:115.

Tasker, GD., Lumb, AM, Thomas, WO Jr and Flynn, KM (1987). Computer Procedures for Hydrologic Regression and Network Analysis Using Generalised Least Squares. USGS.

Tasker, G.D., Hodge, S.A. and Barks, C.S. (1996). Region of Influence regression for estimating the 50-year flood at ungauged sites. Water Resources Bulletin, 32(1), 163-170.

Taylor, A. and Schwarz, H. (1952). Unit hydrograph lag and peak flow related to basin characteristics. Transaction of the Am. Geophy. Union, 33: 235-246.

Thomas, D.M. and Benson, M.A. (1970). Generalization of streamflow characteristics from drainage basin characteristics. U.S.Geol. Water Supply Pap. No.1975

Thomas, Jr., W.O. and Olsen, S.A. (1992). Regional analysis of minimum streamflow. In: Proceedings of 12th Conference on Probability and Statistics in the Atmospheric Sciences, 5th International Meeting on Statistical Climatology, Toronto, Ont., 22-26 June, 1992, pp 261-266.

Trenberth, K. E. (1997). The definition of El Nino, Bulletin of the American Meteorological Society, 78, 2771-2777.

Verdon, D.C., Wyatt, A.K., Kiem, A.S. and Franks, S.W., (2004). Multidecadal variability of rainfall and streamflow: Eastern Australia. Water Resour. Res. 40 (10), W10201, doi:10.1029/2004WR003234.

Vogel, R.M, and Kroll, C.N. (1989). Low – frequency analysis using probability – plot correlation coefficients. J. Water Resour. Plng. And Mgmt, ASCE, 115(3): 338-357.

Vogel, R.M., McMahon, T.A. and Chiew, F.H.S. (1993): Flood flow frequency model selection in Australia. J. Hydrol., 146, 421-449.

Wallis, J.R. and Wood, E.F. (1985). Relative accuracy of log Pearson III procedures. J. Hydraul. Eng., ASCE., 111(7): 1043-1056.

Weeks, W.D. (1991). Design Floods for Small Rural Catchments in Queensland, Civil Engineering Transactions, IEAust, Vol CE33, No 4, pp 249-260.

Weeks, W.D. and Rajaratnam, L. (2005). Regional flood estimation – Northern Territory. Unpublished Technical Report, Department of Infrastructure, Planning and Environment – NT.

Westra, S., Sharma, A. (2006). Dominant modes of interannual variability in Australian Rainfall Analyzed using wavelets. J. Geophys. Res. 111 (D5), D05102, doi:10.1029/2005JD005996.

Whetton, P.H., Suppiah, R., McInness, K.L., Hennessy, K.J., and Jones, R.N. (2002). Climate Change in Victoria: high-resolution regional assessment of climate change impacts, CSIRO Consultancy Report for the Department of Natural Resources and Environment, Victoria, 44pp.

Whetton, P.H. (2002). Climate Change in Queensland under Enhanced Greenhouse Conditions, Report on research undertaken for the Queensland Departments of State Development, Main Roads, Health, Transport, Mines and Energy, Tresury, Public Works, Primary Industries and Natural Tesources, CSIRO.

Williamson, D.R. and Van Der Wel B. (1991). Quantification of the impact of dryland salinity on the Mount Lofty Ranges, SA, Intl. Hydrology and Water Resour. Symp., p 48-52.

Wiltshire, S.E. (1986). Identification of homogeneous regions for flood frequency analysis. J. Hydrol., vol 84, pp 287-302.

Zhang, X., Harvey, K.D., Hogg, W.D., Yuzyk, T.R., (2001). Trends in Canadian streamflow. Water Resour. Res. 37/4, 987–998.

Zhang, Z., Zhang, Q. and Jiang, T. (2007). Changing features of extreme precipitation in the Yangtze 24 River basin during 1961-2002. Journal of Geographical Sciences, 17(1), 33-42.

Zrinji, Z. and Burn, D.H. (1994). Flood Frequency analysis for ungauged sites using a region of influence approach. Journal of hydrology, 153, 1-21, 1994.

Zrinji, Z. and Burn, D.H. (1996). Regional flood frequency with hierarchical region of influence. J. Water Resour. Planning and Management, ASCE, 122 (4), 245-252.

Appendix A Streamflow and Catchment Data Sets

Table A1 Selected catchments from Victoria

Station ID	Station Name	River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
221207	Errinundra	Errinundra	-37.45	148.91	158	35	1971 - 2005
221209	Weeragua	Cann(East Branch	-37.37	149.20	154	33	1973 - 2005
221210	The Gorge	Genoa	-37.43	149.53	837	33	1972 - 2005
221211	Combienbar	Combienbar	-37.44	148.98	179	32	1974 - 2005
221212	Princes HWY	Bemm	-37.61	148.90	725	31	1975 - 2005
222202	Sardine Ck	Brodribb	-37.51	148.55	650	41	1965 - 2005
222206	Buchan	Buchan	-37.50	148.18	822	32	1974 - 2005
222210	Deddick (Caseys)	Deddick	-37.09	148.43	857	35	1970 - 2005
222213	Suggan Buggan	Suggan Buggan	-36.95	148.33	357	35	1971 - 2005
222217	Jacksons Crossing	Rodger	-37.41	148.36	447	30	1976 - 2005
223202	Swifts Ck	Tambo	-37.26	147.72	943	32	1974 - 2005
223204	Deptford	Nicholson	-37.60	147.70	287	34	1974 - 2005
224213	Lower Dargo Rd	Dargo	-37.50	147.27	676	33	1973 - 2005
224214	Tabberabbera	Wentworth	-37.50	147.39	443	32	1974 - 2005
225213	Beardmore	Aberfeldy	-38.76	146.42	311	33	1973 - 2005
225218	Briagalong	Freestone Ck	-37.81	147.09	309	34	1971 - 2005
225219	Glencairn	Macalister	-37.52	146.57	570	39	1967 - 2005
225223	Gillio Rd	Valencia Ck	-37.73	146.98	195	35	1971 - 2005
225224	The Channel	Avon	-37.80	146.88	554	34	1972 - 2005
226204	Willow Grove	Latrobe	-38.09	146.16	580	35	1971 - 2005
226205	Noojee	Latrobe	-37.91	146.02	290	46	1960 - 2005
226209	Darnum	Moe	-38.21	146.00	214	34	1972 - 2005
226217	Hawthorn Br	Latrobe	-37.98	146.08	440	34	1955 - 1988
226218	Thorpdale	Narracan Ck	-38.27	146.19	66	35	1971 - 2005

Station ID	Station Name	River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
226222	Near Noojee (U/S Ada R Jun	Latrobe	-37.88	145.89	62	31	1971 - 2005
226226	Tanjil Junction	Tanjil	-38.01	146.20	289	46	1960 - 2005
226402	Trafalgar East	Moe Drain	-38.18	146.21	622	31	1975 - 2005
227200	Yarram	Tarra	-38.46	146.69	25	41	1965 - 2005
227205	Calignee South	Merriman Ck	-38.36	146.65	36	31	1975 - 2005
227210	Carrajung Lower	Bruthen Ck	-38.40	146.74	18	33	1973 - 2005
227211	Toora	Agnes	-38.64	146.37	67	32	1974 - 2005
227213	Jack	Jack	-38.53	146.53	34	36	1970 - 2005
227219	Loch	Bass	-38.38	145.56	52	32	1973 - 2004
227225	Fischers	Tarra	-38.47	146.56	16	33	1973 - 2005
227226	Dumbalk North	Tarwineast Branc	-38.50	146.16	127	36	1970 - 2005
227231	Glen Forbes South	Bass	-38.47	145.51	233	31	1974 - 2005
227236	D/S Foster Ck Jun	Powlett	-38.56	145.71	228	27	1979 - 2005
228212	Tonimbuk	Bunyip	-38.03	145.76	174	30	1975 - 2004
228217	Pakenham	Toomuc Ck	-38.07	145.46	41	28	1974 - 2002
229218	Watsons Ck	Watsons Ck	-37.67	145.26	36	26	1974 - 1999
230202	Sunbury	Jackson Ck	-37.58	144.74	337	31	1975 - 2005
230204	Riddells Ck	Riddells Ck	-37.47	144.67	79	32	1974 - 2005
230205	Bulla (D/S of Emu Ck Jun)	Deep Ck	-37.63	144.80	865	31	1974 - 2005
230211	Clarkefield	Emu Ck	-37.47	144.75	93	31	1975 - 2005
231200	Bacchus Marsh	Werribee Ck	-37.68	144.43	363	28	1978 - 2005
231213	Sardine Ck- O'Brien Cro	Lerderderg Ck	-37.50	144.36	153	47	1959 - 2005
231225	Ballan (U/S Old Western H)	Werribee Ck	-37.60	144.25	71	33	1973 - 2005
231231	Melton South	Toolern Ck	-37.91	144.58	95	27	1979 - 2005
232200	Little	Little Ck	-37.96	144.48	417	32	1974 - 2005

Station ID	Station Name	River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
232210	Lal Lal	Mooraboolwest Br	-37.65	144.04	83	33	1973 - 2005
232213	U/S of Bungal Dam	Lal Lal Ck	-37.66	144.03	157	29	1977 - 2005
233211	Ricketts Marsh	Birregurra Ck	-38.30	143.84	245	31	1975 - 2005
233214	Forrest (above Tunnel)	Barwoneast Branc	-38.53	143.73	17	28	1978 - 2005
234200	Pitfield	Woady Yaloak	-37.81	143.59	324	34	1972 - 2005
235202	Upper Gellibrand	Gellibrand	-37.56	143.64	53	31	1975 - 2005
235203	Curdie	Curdies	-38.45	142.96	790	31	1975 - 2005
235204	Beech Forest	Little Aire Ck	-38.66	143.53	11	30	1976 - 2005
235205	Wyelangta	Arkins Ck West B	-38.65	143.44	3	28	1978 - 2005
235227	Bunkers Hill	Gellibrand	-38.53	143.48	311	32	1974 - 2005
235233	Apollo Bay- Paradise	Barhameast Branc	-38.76	143.62	43	29	1977 - 2005
235234	Gellibrand	Love Ck	-38.49	143.57	75	27	1979 - 2005
236205	Woodford	Merri	-38.32	147.48	899	32	1974 - 2005
236212	Cudgee	Brucknell Ck	-38.35	147.65	570	31	1975 - 2005
237207	Heathmere	Surry	-38.25	141.66	310	31	1975 - 2005
238207	Jimmy Ck	Wannon	-37.37	142.50	40	32	1974 - 2005
238219	Morgiana	Grange Burn	-37.71	141.83	997	33	1973 - 2005
401208	Berringama	Cudgewa Ck	-36.21	147.68	350	41	1965 - 2005
401209	Omeo	Livingstone Ck	-37.11	147.57	243	27	1968 - 1994
401210	below Granite Flat	Snowy Ck	-36.57	147.41	407	38	1968 - 2005
401212	Upper Nariel	Nariel Ck	-36.45	147.83	252	52	1954 - 2005
401215	Uplands	Morass Ck	-36.87	147.70	471	35	1971 - 2005
401216	Jokers Ck	Big	-36.95	141.47	356	52	1952 - 2005
401217	Gibbo Park	Gibbo	-36.75	147.71	389	35	1971 - 2005
401220	McCallums	Tallangatta Ck	-36.21	147.50	464	29	1976 - 2005

Station ID	Station Name	River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
402203	Mongans Br	Kiewa	-36.60	147.10	552	36	1970 - 2005
402204	Osbornes Flat	Yackandandah Ck	-36.31	146.90	255	39	1967 - 2005
402206	Running Ck	Running Ck	-36.54	147.05	126	31	1975 - 2005
402217	Myrtleford Rd Br	Flaggy Ck	-36.39	146.88	24	36	1970 - 2005
403205	Bright	Ovens Rivers	-36.73	146.95	495	35	1971 - 2005
403209	Wangaratta North	Reedy Ck	-36.33	146.34	368	33	1973 - 2005
403213	Greta South	Fifteen Mile Ck	-36.62	146.24	229	33	1973 - 2005
403221	Woolshed	Reedy Ck	-36.31	146.60	214	30	1975 - 2004
403222	Abbeyard	Buffalo	-36.91	146.70	425	33	1973 - 2005
403224	Bobinawarrah	Hurdle Ck	-36.52	146.45	158	31	1975 - 2005
403226	Angleside	Boggy Ck	-36.61	146.36	108	32	1974 - 2005
403227	Cheshunt	King	-36.83	146.40	453	33	1973 - 2005
403233	Harris Lane	Buckland	-36.72	146.88	435	34	1972 - 2005
404206	Moorngag	Broken	-36.80	146.02	497	33	1973 - 2005
404207	Kelfeera	Holland Ck	-36.61	146.06	451	31	1975 - 2005
405205	Murrindindi above Colwells	Murrindindi	-37.41	145.56	108	31	1975 - 2005
405209	Taggerty	Acheron	-37.32	145.71	619	33	1973 - 2005
405212	Tallarook	Sunday Ck	-37.10	145.05	337	31	1975 - 2005
405214	Tonga Br	Delatite	-37.15	146.13	368	49	1957 - 2005
405215	Glen Esk	Howqua	-37.23	146.21	368	32	1974 - 2005
405217	Devlins Br	Yea	-37.38	145.48	360	31	1975 - 2005
405218	Gerrang Br	Jamieson	-37.29	146.19	368	47	1959 - 2005
405219	Dohertys	Goulburn	-37.33	146.13	694	39	1967 - 2005
405226	Moorilim	Pranjip Ck	-36.62	145.31	787	32	1974 - 2005
405227	Jamieson	Big Ck	-37.37	146.06	619	36	1970 - 2005

Station ID	Station Name	River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
405229	Wanalta	Wanalta Ck	-36.64	144.87	108	36	1969 - 2005
405230	Colbinabbin	Cornella Ck	-36.61	144.80	259	33	1973 - 2005
405231	Flowerdale	King Parrot Ck	-37.35	145.29	181	32	1974 - 2005
405237	Euroa Township	Seven Creeks	-36.76	145.58	332	33	1973 - 2005
405240	Ash Br	Sugarloaf Ck	-37.06	145.05	609	33	1973 - 2005
405241	Rubicon	Rubicon	-37.29	145.83	129	33	1973 - 2005
405245	Mansfield	Ford Ck	-37.04	146.05	115	36	1970 - 2005
405248	Graytown	Major Ck	-36.86	144.91	282	35	1971 - 2005
405251	Ancona	Brankeet Ck	-36.97	145.78	121	33	1973 - 2005
405263	U/S of Snake Ck Jun	Goulburn	-37.46	146.25	327	31	1975 - 2005
405264	D/S of Frenchman Ck Jun	Big	-37.52	146.08	333	31	1975 - 2005
405274	Yarck	Home Ck	-37.11	145.60	187	29	1977 - 2005
406213	Redesdale	Campaspe	-37.02	144.54	629	30	1975 - 2004
406214	Longlea	Axe Ck	-36.78	144.43	234	34	1972 - 2004
406215	Lyal	Coliban	-36.96	144.49	717	32	1974 - 2005
406216	Sedgewick	Axe Ck	-36.90	144.36	34	26	1975 - 2005
406224	Runnymede	Mount Pleasant C	-36.55	144.64	248	30	1975 - 2004
406226	Derrinal	Mount Ida Ck	-36.88	144.65	174	28	1978 - 2005
407214	Clunes	Creswick Ck	-37.30	143.79	308	31	1975 - 2005
407217	Vaughan atD/S Fryers Ck	Loddon	-37.16	144.21	299	38	1968 - 2005
407220	Norwood	Bet Bet Ck	-37.00	143.64	347	33	1973 - 2005
407221	Yandoit	Jim Crow Ck	-37.21	144.10	166	33	1973 - 2005
407222	Clunes	Tullaroop Ck	-37.23	143.83	632	33	1973 - 2005
407230	Strathlea	Joyces Ck	-37.17	143.96	153	33	1973 - 2005
407246	Marong	Bullock Ck	-36.73	144.13	184	33	1973 - 2005

Station ID	Station Name	River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
407253	Minto	Piccaninny Ck	-36.45	144.47	668	33	1973 - 2005
415207	Eversley	Wimmera	-37.19	143.19	304	31	1975 - 2005
415217	Grampians Rd Br	Fyans Ck	-37.26	142.53	34	33	1973 - 2005
415220	Wimmera HWY	Avon	-36.64	142.98	596	32	1974 - 2005
415226	Carrs Plains	Richardson	-36.75	142.79	130	31	1971 - 2001
415237	Stawell	Concongella Ck	-37.02	142.82	239	29	1977 - 2005
415238	Navarre	Wattle Ck	-36.90	143.10	141	30	1976 - 2005

Table A2 Selected catchments from NSW and ACT

Station ID	Station Name	River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
201001	Eungella	Oxley	-28.36	153.29	213	48	1958 - 2005
203002	Repentance	Coopers Ck	-28.64	153.41	62	28	1977 - 2004
203012	Binna Burra	Byron Ck	-28.71	153.50	39	28	1978 - 2005
203030	Rappville	Myrtle Ck	-29.11	153.00	332	27	1980 - 2006
204025	Karangi	Orara	-30.26	153.03	135	35	1970 - 2004
204026	Bobo Nursery	Bobo	-30.25	152.85	80	29	1956 - 1984
204030	Aberfoyle	Aberfoyle	-30.26	152.01	200	28	1978 - 2005
204036	Sandy Hill(below Snake Cre	Cataract Ck	-28.93	152.22	236	28	1953 - 1980
204037	Clouds Ck	Clouds Ck	-30.09	152.63	62	34	1972 - 2005
204056	Gibraltar Range	Dandahra Ck	-29.49	152.45	104	30	1976 - 2005
204906	Glenreagh	Orara	-30.07	152.99	446	32	1973 - 2004
206009	Tia	Tia	-31.19	151.83	261	51	1955 - 2005
206025	near Dangar Falls	Salisbury Waters	-30.68	151.71	594	33	1973 - 2005
206026	Newholme	Sandy Ck	-30.42	151.66	8	31	1975 - 2005
207006	Birdwood(Filly Flat)	Forbes	-31.39	152.33	363	30	1976 - 2005
208001	Bobs Crossing	Barrington	-32.03	151.47	20	50	1955 - 2004
209001	Monkerai	Karuah	-32.24	151.82	203	34	1946 - 1979
209002	Crossing	Mammy Johnsons	-32.25	151.98	156	29	1976 - 2004
209003	Booral	Karuah	-32.48	151.95	974	32	1974 - 2005
209006	Willina	Wang Wauk	-32.16	152.26	150	27	1979 - 2005
209018	Dam Site	Karuah	-32.28	151.90	300	25	1980 - 2004
210011	Tillegra	Williams	-32.32	151.69	194	74	1932 - 2005
210014	Rouchel Brook (The Vale)	Rouchel Brook	-32.15	151.05	395	27	1975 - 2001
210017	Moonan Brook	Moonan Brook	-31.94	151.28	103	26	1980 - 2005

Station ID	Station Name	River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
210022	Halton	Allyn	-32.31	151.51	205	36	1970 - 2005
210040	Wybong	Wybong Ck	-32.27	150.64	676	43	1963 - 2005
210042	Ravensworth	Foy Brook	-32.40	151.05	170	30	1967 - 1996
210044	Middle Falbrook(Fal Dam Si	Glennies Ck	-32.45	151.15	466	32	1974 - 2005
210068	Pokolbin Site 3	Pokolbin Ck	-32.80	151.33	25	41	1965 - 2005
210076	Liddell	Antiene Ck	-32.34	150.98	13	30	1976 - 2005
210079	Gostwyck	Paterson	-32.55	151.59	956	31	1975 - 2005
210080	U/S Glendon Brook	West Brook	-32.47	151.28	80	27	1979 - 2005
211009	Gracemere	Wyong	-33.27	151.36	236	27	1979 - 2005
211013	U/S Weir	Ourimbah Ck	-33.35	151.34	83	29	1977 - 2005
212008	Bathurst Rd	Coxs	-33.43	150.08	199	30	1952 - 1981
212018	Glen Davis	Capertee	-33.12	150.28	1010	29	1972 - 2000
212040	Pomeroy	Kialla Ck	-34.61	149.54	96	25	1980 - 2004
213005	Briens Rd	Toongabbie Ck	-33.80	150.98	70	25	1980 - 2004
215004	Hockeys	Corang	-35.15	150.03	166	47	1958 - 2004
218002	Belowra	Tuross	-36.20	149.71	556	29	1955 - 1983
218005	D/S Wadbilliga R Junct	Tuross	-36.20	149.76	900	41	1955 - 2005
218007	Wadbilliga	Wadbilliga	-36.26	149.69	122	31	1975 - 2005
219003	Morans Crossing	Bemboka	-36.67	149.65	316	62	1944 - 2005
219017	near Brogo	Double Ck	-36.60	149.81	152	39	1967 - 2005
219022	Candelo Dam Site	Tantawangalo Ck	-36.73	149.68	202	34	1972 - 2005
219025	Angledale	Brogo	-36.62	149.88	717	29	1977 - 2005
220001	New Buildings Br	Towamba	-36.96	149.56	272	26	1955 - 1980
220003	Lochiel	Pambula	-36.94	149.82	105	39	1967 - 2005
220004	Towamba	Towamba	-37.07	149.66	745	35	1971 - 2005

Station ID	Station Name	River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
221002	Princes HWY	Wallagaraugh	-37.37	149.71	479	34	1972 - 2005
222004	Wellesley (Rowes)	Little Plains	-37.00	149.09	604	64	1942 - 2005
222007	Woolway	Wullwye Ck	-36.42	148.91	520	56	1950 - 2005
222009	The Falls	Bombala	-36.92	149.21	559	43	1952 - 1994
222015	Jacobs Ladder	Jacobs	-36.73	148.43	187	26	1976 - 2001
222016	The Barry Way	Pinch	-36.79	148.40	155	30	1976 - 2005
222017	The Hut	Maclaughlin	-36.66	149.11	313	27	1979 - 2005
401009	Maragle	Maragle Ck	-35.93	148.10	220	54	1950 - 2003
401013	Jingellic	Jingellic Ck	-35.90	147.69	378	32	1973 - 2004
401015	Yambla	Bowna Ck	-35.92	146.98	316	29	1975 - 2003
410038	Darbalara	Adjungbilly Ck	-35.02	148.25	411	28	1978 - 2005
410048	Ladysmith	Kyeamba Ck	-35.20	147.51	530	48	1939 - 1986
410057	Lacmalac	Goobarragandra	-35.33	148.35	673	48	1958 - 2005
410061	Batlow Rd	Adelong Ck	-35.33	148.07	155	58	1948 - 2005
410062	Numeralla School	Numeralla	-36.18	149.35	673	41	1965 - 2005
410076	Jerangle Rd	Strike-A-Light C	-35.92	149.24	212	30	1975 - 2004
410088	Brindabella (No.2&No.3-Cab	Goodradigbee	-35.42	148.73	427	38	1968 - 2005
410112	Jindalee	Jindalee Ck	-34.58	148.09	14	30	1976 - 2005
410114	Wyangle	Killimcat Ck	-35.24	148.31	23	29	1977 - 2005
411001	Bungendore	Mill Post Ck	-35.28	149.39	16	25	1960 - 1984
411003	Butmaroo	Butmaroo Ck	-35.26	149.54	65	25	1979 - 2003
412050	Narrawa North	Crookwell	-34.31	149.17	740	34	1970 - 2003
412063	Gunning	Lachlan	-34.74	149.29	570	39	1961 - 1999
412081	near Neville	Rocky Br Ck	-33.80	149.19	145	33	1969 - 2001
412083	Tuena	Tuena Ck	-34.02	149.33	321	33	1969 - 2001

Station ID	Station Name	River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
416003	Clifton	Tenterfield Ck	-29.03	151.72	570	25	1979 - 2003
416008	Haystack	Beardy	-29.22	151.38	866	33	1972 - 2004
416016	Inverell (Middle Ck)	Macintyre	-29.79	151.13	726	33	1972 - 2004
416020	Coolatai	Ottleys Ck	-29.23	150.76	402	26	1979 - 2004
416023	Bolivia	Deepwater	-29.29	151.92	505	26	1979 - 2004
418005	Kimberley	Copes Ck	-29.92	151.11	259	34	1972 - 2005
418014	Yarrowyck	Gwydir	-30.47	151.36	855	35	1971 - 2005
418017	Molroy	Myall Ck	-29.80	150.58	842	27	1979 - 2005
418021	Laura	Laura Ck	-30.23	151.19	311	27	1978 - 2004
418025	Bingara	Halls Ck	-29.94	150.57	156	26	1980 - 2005
418027	Horton Dam Site	Horton	-30.21	150.43	220	33	1972 - 2004
418034	Black Mountain	Boorolong Ck (North Arm	-30.30	151.64	14	29	1976 - 2004
419010	Woolbrook	Macdonald	-30.97	151.35	829	26	1980 - 2005
419016	Mulla Crossing	Cockburn	-31.06	151.13	907	32	1974 - 2005
419029	Ukolan	Halls Ck	-30.71	150.83	389	27	1979 - 2005
419051	Avoca East	Maules Ck	-30.50	150.08	454	29	1977 - 2005
419053	Black Springs	Manilla	-30.42	150.65	791	31	1975 - 2005
419054	Limbri	Swamp Oak Ck	-31.04	151.17	391	31	1975 - 2005
420003	Warkton (Blackburns)	Belar Ck	-31.39	149.20	133	27	1976 - 2002
421026	Sofala	Turon	-33.08	149.69	883	32	1974 - 2005
421036	below Dam Site	Duckmaloi	-33.75	149.94	112	25	1956 - 1980
421050	Molong	Bell	-33.03	148.95	365	30	1975 - 2004
416003	Clifton	Tenterfield Ck	-29.03	151.72	570	25	1979 - 2003

Table A3 Selected catchments from Tasmania

Station ID	Station Name	River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
302791	At Bashan Rd	Boggy Marsh Rivulet	-42.20	146.70	26.2	15	1994 - 2008
304040	U/S Derwent Junction	Florentine River	-42.40	146.50	435.8	58	1951 - 2008
304125	Below Lagoon	Travellers Rest River	-42.10	146.20	43.6	25	1949 - 1973
304136	Florentine at Eleven Rd Br	Florentine River	-42.60	146.40	166	14	1995 - 2008
304373	U/S Derwent	Broad River	-42.50	146.70	138.2	13	1963 - 1975
304446	At Catagunya Rd	Black Bobs Ck	-42.40	146.60	75.3	13	1963 - 1975
304597	At Lake Highway	Pine Tree Rivulet Ck	-41.80	146.70	19.4	40	1969 - 2008
308145	At Mount Ficham Track	Franklin River	-42.20	145.80	757	56	1953 - 2008
308183	Below Jane River	Franklin River	-42.50	145.80	1590.3	22	1957 - 1978
308225	Below Darwin Dam	Andrew River	-42.20	145.60	5.28	21	1988 - 2008
308274	At Park Boundary	Andrew River	-42.20	145.60	5.81	19	1990 - 2008
308446	Below Huntley	Gordon River	-42.70	146.40	458	27	1953 - 1979
308674	At Road Bridge	White Spur Creek	-41.90	145.50	12.9	15	1994 - 2008
308799	B/L Alma	Collingwood Ck	-42.20	145.90	292.5	28	1981 - 2008
308819	Above Kelly Basin Rd	Andrew River	-42.20	145.60	4.6	26	1983 - 2008
308850	Above White Spur	White Spur Creek	-41.90	145.50	14.4	10	1986 - 1995
309841	At Below Sailor Jack	King River	-42.20	145.50	731	11	1985 - 1995
309854	Above Henty River	Lost Creek	-42.10	145.30	30	11	1986 - 1996
310061	At Murchison Highway	Que River	-41.60	145.70	18.4	22	1987 - 2008
310077	Above Rosebery	Stitt River	-41.80	145.50	34	18	1991 - 2008
310148	Above Sterling	Murchison River	-41.80	145.60	756.3	28	1955 - 1982
310149	Below Sophia River	Mackintosh River	-41.70	145.60	523.2	27	1954 - 1980
310472	Below Bulgobac Creek	Que River	-41.60	145.60	119.1	32	1964 - 1995

Station ID	Station Name	River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
310807	Below Quehatfield	Huskisson River	-41.60	145.50	298	15	1994 - 2008
312204	At Hampshire	Loud Water Ck	-41.30	145.80	13.6	18	1964 - 1981
314821	At Mayday Road	Leven River	-41.50	145.80	37.6	12	1983 - 1994
315074	At Moina	Wilmot River	-41.5	146.1	158.1	46	1923 - 1968
315450	U/S Lemonthyme	Forth River	-41.60	146.10	311	46	1963 - 2008
315815	At Middlesex Plains	Iris River	-41.50	146.00	35.64	15	1994 - 2008
316624	Above Mersey	Arm River	-41.70	146.20	86	37	1972 - 2008
316632	At Weir	Gun Lagoon River	-41.70	146.30	9.1	11	1997 - 2007
318065	Below Deloraine	Meander River	-41.50	146.70	474	28	1969 - 1996
318225	At Deddington	Nile River	-41.60	147.50	181	14	1983 - 1996
318350	Above Rocky Creek	Whyte River	-41.60	145.20	310.8	33	1960 - 1992

Table A4 Selected catchments from Queensland

Station ID	Station and River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
102101A	Pascoe River at Fall Creek	-12.88	142.98	651	33	1967-2005
104001A	Stewart River at Telegraph Road	-14.17	143.39	470	32	1970-2005
105002A	Jungle Creek at Kalinga	-15.35	143.77	306	17	1970-1988
105104A	Deighton River at Deighton	-15.49	144.53	590	18	1969-1988
105105A	East Normanby River at Developmenta	-15.77	145.01	297	34	1969-2005
106001A	McIvor River at Elderslie	-15.13	145.09	175	17	1969-1988
106002A	Jeannie River at Wakooka Road	-14.76	144.86	323	16	1970-1988
106003A	Starcke River at Causeway	-14.82	144.97	192	16	1970-1988
107001B	Endeavour River at Flaggy	-15.42	145.07	337	34	1967-2005
107002A	Annan River at Mount Simon	-15.64	145.19	373	19	1969-1991
107003A	Annan River at Beesbike	-15.69	145.21	247	11	1990-2005
108002A	Daintree River at Bairds	-16.18	145.28	911	29	1968-2005
108003A	Bloomfield River at China Camp	-15.99	145.29	264	32	1970-2005
108008A	Whyanbeel Creek at Upstream Little	-16.39	145.34	15	12	1990-2005
110003A	Barron River at Picnic Crossing	-17.26	145.54	228	80	1925-2005
110004B	Emerald Creek at Malones	-16.99	145.49	58	21	1941-1963
110011B	Flaggy Creek at Recorder	-16.78	145.53	150	44	1955-2005
110013A	Clohesy River at Main Road	-16.91	145.56	78	18	1956-1981
110017A	Kauri Creek at Main Road	-17.13	145.60	15	12	1991-2005
110018A	Mazlin Creek at Railway Bridge	-17.23	145.55	53	14	1991-2005
110101B	Freshwater Creek at Freshwater	-16.94	145.70	70	11	1947-1959
111001A	Mulgrave River at Gordonvale	-17.10	145.79	552	43	1916-1973
111003C	Behana Creek at Aloomba	-17.13	145.84	86	28	1942-1971
111005A	Mulgrave River at The Fisheries	-17.19	145.72	357	34	1966-2005

Station ID	Station and River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
111007A	Mulgrave River at Peets Bridge	-17.14	145.76	520	31	1972-2005
111104A	Russell River at Powerline	-17.42	145.92	224	21	1966-1989
111105A	Babinda Creek at The Boulders	-17.35	145.87	39	29	1966-2005
112004A	North Johnstone River at Tung Oil	-17.55	145.93	925	31	1966-2005
112101B	South Johnstone River at Upstream C	-17.61	145.98	400	23	1974-2005
112102A	Liverpool Creek at Upper Japoonvale	-17.72	145.90	78	24	1970-2005
113002A	Tully River at Koombooloomba	-17.83	145.60	164	14	1949-1964
113003A	Nitchaga Creek at Upper Tully	-17.83	145.56	72	14	1949-1964
113004A	Cochable Creek at Powerline	-17.75	145.63	95	32	1966-2005
113007A	Koolmoon Creek at Ebony Road	-17.73	145.56	29	17	1986-2005
114001A	Murray River at Upper Murray	-18.11	145.80	156	31	1970-2005
116005B	Stone River at Peacocks Siding	-18.69	145.98	368	36	1935-1972
116011A	Millstream at Ravenshoe	-17.60	145.48	89	42	1960-2005
116012A	Cameron Creek at 8.7km	-18.07	145.34	360	41	1961-2005
116013A	Millstream at Archer Creek	-17.65	145.34	308	42	1961-2005
116014A	Wild River at Silver Valley	-17.63	145.30	591	44	1961-2005
116015A	Blunder Creek at Wooroora	-17.74	145.44	127	38	1966-2005
116017A	Stone River at Running Creek	-18.77	145.95	157	33	1970-2005
117002A	Black River at Bruce Highway	-19.24	146.63	256	31	1973-2005
117003A	Bluewater Creek at Bluewater	-19.18	146.55	86	30	1973-2005
118003A	Bohle River at Hervey Range Road	-19.32	146.70	143	20	1985-2005
118004A	Little Bohle River at Middle Bohle	-19.33	146.68	54	20	1985-2005
118101A	Ross River at Gleesons Weir	-19.32	146.74	797	44	1915-1961
118106A	Alligator Creek at Allendale	-19.39	146.96	69	30	1974-2005
119004A	Bullock Creek at Bomb Range	-19.70	146.92	59	20	1971-1993

Station ID	Station and River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
119006A	Major Creek at Damsite	-19.67	147.02	468	25	1978-2005
120014A	Broughton River at Oak Meadows	-20.18	146.32	182	28	1970-1999
120102A	Keelbottom Creek at Keelbottom	-19.37	146.36	193	38	1967-2005
120114A	Douglas Creek at Kangaroo Hills	-18.93	145.67	663	18	1969-1988
120115A	Gray Creek at Carter's Mill	-19.02	144.98	938	18	1969-1988
120116A	Maryvale Creek at Maryvale	-19.59	145.22	132	12	1969-1982
120117A	Wyandotte Creek at Wyandotte	-18.75	144.83	523	17	1970-1988
120119A	Fanning River at Fanning River	-19.72	146.44	498	14	1974-1993
120120A	Running River at Mt. Bradley	-19.13	145.91	490	30	1975-2005
120203A	Bee Creek at Upsan Downs	-21.11	148.46	19	12	1955-1968
120204B	Broken River at Crediton Recorder	-21.17	148.51	41	24	1963-1988
120212A	Emu Creek at The Saddle	-20.80	148.16	431	18	1969-1988
120213A	Grant Creek at Grass Humpy	-20.82	148.31	325	18	1969-1988
120220A	Pelican Creek at Kerale	-20.60	147.70	528	13	1992-2005
120307A	Cape River at Pentland	-20.48	145.47	775	34	1969-2005
120308A	Rollston River at Pallamana	-20.61	146.64	735	17	1970-1988
121001A	Don River at Ida Creek	-20.29	148.12	604	48	1957-2005
121002A	Elliot River at Guthalungra	-19.94	147.84	273	32	1973-2005
122004A	Gregory River at Lower Gregory	-20.30	148.55	47	33	1972-2005
124002A	St.Helens Creek at Calen	-20.91	148.76	118	32	1973-2005
124003A	Andromache River at Jochheims	-20.58	148.47	230	29	1976-2005
125002C	Pioneer River at Sarich's	-21.27	148.82	757	43	1958-2005
125004B	Cattle Creek at Gargett	-21.18	148.74	326	38	1967-2005
125006A	Finch Hatton Creek at Dam Site	-21.11	148.63	35	29	1976-2005
126002A	Plane Creek at Sarina	-21.43	149.23	92	15	1972-1988

Station ID	Station and River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
126003A	Carmila Creek at Carmila	-21.92	149.40	84	31	1973-2005
130004A	Raglan Creek at Old Station	-23.82	150.82	389	41	1963-2005
130006A	Gogango Creek at Evergreen	-23.69	150.10	436	15	1972-1988
130008A	Neerkol Creek at Neerkol	-23.48	150.34	503	18	1987-2005
130108B	Blackwater Creek at Curragh	-23.50	148.88	776	15	1990-2005
130207A	Sandy Creek at Clermont	-22.80	147.58	409	40	1965-2005
130208A	Theresa Creek at Ellendale	-22.98	147.58	758	37	1964-2005
130211B	Wolfang Creek at Innisfree	-22.67	147.72	438	11	1976-1988
130214A	Kettle Creek at Fork Lagoon	-23.44	147.96	401	15	1972-1988
130215A	Crinum Creek at Lilyvale Lagoon	-23.21	148.34	252	29	1976-2005
130308A	Lonesome Creek at Gonyelinka	-24.81	150.22	165	18	1948-1968
130319A	Bell Creek at Craiglands	-24.15	150.52	300	44	1960-2005
130321A	Kroombit Creek at Mt. Kroombit	-24.41	150.72	373	41	1963-2005
130334A	South Kariboe Creek at Pump Station	-24.56	150.75	284	33	1972-2005
130335A	Dee River at Wura	-23.77	150.36	472	34	1971-2005
130336A	Grevillea Creek at Folding Hills	-24.58	150.62	233	33	1972-2005
130339A	Conciliation Creek at Barranga	-24.45	149.35	407	15	1972-1988
130347A	Callide Creek at AMTD 96.0 Km	-24.33	150.68	415	16	1986-2002
130348A	Prospect Creek at Red Hill	-24.45	150.42	369	30	1975-2005
130349A	Don River at Kingsborough	-23.97	150.39	593	28	1976-2005
130353A	Stag Creek at Malakoff Junction	-24.31	150.78	52	16	1986-2002
130402A	Isaac River at Burton Gorge	-21.63	148.12	551	21	1964-1988
130405A	Funnel Creek at Colston Park	-21.56	149.10	108	19	1965-1988
130407A	Nebo Creek at Nebo	-21.68	148.68	258	21	1965-1988
130408A	Lotus Creek at Main Road	-22.35	149.10	556	21	1966-1988

Station ID	Station and River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
130409A	Phillips Creek at Tayglen	-22.52	148.31	344	17	1968-1988
130415A	Scott Creek at Norwich Park	-22.71	148.39	388	15	1972-1988
130503A	Carnarvon Creek at Wyseby Station	-24.97	148.53	561	21	1966-1992
130505A	Humboldt Creek at Sunlight	-24.28	148.78	356	16	1971-1988
130507A	Planet Creek at Planet Downs	-24.54	148.91	776	20	1972-1993
130508A	Meteor Creek at Springwood	-24.57	148.28	541	15	1972-1988
130509A	Carnarvon Creek at Rewan	-24.98	148.39	351	19	1985-2005
132002A	Calliope River at Mount Alma	-24.07	150.83	165	19	1968-1988
132004A	Munduran Creek at Rundle Hills	-23.70	151.03	60	24	1978-2005
133003A	Diglum Creek at Marlua	-24.19	151.16	203	36	1968-2005
135002A	Kolan River at Springfield	-24.75	151.59	551	40	1965-2005
135006A	Croome Creek at Moore Park Road	-24.75	152.27	17	14	1968-1983
136006A	Reid Creek at Dam Site	-25.27	151.52	219	40	1965-2005
136011A	Degilbo Creek at Coringa	-25.38	151.99	687	17	1986-2005
136102A	Three Moon Creek at Meldale	-24.69	150.96	310	32	1948-1981
136107A	Three Moon Creek at Cania Gorge	-24.73	151.01	370	26	1962-1989
136108A	Monal Creek at Upper Monal	-24.61	151.11	92	43	1962-2005
136110A	Baywulla Creek at The Gorge	-25.08	151.38	168	22	1964-1988
136111A	Splinter Creek at Dakiel	-24.75	151.26	139	41	1964-2005
136112A	Burnett River at Yarrol	-24.99	151.35	370	40	1965-2005
136118A	Eastern Creek at Lands End	-25.22	151.27	450	19	1986-2005
136202D	Barambah Creek at Litzows	-26.30	152.04	681	41	1964-2005
136203A	Barker Creek at Brooklands	-26.74	151.82	249	64	1940-2005
136204A	Barker Creek at Nanango Weir HW	-26.65	151.92	629	21	1953-1988
136301B	Stuart River at Weens Bridge	-26.50	151.77	512	36	1935-2005

Station ID	Station and River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
137001B	Elliott River at Elliott	-24.99	152.37	220	42	1958-2005
137003A	Elliott River at Dr Mays Crossing	-24.97	152.42	251	30	1974-2005
137102A	Sandy Creek at Eureka	-25.34	152.14	158	21	1966-1988
137202A	Oaky Creek at Childers	-25.29	152.29	161	21	1966-1988
138002C	Wide Bay Creek at Brooyar	-26.01	152.41	655	38	1966-2005
138003D	Glastonbury Creek at Glastonbury	-26.22	152.52	113	26	1979-2005
138009A	Tinana Creek at Tagigan Road	-26.08	152.78	100	31	1974-2005
138010A	Wide Bay Creek at Kilkivan	-26.08	152.22	322	97	1974-2005
138101B	Mary River at Kenilworth	-26.60	152.73	720	47	1925-1974
138102C	Amamoor Creek at Zachariah	-26.37	152.62	133	21	1984-2005
138103A	Kandanga Creek at Knockdomny	-26.40	152.64	142	34	1920-1955
138104A	Obi Obi Creek at Kidaman	-26.63	152.77	174	42	1920-1964
138106A	Obi Obi Creek at Baroon Pocket	-26.71	152.86	67	39	1940-1987
138107B	Six Mile Creek at Cooran	-26.33	152.81	186	24	1981-2005
138108A	Kandanga Creek at Upper Kandanga	-26.40	152.63	139	17	1955-1973
138110A	Mary River at Bellbird Creek	-26.63	152.70	486	45	1959-2005
138111A	Mary River at Moy Pocket	-26.53	152.74	820	39	1963-2005
138113A	Kandanga Creek at Hygait	-26.39	152.64	143	34	1971-2005
138120A	Obi Obi Creek at Gardners Falls	-26.76	152.87	26	16	1986-2005
138903A	Tinana Creek at Bauple East	-25.82	152.72	783	22	1981-2005
140002A	Teewah Creek near Coops Corner	-26.06	153.04	53	27	1972-2005
141001B	South Maroochy River at Kiamba	-26.59	152.90	33	19	1985-2005
141002A	South Maroochy River at Kureelpa	-26.60	152.89	20	14	1952-1967
141003C	Petrie Creek at Warana Bridge	-26.62	152.96	38	26	1978-2005
141004B	South Maroochy River at Yandina	-26.56	152.94	75	22	1982-2005

Station ID	Station and River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
141006A	Mooloolah River at Mooloolah	-26.76	152.98	39	33	1971-2005
141008A	Eudlo Creek at Kiels Mountain	-26.66	153.02	62	22	1982-2005
141009A	North Maroochy River at Eumundi	-26.50	152.96	38	22	1982-2005
142001A	Caboolture River at Upper Caboolture	-27.08	152.89	94	40	1965-2005
142201D	South Pine River at Cashs Crossing	-27.34	152.96	178	12	1951-1964
142202A	South Pine River at Drapers Crossin	-27.35	152.92	156	39	1965-2005
143006A	Cressbrook Creek at Tinton	-27.20	152.30	422	24	1952-1986
143010B	Emu Creek at Boat Mountain	-26.98	152.29	915	23	1976-2005
143011A	Emu Creek at Raeburn	-27.05	152.00	439	20	1965-1989
143013A	Cressbrook Creek at the Damsite	-27.26	152.21	321	13	1965-1981
143015B	Cooyar Creek at Damsite	-26.74	152.14	963	14	1990-2005
143033A	Oxley Creek at New Beith	-27.73	152.95	60	25	1976-2005
143101A	Warrill Creek at Mutdapily	-27.75	152.69	771	39	1914-1957
143102B	Warrill Creek at Kalbar No.2	-27.92	152.60	468	12	1958-1971
143103A	Reynolds Creek at Moogerah	-28.03	152.55	190	36	1917-1954
143104B	Bremer River at Rosevale	-27.87	152.49	67	14	1952-1973
143107A	Bremer River at Walloon	-27.60	152.69	622	36	1961-2005
143108A	Warrill Creek at Amberley	-27.67	152.70	914	36	1961-2005
143110A	Bremer River at Adams Bridge	-27.83	152.51	125	29	1968-2005
143203C	Lockyer Creek at Helidon Number 3	-27.54	152.11	357	16	1987-2005
143208A	Fifteen Mile Creek at Dam Site	-27.46	152.10	87	26	1956-1989
143209B	Laidley Creek at Mulgowie	-27.73	152.36	167	27	1967-2005
143212A	Tenthill Creek at Tenthill	-27.64	152.21	447	29	1968-2005
143214A	Flagstone Creek at Windolfs	-27.62	152.11	142	13	1972-1986
143215A	Laidley Creek at Mulgowie Weir	-27.75	152.37	154	13	1972-1986

Station ID	Station and River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
143219A	Murphys Creek at Spring Bluff	-27.47	151.98	18	21	1979-2005
143229A	Laidley Creek at Warrego Highway	-27.56	152.39	450	15	1990-2005
143303A	Stanley River at Peachester	-26.84	152.84	104	77	1927-2005
143306A	Reedy Creek at Upstream Byron Creek	-27.14	152.64	56	26	1975-2005
143307A	Byron Creek at Causeway	-27.13	152.65	79	26	1975-2005
143921A	Cressbrook Creek at Rosentreters Br	-27.14	152.33	447	17	1986-2005
145003B	Logan River at Forest Home	-28.20	152.77	175	51	1953-2005
145005A	Running Creek at Avonmore	-28.30	152.91	89	30	1922-1953
145007A	Christmas Creek at Hillview	-28.22	153.00	132	20	1954-1975
145010A	Running Creek at Deickmans Bridge	-28.25	152.89	128	40	1965-2005
145011A	Teviot Brook at Croftby	-28.15	152.57	83	38	1966-2005
145012A	Teviot Brook at the Overflow	-27.93	152.86	503	39	1966-2005
145013A	Christmas Creek at Rudds Lane	-28.17	152.98	157	20	1967-1989
145020A	Logan River at Rathdowney	-28.22	152.87	533	32	1973-2005
145101D	Albert River at Lumeah Number 2	-28.06	153.04	169	49	1953-2005
145102B	Albert River at Bromfleet	-27.91	153.11	544	74	1927-2005
145103A	Cainbable Creek at Dam Site	-28.09	153.08	42	32	1962-2005
145104A	Canungra Creek at 32.2km	-28.06	153.12	76	22	1965-1989
145107A	Canungra Creek at Main Road Bridge	-28.00	153.16	101	32	1973-2005
146001A	Coomera River at Withern	-28.05	153.19	80	19	1918-1954
146003B	Currumbin Creek at Camberra Number	-28.20	153.41	24	28	1954-1983
146004A	Little Nerang Creek at Neranwood	-28.13	153.29	40	35	1926-1962
146005A	Tallebudgera Creek at Chippendale	-28.16	153.40	55	27	1926-1969
146012A	Currumbin Creek at Nicolls Bridge	-28.18	153.42	30	31	1970-2005
146014A	Back Creek at Beechmont	-28.12	153.19	7	31	1971-2005

Station ID	Station and River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
146020A	Mudgeeraba Creek at Springbrook Roa	-28.09	153.35	36	15	1989-2005
146095A	Tallebudgera Creek at Tallebudgera	-28.15	153.40	56	29	1970-2005
416303C	Pike Creek at Clearview	-28.81	151.52	950	48	1975-1988
416305B	Brush Creek at Beebo	-28.69	150.98	335	36	1968-2005
416312A	Oaky Creek at Texas	-28.81	151.15	422	35	1969-2005
416317A	Broadwater Creek at Dam Site	-28.60	151.89	108	16	1987-2005
416404C	Bracker Creek at Terraine	-28.49	151.28	685	31	1966-2002
416410A	Macintyre Brook at Barongarook	-28.44	151.46	465	32	1967-2002
422210A	Bungil Creek at Tabers	-26.41	148.78	710	32	1966-2005
422305A	Emu Creek at Gillespies	-28.22	152.28	98	22	1919-1946
422306A	Swan Creek at Swanfels	-28.16	152.28	83	85	1919-2005
422307A	Kings Creek at Kings Creek	-27.90	151.91	334	42	1920-1967
422311A	Rosenthal Creek at Gilmours	-28.37	152.01	91	17	1928-1946
422313B	Emu Creek at Emu Vale	-28.23	152.23	148	32	1972-2005
422317B	Glengallan Creek at Rocky Pond	-28.13	151.92	520	38	1953-1992
422318A	Sandy Creek at Allan	-28.19	151.94	650	13	1949-1963
422319B	Dalrymple Creek at Allora	-28.04	152.01	246	36	1968-2005
422321B	Spring Creek at Killarney	-28.35	152.33	35	32	1972-2005
422326A	Gowrie Creek at Cranley	-27.52	151.94	47	34	1969-2005
422331A	Westbrook Creek at Arcadia	-27.51	151.76	256	10	1967-1981
422332B	Gowrie Creek at Oakey	-27.47	151.74	142	12	1992-2005
422337A	Brigalow Creek at Meandarra	-27.31	149.89	340	13	1972-1992
422338A	Canal Creek at Leyburn	-28.03	151.59	395	27	1972-2005
422339A	Jimbour Creek at Bunginie	-26.91	151.28	235	19	1972-1992
422341A	Condamine River at Brosnans Barn	-28.33	152.31	92	29	1976-2005

Station ID	Station and River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
422352A	Hodgson Creek at Balgownie	-27.83	151.69	560	17	1987-2005
422394A	Condamine River at Elbow Valley	-28.37	152.14	325	32	1972-2005
422405A	Johnson Creek at Womalillac	-26.78	147.90	365	16	1971-1992
912112A	Seymour River at Main Road	-19.34	139.01	289	17	1970-1988
912113A	Elizabeth Creek at Mining Camp	-18.22	138.36	670	13	1974-1988
912115A	O Shannassy River at Morestone	-19.60	138.38	425	17	1970-1988
913005A	Paroo Creek at Damsite	-20.34	139.52	305	19	1968-1988
913009A	Gorge Creek at Flinders Highway	-20.69	139.65	248	17	1970-1988
913010A	Fiery Creek at 16 Mile Waterhole	-18.88	139.36	722	29	1972-2005
915006A	Mountain Creek at Revenue Downs	-20.64	143.22	203	17	1970-1988
915011A	Porcupine Creek at Mt Emu Plains	-20.18	144.52	540	31	1971-2005
915205A	Malbon River at Black Gorge	-21.06	140.08	425	17	1970-1988
915206A	Dugald River at Railway Crossing	-20.20	140.22	660	31	1969-2005
915211A	Williams River at Landsborough High	-20.87	140.83	415	31	1970-2005
916002A	Norman River at Strathpark	-19.54	143.26	285	18	1969-1988
916003A	Moonlight Creek at Alehvale	-18.28	142.34	127	18	1969-1989
917005A	Agate Creek at Cave Creek Junction	-18.93	143.47	218	18	1969-1988
917007A	Percy River at Ortana	-19.16	143.50	526	18	1969-1988
917008A	Little River at Inorunie	-18.27	142.68	436	17	1971-1993
917104A	Etheridge River at Roseglen	-18.31	143.58	867	32	1967-2005
917107A	Elizabeth Creek at Mount Surprise	-18.14	144.31	651	32	1968-2005
917114A	Routh Creek at Beef Road	-18.29	143.70	81	23	1972-2005
918002A	Mentana Creek at Mentana Yards	-16.38	142.10	591	16	1972-1989
919001B	Mary Creek at Mary Farms	-16.57	145.19	89	15	1962-1989
919005A	Rifle Creek at Fonthill	-16.68	145.23	366	32	1968-2005

Station ID	Station and River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
919013A	McLeod River at Mulligan Highway	-16.50	145.00	532	25	1973-2005
919201A	Palmer River at Goldfields	-16.11	144.78	533	30	1967-2005
919205A	North Palmer River at 4.8 Km	-16.01	144.29	420	14	1973-1988
919305B	Walsh River at Nullinga	-17.18	145.30	326	35	1956-2005
919312A	Elizabeth Creek at Greenmantle	-16.66	144.11	629	18	1969-1988
921001A	Holroyd River at Ebagoola	-14.25	143.17	379	17	1970-1988
922101B	Coen River at Racecourse	-13.96	143.17	172	32	1967-2005
924001A	Embley River at Kurracoo Creek	-12.82	142.18	363	14	1971-1986
924101A	Mission River at York Downs	-12.61	142.25	544	14	1973-1988
925002A	Wenlock River at Wenlock	-13.10	142.94	718	17	1969-1992
926001A	Ducie River at Bertiehaugh	-12.13	142.38	636	17	1968-1988
926002A	Dulhunty River at Dougs Pad	-11.83	142.42	332	30	1970-2005
926003A	Bertie Creek at Swordgrass Swamp	-11.83	142.51	142	17	1972-1991
919013A	McLeod River at Mulligan Highway	-16.50	145.00	532	25	1973-2005
919201A	Palmer River at Goldfields	-16.11	144.78	533	30	1967-2005
919205A	North Palmer River at 4.8 Km	-16.01	144.29	420	14	1973-1988

Table A5 Selected catchments from South Australia

Station ID	Station Name	River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
A4260504	4KM East of Yundi	Finniss	-35.32	138.67	191	38	1970-2007
A4260529	U/S Cambrai	Marne	-34.68	139.23	239	29	1973-2005
A4260533	near Hartley	Bremer	-35.21	139.01	473	34	1974-2007
A4260536	Worlds end	Burra Ck	-33.84	139.09	704	31	1974-2004
A4260557	D/S Mt. Barker	Mount Barker Ck	-35.09	138.92	88	28	1980-2007
A4260558	Dawesley	Dawesley Ck	-35.04	138.95	43	29	1979-2007
A5020502	U/S Dam and Rd Br	Myponga	-35.38	138.48	76.5	29	1979-2007
A5030502	Scott Bottom	Scott Ck	-35.10	138.68	26.8	38	1970-2007
A5030503	4.5KM Wnw Kangarilla	Baker Gully	-35.14	138.61	48.7	28	1970-2007
A5030504	Houlgrave	Onkaparinga	-35.08	138.73	321	34	1974-2007
A5030506	U/S Mt Bold Res.	Echunga Ck	-35.13	138.73	34.2	34	1974-2007
A5030507	Lenswood	Lenswood Ck	-34.94	138.82	16.5	29	1973-2007
A5030508	Craigbank	Inverbrackie ck	-34.95	138.93	8.4	34	1973-2007
A5030509	Aldgate Rly Stn	Aldgate Ck	-35.02	138.73	7.8	30	1973-2007
A5030526	Uraidla	Cox Ck	-34.97	138.74	4.3	25	1977-2007
A5030529	U/S Mt Bold Reservoir	Burnt Out Ck	-35.13	138.71	0.6	18	1978-2007
A5040500	Gumeracha Weir	Torrens	-34.82	138.85	194	66	1941-2007
A5040512	Mt Pleasant	Torrens	-34.79	139.03	26	34	1974-2007
A5040517	Waterfall Gully	First Ck	-34.97	138.68	5	27	1977-2003
A5040518	U/S Minno Ck junction	Sturt	-35.04	138.63	19	30	1978-2007
A5040523	Castambul	Sixth Ck	-34.87	138.76	44	29	1978-2007
A5040525	U/S Millbrook Res	Kersbrook Ck	-34.81	138.84	23	17	1990-2007
A5050502	Yaldara	North Para	-34.57	138.88	384	35	1973-2007
A5050504	Turretfield	North Para	-34.56	138.77	708	35	1973-2007

Station ID	Station Name	River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
A5050517	Penrice	North Para	-34.46	139.06	118	30	1978-2007
A5060500	near Rhynie	Wakefield	-34.10	138.63	417	48	1957-2007
A5070500	near Andrews	Hill	-33.61	138.63	235	38	1970-2007
A5070501	near Spalding	Hutt	-33.54	138.60	280	37	1970-2006
A5090503	Old Kanyaka Ruins	Kanyaka Ck	-32.10	138.29	180	33	1974-2006
A5130501	U/S Gorge Falls (K.I.)	Rocky	-35.96	136.70	190	34	1974-2007

Table A6 Selected catchments from Northern Territory

Station ID	Station and River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
G0010006	James River at Avon Downs Police Station	-20.02	137.50	506	23	1965 -1987
G0010008	Algamba Creek at Tarlton Downs Homestead	-22.57	136.82	37	19	1969 -1987
G0010009	Shakespeare Creek at U/s Lily Waterhole	-20.22	137.67	398	19	1969 -1987
G0050005	Jay Creek at Ildjarabada	-23.77	133.52	181	13	1970 -1982
G0050006	Jay Creek at Pyberinge	-23.72	133.54	115	26	1970 -1995
G0050154	Hugh River at Stuart Pass	-23.73	133.34	123	15	1973 -1987
G0050156	Hugh River at Birthday Gap	-23.75	133.32	287	15	1973 -1987
G0060003	Gillen Creek at Soil Erosion Project	-23.70	133.82	3.8	28	1967 -1994
G0060005	Trephina Creek at Trephina Gorge	-23.54	134.38	417	42	1967 -2008
G0060006	Tug Creek at Red Ochre Dam	-23.28	134.74	256	16	1972 -1987
G0060008	Roe Creek at South Road Xing	-23.82	133.84	560	37	1972 -2008
G0060009	Todd River at Wills Tce	-23.70	133.89	443	50	1959 -2008
G0060011	Star Creek at Ruby Gorge	-23.45	134.94	132	20	1968 -1987
G0060012	Station Creek at Bond Springs	-23.53	133.92	34	12	1972 -1983
G0060013	Phillipson Creek at Santa Rodinga	-24.08	134.45	197	28	1968 -1995
G0060015	Station Creek at Bond Springs	-23.53	133.92	34	18	1978 -1995
G0060017	Emily Creek at U/s Undoolya Road	-23.69	133.98	60	28	1981 -2008
G0060040	Todd River at Amoonguna	-23.76	133.92	600	31	1978 -2008
G0060046	Todd River at Wigley Gorge	-23.64	133.88	360	37	1972 -2008
G0060047	Charles river at Big Dipper	-23.65	133.86	52	51	1958 -2008
G0060126	Todd River at Heavitree Gap	-23.73	133.87	502	50	1959 -2008
G0070002	Euroba Creek at Euroba Gorge	-22.70	135.74	26	20	1968 -1987
G0070004	Entire River at Plenty Highway	-22.92	135.19	622	19	1969 -1987
G0070007	Huckitta Creek at Quartz Hill Mine	-22.78	135.64	142	4	1969 -1972
G0070009	Unca Creek at Jervois Mine	-22.65	136.24	16	37	1972 -2008
G0280006	Powell Creek at telegraph Station	-18.08	133.66	105	22	1966 -1987
G0280010	Woodforde River at Arden Soak Bore	-22.37	133.32	393	35	1974 -2008

Station ID	Station and River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
G0280114	McLaren Creek at Stuart Highway	-20.34	134.23	417	45	1964 -2008
G0290012	Kelly Creek at Kelly Well Stuart Highway	-19.97	134.21	62	35	1974 -2008
G0290227	Morphett Creek at Stuart Highway	-18.88	134.09	211	19	1965 -1983
G0290228	Morphett Creek at D/s Stuart Highway	-18.88	134.09	211	30	1979 -2008
G0290240	Tennant Creek at Old Telegraph	-19.56	134.23	72	37	1972 -2008
G0290242	Attack Creek at Stuart Highway	-19.01	134.15	259	23	1965 -1987
G8150233	PALMERSTON CATCHMENT URB.DRAIN AT McARTHUR PARK	-12.49	130.98	1	26	1983 -2008
G8150003	SANDY CREEK AT CASUARINA HOSPITAL	-12.37	130.89	2	8	1974 -1981
G8200083	Catchment G at Kapalga Research Station	-12.62	132.39	6	17	1992 -2008
G8140062	COPPERFIELD CREEK AT CHINAMANS CAMP	-13.83	131.79	9	16	1972 -1987
G8150036	Bees Creek at Horne Road	-12.59	131.06	9	8	2001 -2008
G8160001	BLUEWATER CREEK AT GARDEN POINT	-11.40	130.44	11	21	1966 -1986
G8170085	Acacia Creek At Stuart Highway	-12.78	131.12	11	46	1963 -2008
G8170059	LEN GRAHAM CREEK AT UPSTREAM FOGG DAM	-12.58	131.29	13	13	1957 -1969
G8260054	Yirrkala Creek At Yirrkala Mission	-12.25	136.89	14	45	1964 -2008
G8180065	Opium Creek At Old Point Stuart Road Crossing	-12.55	131.79	15	24	1963 -1986
G8200049	Koongarra Creek At Near Nourlangie Rock	-12.88	132.83	15	30	1977 -2006
G8160003	TARAKUMBY CREEK AT PINE PLANTATION	-11.61	130.71	17	21	1966 -1986
G8150127	Rapid Creek Downstream Mcmillans Road	-12.39	130.87	18	49	1960 -2008
G8210026	Baralil Creek At Arnhem Highway Crossing	-12.67	132.86	21	9	1978 -1986
G8260134	North River At Near Conveyer Terminal	-12.23	136.79	22	19	1963 -1981
G8140013	BILLYCAN CREEK AT PIG HOLE	-13.64	131.11	26	10	1968 -1977
G8170075	Manton River At Upstream Manton Dam	-12.88	131.13	28	46	1963 -2008
G8260052	Upper Latram River At Upstream Eldo Road Crossing	-12.32	136.82	31	43	1966 -2008
G8100301	GUM CREEK AT THE HILL	-15.37	128.85	32	38	1971 -2008
G8230258	Gudjarama Creek At Maningrida	-12.10	134.30	33	16	1966 -1981
G8170062	BURRELL CREEK AT EIGHTY-SEVEN MILE JUMP UP	-13.42	131.15	36	30	1957 -1986
G8170089	Snake Creek At Stuart Highway	-13.23	131.09	37	11	1959 -1969
G8150096	Carawarra Creek at Cox Peninsula Road	-12.53	130.67	38	44	1965 -2008

Station ID	Station and River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
G8260001	Rinderry Creek At Damsite	-12.31	136.62	43	21	1966 -1986
G8110222	WALSH CREEK AT SUGARLOAF HILL	-16.37	130.85	45	13	1965 -1977
G8210012	Gulungul Creek (Boggy Creek) At George Town Crossing	-12.69	132.89	47	23	1971 -1993
G8170076	Stapleton Creek At Stuart Highway	-13.18	131.10	50	24	1958 -1981
G8150151	Celia Creek Upstream Darwin River Dam	-12.91	131.05	52	37	1972 -2008
G8150200	EAST FINNISS RIVER AT RUM JUNGLE ROAD CROSSING + EB6	-12.99	131.00	52	28	1981 -2008
G9010002	Wyonga River At East Arm	-12.87	136.37	54	19	1968 -1986
G8150097	East Finnis River at Rum Jungle	-12.97	130.97	71	44	1965 -2008
G8210037	Cooper Creek At Rainbow Flat	-12.33	133.40	81	7	1979 -1985
G8170066	Coomalie Creek At Stuart Highway	-13.01	131.12	82	51	1958 -2008
G8260053	Lower Latram River At Above Tidal Reach	-12.31	136.78	85	23	1963 -1985
G8100189	Moriarty Creek at Victoria Highway	-16.07	129.19	88	20	1967 -1986
G9030090	Chambers Creek At Wattle Hill	-14.50	133.36	89	21	1973 -1993
G8150018	Elizabeth River at Stuart Highway	-12.61	131.07	101	56	1953 -2008
G8260219	Giddy River At Yirrkala Road Crossing	-12.36	136.71	111	21	1966 -1986
G8110184	MIDDLE CREEK AT V.R.D. ROAD CROSSING	-16.38	131.22	120	19	1963 -1981
G8170008	Adelaide River Downstream Daly Road	-13.42	131.09	122	28	1981 -2008
G8180252	Harriet Creek At Downstream El Sherana Road	-13.68	131.99	122	44	1965 -2008
G8170006	Bridge Creek At Upstream Railway	-13.42	131.31	126	43	1966 -2008
G8140158	McAddens Creek at Dam Site	-14.35	132.34	133	47	1962 -2008
G8150028	Berry Creek U/S Cox Peninsula Road	-14.35	132.34	136	10	1999 -2008
G8110074	Montejnnie Creek at Montejinni Homestead	-16.67	131.75	139	14	1973 -1986
G8150027	BERRY RIVER AT MARCH FLY WEIR	-12.70	130.99	140	26	1956 -1981
G8110014	Sullivans Creek at u/s of Fig Tree Yard	-15.57	131.29	143	24	1970 -1993
G8150179	Howard River at Koolpinya Stockyard (Iron Bridge)	-12.46	131.08	149	47	1962 -2008
G8200048	Baroalba Creek At Oenpelli Road Crossing	-12.78	132.77	155	14	1972 -1985
G8200044	Goodparla Creek At Coirwong Gorge	-13.23	132.15	161	28	1966 -1993
G8110012	Timber Creek Upstream of Victoria Highway	-15.77	130.52	164	41	1968 -2008
G8160235	TAKAMPRIMILI RIVER AT DAMSITE	-11.78	130.78	166	20	1967 -1986

Station ID	Station and River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
G8150098	Blackmore River at Tumbling Waters	-12.77	130.95	174	50	1959 -2008
G9010003	Wonga Creek At Breakdown	-12.47	136.67	186	18	1969 -1986
G8200004	Jim Jim Creek At Above Five Sisters	-13.28	132.90	202	13	1974 -1986
G8150149	DARWIN RIVER AT DAM SITE (UPPER)	-12.83	130.97	206	11	1960 -1970
G8170033	MANTON RIVER AT ACACIA GAP	-12.80	131.20	222	31	1956 -1986
G8210024	Cooper Creek At Downstream Nabarlek	-12.29	133.34	225	30	1977 -2006
G8110107	SADDLE CREEK AT VICTORIA HIGHWAY	-15.95	129.57	234	25	1962 -1986
G8140234	BRADSHAW CREEK AT WAMBUNGI ROAD CROSSING	-14.57	131.30	240	17	1965 -1981
G8260007	Habgood River At Surprise Point	-12.55	135.89	243	17	1969 -1985
G8210007	Magela Creek At Upstream Bowerbird Waterhole	-12.78	133.05	260	30	1977 -2006
G8210008	Magela Creek At Bowerbird Waterhole	-12.77	133.05	260	10	1971 -1980
G8150153	Darwin River At Old Army Road Crossing	-12.75	130.97	284	17	1961 -1977
G8140061	COPPERFIELD CREEK AT BLUE HOLE	-13.99	131.90	306	22	1957 -1978
G8190001	West Alligator River At Upstream Arnhem Highway	-12.79	132.18	316	33	1976 -2008
G8180069	Mckinlay River At Near Burrundie	-13.53	131.72	352	52	1957 -2008
G8150010	Finniss River at Batchelor Dam Site	-13.03	130.95	360	35	1974 -2008
G8110110	SURPRISE CREEK AT V.R.D. ROAD CROSSING	-16.08	130.90	361	50	1959 -2008
G8230002	Maragulidban Creek At Maningrida Road Crossing	-12.23	134.05	390	19	1968 -1986
G8210028	Magela Creek At Arnhem Border Site	-12.70	132.98	412	16	1978 -1993
G8210011	Tin Camp Creek At Downstream Myra Falls	-12.45	133.29	413	12	1971 -1982
G8140161	Green Ant Creek at Tipperary	-13.74	131.10	435	43	1966 -2008
G8140060	Cullen River at Railway Bridge	-14.03	131.95	445	51	1958 -2008
G8180026	Mary River At El Sherana Road Crossing	-13.60	132.22	466	49	1960 -2008
G8110263	BULLOCK CREEK AT 1.5 MILES DOWNSTREAM BORE	-17.13	131.45	474	27	1966 -1992
G8140086	KING RIVER AT DOWNSTREAM STUART HIGHWAY	-14.63	132.59	484	24	1964 -1987
G9010001	Durabudboi River At Flare Point	-12.88	136.17	487	19	1968 -1986
G8200046	Deaf Adder Creek At Coljon (\034c\034 Part)	-13.10	133.02	513	23	1972 -1994
G8140214	SCOTT CREEK AT VICTORIA HIGHWAY	-14.92	131.87	528	25	1963 -1987
G9090248	Little Calvert At Calvert Hills Homestead	-17.23	137.32	560	19	1968 -1986

Station ID	Station and River Name	Lat	Long	Area (km^2)	Record length (years)	Period of Record
G8140152	Edith River Upstream of Stuart Highway	-14.17	132.08	590	47	1962 -2008
G8210009	Magela Creek At Downstream Jabiru	-12.64	132.90	605	38	1971 -2008
G8140159	Seventeen Mile Creek at Waterfall View	-14.28	132.40	619	47	1962 -2008
G8170002	Adelaide River at Railway Bridge	-13.24	131.11	632	57	1952 -2008
G8210001	Cooper Creek At Nimbuwah (\034c\034)	-12.19	133.35	645	28	1966 -1993
G8110238	DELAMERE CREEK AT DELAMERE HOMESTEAD	-15.73	131.52	653	22	1966 -1987
G8140151	MATHIESON CREEK AT VICTORIA HIGHWAY	-15.07	131.74	725	27	1961 -1987
G9030124	Daly Waters Creek at Daly Waters	-16.26	133.38	777	48	1961 -2008
G8220217	Goomadeer River At P. L. Tree D/s Gorge	-12.38	133.57	780	15	1966 -1980
G8110073	ARMSTRONG RIVER AT TOP SPRINGS	-16.62	131.69	810	28	1959 -1986
G8140005	FLORA RIVER (UPPER) & PICKER POCKET	-14.75	131.27	829	20	1967 -1986
G8140063	Douglas River Downstream Old Douglas Homestead	-13.80	131.34	842	52	1957 -2008
G8110101	DICK CREEK AT VICTORIA HIGHWAY	-15.83	129.90	888	17	1962 -1978
G8170240	Margaret River At Bob's Hill	-13.15	131.40	896	22	1965 -1986
G8140166	FISH RIVER AT GORGE	-14.24	130.90	992	25	1963 -1987
G8100106	Border Creek at Weaber Range	-15.40	129.01	1015	38	1971 -2008

Appendix B Climate Change Indices Data Set

Table B1 SOI monthly index data

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1876	11.3	11	0.2	9.4	6.8	17.2	-5.6	12.3	10.5	-8	-2.7	-3
1877	-9.7	-6.5	-4.7	-9.6	3.6	-16.8	-10.2	-8.2	-17.2	-16	-12.6	-12.6
1878	-8.7	-21.1	-15.5	-8.8	2.1	-3.1	15.9	13	17.7	10.9	15.1	17.9
1879	12.7	14.3	13.2	12.7	2.1	16.4	21.8	22.6	18.9	15.2	9.8	-5.5
1880	10.8	7.7	14.3	5.3	12.3	9.1	1.6	14.3	8.1	4.8	7.2	-1.9
1881	-7.3	-5.5	1.8	0.3	-4.3	-4.7	-5.6	-11.4	-13.6	-23.9	7.2	9.8
1882	-6.8	-1.3	5.1	1.2	6.8	-12	-21.3	-25.6	-14.8	-2.5	2.6	10.3
1883	6	9.1	-25.3	14.4	13.9	3.4	-10.2	1.4	-8.2	4.8	5.2	-15.2
1884	-12.5	-5	9.4	-15.4	1.3	9.1	-3	-5	-7	4.2	-1.4	-12.6
1885	-16.3	1.6	5.1	-0.5	-4.3	-14.4	-5	-9.5	-4	-17.8	-15.9	5.2
1886	-0.6	1.6	2.9	4.5	6	5	7.4	13.6	13.5	13.4	10.5	14.4
1887	12.2	11	10	9.4	-4.3	5	4.8	4.6	5.1	4.8	-5.3	5.2
1888	-3	-2.2	-11.7	-23.6	-9.8	-16	-16.7	-8.9	-9.4	-14.7	-12.6	-2.4
1889	-25.9	-1.7	-27.5	-0.5	-1.9	22	1.6	2.1	11.1	4.2	23	22
1890	20.8	11	14.3	6.9	3.6	5.8	-2.3	-3.1	9.3	3.6	2.6	0.6
1891	15.6	-3.6	-9.5	4.5	-0.3	-1.5	-6.3	-8.9	-10.6	0.6	-4.7	-4.5
1892	2.7	-10.2	11.1	6.9	10	19.6	7.4	5.9	6.3	8.5	-0.7	3.7
1893	11.3	7.7	-1.4	1.2	-3.5	10.7	14	7.8	5.7	7.9	2.6	1.6
1894	17.5	10	5.6	-3	-5.1	-1.5	-2.3	-5.7	-1.6	1.8	7.2	0.1
1895	5.6	3	-0.3	-7.1	-8.2	-4.7	-0.4	-6.3	-4	-5.6	-8.6	-3.5
1896	1.3	4.9	-6.3	-8.8	-42.2	-30.6	-20.6	-22.4	-19	-19	-11.9	-14.2
1897	-12.5	-7.4	-16.6	-17.8	-16.9	0.2	-2.3	0.8	0.2	1.8	-8	10.3
1898	7	6.3	19.2	11.1	-1.9	-2.3	6.1	2.1	3.2	-0.7	-2.7	-0.4
1899	13.2	9.1	13.8	4.5	-7.4	-10.4	-5.6	-10.1	-1.6	6.1	15.8	-3
1900	-7.3	-6.5	-25.3	-18.7	-7.4	26.1	10	7.8	-16.6	-17.2	-6	-5.5
1901	-0.1	3	9.4	4.5	-0.3	19.6	14.6	9.8	-16	-22.1	-8.6	-1.9
1902	17	-2.2	11.6	7.8	7.6	2.6	1.6	-8.9	-17.8	-7.4	-3.4	-3
1903	-9.2	-10.2	17.6	17.7	7.6	-0.6	6.1	0.1	8.7	4.2	1.3	15.9
1904	14.1	16.2	9.4	31.7	9.2	-7.1	-8.9	0.8	0.2	1.2	-17.2	2.6
1905	-9.2	-16.8	-30.2	-42.6	-37.4	-31.4	-21.3	-7.6	-7	-5.6	-17.9	-13.1
1906	-3.5	-7.4	-5.2	-8.8	1.3	-3.9	6.8	15.5	18.3	9.1	21.7	4.7
1907	5.1	1.6	-0.3	4.5	10	8.3	-4.3	-8.2	0.2	0.6	-2	8.8
1908	-10.6	7.7	0.2	16.8	-1.1	-2.3	2.2	5.3	17.7	7.9	2.6	-5.5
1909	-2.5	-3.2	-0.3	-14.5	2.1	22.8	10.7	9.8	0.8	4.2	9.2	4.7
1910	5.6	15.2	12.7	5.3	0.5	22	20.5	9.8	15.3	10.3	19.7	15.9
1911	3.2	1.6	3.5	2	-8.2	-12	-12.8	-12.1	-8.8	-11.7	-7.3	-1.4
1912	-9.7	-17.3	-9	-21.1	-13	-6.3	-0.4	-7.6	-4	-8	2.6	-8
1913	-3.5	-5	1.3	-6.3	-8.2	-3.9	-1.7	-7.6	-9.4	-9.2	-11.9	-7

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1914	-5.4	2	9.4	-14.5	-0.3	-16.8	-18	-17.2	-12.4	-8.6	-11.9	-1.4
1915	-21.6	-2.2	-20.4	-17.8	-12.2	6.6	14	7.2	7.5	2.4	-14.6	9.8
1916	5.6	-3.6	-6.3	-0.5	6.8	9.1	25.7	16.2	4.5	6.1	9.8	15.4
1917	5.1	10	18.1	21.8	21.8	21.2	28.3	34.8	29.7	15.2	21	22.5
1918	14.6	16.6	-2	16.8	10	-4.7	-14.1	-4.4	-8.2	-5	1.3	-8
1919	-14.9	-11.2	-12.8	-3	-7.4	-10.4	-8.9	-6.9	-5.8	-10.5	-11.3	-9.1
1920	1.8	-1.7	-4.1	0.3	-2.7	6.6	9.4	5.3	5.1	-4.3	-0.1	9.8
1921	10.8	6.7	8.9	-7.1	2.1	22	2.9	-6.9	5.1	9.7	8.5	8.2
1922	8	9.1	5.6	-5.5	-5.1	5.8	2.2	-1.2	5.1	6.1	8.5	11.8
1923	5.6	4.4	8.9	8.6	2.1	1	-11.5	-18.5	-14.8	-6.2	-12.6	2.1
1924	-5.4	1.1	2.4	-15.4	11.5	8.3	7.4	10.4	8.1	7.9	11.8	5.2
1925	5.6	13.8	14.9	14.4	-1.1	-4.7	-13.4	-10.8	-6.4	-12.9	-9.3	-7
1926	-5.4	-14.5	-13.3	-7.1	-2.7	-7.1	-1	-7.6	1.4	4.2	1.3	6.2
1927	5.1	1.1	18.1	6.9	6	8.3	6.1	-5	-0.4	-4.3	-8	7.7
1928	-10.1	10.5	13.8	11.9	-2.7	-7.9	-0.4	9.8	8.1	9.1	2.6	11.8
1929	16	18	5.1	4.5	-12.2	1	1.6	0.1	-0.4	7.9	11.1	5.7
1930	12.7	7.7	1.8	-3.8	2.1	-5.5	-4.3	-1.8	-7	3.6	1.9	-1.4
1931	7	-14.9	5.6	8.6	13.1	18.8	9.4	0.1	5.1	-12.9	-4.7	4.7
1932	1.8	-3.6	-2.5	-2.1	2.8	-4.7	-5	-6.9	-8.8	-4.3	-4.7	3.2
1933	-11.1	4.9	-2	3.6	6	-3.9	3.5	-0.5	2	3.6	7.2	8.2
1934	6.5	0.1	0.2	6.1	-7.4	10.7	2.9	-22.4	-6.4	4.2	13.1	-2.4
1935	6.5	-4.6	12.2	2.8	-6.6	-2.3	-0.4	2.1	6.3	7.3	3.9	-4
1936	-2	0.6	1.8	22.6	4.4	-1.5	4.2	-8.9	2.6	-0.1	-13.9	0.6
1937	9.4	-5	6.2	2	-0.3	3.4	-5.6	3.3	0.8	-2.5	-2	6.7
1938	7.5	3.4	-3.6	3.6	13.1	18	18.5	13	7.5	12.8	1.9	13.8
1939	17	7.7	11.6	9.4	-1.1	-1.5	8.1	-0.5	-9.4	-14.7	-8	-8.6
1940	-0.1	-4.1	-10.6	-9.6	-14.5	-19.3	-15.4	-18.5	-19.6	-18.4	-6.7	-29.4
1941	-9.7	-15.4	-10.6	-11.2	-6.6	-14.4	-20.6	-19.1	-8.2	-20.2	-9.3	-8.6
1942	-13	-3.6	-5.8	-5.5	5.2	8.3	-1	4	8.7	8.5	-4	13.8
1943	9.4	10.5	4	13.5	2.8	-7.9	2.9	7.8	5.7	9.1	3.9	-8.6
1944	-8.2	3.9	5.6	-5.5	-1.1	-3.9	-8.9	3.3	2.6	-8.6	-6.7	4.2
1945	5.1	6.3	13.2	-7.1	-0.3	8.3	3.5	11.7	8.7	2.4	-3.4	6.7
1946	-2.5	4.4	-2	-9.6	-11.4	-9.6	-10.2	-4.4	-16	-12.3	-1.4	-5.5
1947	-4.9	-4.1	11.6	-4.6	-13.7	2.6	9.4	7.2	11.7	-1.9	9.2	5.2
1948	-3	-2.7	-4.1	2.8	3.6	-4.7	0.9	-4.4	-7.6	6.1	4.6	-5.5
1949	-7.3	2	5.6	1.2	-5.8	-12	-1.7	-4.4	2	5.4	-6	7.7
1950	5.1	17.6	17.6	16.8	7.6	26.9	21.1	12.3	6.9	17.1	12.5	23
1951	16.5	9.6	-1.4	-1.3	-6.6	5	-8.2	-0.5	-7	-8	-3.4	-3
1952	-9.2	-7.9	0.2	-8.8	6	7.4	3.5	-3.7	-3.4	1.8	-0.7	-12.6
1953	2.2	-6	-5.8	-0.5	-31.9	-2.3	-1	-17.2	-13	-0.1	-2	-4
1954	6	-3.6	-0.9	6.9	4.4	-1.5	4.2	10.4	4.5	1.8	3.9	12.8
1955	-5.4	15.2	2.9	-3	13.1	16.4	19.2	14.9	14.1	15.2	15.1	9.3

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1956	11.3	12.4	9.4	11.1	17.9	12.3	12.6	11	0.2	18.3	1.9	10.3
1957	5.6	-2.2	-0.9	1.2	-12.2	-2.3	0.9	-9.5	-10.6	-1.3	-11.9	-3.5
1958	-16.8	-6.9	-1.4	1.2	-8.2	0.2	2.2	7.8	-3.4	-1.9	-4.7	-6.5
1959	-8.7	-14	8.4	3.6	2.8	-6.3	-5	-5	0.2	4.2	11.1	8.2
1960	0.3	-2.2	5.6	7.8	5.2	-2.3	4.8	6.6	6.9	-0.7	7.2	6.7
1961	-2.5	6.3	-20.9	9.4	1.3	-3.1	2.2	0.1	0.8	-5	7.2	13.8
1962	17	5.3	-1.4	1.2	12.3	5	-0.4	4.6	5.1	10.3	5.2	0.6
1963	9.4	3	7.3	6.1	2.8	-9.6	-1	-2.4	-5.2	-12.9	-9.3	-11.6
1964	-4	-0.3	8.4	13.5	2.8	7.4	6.8	14.3	14.1	12.8	2.6	-3
1965	-4	1.6	2.9	-12.9	-0.3	-12.8	-22.6	-11.4	-14.2	-11.1	-17.9	1.6
1966	-12	-4.1	-13.9	-7.1	-9	1	-1	4	-2.2	-2.5	-0.1	-4
1967	14.6	12.9	7.8	-3	-3.5	6.6	1.6	5.9	5.1	-0.1	-4	-5.5
1968	4.1	9.6	-3	-3	14.7	12.3	7.4	0.1	-2.8	-1.9	-3.4	2.1
1969	-13.5	-6.9	1.8	-8.8	-6.6	-0.6	-6.9	-4.4	-10.6	-11.7	-0.1	3.7
1970	-10.1	-10.7	1.8	-4.6	2.1	9.9	-5.6	4	12.9	10.3	19.7	17.4
1971	2.7	15.7	19.2	22.6	9.2	2.6	1.6	14.9	15.9	17.7	7.2	2.1
1972	3.7	8.2	2.4	-5.5	-16.1	-12	-18.6	-8.9	-14.8	-11.1	-3.4	-12.1
1973	-3	-13.5	0.8	-2.1	2.8	12.3	6.1	12.3	13.5	9.7	31.6	16.9
1974	20.8	16.2	20.3	11.1	10.7	2.6	12	6.6	12.3	8.5	-1.4	-0.9
1975	-4.9	5.3	11.6	14.4	6	15.5	21.1	20.7	22.5	17.7	13.8	19.5
1976	11.8	12.9	13.2	1.2	2.1	0.2	-12.8	-12.1	-13	3	9.8	-3
1977	-4	7.7	-9.5	-9.6	-11.4	-17.7	-14.7	-12.1	-9.4	-12.9	-14.6	-10.6
1978	-3	-24.4	-5.8	-7.9	16.3	5.8	6.1	1.4	0.8	-6.2	-2	-0.9
1979	-4	6.7	-3	-5.5	3.6	5.8	-8.2	-5	1.4	-2.5	-4.7	-7.5
1980	3.2	1.1	-8.5	-12.9	-3.5	-4.7	-1.7	1.4	-5.2	-1.9	-3.4	-0.9
1981	2.7	-3.2	-16.6	-5.5	7.6	11.5	9.4	5.9	7.5	-5	2.6	4.7
1982	9.4	0.6	2.4	-3.8	-8.2	-20.1	-19.3	-23.6	-21.4	-20.2	-31.1	-21.3
1983	-30.6	-33.3	-28	-17	6	-3.1	-7.6	0.1	9.9	4.2	-0.7	0.1
1984	1.3	5.8	-5.8	2	-0.3	-8.7	2.2	2.7	2	-5	3.9	-1.4
1985	-3.5	6.7	-2	14.4	2.8	-9.6	-2.3	8.5	0.2	-5.6	-1.4	2.1
1986	8	-10.7	0.8	1.2	-6.6	10.7	2.2	-7.6	-5.2	6.1	-13.9	-13.6
1987	-6.3	-12.6	-16.6	-24.4	-21.6	-20.1	-18.6	-14	-11.2	-5.6	-1.4	-4.5
1988	-1.1	-5	2.4	-1.3	10	-3.9	11.3	14.9	20.1	14.6	21	10.8
1989	13.2	9.1	6.7	21	14.7	7.4	9.4	-6.3	5.7	7.3	-2	-5
1990	-1.1	-17.3	-8.5	-0.5	13.1	1	5.5	-5	-7.6	1.8	-5.3	-2.4
1991	5.1	0.6	-10.6	-12.9	-19.3	-5.5	-1.7	-7.6	-16.6	-12.9	-7.3	-16.7
1992	-25.4	-9.3	-24.2	-18.7	0.5	-12.8	-6.9	1.4	0.8	-17.2	-7.3	-5.5
1993	-8.2	-7.9	-8.5	-21.1	-8.2	-16	-10.8	-14	-7.6	-13.5	0.6	1.6
1994	-1.6	0.6	-10.6	-22.8	-13	-10.4	-18	-17.2	-17.2	-14.1	-7.3	-11.6
1995	-4	-2.7	3.5	-16.2	-9	-1.5	4.2	0.8	3.2	-1.3	1.3	-5.5
1996	8.4	1.1	6.2	7.8	1.3	13.9	6.8	4.6	6.9	4.2	-0.1	7.2
1997	4.1	13.3	-8.5	-16.2	-22.4	-24.1	-9.5	-19.8	-14.8	-17.8	-15.2	-9.1

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1998	-23.5	-19.2	-28.5	-24.4	0.5	9.9	14.6	9.8	11.1	10.9	12.5	13.3
1999	15.6	8.6	8.9	18.5	1.3	1	4.8	2.1	-0.4	9.1	13.1	12.8
2000	5.1	12.9	9.4	16.8	3.6	-5.5	-3.7	5.3	9.9	9.7	22.4	7.7
2001	8.9	11.9	6.7	0.3	-9	1.8	-3	-8.9	1.4	-1.9	7.2	-9.1
2002	2.7	7.7	-5.2	-3.8	-14.5	-6.3	-7.6	-14.6	-7.6	-7.4	-6	-10.6
2003	-2	-7.4	-6.8	-5.5	-7.4	-12	2.9	-1.8	-2.2	-1.9	-3.4	9.8
2004	-11.6	8.6	0.2	-15.4	13.1	-14.4	-6.9	-7.6	-2.8	-3.7	-9.3	-8
2005	1.8	-29.1	0.2	-11.2	-14.5	2.6	0.9	-6.9	3.9	10.9	-2.7	0.6
2006	12.7	0.1	13.8	15.2	-9.8	-5.5	-8.9	-15.9	-5.1	-15.3	-1.4	-3
2007	-7.3	-2.7	-1.4	-3	-2.7	5	-4.3	2.7	1.5	5.4	9.8	14.4
2008	14.1	21.3	12.2	4.5	-4.3	5	2.2	9.1	14.1	13.4	17.1	13.3

Table B2 Nino set of indices (sample data)

Year	Month	NINO3	NINO34	NINO4
2006	1	-0.432	-0.771	-0.425
2006	2	-0.129	-0.633	-0.654
2006	3	-0.293	-0.603	-0.380
2006	4	-0.007	-0.130	-0.170
2006	5	0.341	0.205	0.104
2006	6	0.198	0.348	0.336
2006	7	0.197	0.268	0.450
2006	8	0.541	0.487	0.787
2006	9	1.122	0.940	0.995
2006	10	1.181	0.946	1.001
2006	11	1.233	1.290	1.129
2006	12	1.394	1.344	1.148
2007	1	1.046	0.803	0.752
2007	2	0.312	0.319	0.552
2007	3	-0.063	0.073	0.349
2007	4	0.025	0.212	0.291
2007	5	-0.238	0.012	0.137
2007	6	-0.296	0.137	0.202
2007	7	-0.603	-0.215	0.206
2007	8	-0.820	-0.386	0.243
2007	9	-0.885	-0.593	-0.198
2007	10	-1.171	-1.155	-0.546
2007	11	-1.418	-1.247	-0.828
2007	12	-1.207	-1.310	-0.891
2008	1	-1.283	-1.649	-1.304
2008	2	-1.113	-1.827	-1.566
2008	3	-0.418	-1.186	-1.354
2008	4	-0.175	-0.818	-1.045
2008	5	0.282	-0.370	-0.805
2008	6	0.282	-0.192	-0.612
2008	7	0.489	0.081	-0.378
2008	8	0.688	0.193	-0.082
2008	9	0.534	0.155	-0.030
2008	10	0.167	-0.225	-0.197
2008	11	-0.001	-0.276	-0.441
2008	12	-0.291	-0.702	-0.565

Table B3 Unfiltered monthly IPO data (source: Chris Folland, Met Office Hadley Centre for Climate Change, Exeter, UK)

Year	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sep	Oct	Nov	Dec
1871	-0.96	-0.36	0.1	-0.45	-1.12	-1.05	-0.26	0.41	-0.31	-0.43	-0.62	-1.15
1872	-1.85	-1.85	-1.37	-2.14	-1.41	-1.11	-0.16	-2.4	-2.5	-3.37	-3.06	-3.77
1873	-3.49	-4.05	-4	-1.84	-0.77	-1.49	-1.76	-2.53	-3.02	-3.47	-3.56	-3.34
1874	-2.9	-2.99	-2.4	-1.62	-1.01	-1.18	-2.09	-3.14	-3.83	-3.86	-3.28	-2.41
1875	-1.07	-1.44	-1.43	-1.79	-3.15	-2.85	-3.28	-3.21	-2.79	-2.06	-0.68	-2.47
1876	-2.56	-2.83	-2.78	-2.79	-2.4	-1.64	-1.86	-2.03	-0.98	0.84	2.11	2.56
1877	2.41	2.13	2.01	1.78	2.21	1.92	5.06	4.22	5.53	5.67	5.78	6.14
1878	6.88	7.25	4.63	4.2	4.02	4.55	3.68	1.94	0.2	-0.03	0.5	0.86
1879	1.59	0.88	1.21	0.29	-0.2	-0.81	-0.62	-0.42	-0.65	-0.86	-1.69	-0.7
1880	-0.85	-1.45	-1.67	-1.49	-1.48	-1.4	-0.83	-0.59	-0.16	0.51	1.29	1.19
1881	0.68	0.59	1.47	2.52	3.15	2.46	1.75	0.5	0.47	0.33	0.08	-0.45
1882	-0.82	-1.34	-0.65	0.47	0.83	0.15	-0.77	-0.22	-0.49	-0.37	-0.87	-0.51
1883	0.72	-0.11	-0.44	0.59	0.48	1.26	1.23	0.1	-0.12	-0.46	0.15	-0.42
1884	-0.57	-0.53	0.72	2	2.69	1.7	1.83	2.1	1.94	1.91	2.17	2.95
1885	2.75	2.04	2.16	2	2.61	2.11	1.44	2.06	2.55	3.09	2.99	2.96
1886	1.84	1.81	1.71	1.69	-1.43	-2.53	-1.03	-1.17	-1.61	-1.65	-2.15	-2.68
1887	-2.48	-0.95	-1.37	-1.66	-0.84	-0.03	-0.65	-1.59	-0.76	0.22	0.96	0.85
1888	1.38	2.96	2.8	2.56	3.56	3.56	3.35	3.37	4.2	5.25	5.8	5.45
1889	3.25	2.66	2.45	2.83	3.26	0.99	1.13	0.01	-0.69	-2.03	-1.61	-2.53
1890	-4.65	-4.03	-1.95	-1.81	-2.04	-2.58	-1.94	-2.17	-2.42	-2.29	-1.83	-0.78
1891	-0.31	-0.39	0.44	0.82	1.31	1.07	1.03	0.25	-0.18	0.19	-0.14	-0.01
1892	-0.36	0	-0.46	-0.33	-0.3	0.03	-0.4	-1.37	-2.34	-3.62	-2.66	-1.83
1893	-1.42	-1.96	-2.36	-2.4	-2.89	-3.21	-4.34	-4.61	-4.13	-4.07	-3.25	-3.48
1894	-2.99	-3.13	-3.24	-2.88	-2.48	-2.08	-1.69	-2.03	-2.84	-2.8	-2.58	-0.93
1895	-0.7	-0.38	-0.01	-0.1	0.15	0.34	0.41	1.86	1.5	1.8	1.66	1.36
1896	1.5	0.71	0.03	0.23	0.81	1.15	2.2	3.31	4.15	3.7	3.99	3.91
1897	4.04	3.72	2.55	2.14	2.38	2.48	2.24	2.12	1.6	1.95	0.83	-0.31
1898	-1.15	-1.02	-0.62	-0.22	0.1	0.33	-0.15	-0.41	-0.96	-0.55	0.2	0.49
1899	-0.23	-0.98	-0.71	-0.38	0.75	1.03	-0.01	2.61	2.43	1.76	3.58	4.82
1900	4.57	4.35	4.33	4.18	3.75	3.79	3.8	3.08	2.43	1.72	1.48	3.9
1901	3.76	2.68	1.95	1.33	0.84	0.56	1.01	0.96	0.34	1.01	1.36	1.95
1902	1.8	2.52	2.73	4.7	3.87	5.41	5.9	4.52	3.41	4.21	3.39	2.95
1903	2.88	2.21	2.53	1.49	2.4	2.83	3.01	2.5	2.03	-0.44	-0.6	0.48
1904	-0.44	-1.24	-1.19	-0.64	0.66	2.23	2.96	3.62	2.64	2.53	2.83	4.64
1905	4.15	4.53	5.3	3.7	4.52	4.01	3.6	5.41	4.13	3.07	3.74	2.75
1906	3.16	3.86	4.22	3.87	2.94	2.31	0.37	-0.1	-2.13	-0.79	1.21	0.34
1907	-1.65	0.26	-0.64	-0.84	0.2	1.54	1.03	0.06	0.83	0.07	0.25	0.34

Year	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sep	Oct	Nov	Dec
1908	0.01	0.88	1.44	0.47	0.42	0.93	0.39	-1.71	-0.83	-1.59	-1.56	-1.31
1909	1.01	-0.81	-0.06	-0.93	0.13	-1.1	-1.28	-2.42	-3.98	-4.19	-3.96	-3.04
1910	-3.93	-2.26	-1.85	-2.63	-3.06	-3.14	-1.67	-2.65	-4.11	-3.15	-2	-0.94
1911	-0.66	-1.24	-0.6	-1.75	-2.1	-1.26	-0.05	-1.53	-0.79	-0.65	1.19	2.39
1912	2.37	2.15	1.71	2.37	1.43	1.54	1.37	0.9	1.42	0.58	1.47	-0.27
1913	-0.39	2.54	0.85	-1.9	-0.57	1.26	1.05	0.76	-0.25	0.84	1.24	2.09
1914	2.36	1.9	1.84	2.08	0.88	0.93	-0.17	2.08	1.84	0.42	0.45	1.73
1915	2.68	2.53	3.68	3.42	4.07	4.94	2.57	0.8	0.24	-0.06	-0.39	0.22
1916	0.37	-0.83	-0.25	-0.26	0.09	-0.07	-2.2	-3.08	-3.7	-3.66	-4.49	-3.13
1917	-3.37	-2.83	-2.57	-1.7	-1.4	-0.58	0.37	-0.21	-1.28	-1.3	-1.62	-1.85
1918	-1.21	-1.7	-1.62	-1.11	0.18	2.04	2	2.31	2.6	3.85	3.85	4.08
1919	5.25	3.47	2.69	3.51	4.18	3.5	2.58	2.47	2.37	1.32	0.24	2.3
1920	2.72	1.76	0.59	-0.11	1.4	0.47	-0.47	-0.32	-1.04	-1.81	-1.12	-0.53
1921	-0.22	-0.95	-2.25	-1.05	-2.14	-1.37	-0.86	-1.13	-1.52	-0.45	-0.4	0.18
1922	-1.08	0.1	-0.06	-0.43	-0.06	-1.59	-1.47	-2.06	-1.66	-0.75	-1.34	-1.29
1923	-0.59	-0.3	-0.5	0.65	-0.83	0.57	0.36	0.26	-0.01	1.98	1.83	0.73
1924	-0.73	1.29	0.03	-0.02	-1.37	-0.86	-1.89	-2.29	-2.31	-1.75	-1.54	-0.44
1925	-1.1	0.51	-0.45	1.23	-0.32	-1.44	1.06	0.53	1.73	2.59	3.59	4.56
1926	4.65	4.57	5.58	3.99	4.58	3.55	2.79	1.92	1.11	0.43	1.42	2.44
1927	2.52	3.18	1.27	1.35	-0.63	0.87	-0.92	-1.44	-0.63	-0.33	0.47	-0.06
1928	2.03	2.59	1.67	0.83	1.14	1.25	0.77	-0.67	-1.55	-1.15	-0.07	-0.15
1929	0.22	0.47	0.55	1.09	0.9	0.77	1.32	0.65	1.5	0.95	0.71	2.02
1930	1.15	2.19	1.74	1.65	0.02	1.5	0.71	2.47	2.52	3.65	4.87	4.57
1931	4.86	6.53	5.88	5.01	4.13	3.66	3.07	1.98	1.1	1.59	1.25	0.59
1932	0.9	1.72	2.08	1.86	1.04	1.79	0.89	0.85	-0.4	-0.12	-0.06	-0.73
1933	0.12	-0.33	-0.22	-0.09	-0.79	-1.75	-3.05	-2.91	-3.05	-2.95	-1.29	-1.79
1934	-0.9	-0.38	0.82	1.11	0.23	-0.29	-1.25	0.18	-0.56	0.6	0.86	-0.25
1935	-0.66	-1.08	-0.75	0.11	0.83	0.42	-0.95	0.47	0.12	0.09	0.66	0.57
1936	1.34	2.37	1.76	2.16	2.41	1.27	1.49	-0.12	-0.76	1.99	1.54	2.84
1937	0.58	2.14	1.11	0.3	-0.85	0.89	0.72	-1.33	0.44	-0.4	0.68	0.46
1938	-0.53	-1.06	-0.95	-1.77	-1.48	-1.93	-2.57	-3.84	-1.11	-1.57	-1.69	-1.45
1939	-0.35	-1.89	-2.17	-0.61	0.48	1.18	0.53	-0.11	-0.37	-2.5	0.9	2.96
1940	3.74	4.38	4.25	3.87	3.59	3.98	1.78	3.02	2.12	2.91	3.4	4.51
1941	4.57	4.98	5.69	6.04	5.71	4.25	4.51	4.79	3.41	3.28	3.16	4.49
1942	3.65	1.82	2.22	2.1	1.54	0.64	-0.24	-0.98	-1.78	-2.53	-2.63	-2.07
1943	-1.44	-0.5	-0.46	0.26	0.42	-0.75	-0.69	-1.46	-1.55	-0.65	-0.43	-0.64
1944	0.56	0.44	-0.46	0.17	-0.48	0.02	0.36	-0.43	-0.32	-1.18	-1.06	-1.25
1945	-0.92	0.37	-2.53	-1.97	-0.08	-0.26	0.22	-0.5	-0.88	-1.56	-1.64	-2.28
1946	-2.04	-0.59	-0.8	-0.62	-1.28	-0.15	-0.32	0.06	0.08	-1.56	-1.24	-0.46
1947	0.72	0.52	2.59	-0.5	-0.55	2.27	0.27	-0.85	-0.47	-0.52	-1.48	0.42
1948	0.54	0.02	0.64	-0.97	-0.15	0.42	0.19	-1.51	-1.64	-2.09	-0.54	-0.39
1949	-2.78	-2.01	-2.51	-1.08	-0.45	-0.97	-1.65	-2.24	-3.62	-4.16	-4.3	-2.88

Year	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sep	Oct	Nov	Dec
1950	-3.65	-4.7	-3.66	-3.16	-4.4	-4.08	-5.3	-4.42	-4.61	-3.8	-5.39	-3.61
1951	-3.39	-3.26	-3.33	-2.16	-1.6	-0.38	0.75	-0.76	0.25	0.71	0.9	-0.43
1952	-0.53	0.04	-0.25	-0.18	-0.38	-1.94	-1.75	-2.14	-1.49	-0.95	-1.43	-1.07
1953	0.6	0.5	0.02	0.83	0.62	0.08	-0.31	-1.31	-0.49	-1.45	-1.06	-0.5
1954	-1.37	-1.09	-0.74	-2	-1.8	-1.49	-1.64	-2.63	-3.75	-2.79	-2.97	-3.1
1955	-1.93	-3.33	-3.18	-4.29	-4.34	-4.5	-4.71	-4.32	-4.9	-7.17	-6.14	-5.51
1956	-4.77	-4.11	-3.97	-3.86	-3.92	-4.32	-3.49	-3.07	-2.99	-3.8	-3.62	-2.27
1957	-1.83	-1.42	-0.32	-0.2	1.06	1.25	2.02	0.82	1.27	1.95	1.59	1.99
1958	2.9	2.89	1.84	1.49	2.09	1.37	0.83	1.98	0.54	-0.11	0.57	1.29
1959	1.21	0.86	0.23	0.07	0.26	0.24	-0.2	-0.97	-0.71	0.35	0.22	-0.24
1960	0.29	0.36	0.5	0.65	0.55	-0.38	-0.83	-0.86	-1.47	-1.53	-2.08	-0.26
1961	0.37	1.05	0.48	0.57	-0.52	-0.6	-2.16	-1.59	-2.72	-3.64	-2.83	-3.21
1962	-2.61	-2.06	-2.16	-2.43	-2.53	-2.84	-2	-1.28	-3.05	-2.65	-1.81	-1.44
1963	-0.93	-0.78	-0.69	-0.35	-0.94	-1.27	-0.6	-0.49	1.01	0.75	0.29	0.85
1964	0.51	0.05	-1.27	-2.06	-3.61	-3.08	-2.54	-3.38	-2.81	-2.81	-2.39	-2.32
1965	-1.86	-1.15	-0.51	0.34	0.79	0.52	1.07	2.49	1.93	1.71	2.2	2.01
1966	1.19	0.66	0.21	0.37	0.04	0.12	0.59	0.5	0.5	-0.49	-0.99	-0.77
1967	-1.04	-1.19	-0.77	-1.11	-1.33	-1.34	-2.07	-3.62	-2.66	-2.83	-2.43	-2.42
1968	-2.31	-1.35	-1.64	-2.16	-1.94	-0.37	0.09	0.41	0.54	0.99	1.44	1.7
1969	1.81	1.89	1.84	1.83	1.86	2.3	1.41	0.79	0.78	3.12	2.49	2.56
1970	2.43	1.46	1.49	0.18	-0.29	-0.88	-1.73	-2.74	-2.81	-2.88	-2.78	-3.74
1971	-4.59	-5.29	-4.63	-3.47	-3	-3.92	-3.47	-2.39	-1.94	-2.72	-3.36	-3.56
1972	-1.93	-0.93	-1.26	-0.53	0.02	0.85	0.78	2.48	2.19	2.81	2.46	3.25
1973	2.22	0.21	-0.26	-1.33	-1.43	-2.07	-2.63	-2.73	-3.17	-3.58	-4.55	-5.06
1974	-5.13	-5.15	-4.44	-3.46	-2.42	-2.63	-2.45	-1.77	-2.36	-2.84	-2.43	-2.83
1975	-3.15	-2.68	-2.78	-2.52	-3.82	-2.8	-2.69	-3.33	-4.51	-5.44	-5.34	-5.8
1976	-4.56	-2.91	-2.65	-2.11	-1.13	-0.11	0.87	2.27	2.49	3.04	3.38	2.81
1977	3.31	2.69	1.47	0.55	1.43	2.36	1.96	1.25	1.18	1.83	2.08	1.72
1978	2.54	1.61	1.72	1.02	1.33	0.55	-0.02	-0.01	0.07	1.21	1.67	0.75
1979	0.74	-0.02	-0.02	1.16	1.94	1.37	1.07	1.32	2.32	2.94	2.21	2.67
1980	2.16	2.56	2.58	2.82	2.99	1.45	1.19	1.03	0.71	1.8	2.17	2.56
1981	1.41	0.79	1.91	1.23	2.03	2.11	1.6	0.87	1.78	0.8	0.82	1.27
1982	1.24	0.68	0.79	1.45	2.16	2.35	2.8	3.17	4.55	4.96	4.59	5.33
1983	5.49	6.25	6.18	5.2	4.74	5.52	5.3	4.3	1.9	1.28	1.21	1.79
1984	1.81	1.4	0.99	0.54	0	-0.89	-0.96	-0.6	0.22	-0.6	-0.89	-1.8
1985	-0.79	-0.86	-0.86	-0.82	-1	-0.22	0.14	-0.12	-0.4	-0.79	-1.28	-0.39
1986	-0.46	0.54	0.64	0.72	0.64	1.39	2.07	1.31	1.91	2.99	3.52	3.43
1987	3.39	3.78	4.95	4.88	5.16	4.33	4.79	5.14	5.48	5.12	4.48	3.72
1988	2.88	2.14	2.66	1.84	0.65	-0.64	-1.66	-1.54	-1.81	-2.27	-2.01	-2.44
1989	-3.72	-3.02	-3.01	-2.33	-2.14	-1.68	-0.73	-1.72	-1.36	-1.39	-1.08	0.08
1990	-0.63	-0.73	-1.08	-0.24	0.08	-0.19	-0.1	-0.01	0.07	-0.46	-1.01	-0.94
1991	-0.48	-0.29	-0.01	-0.18	0.96	0.56	0.99	0.75	1.27	2.28	2.68	2.23

Year	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sep	Oct	Nov	Dec
1992	2.46	2.4	2.54	3.74	4.99	3.52	3.48	2.32	2	2.55	2.28	1.16
1993	2.1	2.68	2.87	3.37	4.14	4.01	2.84	2.75	2.08	2.34	1.91	1.62
1994	1.67	0.57	1.36	2.03	2.06	1.83	0.89	-0.25	0.2	1.76	0.84	0.64
1995	1.46	1.57	1.33	1.42	2.03	2.05	2.62	0.95	1.44	0.18	0.01	-0.33
1996	-0.51	-0.02	0.47	0.4	0.69	1.04	0.59	-0.13	-0.1	0.02	0.41	-0.77
1997	0.07	-0.38	1.03	2.1	3.82	4.54	3.88	4.9	5.45	5.67	5.97	5.4
1998	5.51	5.13	4.81	3.24	2.61	1.36	-0.03	-0.21	-0.75	-2.03	-1.94	-2.74
1999	-3.03	-2.96	-2.18	-2.66	-2.85	-3.37	-3.47	-3.22	-3.56	-4.24	-4.02	-4.06
2000	-3.91	-3.15	-2.71	-1.74	-2.47	-2.58	-2.39	-2.29	-2.17	-2.31	-2.54	-2.01
2001	-1.94	-1.94	-0.57	-0.41	-0.6	-0.96	-1.88	-1.61	-1.88	-1.91	-1.41	-1.74
2002	-1.09	-1.41	0.3	-0.12	-0.29	-0.29	0.03	-0.08	0	0.89	2.59	2.67
2003	2.3	1.75	1.62	1.04	-0.63	-0.28	0.08	0.33	-0.35	1.2	1.16	0.85
2004	1.23	0.67	1.05	1.17	0.56	-0.39	-0.47	-0.29	0.22	-0.04	-0.14	-0.13
2005	0.08	-0.24	1.01	0.63	1.49	0.77	-0.28	-0.44	-1.53	-2.52	-3.3	-2.47
2006	-1.12	-0.23	-0.2	-0.6	0.06	0.28	0	-0.26	0.05	0.49	1.25	1.54
2007	0.66	0.64	-0.41	0.01	-0.89	-0.8	-0.03	-1.27	-2.45	-4	-3.96	-4.17

Table B4 Monthly dipole mode index data

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1958			0.153	-0.103	-0.659	-1.262	-1.892	-2.184	-2.041	-1.767	-0.928	-0.460
1959	-0.239	-0.044	-0.075	-0.562	-0.614	-0.862	-1.151	-1.000	-0.891	-0.730	-0.337	0.134
1960	0.123	-0.061	-0.324	-0.625	-1.129	-1.221	-1.044	-1.148	-1.279	-1.286	-1.081	-0.847
1961	-0.400	-0.316	-0.152	-0.015	0.540	1.244	2.171	2.864	3.072	2.741	2.410	2.264
1962	2.055	1.741	1.250	0.559	-0.170	-0.627	-0.686	-0.606	-0.431	-0.194	0.171	0.488
1963	0.769	0.838	0.683	0.304	0.217	0.477	0.668	1.299	1.732	1.479	0.679	-0.008
1964	-0.669	-1.104	-1.389	-1.215	-1.242	-1.443	-1.902	-2.206	-2.137	-1.675	-1.490	-1.183
1965	-0.637	-0.657	-0.860	-0.884	-0.823	-0.790	-0.615	-0.121	0.089	0.192	0.123	0.055
1966	-0.309	-0.482	-0.514	-0.343	-0.151	0.276	0.782	0.940	0.764	0.541	0.179	-0.057
1967	0.255	0.289	0.389	0.657	0.857	0.808	1.197	1.490	1.467	1.346	1.307	1.332
1968	1.214	1.202	1.102	1.056	0.447	0.022	-0.513	-0.779	-1.199	-1.035	-0.929	-0.633
1969	-0.314	-0.065	0.006	-0.294	-0.440	-0.717	-0.807	-0.804	-0.363	-0.195	0.181	0.487
1970	0.563	0.683	0.920	0.449	-0.189	-0.464	-1.010	-1.584	-1.528	-1.331	-1.018	-0.673
1971	-0.148	0.230	0.404	0.145	-0.071	-0.579	-1.239	-1.602	-1.408	-1.024	-0.594	-0.302
1972	0.092	0.147	0.160	0.687	1.457	1.897	2.178	2.375	2.332	2.116	1.674	1.243
1973	0.904	0.297	0.073	-0.042	-0.284	-0.658	-1.046	-1.361	-1.281	-0.892	-0.301	0.306
1974	0.732	0.783	0.623	0.470	0.236	-0.260	-0.616	-0.996	-1.370	-1.488	-1.468	-1.260
1975	-1.070	-0.616	-0.234	0.162	0.387	0.540	-0.077	-0.858	-1.139	-1.275	-1.091	-0.489
1976	0.219	0.534	0.718	1.062	1.504	1.629	1.462	1.348	0.938	0.477	0.308	0.172
1977	0.378	0.467	0.240	0.239	0.363	0.089	-0.001	0.498	0.472	0.535	0.167	-0.143
1978	-0.868	-0.957	-1.286	-0.870	-0.489	-0.142	-0.076	0.022	-0.174	-0.327	-0.020	-0.051
1979	0.194	0.347	0.257	0.168	0.107	0.022	0.063	0.230	-0.029	0.090	0.052	0.001
1980	-0.187	-0.100	-0.019	-0.115	-0.395	-0.633	-1.031	-1.422	-1.457	-1.388	-1.024	-0.605
1981	-0.201	0.151	0.556	0.596	0.253	-0.176	-0.722	-1.108	-1.177	-0.821	-0.342	0.237
1982	0.620	0.918	1.145	1.293	1.420	1.627	1.956	2.310	2.324	1.941	1.280	0.381
1983	-0.773	-1.443	-1.315	-0.600	0.299	1.189	1.641	1.522	0.982	0.457	-0.076	-0.251
1984	-0.234	0.027	-0.074	-0.103	-0.203	-0.427	-0.834	-1.040	-1.083	-1.067	-1.139	-1.270
1985	-1.293	-1.163	-1.068	-1.116	-0.877	-0.748	-0.678	-0.821	-0.281	-0.339	-0.167	-0.196
1986	-0.071	-0.370	-0.109	-0.159	-0.407	-0.495	-0.297	-0.154	-0.122	0.044	0.199	0.242
1987	0.075	0.120	0.520	0.743	0.930	1.326	1.833	1.958	1.843	1.760	1.712	1.195
1988	0.664	0.577	0.131	-0.263	-0.198	-0.118	-0.234	-0.182	-0.112	0.073	-0.015	0.142
1989	0.184	-0.082	-0.606	-0.919	-1.167	-1.107	-0.828	-0.636	-0.308	-0.158	-0.106	-0.278
1990	-0.191	-0.267	-0.357	-0.644	-0.561	-0.695	-0.457	-0.402	-0.046	0.091	0.329	0.269
1991	0.383	0.628	0.957	1.171	1.502	1.626	1.565	1.301	1.126	0.925	0.536	0.048
1992	-0.548	-1.033	-1.454	-1.791	-1.798	-1.811	-1.937	-1.945	-1.599	-1.532	-1.206	-0.668
1993	-0.535	-0.414	-0.147	-0.011	-0.100	-0.054	0.038	-0.013	-0.055	-0.153	-0.006	-0.104
1994	0.047	0.378	0.987	1.353	1.926	2.435	2.655	2.822	2.705	2.428	1.814	1.407
1995	0.717	0.286	-0.066	-0.171	-0.373	-0.394	-0.288	-0.329	-0.506	-0.372	-0.394	-0.409
1996	-0.317	-0.422	-0.653	-0.879	-1.300	-1.709	-1.896	-2.491	-2.807	-2.695	-2.368	-1.895

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1997	-1.144	-0.547	-0.166	0.041	0.378	0.884	1.512	2.207	3.105	3.367	3.179	2.808
1998	2.003	1.048	0.560	0.360	-0.179	-0.501	-0.810	-1.406	-1.999	-2.005	-1.754	-1.507
1999	-0.962	-0.491	-0.308	-0.231	-0.050	-0.039	0.033	0.105	0.146	-0.075	-0.257	-0.314
2000	-0.146	0.041	0.315	0.487	0.636	0.714	0.645	0.525	0.330	0.053	-0.456	-0.495
2001	-0.487	-0.167	0.192	0.702	0.685	0.545	0.370	-0.006	-0.276	-0.254	-0.226	-0.232
2002	0.011	-0.103	-0.256	-0.219	-0.286	-0.394	0.177	0.782	0.990	1.007	0.875	0.551
2003	0.095	-0.097	-0.059	0.290	0.417	0.577	0.680	0.659	0.414	0.386	0.222	0.223
2004	0.344	0.353	-0.178	-0.455	-0.730	-0.856	-0.806	-0.345	-0.190	-0.131	-0.238	-0.708
2005	-1.156	-1.017	-0.898	-0.876	-0.694	-0.574	-0.960	-1.215	-1.290	-1.277	-1.211	-1.147
2006	-1.096	-0.932	-0.810	-0.684	-0.362	0.051	0.482	1.142	1.579	1.643	1.557	1.257
2007	0.819	0.503	0.655	0.605	0.610	0.792	1.011	0.944	0.929	0.697	0.537	0.220
2008	0.162	0.054	0.441	0.609	0.932	1.032	1.329	1.297	1.064	0.811	0.670	0.541

Table B5 Dipole mode index monthly data

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1957	-0.85	-2.24	0.1	-2.03	-2.74	-0.46	1.01	-2.05	0.74	-3.02	-5.52	-2.64
1958	0.11	-2.7	-2.52	-0.22	-3.19	-1.27	-1.78	0.87	1.72	-0.56	-0.06	0.65
1959	1.28	-0.56	-1.03	-2.01	-0.39	-1.87	-0.57	-2.35	2.01	-1.27	2.48	-0.38
1960	0.9	0.85	3.4	-0.35	-0.6	-0.17	0.31	0.43	1.41	-1.17	1.18	1.36
1961	0.91	-4	-0.4	-0.14	1.12	-0.76	0.98	1.1	-1.21	1.64	1.52	2.32
1962	2.68	-0.13	-0.54	1.94	-0.58	-3.87	0.1	-0.47	-0.19	-0.12	-2.37	1.27
1963	3.43	1.77	2	1.41	-0.98	1.72	0.13	-5.53	-1.82	2.35	0.95	-0.26
1964	-3.24	-1.26	-1.11	0.62	2.16	-4.53	-6.54	-2.6	1.66	0.26	-3.17	-1.64
1965	-0.39	-7.93	-1.38	-0.77	-2.12	1.49	-0.11	-0.44	0.15	1.5	1.21	-1.75
1966	0.65	-3.19	-3.19	-1.18	-1.55	-0.05	-2.08	3.46	0.25	1.21	-2.26	-1
1967	-3.5	-4.18	0.96	-0.11	-0.39	2.62	1.22	1.01	1.21	0.64	-2.17	-0.48
1968	-0.07	-1.82	-0.9	-2.72	-2.23	-0.13	1.6	0.25	-0.36	-3.15	-3.36	-0.51
1969	-4.13	-3.14	-0.96	-2.36	1.39	-0.88	1.81	2.1	0.58	-0.35	1.52	-0.41
1970	0.76	1.27	-2.26	-1.57	0.24	0.72	-1.22	1.63	-2.02	-2.19	0.45	-0.72
1971	-0.36	0.16	2.02	-1.24	-2.48	1.31	0.68	-0.78	-1.83	-2.23	-0.5	-1.57
1972	-1.44	-0.36	-2.05	-2.94	-0.09	0.42	-1.24	-1.89	-0.91	-1.48	1.39	-1.38
1973	-0.94	1.39	2.16	0.36	-1.94	-0.12	2.57	1.98	-1.15	-1.28	-0.54	2.17
1974	1.18	1.82	2.81	0.05	0.42	0.08	-1.22	-4.02	1.84	-1.33	-2.24	-2.37
1975	-1.68	-1.22	-1.23	0.56	-3.33	-0.35	-2.42	-0.16	1.23	0.59	0.11	0.35
1976	-1.17	1.02	-0.1	1.56	1.75	-0.01	0.6	0.3	1.67	1.19	-2.88	-5.07
1977	-3.22	0.04	-1.17	-1.36	-0.77	-2.09	-1.82	-0.41	2.69	0.21	-0.2	-0.95
1978	1.5	-0.24	-0.99	0.64	-0.91	0.83	-2.13	2.94	1.19	0.68	-0.96	-0.01
1979	0.74	-0.9	1.51	-0.49	1.54	2.52	3.14	1.39	-0.02	0.54	-1.26	-1.88
1980	0.01	-1.75	-2.58	-1.77	-0.51	3.19	-1.68	-1.68	-2.56	0.45	-2.09	-0.1
1981	0.84	1.76	-2.47	-3.52	0.88	0.38	-1.43	-1.99	-1.49	-0.39	2.34	2.21
1982	-0.77	0.7	4.28	2.89	-0.7	2.4	0.01	1	1.56	-2.14	-2.32	-2.21
1983	-2.44	0.89	-0.71	-0.6	-0.68	0.38	1.63	0.09	-0.72	2.05	3.79	1.52
1984	-1.96	-1.74	-0.38	-0.23	-0.33	1.08	-0.21	-2.33	-0.16	1.06	0.34	-3.22
1985	-2.38	-0.02	-0.08	0.95	0.38	-2.49	2.64	1.26	1.07	0.57	2.28	1.9
1986	0.37	-4.89	-1.26	-0.57	-2.19	-0.95	-0.02	1.68	2.72	-0.38	0.5	1.31
1987	-2.51	-2.49	-1.11	-0.17	-0.34	0.18	-0.26	1.79	-0.72	0.78	1.77	0.3
1988	0.13	0.12	-2.01	2.11	-2.03	-3.06	0.64	-2	-2.7	-6.03	1.77	1.88
1989	-0.02	1.14	0.2	0	3.73	2.91	0.88	-1.21	-0.23	-0.16	0.69	-0.05
1990	-0.23	1.95	0.8	-3.34	-3.35	-0.28	-1.82	0.12	2.08	-0.06	0.29	-0.2
1991	1.5	-1.69	1.07	-1.36	1.02	1.04	-1.56	-0.57	-2.52	1.3	-0.84	-1.23
1992	0.17	-1.89	-1.1	0.53	-2.19	-3.13	-0.8	-0.4	1.06	0.7	1.49	0.58
1993	-2.17	0.77	-0.1	1.8	2.1	0.4	2.82	2.69	1.14	1.21	1.48	1.38
1994	0.53	2.72	1.59	-0.75	-1.5	-2.33	-0.15	1.53	-1.22	-0.47	-2.43	1.91

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1995	2.89	0.31	-1.12	0.74	2.64	-0.79	-4.26	-0.51	3.09	-0.69	0.17	1.93
1996	0.55	-1.74	1.31	-0.28	1.9	-1.4	0.22	-2.46	-3.5	2.79	-2.36	0.03
1997	2.37	0.68	1.43	0.15	1.43	0.69	1.82	0.76	0.69	-1.78	-3.17	-0.89
1998	2.65	0.57	-0.05	2.89	1.11	1.31	2.13	2.66	0.74	-0.26	2.84	2.59
1999	2.26	0.56	-1.39	2.44	2.51	-1.81	0.72	1.44	0.16	3.35	1.83	3.12
2000	3.59	2.32	0.74	0.97	1.9	-0.31	0.52	-1.22	-3.2	1.21	-1.32	-2.05
2001	1.43	-2.7	-0.57	3.49	-1.75	-0.02	0.2	-0.15	1.46	1.36	2.54	1.16
2002	2.22	2.8	-4.42	1.6	-1.69	-0.43	-0.67	1.14	-2.18	-5.77	0.03	1.29
2003	-0.52	-0.98	-0.07	2.21	1.04	-2.52	1.2	2.33	-0.99	0.12	-0.15	-0.69
2004	2.56	-3.33	0.74	1.2	-0.15	1.69	2.52	0	1.77	-0.59	-1.18	-1.02
2005	1.07	1.59	-0.12	3.46	-0.45	-0.41	-0.5	0.5	0.39	-0.11	0.66	-2.76
2006	0.56	-1.85	1.66	-0.69	2.28	2.05	1.61	-2.64	-0.26	1.79	0.14	1.34
2007	0.03	2.36	-0.77	-0.33	-1.02	-0.65	-2.67	-0.28	-1.88	-0.86	0.03	2.8
2008	2.56	1.09	0.63	-0.81	-0.66	3	0.23	0.6	0.46	2.21	1.03	1.01

Table B6 Stations showing trend from Victoria

Station ID	Station Name	River Name	Area (km^2)	Lat	Long	Period of Record
228209	Hamiltons Br	Lang Lang	272	38.14	145.37	1980 - 2005
228228	Cardinia	Cardinia Ck	117	38.70	145.24	1974 - 2005
230210	Bullengarook	Saltwater Ck	39	37.28	144.31	1968 - 2005
230219	Darraweit Guim	Boyd Ck	135	37.23	144.53	1978 - 1997
235232	Painkalac Ck Dam	Painkalac Ck	36	38.26	144.04	1974 - 1992
236204	Streatham	Fiery Ck	956	37.40	143.03	1983 - 2005
236213	Mena Park	Mount Emu Ck	452	37.31	143.27	1966 - 2005
236219	Ararat	Hopkins Ck	258	37.19	142.56	1989 - 2005
238204	Dunkeld	Wannon	671	37.37	142.20	1966 - 2005
238230	Teakettle	Stokes	181	37.52	141.24	1984 - 2005
238235	Lower Crawford	Crawford	606	37.58	141.27	1980 - 2005
403218	Matong North	Dandongadale	182	36.48	146.38	1987 - 2005
405238	Pyalong	Mollison Ck	163	37.07	144.51	1966 - 2005
407213	Carisbrook	McCallums Ck	471	37.05	143.48	1971 - 2005
407227	Smeaton	Birch Ck	146	37.20	143.55	1981 - 2005
407284	Wisharts Rd	Calivil Ck	478	35.53	144.02	1988 - 2005
407285	Coads Rd	Nine Mile Ck	534	35.51	143.58	1988 - 2005
408202	Amphitheatre	Avoca	78	37.11	143.24	1966 - 2005
415223	Wonwondah East	Burnt Ck	80	36.53	147.14	1970 - 2005
415244	Warrak	Shepherds Ck	6	36.91	143.78	1983 - 2005
415259	Banyena	Richardson	1786	36.34	142.49	1993 - 2005

Table B7 Stations showing trend from NSW

Station ID	Station Name	River Name	Area (km^2)	Lat	Long	Period of Record
201900	Uki	Tweed	275	28.42	153.33	1968 - 1982
203010	Rock Valley	Leycester	179	28.74	153.16	1986 - 2005
204039	D/S Wylie Ck	Maryland	373	28.43	152.2	1984 - 2004
206027	Kirby Farm	Pipeclay Ck	9	30.47	151.63	1975 - 1992
207015	Mount Seaview	Hastings	342	31.37	152.25	1985 - 2005
208024	D/S Back R Jctn	Barnard	285	31.56	151.34	1983 - 2004
208026	Jacky Barkers	Myall	560	31.64	151.74	1985 - 2005
210034	Widden	Widden Brook	640	32.52	150.36	1967 - 1978
210074	Liddell (Site 5	McMahons Ck	1	32.36	151.01	1973 - 1982
210082	U/S Goulburn	Wollar Ck	274	32.34	149.95	1981 - 1996
210088	Aberdeen No.2	Dart Brook	799	32.17	150.87	1972 - 1982
210091	Merriwa	Merriwa	465	32.18	150.75	1981 - 1991
219001	Brown Mountain	Rutherford Ck	15	36.6	149.44	1949 - 2005
219006	Tantawangalo Mountain	Tantawangalo Ck	87	36.78	149.54	1952 - 2005
220002	Rocky Hall (Whitbys)	Stockyard Ck	75	36.95	149.5	1961-1984
221003	Bondi	Genoa	235	37.17	149.32	1972 - 1988
401016	The Square	Welumba Ck	52	36.04	148.12	1984 - 2003
401017	Yarramundi	Mannus Ck	197	35.77	147.93	1984 - 2004
410029	Buddong Falls	Buddong Ck	30	35.65	148.22	1956 - 1976
412071	Canomodine	Canomodine Ck	132	33.51	148.79	1983 - 1993
412073	Nyrang	Nyrang Ck	225	33.54	148.55	1983 - 1993
412090	Cudal No.2	Boree Ck	272	33.29	148.74	1971 - 1989
416036	Near Beebo	Campbells Ck	399	28.72	150.88	1979 - 1995
418020	Yarrowyck	Boorolong Ck	311	30.48	151.43	1974 - 1986
418022	Clerkness	Georges Ck	518	30.19	151.14	1979 - 1988
418033	Bundarra	Bakers Ck	173	30.21	151.03	1979 - 1988
419044	Damsite	Maules Ck	171	30.53	150.3	1969 - 1991
419047	Woodsreef	Ironbark Ck	581	30.41	150.73	1990 - 2005
421106	Wiagdon	Cheshire Ck	102	33.25	149.66	1981 - 1991
421126	Loch Lomond	Cainbil Ck	81	32.08	149.66	1983 - 1994
421156	Mumbil	Bonada Ck	7.5	32.7	149.04	1992 - 2001

Table B8 Stations showing trend from Qld

Station ID	Station and River Name	Area (km^2)	Lat	Long	Period of Record
105106A	West Normanby River at Mount Sellhe	839	-15.8	145.0	1970 - 1989
112001A	North Johnstone River at Goondi	936	-17.5	146.0	1928 - 1968
112002A	Fisher Creek at Nerada	15.7	-17.6	145.9	1928 - 2005
116008B	Gowrie Creek at Abergowrie	124	-18.4	145.8	1953 - 2005
116010A	Blencoe Creek at Blencoe Falls	226	-18.2	145.5	1960 - 2005
120206A	Pelican Creek at Mt Jimmy	545	-20.6	147.7	1960 - 1988
120216A	Broken River at Old Racecourse	100	-21.2	148.4	1969 - 2005
124001A	O'Connell River at Caping Siding	363	-20.6	148.6	1969 - 2005
125005A	Blacks Creek at Whitefords	506	-21.3	148.8	1973 - 2005
129001A	Waterpark Creek at Byfield	212	-22.8	150.7	1952 - 2005
130413A	Denison Creek at Braeside	757	-21.8	148.8	1971 - 2005
135004A	Gin Gin Creek at Dam Site	531	-25.0	151.9	1965 - 2005
137101A	Gregory River at Isis Highway	454	-25.1	152.2	1966 - 2005
137201A	Isis River at Bruce Highway	446	-25.3	152.4	1966 - 2005
143113A	Purga Creek at Loamside	215	-27.7	152.7	1973 - 2005
145002A	Christmas Creek at Lamington No.1	95	-28.2	153.0	1909 - 1955
145018A	Burnett Creek at Up Stream Maroon D	82	-28.2	152.6	1970 - 2005
146002B	Nerang River at Nerang	241	-28.0	153.3	1919 - 1970
422301A	Condamine River at Long Crossing	85	-28.3	152.3	1911 - 1978
422302A	Spring Creek at Killarney	21	-28.4	152.3	1909 - 1955
422303A	Spring Creek South at Killarney	10	-28.4	152.3	1909 - 1955
422304A	Condamine River at Elbow Valley	275	-28.4	152.2	1915 - 1972
422334A	Kings Creek at Aides Bridge	516	-27.9	151.9	1969 - 2005

Table B9 Stations showing trend from Tasmania

Station ID	Station Name	River Name	Area (km^2)	Lat	Long	Period of Record
304446	At Catagunya Rd	Black Bobs Ck	75.3	-42.40	146.60	1963 - 1975
309775	Above Linda Creek	Idaho Ck	2.3	-42.06	145.6	1986 - 2008
310154	Above Heemskirk	Pieman River	2541	-41.80	145.20	1955 - 1986