Estimation of Sustainable Diversion Limits for South West Western Australian Catchments

REGIONALISATION OF SUSTAINABLE DIVERSION LIMITS FOR CATCHMENTS

- Final C
- 5 January 2009

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This report is based on the deliberations of a panel of specialists with knowledge of stream ecology, water quality, geomorphology, hydrology, wetlands and catchment management. The overall direction, content and outcomes of this study are the result of their careful thought and judgement.

The members of the expert panel and their field of specialisation and affiliation are listed below in alphabetical order:

Paul Close	- aquatic ecologist, University of Western Australia
Robert Donohue	- environmental officer, Department of Water
A/Prof Ray Froend	- wetland ecologist, Edith Cowan University
Dr Stuart Halse	- aquatic ecologist, Bennelongia Environmental Consultants, formerly Department of Environment and Conservation
Steven Janicke	- geomorphologist, formerly Department of Water
Dr Rory Nathan	- principal hydrologist, Sinclair Knight Merz
Mark Pearcey	- water resources engineer, Department of Water
Dr Andrew Storey	- aquatic ecologist, University of Western Australia

The expert team was advised and supported by a technical team from SKM. Phillip Jordan was the Project Manager of this technical team, and was responsible for the delivery of project outcomes to the Department of Water. This report was authored by Phillip Jordan, Keirnan Fowler and Heath Sommerville. Technical support was provided by Simon Lang, Robert Morden, and Chloe Wiesenfeld.

Together, the expert panel and technical team comprised the study team which developed the rules used to define the Sustainable Diversion Limits for the unregulated rivers of south-west Western Australia.

Executive Summary

With increasing demand and competition for available water, there is a need to establish operational rules for sharing surface water resources in the south-west of Western Australia among users, including the environment. The objective of the SDL project was to develop a method for rapidly and conservatively estimating the winterfill diversion potential for unregulated (and generally ungauged) streams in the south-west.

The key rationale for this output is to allow the determination of a catchment-wide limit on diversion potential which avoids the need for site-specific assessments. As the estimates will be based on a rapid and regionalised set of inputs, they will need to be inherently conservative and would be used for broad regional planning, or preliminary design purposes only. Thus, rather than be viewed as a fixed upper catchment cap, if demand for water approaches the winterfill diversion potential then the limit could be used to trigger the undertaking of more detailed studies of environmental winter flow requirements.

The conceptual basis for the diversion limit was developed by a scientific panel, and the rationale for the manner in which this limit is estimated when streamflow data are available is provided in an earlier report[1]. This document completes the technical description of the project, and describes how the sustainable diversion limit is estimated for all possible catchments across South West Western Australia.

SDL diversions can occur over the winterfill period of 15 June through 15 October. The diversions are governed by three flow-based parameters, namely: a minimum flow threshold below which diversions should cease, a maximum daily extraction rate, and an annual licensed volume associated with a specified reliability of supply.

Regional equations were developed that relate these flow parameters to hydroclimatic and physiographic characteristics. The study area was divided into 1966 catchments, and SDL parameters were estimated for each catchment using the derived equations. The individual catchments typically range in size between 10 km^2 and 1000 km^2, and 864 subcatchments have other subcatchments that drain into them..

The final prediction equations are based on characteristics that are hydrologically meaningful, and a good standard of accuracy was achieved; the proportion of variance explained (R^2) ranges between 90% and 99%, and the standard errors are around 5% to 8%. When estimating the parameters for all catchments across the study area the predicted estimates were combined with estimates based on gauged data where suitable. A minor degree of smoothing was incorporated to ensure consistency between nested and gauged estimates.

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[1] Sinclair Knight Merz (2007): *Approach for Determining Sustainable Diversion Limits for South West Western Australia*, Report for Department of Water, October 2007.

Prediction equations were also derived to provide objective measures of catchment similarity. These measures were used to help identify indicator gauges that can be used to represent low flow conditions in ungauged catchments, and also for the identification of streamflow gauges most suited to transposition to ungauged locations.

Finally, some investigations were undertaken on a representative range of catchments to identify "exchange rates" that can be used to equate diversion limits based on pumped extractions with those obtained by harvesting of natural runoff by farm dams.

1. Introduction

1.1 The Need for Setting Limits

With increasing demand and competition for available water, there is a need to establish operational rules for sharing surface water resources in the south-west of Western Australia among users, including the environment. To address this need, the Department of Water initiated the 'Sustainable Diversion Limit' (SDL) project. The objective of the SDL project was to develop a method for rapidly and conservatively estimating the winterfill diversion potential for unregulated (and generally ungauged) streams in the south-west. The diversion potential represents an upper limit beyond which there is an unacceptable risk that additional extractions may degrade the riverine environment.

The key rationale for this output is to allow the determination of a catchment-wide limit on diversion potential which avoids the need for site-specific assessments. As the estimates will be based on a rapid and regionalised set of inputs, they will need to be inherently conservative and would be used for broad regional planning, or preliminary design purposes only. Thus, rather than be viewed as a fixed upper catchment cap, if demand for water approaches the winterfill diversion potential then the limit could be used to trigger the undertaking of more detailed studies of environmental winter flow requirements.

1.2 Defining the Sustainable Diversion Limit

A scientific panel was assembled to develop the recommendations used to formulate the SDL. The panel was comprised of researchers and practitioners with knowledge of stream ecology, water quality, geomorphology, hydrology, wetlands, and catchment management. All members of the panel had considerable experience in the development of environmental flow recommendations in Western Australia.

The sustainable limit on diversions was established by trialing various diversion rules on streamflow data obtained for a number of gauged sites across the south west of Western Australia. The suitability of different rules was assessed by investigating the impacts of diversions on a range of hydrologic criteria judged to be of ecological importance. The components of the hydrologic regime considered included the frequency and duration of spells above a range of thresholds, the magnitude and sequencing of selected flows, and the magnitude of frequent floods. Considerable attention was given to investigating the impacts over the full range of expected hydroclimatic conditions, and across all possible geographic regions of the study area.

Recommendations for estimating the SDL are based on a:

- winterfill period over which diversions can occur;
- minimum flow threshold below which diversions should cease;
- maximum daily extraction rate; and,
- annual licensed volume associated with a specified reliability of supply.

The minimum flow threshold (MFT), maximum daily extraction rate (MER) and annual licenced volume (or SDL) are referred to as the SDL parameters.

The recommended winterfill period is 15 June to 15 October inclusive for the whole study area, and the maximum and minimum thresholds are based on the same hydrologic criteria for all sites. The rules were developed assuming a notional supply reliability of 80%.

Application of these four rules to all gauged sites indicated that the average winterfill diversion is equivalent to 9.2% of the mean annual flow. The sustainable limit on diversions varies considerably from one catchment to the next. Diversion potential is high for those streams with a high proportion of groundwater contribution, and it is low for ephemeral streams which flow intermittently in direct response to rainfall.

Details of the scientific panel's recommendations are published in their final report (Sinclair Knight Merz, 2007) and a more concise description is published in Lang *et al*. (2008).

1.3 Purpose and Overall Approach of the Study

The outcomes of the scientific panel provided a method to calculate the SDL parameters (winterfill period, minimum flow threshold, maximum diversion rate and annual volume) from streamflow data recorded at gauges whose catchments are not greatly effected by current diversions.

This report builds upon this work by developing the methods required to estimate the SDL parameters for ungauged catchments.

The outcomes of the scientific panel indicated that the SDL parameters varied considerably between catchments. The volume of water that can be sustainably diverted from a catchment depends on both climatic factors, as well as the physical attributes of each individual catchment. There is considerable variation in SDL values across the South West of Western Australia because there is considerable variation in climatic and physiographic characteristics. It follows that if the climatic and physiographic characteristics of a catchment are known the SDL parameters can be estimated even without streamflow data.

Hydroclimatic and physiographic variables were used to develop prediction equations for three SDL parameters (minimum flow threshold, maximum diversion rate and annual volume). These equations were developed using the calculated SDL parameters and catchment characteristics of a large number of gauged sites across South West Western Australia.

In consultation with the Department of Water the catchments to which the SDL parameters would be provided were defined. The SDL parameters for these largely ungauged catchments were estimated using the prediction equations.

In order to apply the minimum flow threshold in ungauged catchments, each catchment needs to be assigned to an 'indicator gauge'. The concept here is to assign an ungauged catchment to a gauged catchment (the indicator gauge) that can be considered to behave in a similar manner during low flow conditions. Thus, when flows at the indicator site fall below some selected threshold, diversions in the ungauged catchment should cease. To aid identification of indicator gauges an assessment of streamflow regime was undertaken using information on hydroclimatic and physiographic characteristics. Indicator gauges can thus be allocated by reference to the similarity in streamflow regime, as well as to geographical proximity. In addition to the selection of indicator gauges, the identification of hydrologic similarity also facilitates the transposition of gauged streamflow data to an ungauged site.

Another aspect included in this study is the impact of farm dams. The proposed process for determining SDL extractions by the scientific panel were based on the assumption that all extractions were obtained by pumped diversions. However, some proportion of current level of diversions and, presumably, any future additional development, will be harvested by catchment dams. The two types of diversion impact on the streamflow in different ways. Hence the level of farm dam development needs to be modified so that the impacts are not greater than those experienced by pumped diversions.

There are a number of other issues that need to be addressed before the SDL can be implemented across South West Western Australia. These issues include the calculation of current development within each of the catchments, the equitable distribution of the sustainable diversion limit not currently allocated and the monitoring of indicator gauges. These issues are being considered by the Department of Water and are not covered in this report.

The objectives of this study are to:

- develop prediction equations for all SDL parameters based on climatic and physiographic catchment characteristics;
- estimate the SDL parameters for ungauged catchment in the South West of Western Australia;
- allocate each ungauged catchment to an indicator gauge for the purpose of monitoring the minimum flow threshold; and
- recommend an approach to deal with the issue of farm dams.

1.4 Structure of the report

The purpose of this report is to document and explain the work undertaken to meet the objectives of this study.

Chapter 2 describes how the gauged catchments used to derive prediction equations were selected and the delineation of ungauged catchments to which the prediction equations were applied. A summary of the selected streamflow gauges is provided in Appendix A. The preparation of streamflow data of the selected gauged catchments is described in chapter 3. The collection of climatic and physiographic characteristics of all catchments is outlined in chapter 4.

Chapters 5 and 6 describe the calculation of the SDL parameters from gauged data, the development of prediction equations for the parameters and estimation of the parameters for ungauged catchments. Each chapter follows the same format, and Appendix E contains the diagnostic plots relevant to the derived prediction equations. Chapter 8 describes the allocation of ungauged catchments to an indicator gauge. Estimation of the relative impacts of farm dams to pumped diversions is discussed in chapter 9.

The procedures described in chapters 5 to 9 make use of a number of multivariate statistical techniques, and these are described in Appendix B.

2. Catchment Selection

2.1 Introduction

For this study, two sets of catchments were required. The first was a set of gauged catchments that was required to calculate the SDL parameters and develop the regional prediction equations. The remaining catchments included all catchments from south west Western Australia that would have the SDL parameters applied. The majority of these catchments were ungauged.

Section 2.2 outlines the methods used to select the gauged catchments. The selection of gauged catchments was based predominantly on the quality of streamflow data and the level of upstream diversions.

In section 2.3 the methodology used to define all South West Western Australian catchments to which the SDL would be assigned using the regional equations is described. The majority of these catchments are ungauged. The catchments were developed in consultation with the Department of Water to ensure that the SDL could be easily applied and managed.

2.2 Selection of Gauged Catchments

A number of criteria were applied to select sites suitable for the derivation of the hydrologic indices and prediction equations. To be considered, the catchments needed to be:

- Located in the South West of Western Australia (basins 601-619 and 701);
- Unregulated;
- Gauged with more than 10 years of data from the period after January 1975 and with less than 10% of missing records;
- Free from the effect of large reservoirs;
- Largely non-urban and mostly unaffected by channel and drainage networks; and,
- Relatively unaffected by upstream diversions.

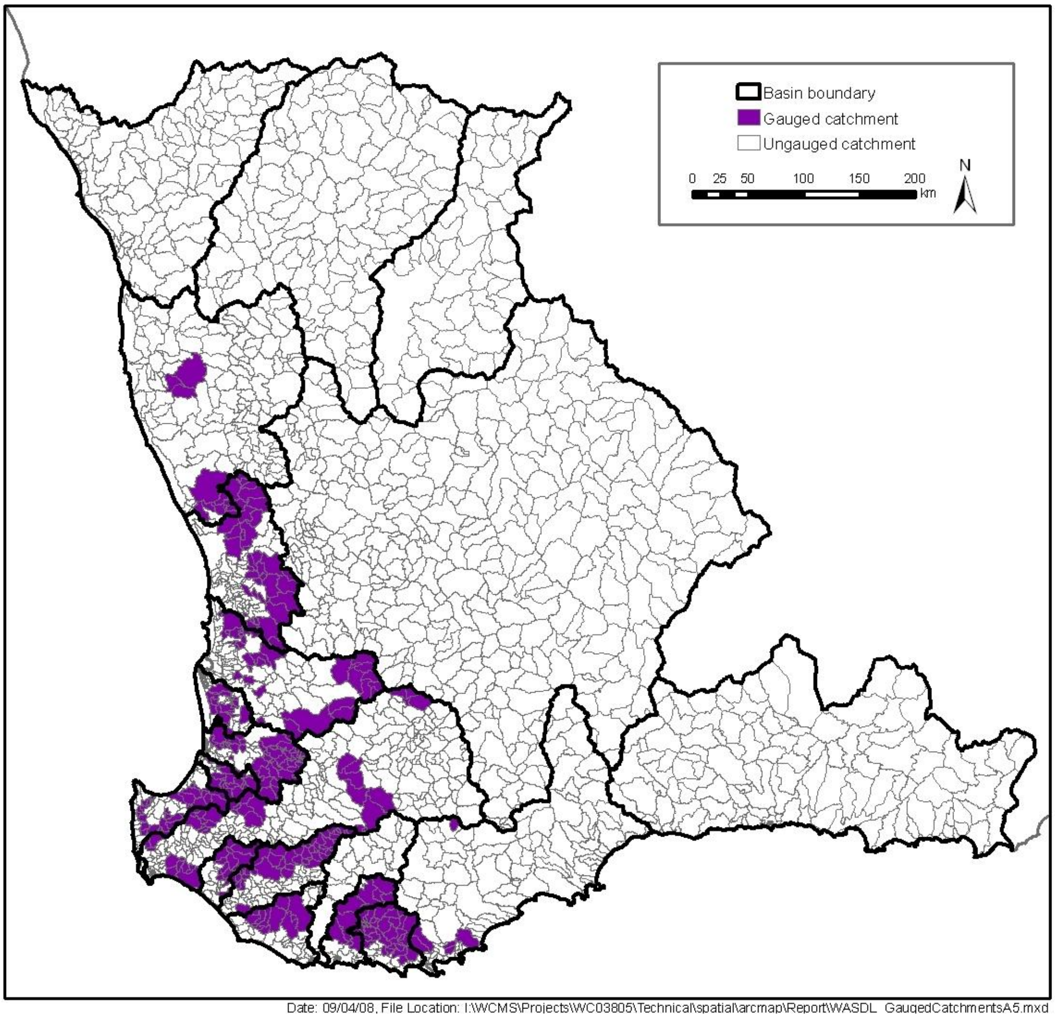
Sites meeting these criteria were identified using summary information on stream gauging supplied by the Department of Water. The summary information considered on stream gauging stations included details on catchment area, location, record length, operational status and percentage of missing record. Catchments with large reservoirs or considerable urbanisation or channel and drainage networks were identified in discussion with Department of Water hydrologists and hydrographers.

While the farm dams have an impact on streamflows it was not possible to systematically check all candidate catchments for the level of farm dam development as the required information is not available. Indeed the effort required to identify the level of farm dam development in candidate gauged catchments would be large compared with the resources expended on other parts of this project, and thus this is not a feasible selection criterion. Given the manner in which the SDL parameters are derived it appears reasonable to assume that the annual volume and maximum rate parameters of the SDL estimated from gauged data would not be particularly sensitive to the level of farm dam development, but that the low flow threshold would be. Accordingly, while it is likely that the data set compiled contains some catchments with an appreciable level of farm dam development, their influence on results was minimised by the identification and exclusion of outliers during development of the prediction equations.

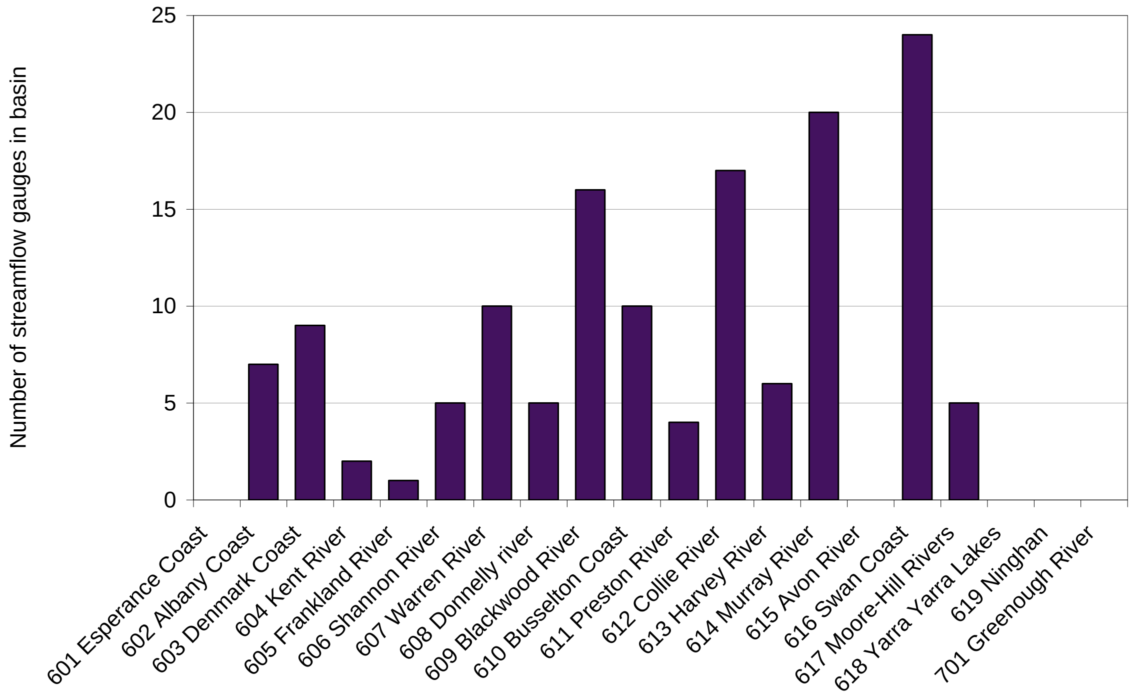
Using the above criteria 142 catchments were selected, with their details provided in section 3.2. Figure 2-1 presents a map of South West Western Australia indicating the selected catchments and a frequency distribution of the number of sites within each drainage basin is presented in Figure 2-2. The station number, river name and location of the selected catchments are listed in Appendix A.

In general the catchments selected tend to be located in the higher rainfall areas closest to the southern and western coastlines because there is a higher density of well gauged streamflow sites already in these catchments and these catchments were more likely to meet the selection criteria. The expert panel and study team analysed streamflow data from gauges across the study area and found that catchments in the northern and eastern parts of the study area (Esperance Coast, Avon River, Yarra Yarra Lakes, Ninghan or Greenough River basins) have lower mean daily flows, greater variability in flows and less contribution from baseflows during months which were candidates for the winterfill period (Sinclair Knight Merz, 2007). Gauges in these basins were therefore not used to directly calculate SDL volumes.

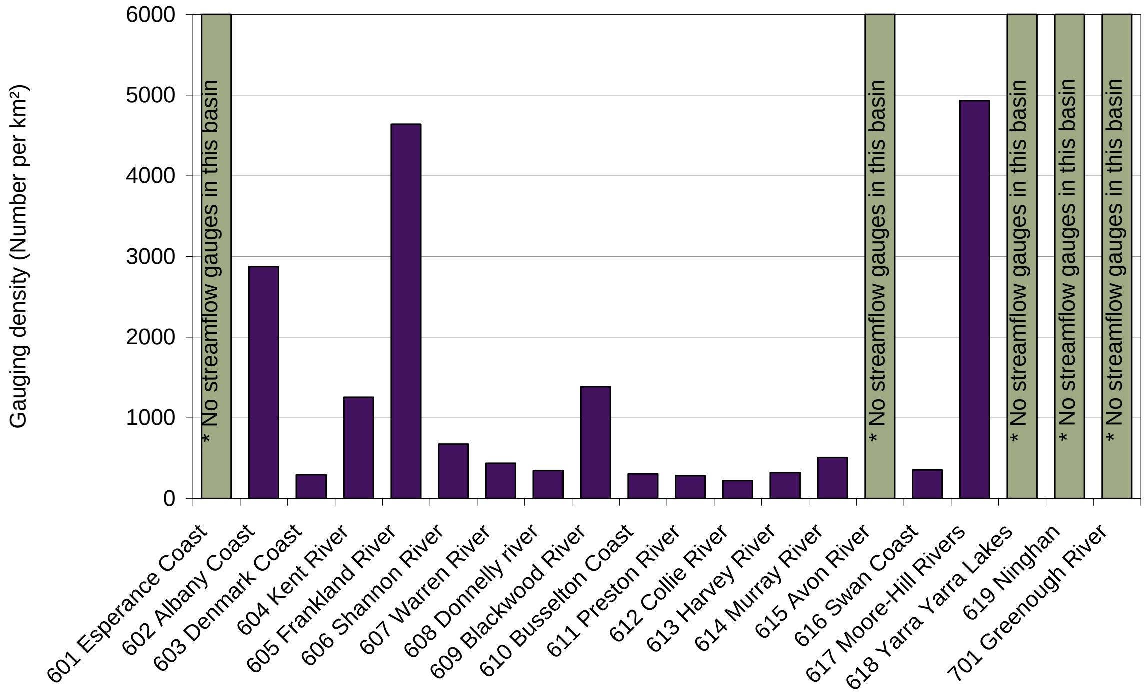
To illustrate the spatial variability in gauging density, the average area of each basin served by the selected gauges is illustrated in Figure 2-3. The average gauging density for the whole study area is one gauge for every 2600 km^2 of catchment area, although there were no selected streamflow gauges in the Esperance Coast, Avon River, Yarra Yarra Lakes, Ninghan or Greenough River basins. The average gauging density across those basins that have gauges (602 through 614, 616 and 617) is 827 km^2. Of those basins that have gauges used in this study, the lowest densities are in the Albany Coast, Moore-Hill River and Frankland River basins. It should be noted that the regional estimates of SDL parameters are not constrained by basin boundaries, though the distribution of gauging density illustrated in Figure 2-3 provides some indication of the spatial reliability of the estimates.



- **Figure 2-1 Spatial distribution of selected gauged and ungauged catchments.**



- **Figure 2-2 Histogram of the number of selected gauged catchments within each drainage basin in the study area.**



- **Figure 2-3 Gauging density (the ratio of the number of selected gauges and the total basin area) within each drainage basin.**

2.3 Delineation of Ungauged Catchments

This section of the report outlines the approach used to define the catchments for which a sustainable diversion limit (SDL) will be applied. Each of the Department of Water's Surface Water Management Subareas (SWMSA) were divided into sub-catchments based on a number of criteria that reflect the basis of the SDL derivation method. These divisions are at a spatial scale that is practical for use by the Department of Water. To ensure that the defined catchments meet the requirements for water resource allocation management in the region, the Department have reviewed the sub-catchments and their boundaries align with the boundaries of the Department's surface water management areas and surface water management subareas.

The following key criteria were used to delineate the catchment boundaries:

- *Overall catchment area between 10 km² and 1200 km²* - The catchments were generally defined to fall within the size range of between 10 km² and 1200 km². This range reflects the dominant range of catchment areas of the 142 gauged sites that were used to derive the equations for the calculation of the SDL. In some cases smaller catchment areas were defined where they were required to align with SWMSA boundaries.
- *Downstream boundary point at a confluence point* – Confluence points were selected for major tributaries to facilitate the implementation of the SDL by the Department of Water.
- *Downstream boundary point at a streamflow gauge* – Existing stream gauges were selected where the gauge is one of the 142 gauges selected to derive the SDL prediction equation. For these catchments the SDL could be directly calculated. Other existing gauges were also used to define downstream boundary points to enable streamflow data from these gauges to be used in future investigations.
- *Regular topographic and landuse characteristics* – Boundaries were selected to define areas of similar topographic and landuse characteristics as the SDL equations are derived as a function of physiographic and climatic characteristics. Attributes such as slope, elevation, landuse and stream density were used to place boundaries additional to the topographically defined watershed divides.

A naming system was developed that assigns a unique identifier to each sub-catchment. The system identifies the drainage basin number, the surface water management area number, the surface water management subarea number and the sub-catchment number. Surface water management areas were defined with numbers starting at high numbers in the upper reaches of the basin and increasing moving downstream. For basins with several outlet points to the sea (Esperance, Albany and Denmark Coast basins), the surface water management area numbers increase from east to west across the basin. Similarly, within each surface water management area, the surface water management subareas were numbered with increasing numbers from upstream to downstream or from east to west across the basin. Finally, each SDL catchment within each surface water management subarea was numbered in a similar manner, numerically increasing from upstream to downstream or from west to east.

Figure 2-4 shows an example of SDL subcatchment numbering in the Scott River surface water management subarea. For example 609_3_24_4 indicates the sub-catchment is in the Blackwood River Basin (609), in the Lower Blackwood SWMA (3), in the Scott River SWMSA (24) and is the fourth subcatchment in the SWMSA.

A total of 1966 SDL subcatchments were defined for South West Western Australia. The gauged catchments are shaded purple in Figure 2-1. While there are 1966 defined catchments many of these catchments are nested within other catchments. This is illustrated well in Figure 2-4 where it is seen that subcatchments 609_3_24_1 and 609_3_24_2 flow into sub-catchment 609_3_24_4 and hence are 'nested' within the downstream catchment. Similarly, sub-catchments 609_3_24_3, 609_3_24_4 and 609_3_24_5 flow into 609_3_24_6 so that all subcatchments 609_3_24_1 through 609_3_24_5 are nested within catchment 609_3_24_6. A total of 1102 catchments have other catchments nested within them.

- **Figure 2-4 Sub-catchments identified within the Scott River SWMSA in the Blackwood River Basin**

2.4 Subcatchments ending in terminal lakes

Several subcatchments within the study area end in terminal lakes that rarely, if ever, overflow into the downstream catchment. These catchments were flagged by the Department of Water in the GIS layer of initial catchment boundaries that were provided during the project. The downstream boundary of these terminal lake catchments were assumed to form part of the upstream boundary of any catchments that would notionally be defined as being downstream of them using an analysis of digital terrain data. In other words, it was assumed that overflow from catchments with a terminal lake at the downstream boundary is occurring sufficiently rarely that they are not part of the effective catchment area of any streams that are downstream of them. Catchment areas upstream of terminal lakes therefore do not contribute to the overall catchment area or to any of the overall upstream catchment characteristics of catchments that would notionally be downstream of them from a naive analysis of digital terrain data.

2.5 Summary

A total of 142 gauged catchments were selected that have a streamflow regime that is relatively unaffected by human activities and that have more than 10 years of data with less than 10% of missing records. These catchments were used to calculate SDL parameters and develop regional prediction equations.

South West Western Australia was delineated into 1966 catchments that are largely ungauged. Of these catchments, 864 subcatchments have other subcatchments that drain into them. The SDL was estimated for all of the ungauged catchments using the regional prediction equations. The definition of these catchments was based on a set of criteria to enable the prediction equations to be adequately applied and for the SDL to be easily managed by the Department of Water.

Figure 2-1 shows both the coverage of selected gauged catchments and the catchments for which the SDL parameters are provided.

3. Streamflow Characteristics

3.1 Introduction

Streamflow data was required for the 142 gauged catchments selected in chapter 2 to develop the regional prediction equations. The streamflow data was used to calculate the SDL parameters of maximum extraction rate, minimum flow threshold and annual volume.

This chapter describes the preparation of the streamflow data and describes the variation in the streamflow regime of the selected catchments.

3.2 Preparation of Streamflow Data

The need for infilling of missing data in the daily streamflow records was minimised by selecting sites with less than 10% of missing record. In total 76 of the 142 sites had period of missing data that required infilling.

For all 76 sites gaps less than 7 days in length were infilled using linear interpolation. A multivariate relationship between sites with missing data and other sites within the same drainage basin was developed and used to estimate the flows during periods of missing data of longer duration. Logarithmic and power transformations were commonly used on the data to produce better relationships. The coefficients of determination (r^2) of the resulting multiple regression equations ranged between 0.70 and 0.98.

The data record of some stations contained long periods of missing data. Periods of missing data greater than one year in length were not infilled, and instead the longest period of contiguous data was adopted.

Scatterplots of observed data and estimated data for streamflow records that were infilled were examined to make an assessment of the quality of the infilling method. A visual check of the data at these sites showed that periods of infilled data were consistent with the surrounding recorded data. No sites were rejected.

The data was examined for abnormalities that were not identified by the associated quality codes. A computer program was developed that identified periods where zero flow was preceded by a high flow event (a decrease from a flow above the 95th flow percentile to zero) or an unusually large change in flow from one day to the next. An unusually large change in flow was defined as a change that exceeded 4.5 times the standard deviation of the 20 largest changes found in the record. The program identified 32 sites that appeared to contain abnormal, or incorrect, data. A visual inspection of the 32 data series was undertaken and the few periods of data that appeared suspect following the visual inspection were deleted and infilled using multivariate relationships with other stream gauging sites within the same drainage basin.

Initially sites were selected if they had more than 10 years of gauged data from the period post-1975 with less than 10% of missing record. In the preparation of streamflow data the record of some stations was truncated to remove large periods of missing data. The length and percentage of missing data was examined for each infilled data record. Frequency distributions of the number of years of streamflow record and percentage of streamflow record infilled for all 142 sites are given in Figure 3-1 and Figure 3-2.

3.3 Variation of Streamflow Characteristics

The variation in the hydrology of the 142 selected sites has been characterised in this section using a range of descriptive statistics. The results represent a range of hydrological regimes across the study area. Where appropriate, annual and winter statistics have been extracted where the period of June to October inclusive was selected as indicative of high winter flow months in most catchments across the study area. The summer months have been defined as December to February. Information is presented in the form of frequency distributions of the 142 selected catchments. A brief description of each hydrological characteristic is given below.

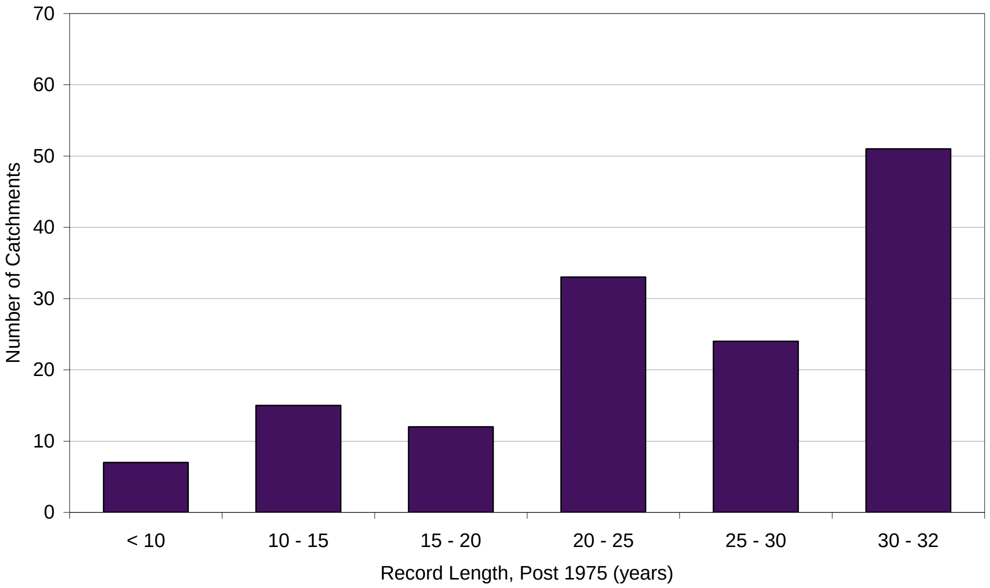
Mean Annual and Winter Flow

The frequency distribution of mean daily flow is presented in Figure 3-3. The variation in mean daily flow due to different catchment sizes has been removed by dividing the mean daily flow by the catchment area. Mean daily flow for the complete period and the June to October period have been included to allow comparison.

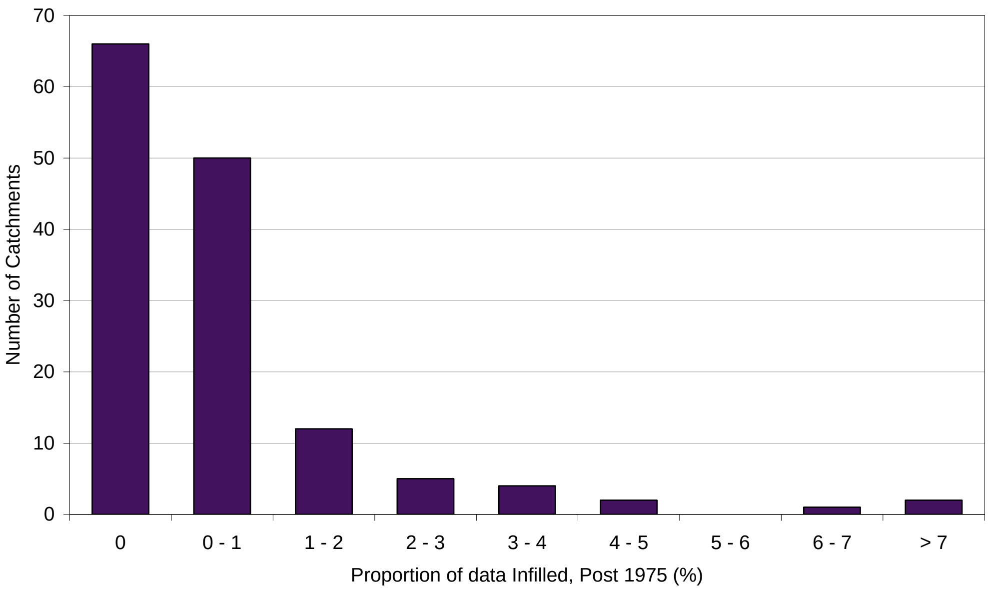
The mean daily flow varies between 0.006 ML/day/km^2 and 0.939 ML/day/km^2 for the complete period (mean annual flow range 2.2 to 343 ML/km^2). The majority of selected catchments have mean daily flows near the lower end of the range with only 29 sites with mean daily flow greater than 0.5 ML/day/km^2 (mean annual flow 183 ML/km^2). As expected the mean daily flow for the winterfill period is greater than for the complete period with a maximum mean daily flow of 1.94 ML/day/km^2, which is more than double the mean daily flow for the whole period at the same site.

Annual and Winter Coefficient of Variation

The coefficient of variation (CV) is a measure of the spread of daily flows, and is defined as the standard deviation divided by the mean daily flow. Again the results for both the June to October and annual periods of streamflow data and are presented in Figure 3-3. In general the variation in the June to October period is lower than the annual period with the annual results ranging between 0.47 and 14.9 and the winter results ranging between 0.29 and 10.



- **Figure 3-1 Frequency distribution of the number of years of streamflow record post-1975 for all 142 selected gauged catchments.**



- **Figure 3-2 Frequency distributions of the percentage of streamflow data requiring infilling for all 142 selected gauged catchments.**

Annual and Winter Base Flow Index

The base flow index is the proportion of base flow contributing to the mean daily flow. Base flow has been separated from the surface flow using the digital filter method (Nathan and McMahon, 1990). The base flow indices have been calculated for both the annual period of daily flow record and also for the June to October periods. The frequency distribution of the annual and the June to

October period base flow index is presented in Figure 3-4. The contribution of base flow to the overall streamflow is similar for both periods considered.

Probability of Zero Flow in Summer and Winter

The probability of zero flow during the summer months and the July to October period has been derived and the frequency distribution of the 142 selected catchments is presented in Figure 3-4. The number of sites with a zero probability of zero flow increases from 17 to 60 between summer and winter. Twenty-one sites had probabilities of zero flow of more than 90% for the summer period, with one site never having flowed in its period of record between December and February. The maximum probability of zero flow for the July through October period was 67%.

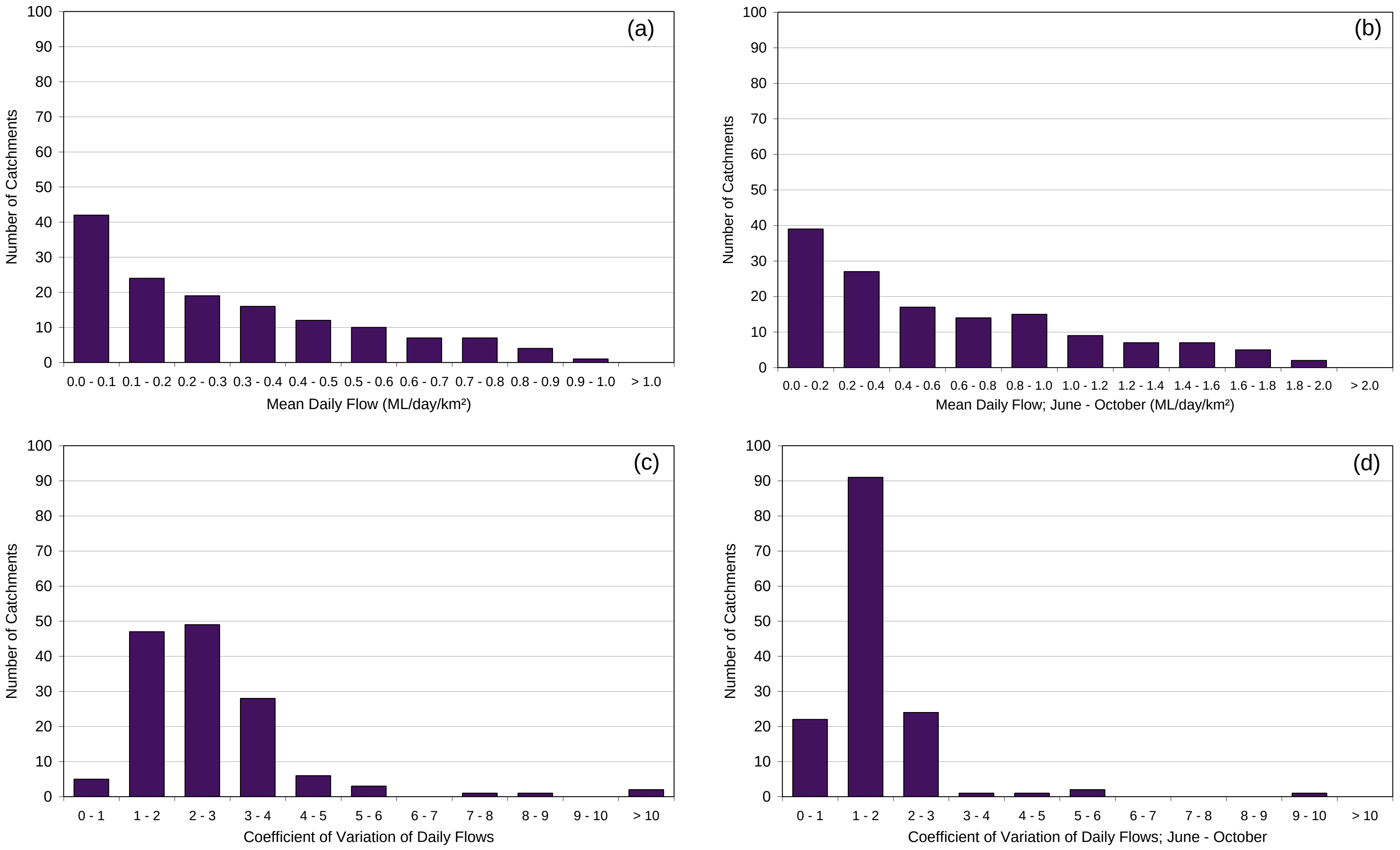
Annual 90th Flow Percentile

The annual 90th flow percentile is the daily flow per square kilometre that is exceeded 90 percent of the time. For the selected catchment this value ranges between 0 ML/day/km^2 and 0.263 ML/day/km^2, however the annual 90th flow percentile is less than 0.0001 ML/day/km^2 for the majority of catchments.

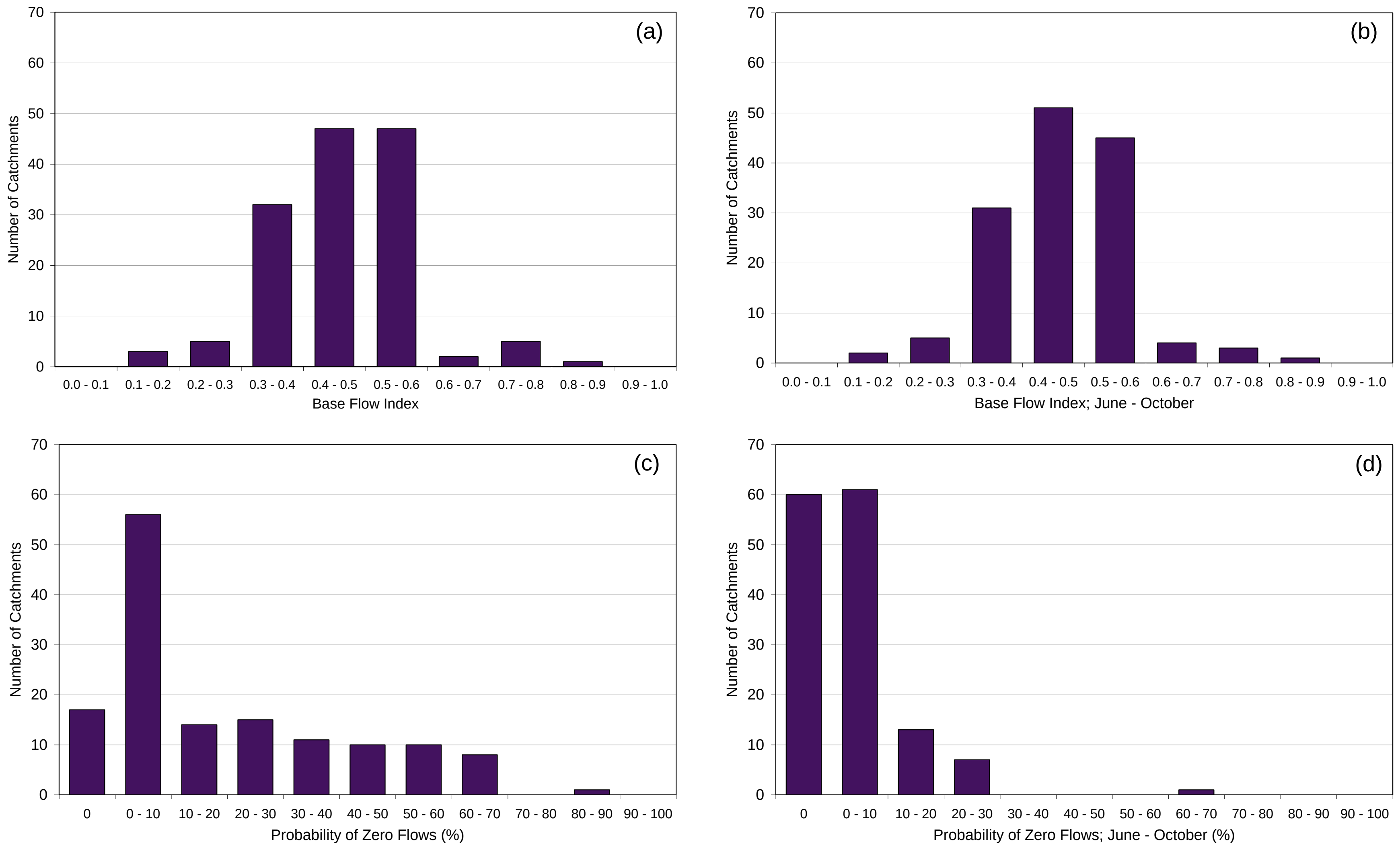
Catchment Area

The frequency distribution of catchment area is given in Figure 3-5. Although there were seven catchments selected with catchment areas exceeding 5000 km^2, the vast majority of the catchments (123) had areas of less than 1000 km^2. A higher number of small catchments were selected, as these were less likely to be effected by regulation or upstream diversions.

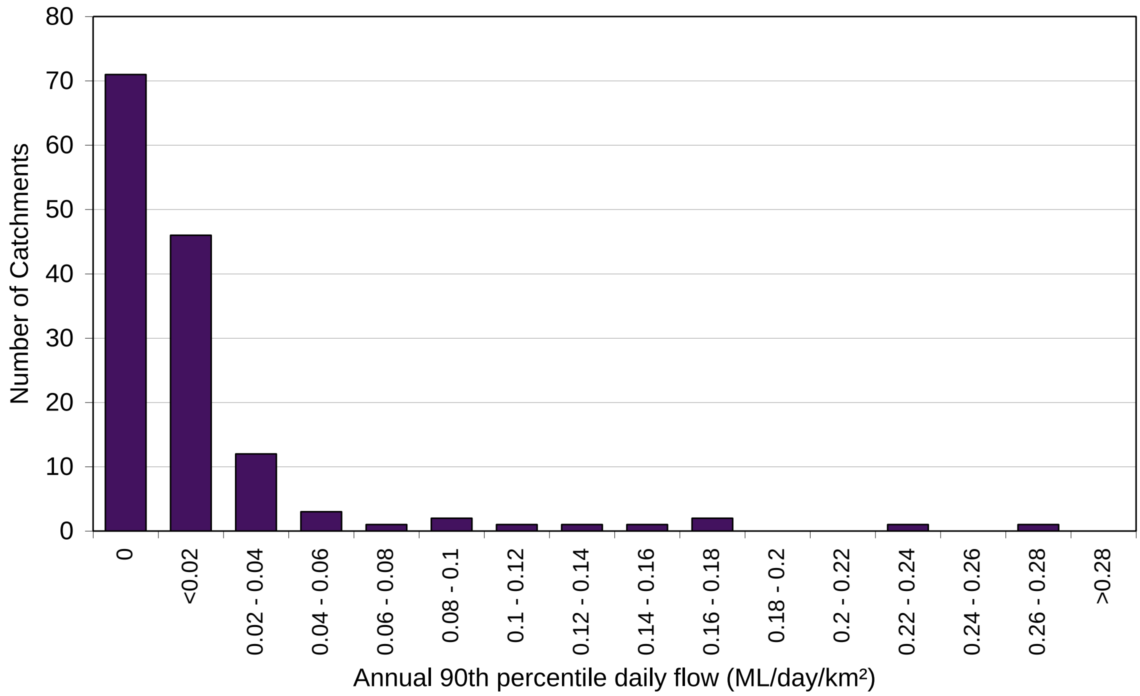
Overall Figure 3-3 - Figure 3-6 show that a large variety of stream regimes were selected to develop the SDL regional prediction equations. Catchments have been selected that have large areas, a high base flow index, and a very low probability of zero flow and low coefficient of variation. Lendard Brook at Molecap Hill (BFI = 0.86, perennial, CoV = 0.47) and McKnoes Brook at Urquharts (BFI = 0.75, perennial, CoV = 0.85) are two examples of this regime. Ephemeral catchments with low baseflow indices such as Jackitup Creek at Wellards (BFI = 0.15, zero flow on 25% of days, CoV = 14.9) and the Northern Arthur River (BFI = 0.13, zero flow on 85% of days, CoV = 14.3) have also been selected. Ephemeral streams exhibit a small mean annual flow, a low base flow index, a high probability of zero flow and a high coefficient of variation. The large variation in streamflow regimes allowed the majority of streams in the study area to be represented.



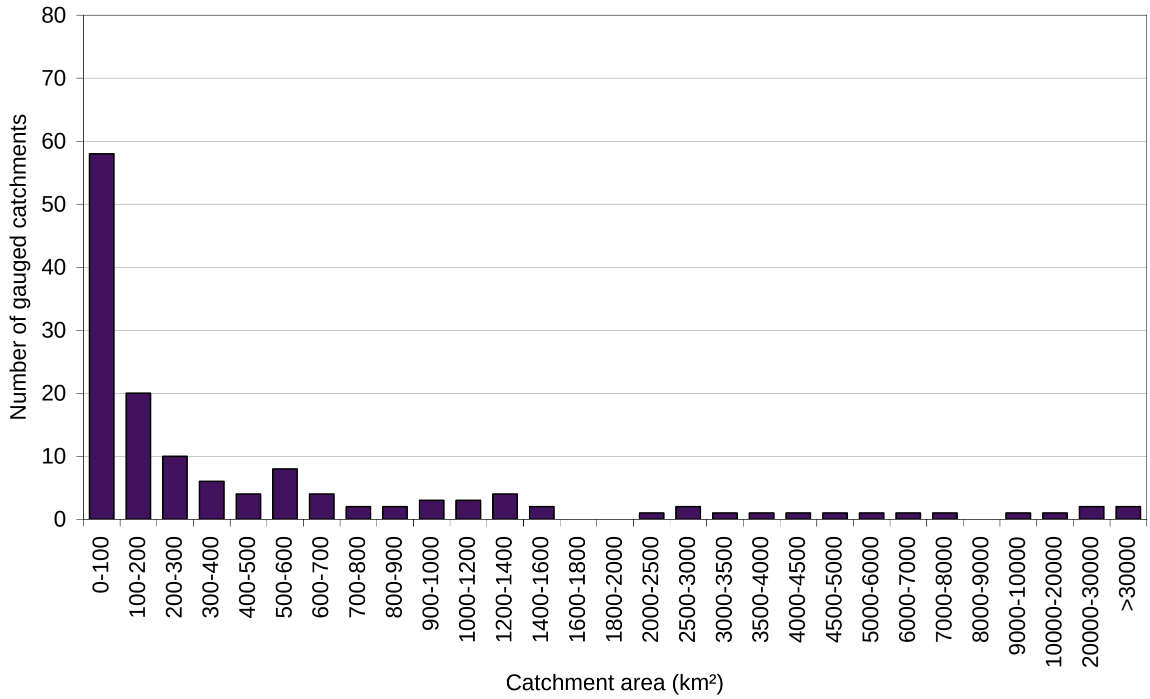
▪ **Figure 3-3 Frequency Distributions for all 142 selected catchments of values of mean daily flow for (a) whole year and (b) July to October period, and coefficient of variation of daily flows for (c) whole year and (d) July to October periods.**



- **Figure 3-4 Frequency distributions for all 142 selected catchments of values of the base flow index for (a) whole year and (b) July to October periods and probability of zero flow during (a) summer periods and (b) July to October periods.**



- **Figure 3-5 Frequency distribution for all 142 selected catchments of the annual 90th percentile of daily flow.**



- **Figure 3-6 Frequency distribution for all 142 selected catchments of the catchment area.**

3.4 Summary

Streamflow was required for the 142 selected gauged catchments in order to calculate the SDL parameters and develop regional prediction equations.

The streamflow data was infilled or truncated where necessary to remove any gaps in the time series. The quality of the data was thoroughly checked. The streamflow data for all 142 sites had more than 10 years of record from the period post-1975 and less than 7% of the time series was infilled.

The variations in key streamflow statistics are illustrated in Figure 3-3- Figure 3-6 using key streamflow statistics. The sites selected represent a range of streamflow regimes and represent conditions across the wetter southern and western basins of the study area well, although the lack of selected sites in the drier northern and eastern parts of the study area means that the gauged sites are less representative of these catchments.

4. Physiographic Characteristics

4.1 Introduction

In the previous chapter the streamflow data used to calculate the SDL parameters for the 1966 selected gauged catchments was discussed. The streamflow regimes and the SDL parameters vary between catchments due to different climatic and physiographic characteristics of the catchments. These characteristics have been used to develop prediction equations for the SDL parameters in later chapters.

This chapter describes the characteristics used, the methods used to obtain the characteristics for all catchments and the variation between catchments.

4.2 Description of Statistics

This section outlines the physiographic characteristics considered and the source of information. The characteristics derived are outlined below.

Shape

The shape of a catchment will affect the shape of a hydrograph, particularly the rate of increase of the hydrograph during a storm event. The shape of the catchment is characterised by its area and perimeter.

Location

The location of the centroid of each catchment in Eastings and Northings were derived using GIS tools and the catchment boundaries.

Elevation

The mean, maximum, minimum and range of elevations within the catchment were derived using a 9"Digital Elevation Model (DEM) produced by Auslig.

Slope

The mean, maximum, minimum and range of slope within the catchment were derived. A 9" Digital Elevation Model (DEM) was used to determine the slope for each 9" cell within the catchment based on the elevation of each 8 neighbouring cells.

Aspect

The aspect of the catchment is presented as the percentage of the catchment that faces North, South, East and West. These percentages were derived using the 9" Digital Elevation Model.

Rainfall and Evapotranspiration

GIS grid information produced by the Bureau of Meteorology and the CRC for Catchment Hydrology (BoM, 2001a, 2001b) has been used to extract mean annual and monthly rainfall and evaporation for the 1961 through 1990 reference period. The rainfall and evaporation layers obtained for this reference period included:

- Rainfall;
- Point potential evapotranspiration;
- Areal potential evapotranspiration; and,
- Areal actual evapotranspiration.

Southwestern Australia experienced a climate change shift during the period of 1975 to 2006. Mean annual and winterfill (June through October) rainfall statistics for this alternate reference period were computed using daily rainfall averages at rainfall gauges for this period. At each rainfall gauge, a ratio was computed of the 1975-2006 value to the 1961-1990 value from the BoM grid. This new ratio value was then spatially interpolated to a grid across the entire area using Kriging. Finally, the ratio grid was multiplied by the BoM grid to produce a field of spatially interpolated mean annual and mean winterfill period rainfall representing the 1975-2006 period. The use of the BoM dataset was important in order to incorporate into the new rainfall grid the topographical and meteorological conditions inherent in the BoM dataset.

The rainfall and evaporation characteristic values presented are the averages of all grid cells within each catchment.

Stream Density

The stream density of a catchment is defined as the total length of stream within the catchment divided by the catchment area. The total stream length for the selected catchments was measured using a derived stream network dataset that was based on Geoscience Australia's 1:250,000 WatercourseLines dataset and a flow accumulation layer that was created using the 9" Digital Elevation Model. This approach was taken because no consistent larger scale stream network dataset for the region was available as the WA hydrography layers do not have consistent detail across the landscape and are therefore not useful for comparison of stream density between catchments. Using the 1:250,000 dataset alone would have resulted in many catchments having no stream density as many significant streams are missing from the dataset. The inclusion of the flow accumulation derived lines ensured that almost all catchments have a stream density value greater than zero.

Stream Frequency

The stream frequency of a catchment is defined as the total number of stream junctions within the catchment divided by the catchment area. Junctions are defined as the number of points where 2 stream lines intersect (eg a stream running straight through the catchment will have no junctions). The number of stream junctions was based on the derived stream network coverage discussed above for the Stream Density characteristic.

Vegetation Cover

Vegetation cover has been expressed as the percentage of a catchment covered by woody vegetation. The source of this information are datasets used by the Australian Greenhouse Office (AGO) in their National Carbon Accounting System (NCAS) for reporting on the extent and changes in tree cover throughout Australia. These datasets were originally derived using Landsat MSS and Landsat TM imagery and remote sensing analysis techniques. AGO datasets from the most recent years of 1989 and 2005 were used.

Soil Type

For each selected catchment, various soil hydrological characteristics were calculated. These calculations were either a weighted average of the characteristic, or a weighted average of the characteristic's rating class.

McKenzie *et al*. (2000) have assigned either values or ratings for a number of useful hydrological characteristics associated with soil types in the Northcote soil classification system. The hydrological characteristics of interest are:

- Profile Permeability (K_s);
- Available Water Holding Capacity (AWHC for A Horizon and PAWHC for solum);
- Depth of Soil Profile; and,
- Texture.

Not all of the 671 different Northcote soil types have been assigned values or ratings for the four hydrological characteristics because the information provided by Northcote (1979) was not detailed enough to make a reasonable interpretation. Estimated ratings were based on ratings of similar soil types according to Northcote (1979).

An example of each value or a description of the rating system used for each characteristic is presented in the table below, as provided by McKenzie et al 2000.

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- **Table 4-1 Rating system used for interpreting classes from Northcote's Factual Key (McKenzie *et al*., 2000).**

Value or Rating	Physical Property	Description
Permeability - median Ks for the A and B horizons		
1 - 3	< 0.3 mm/hr	Very Slow
4 - 5	0.3 – 3.0 mm/hr	Slow
6 - 7	3.0 – 30 mm/hr	Moderate
8 - 9	30 – 300 mm/hr	High
10 - 11	> 300 mm/hr	Extreme
Available Water Holding Capacity – AWHC for Horizon A and PAWHC for the solum (A + B horizons), in mm		
Example: 51 mm		
Soil Texture Profile - median value for A and B horizon Northcote texture group		
1	Sands	
2	Sandy Loams	
3	Loams	
4	Clay Loams	
5	Light Clays	
6	Clays	
Soil Depth - median thickness value of A + B horizons and solum, in m		
Example: 0.6 m		

A summary of the catchment characteristics is provided in Table 4-2.

- **Table 4-2 Summary of catchment characteristics**

Variable	Abbreviation	Units
Shape		
Catchment Area	AREA	km^2
Catchment Perimeter	PERIM	km
Location		
Catchment Centroid Easting	EASTING	m
Catchment Centroid Northing	NORTHING	m
Elevation		
Maximum	ELEV_MAX	m
Minimum	ELEV_MIN	m
Range	ELEV_RAN	m
Mean	ELEV_MN	m
Standard Deviation	ELEV_STD	m
Slope		
Maximum	SLOPE_MAX	

Variable	Abbreviation	Units
Minimum	SLOPE_MIN	
Range	SLOPE_RNG	
Mean	SLOPE_AV	
Standard Deviation	SLOPE_STD	
Aspect		
North	PCNORTH	%
East	PCEAST	%
South	PCSOUTH	%
West	PCWEST	%
Rainfall		
Annual (1961-1990)	RAIN_ANN	mm
June – October (1961-1990)	RAIN_WINT	mm
Annual (1975-2006)	RCANN_MN	mm
June – October (1975-2006)	RCWINT_MN	mm
Actual Evapotranspiration		
Annual	AEVAP_ANN	mm
June – October	AEVAP_WINT	mm
Areal Potential Evapotranspiration		
Annual	APEVAP_ANN	mm
June – October	APEVAP_WINT	mm
Point Evapotranspiration		
Annual	PPEVAP_ANN	mm
June – October	PPEVAP_WINT	mm
Stream Density	SDENSITY	km/km^2
Stream Frequency	SFREQ	$nodes/km^2$
Vegetation Cover in1989	PCT_VEG89	%
Vegetation Cover in 2005	PCT_VEG05	%
Soil Characteristics		
Horizon A Soil Permeability	AKS_MN	rating
Horizon A Median Depth	ATHK50_MN	m
Horizon A Median Texture	ATXT50_MN	rating
Horizon A Available Water Holding Capacity	AAWHC_MN	mm
Horizon B Soil Permeability	BKS_MN	rating
Horizon B Median Depth	BTHK50_MN	m
Horizon B Median Texture	BTXT50_MN	rating
Profile (Horizons A and B) Available Water Holding Capacity	PAWHC_MN	mm
Profile (Horizons A and B) Median Depth	SOLUMTH_MN	m

4.3 Extraction of Physiographic Characteristics

The characteristics needed to be derived for all gauged and non-gauged catchments defined in chapter 2. Digitised boundaries were created in order to derive the catchment characteristics using various Geographic Information System (GIS) tools.

The source data formats included vector and raster formats and the data sets were analysed using intersection and summary tools within Arcinfo and ArcView, including the GRID and Spatial Analyst extensions.

A summary of the formats and approaches used to derive the characteristics is presented in Table 4-3. A series of programs in ArcInfo were written to aggregate the results for each catchment and intermediate area for nested catchments.

Table 4-3 Summary of catchment characteristics

Characteristic	Format of Source Data	Analysis technique
Elevation	Grid	Overlay catchments and summarise
Slope	Grid	Overlay catchments and summarise
Rainfall and Evapotranspiration	Grid	Overlay catchments and summarise
Aspect	Grid	Overlay catchments and summarise
Stream density	Vector - line	Intersect with catchments and summarise
Stream frequency	Vector - line	Automated technique using data produced from the stream density analysis
Vegetation cover	Grid	Overlay catchments and summarise
Soil type	Vector – polygons	Intersect with catchments and summarise

4.4 Variation of Physiographic Characteristics

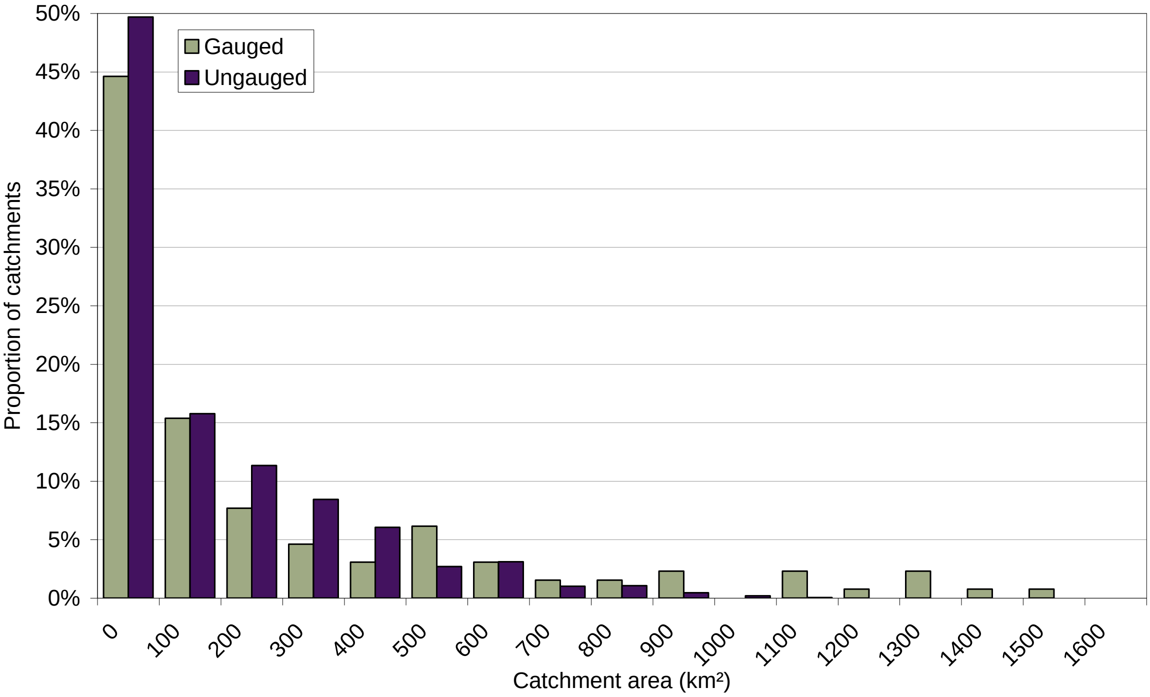
The variation in the characteristics of the selected gauged catchments and all of the ungauged catchments have been characterised and compared in this section. Information is presented in the form of frequency distributions for key characteristics in Figure 4-1 through Figure 4-8. The results for the selected gauged catchments are shown in light olive and all other catchments in dark purple.

The gauged catchments span a larger range of catchment areas than the ungauged catchments (Figure 4-1). This is because all of the ungauged catchments were intentionally subdivided down until their catchment area was less than 1200 km² but some larger gauged catchments were included to represent the spatial variability in unregulated streamflows. There are fairly similar proportions of gauged and ungauged catchments in each size class up to 800 km².

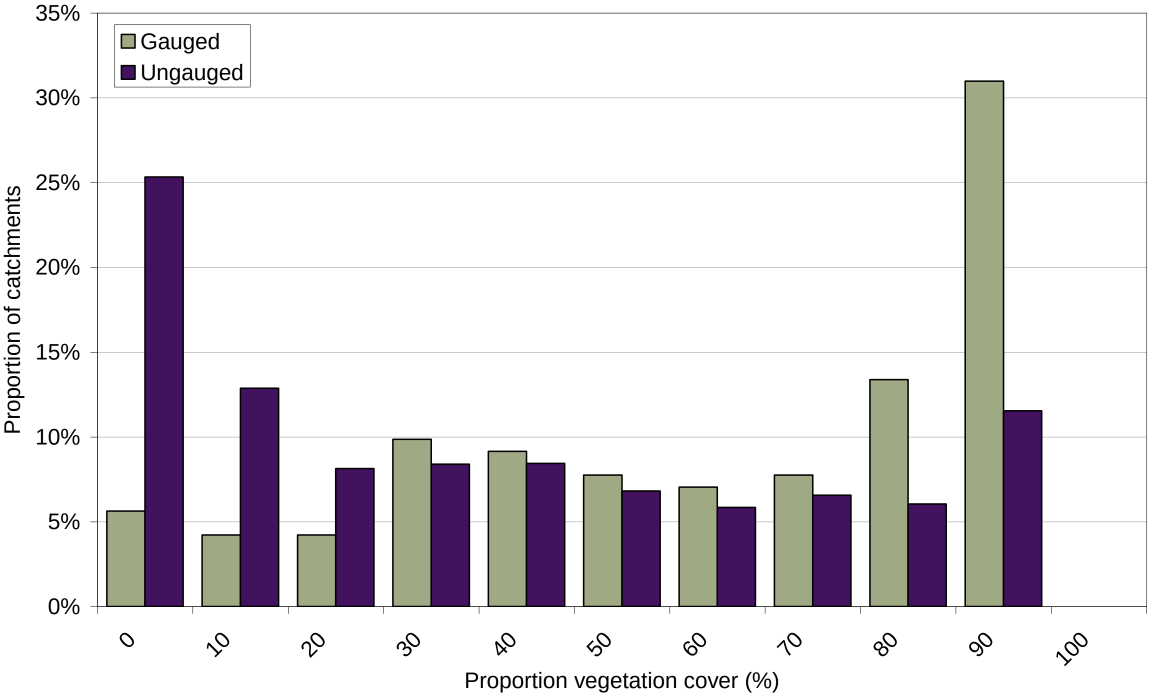
These catchments are located toward the northern-eastern margin of the study area and there were no selected gauged catchments in this part of the region.

Selected gauged catchments were located only in the southern and western basins of the study area (basins 602 through 614, 616 and 617) and this is reflected in the differences in the other physiographic characteristics with those from the whole study area. For this reason:

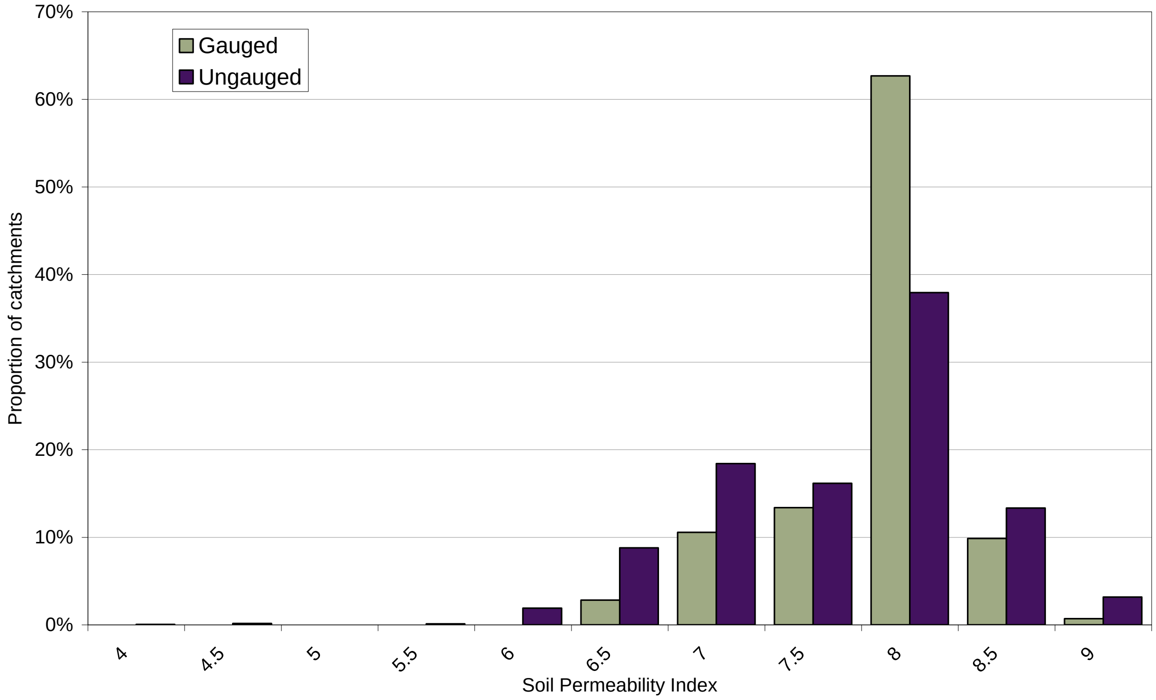
- The gauged catchments generally have higher mean annual rainfall (see Figure 4-5) and June through October rainfall (see Figure 4-6) than the ungauged catchments.
- The gauged catchments are much more likely to have a high proportion of woody vegetation cover than the ungauged catchments (see Figure 4-2).
- The gauged catchments exhibit less variability in soil permeability index than the ungauged catchments (see Figure 4-3), although the median soil permeability is very similar for both the gauged and ungauged catchment data sets.
- There is a slight bias toward having a higher proportion of ungauged catchments with mean elevations above 350 m AHD (see Figure 4-4).
- Annual potential evapotranspiration is lower for the gauged catchments than the ungauged catchments (see Figure 4-8) because the gauged catchments are in areas with lower mean temperature and higher humidity.
- But annual actual evapotranspiration is higher for the gauged catchments than the ungauged catchments (see Figure 4-7) because the gauged catchments are in higher rainfall areas with more water available for evapotranspiration.



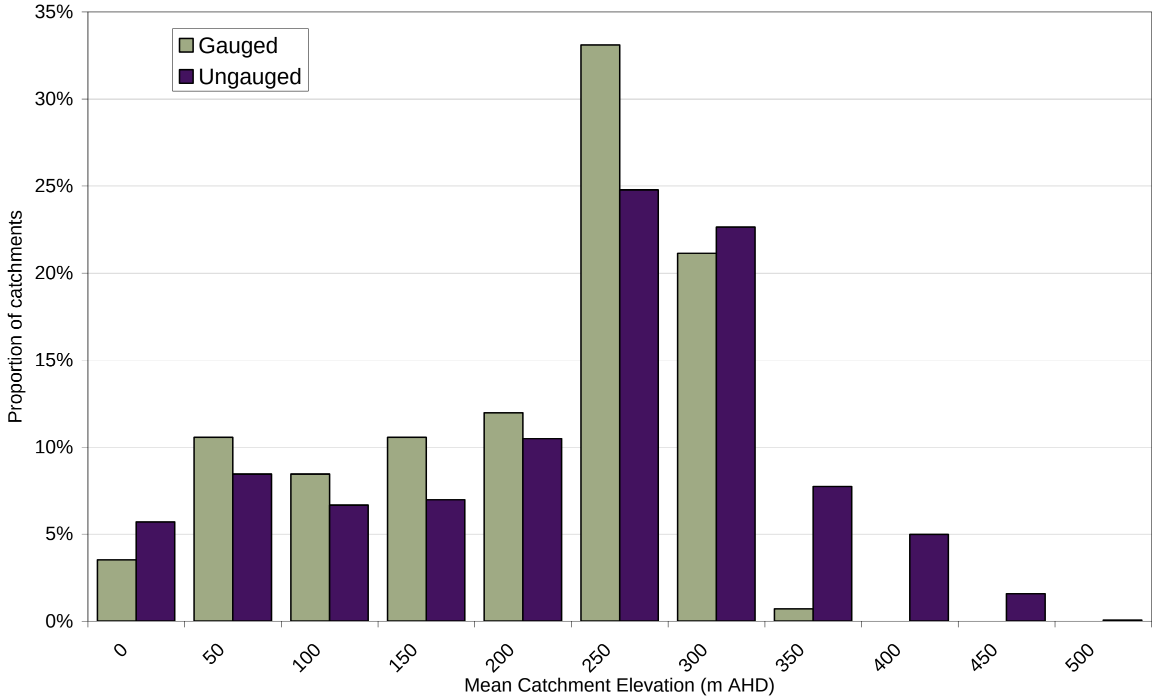
▪ **Figure 4-1 Histogram of area for all ungauged catchments and for the catchments of the selected streamflow gauges**



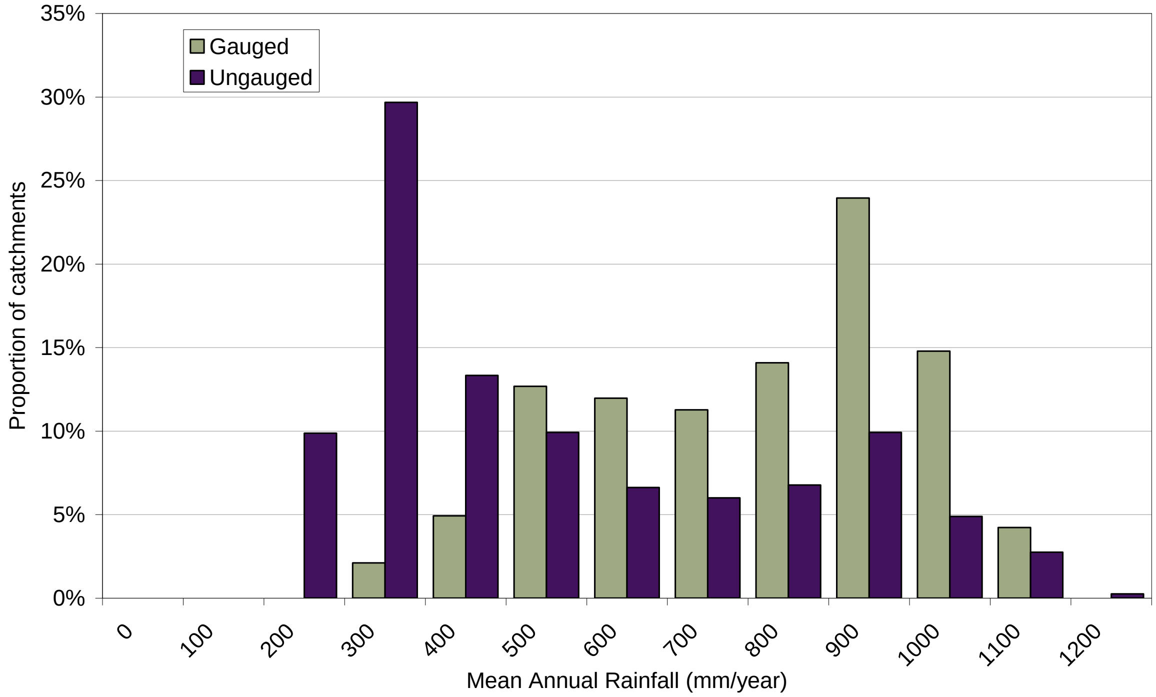
▪ **Figure 4-2 Histogram of proportion of woody vegetation cover (in 2005) for all ungauged catchments and for the catchments of the selected streamflow gauges**



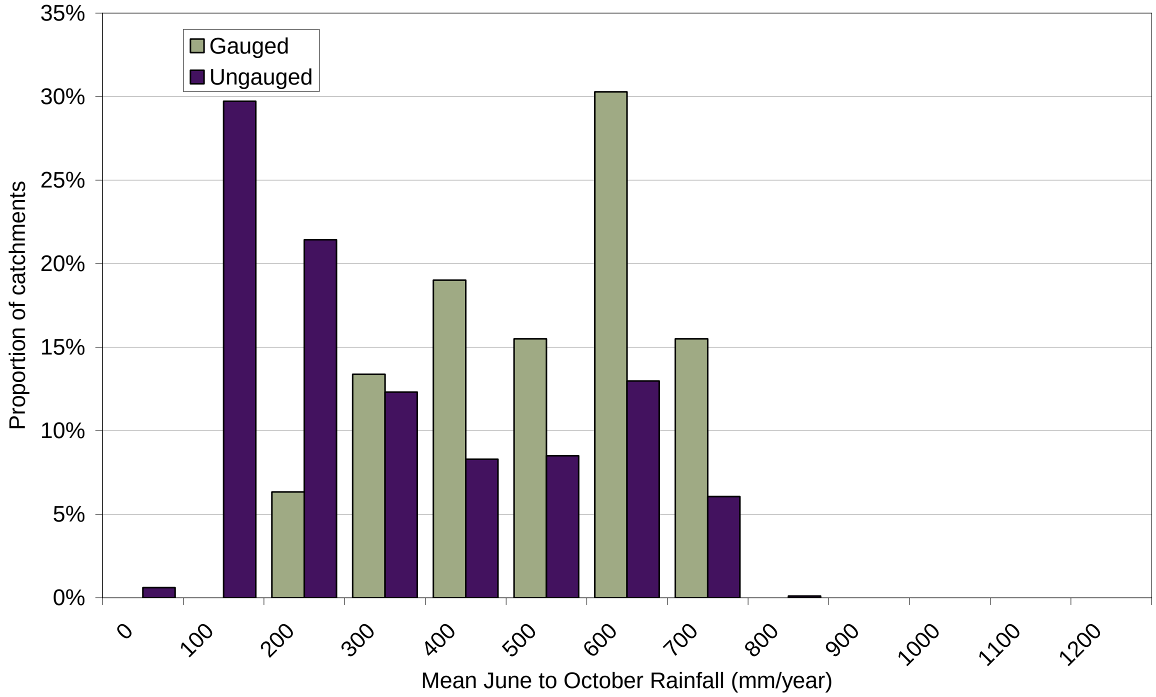
▪ **Figure 4-3 Histogram of mean soil permeability index for all ungauged catchments and for the catchments of the selected streamflow gauges**



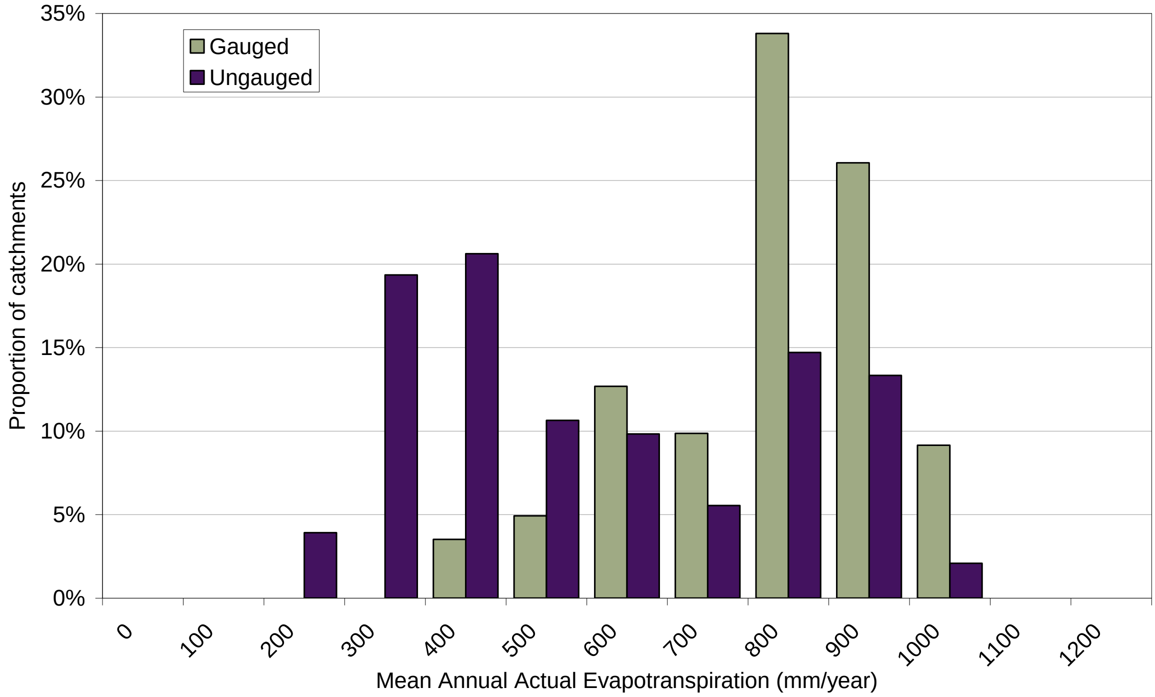
▪ **Figure 4-4 Histogram of mean catchment elevation for all ungauged catchments and for the catchments of the selected streamflow gauges**



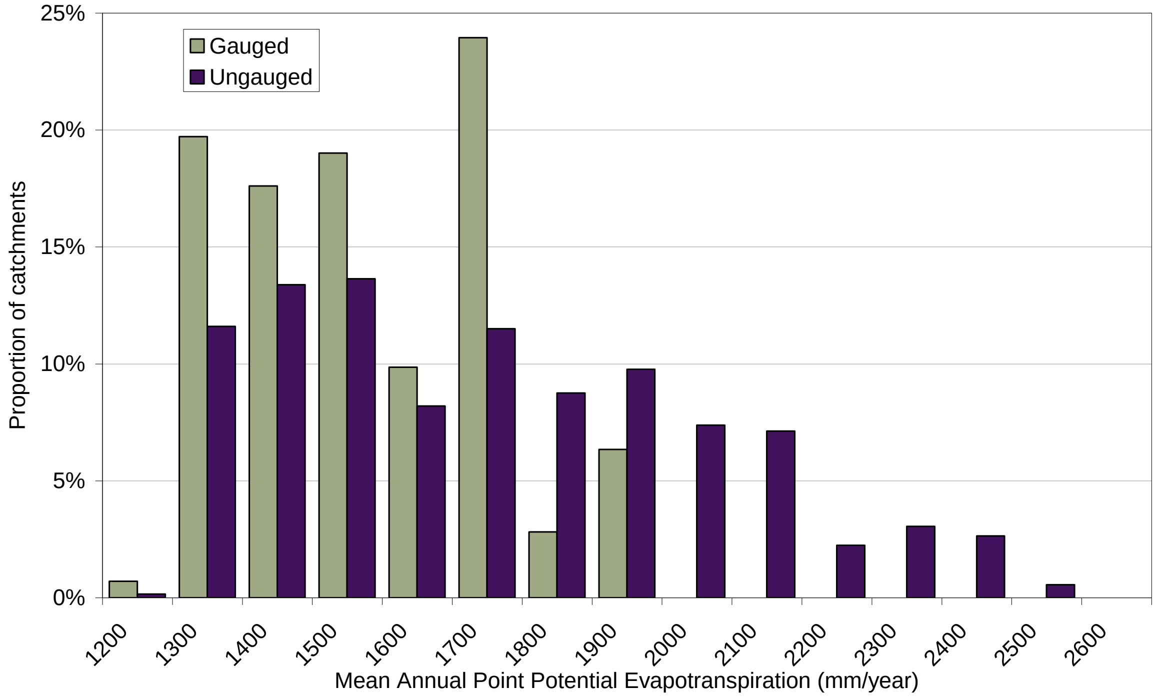
■ **Figure 4-5 Histogram of mean annual rainfall (1975-2005 reference period) for all ungauged catchments and for the catchments of the selected streamflow gauges**



■ **Figure 4-6 Histogram of mean June through October rainfall (1975-2005 reference period) for all ungauged catchments and for the catchments of the selected streamflow gauges**



▪ **Figure 4-7 Histogram of mean annual actual evapotranspiration for all ungauged catchments and for the catchments of the selected streamflow gauges**



▪ **Figure 4-8 Histogram of mean annual point potential evapotranspiration for all ungauged catchments and for the catchments of the selected streamflow gauges**

4.5 Summary

Physiographic characteristics were derived for each catchment for the development and application of regional prediction equations of the SDL parameters. A total of 41 physiographic characteristics were extracted for the catchments using a variety of GIS tools.

The selected gauged catchments are biased towards catchments in the southern and western basins of the study area (basins 602 through 604, 616 and 617) and the differences between the selected catchments and the ungauged catchments physiographic characteristics reflects this.

Both the individual and combination of physiographic characteristics for the selected gauged catchments were compared against the ungauged catchments to see if there were any unusual catchments that may influence the development of the regional prediction equations. No catchments were removed.

5. The Sustainable Diversion Limit

5.1 Introduction

The sustainable diversion limit (SDL) represents the maximum volume of diversions that can be licensed in the catchment. It represents the volume of water that can be provided with an annual reliability of supply of 80%, given the constraints of the winterfill period, the minimum flow threshold and the maximum extraction rate. This applies to the whole catchment and the total volume of licenses granted to individual land-holders within the management unit should not exceed this value.

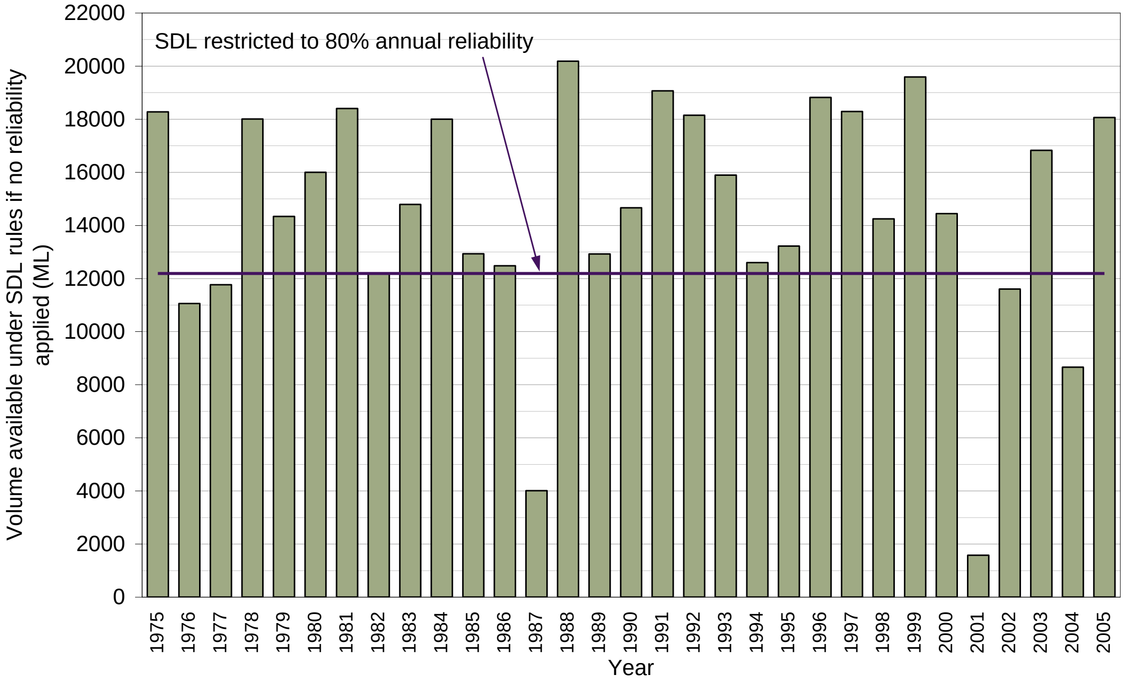
This chapter outlines how the SDL was calculated for the 142 gauged catchments, the development of the regional prediction equation and application to ungauged catchments.

5.2 Gauged Catchments

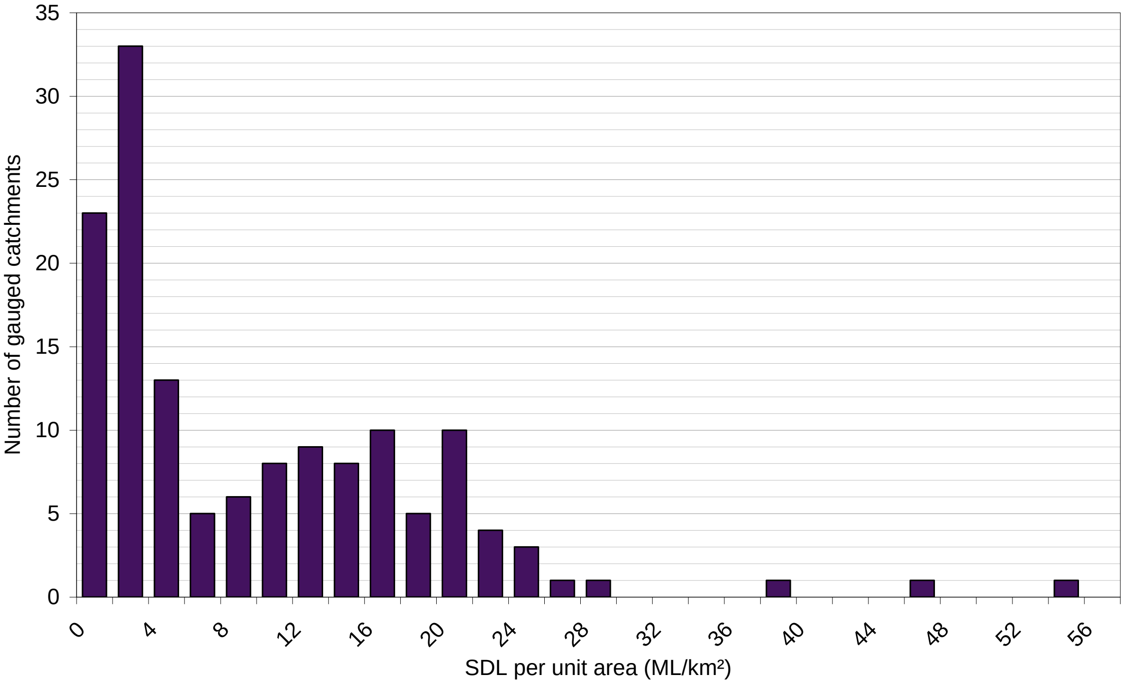
The SDL was calculated for the 142 selected gauged catchments in the study area, using the available streamflow data. For each site, the volume that could be extracted during each winterfill period on record was calculated by applying the minimum flow threshold and maximum extraction rate. This series was used to calculate the volume that could be extracted with a reliability of 80%. This volume is the SDL. Further detail of the SDL for gauged catchments is provided in Sinclair Knight Merz (2007).

For example, the SDL for the streamflow gauge 608151 Donnelly River at Strickland was calculated using gauged data between 1 January 1975 and 31 December 2005. The minimum flow threshold was calculated to be 225 ML/d and the maximum extraction rate was 164 ML/d. The volume of winterfill diversions that could be extracted each year without exceeding the maximum diversion rate or reducing the flows below the minimum flow threshold was calculated. The annual volumes are illustrated in Figure 5-1. The 80th percentile of these volumes is 12,187 ML because in 6 out of 31 years in the historical record (1976, 1977, 1987, 2001, 2002 and 2004) the volume available under the SDL rules is less than this value. Therefore the SDL for the Donnelly River at Strickland catchment is 12,187 ML and has a reliability of 80%.

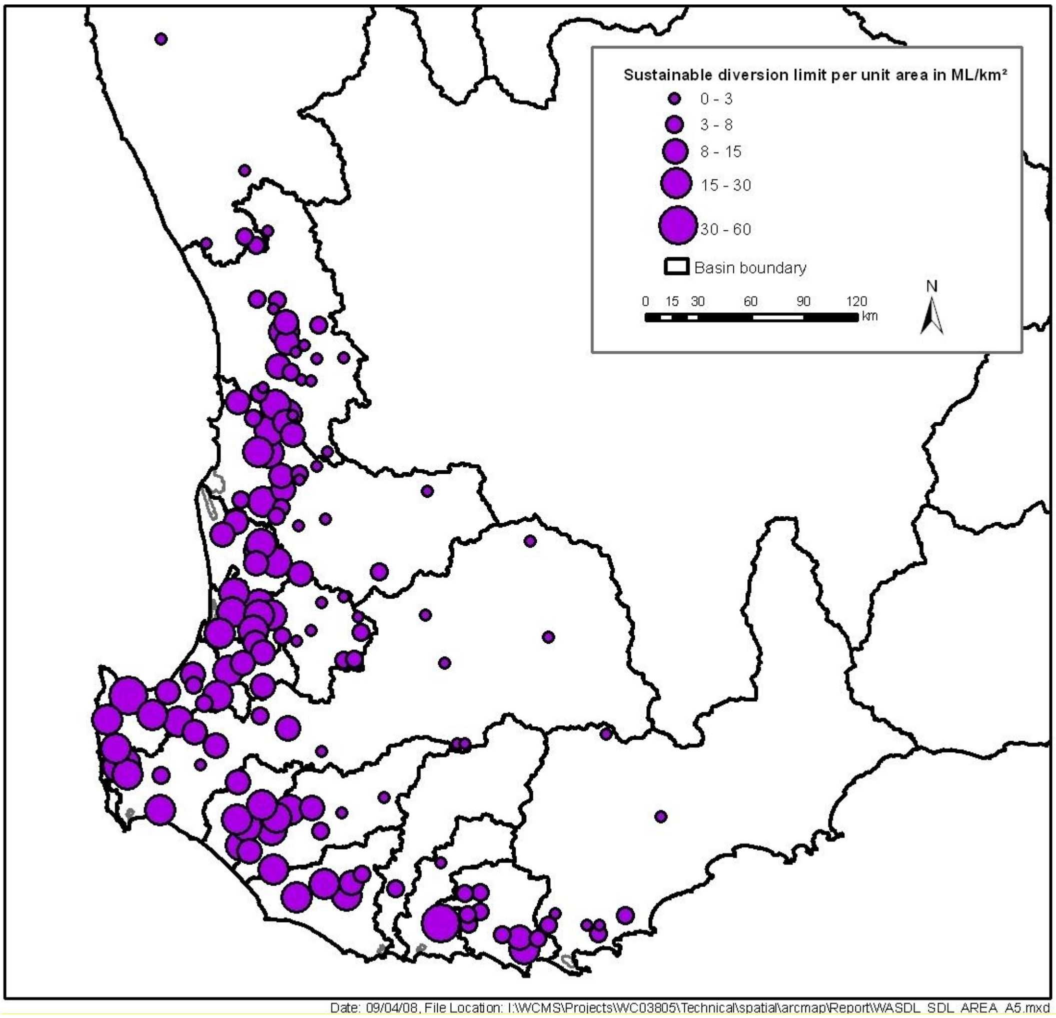
The calculated SDL per km^2 for the 142 gauged catchments varied between 0 ML/km^2 and 39.4 ML/km^2 with an average of 9.9 ML/km^2. A histogram of SDL per unit area is presented in Figure 5-2. The spatial distributions of the standardised SDL volumes for all available 142 sites are shown in Figure 5-3. It is evident that in general the larger SDL volumes (per unit area of catchment) occur in the high rainfall areas in the south west corner of the study area. SDL volumes per unit catchment area decline markedly in line with the reduction in mean annual rainfall toward the eastern and northern parts of the study area.



- **Figure 5-1 Annual time series of volume available under SDL rules for the Donnelly River at Strickland (site 608151) for the winterfill period (15 June – 15 October) whilst complying with the minimum flow and maximum extraction rate rules. The solid purple line represents the volume exceeded in 80% of years, which is defined as the SDL volume for this catchment.**



- **Figure 5-2 Histogram of sustainable diversion limit per unit catchment area for gauged catchments**

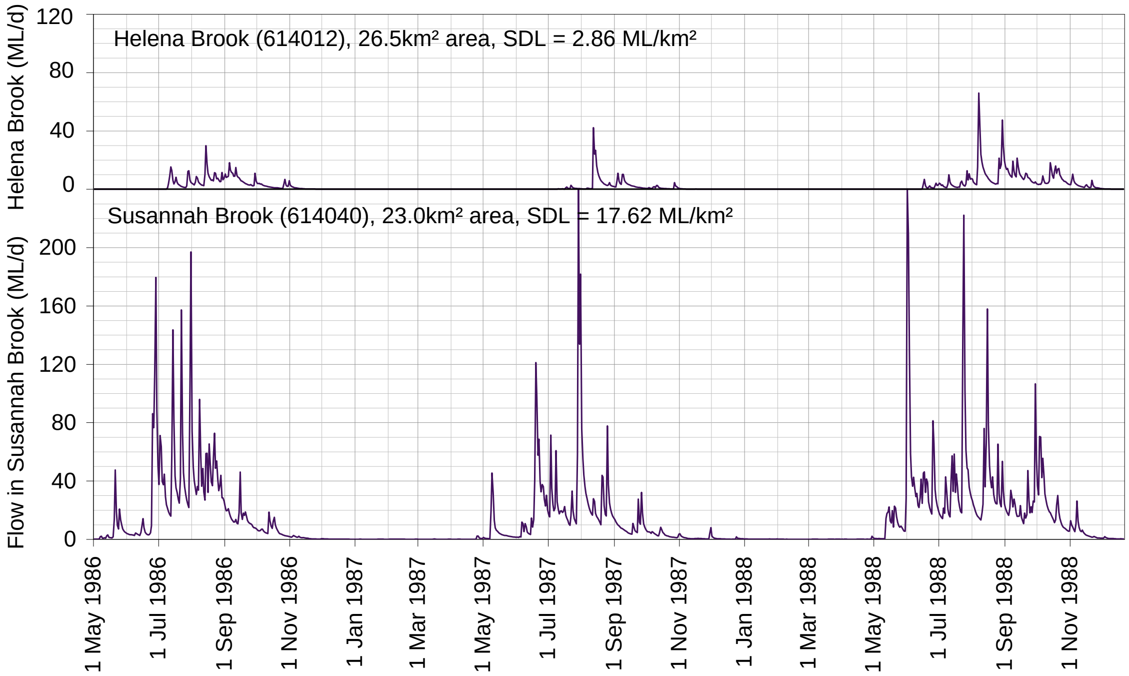


- **Figure 5-3 Geographic distribution of sustainable diversion limit volume per unit catchment area (ML/km²)**

Streamflows in areas with high SDL volumes exhibit high persistence, that is, flows tend to vary gradually from one day to the next in comparison with catchments elsewhere. For areas that are similar in climate, the physical controls that determine streamflow persistence are related to the amount of storage available in the underlying soils and regolith.

An example of two catchments that are located in the same river basin (with only 14 km between their catchment centroids) and with very similar catchment areas (27 and 23 km²) but which have distinctly different storage attributes is illustrated in Figure 5-4. While both catchments experience wet conditions at the same time, it is clear that Helena Brook is ephemeral and streamflows cease soon after rainfall stops. Susannah Brook on the other hand is less ephemeral, and streamflows are fed from water stored in the soils and regolith of the catchment long after rainfall ceases. The difference in response is related to the fact that Helena Brook is almost entirely forested while Susannah Brook is only half covered in forest (99% versus 49% woody vegetation cover respectively in 1989) and may also be related to slight differences in mean annual rainfall (813 versus 915 mm/year respectively).

In essence, these results emphasise that the volume of water that can be sustainably diverted from a catchment depends on both climatic factors, as well as the physical attributes of each individual catchment. There is considerable variation in SDL values across the study area precisely because there is considerable variation in climatic and physiographic characteristics. This is the basis on which the SDL can be estimated from the climatic and physiographic characteristics of an ungauged catchment.



- **Figure 5-4 Hydrograph response of two catchments with distinctly different catchment storage attributes within the same climatic region**

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5.3 Regional Prediction Equation

In the initial fitting of the regression equation, the SDL was fitted to an equation that included catchment area as one of the predictor variables. The resulting equation had a regression coefficient on catchment area that was insignificantly different from unity. Since the regression coefficient on catchment area was very close to one, it was appropriate to use SDL per unit area as the dependent variable and then to remove catchment area from the list of predictor variables.

The prediction equation was fitted based on the gauged catchment SDLs and was developed as an SDL per km^2 measure. The equation found to provide the best prediction of the SDL per unit area is:

$$\mathbf{ln}(\mathrm{SDL/km^2}) = 7.75\ \mathbf{ln}(\mathrm{RAIN}) - 1.356\ \mathbf{ln}(\mathrm{APEVAP\_WIN}) - 0.0045\ \mathrm{AREVAP\_ANN} - 0.0169\ \mathrm{PCT\_VEG89} + 0.0024\ \mathrm{ELEV\_MN} + 0.0012\ \mathrm{PERIMETER} - 38.09$$

Where;	SDL/km^2	=	Sustainable diversion limit volume per area (ML/km^2)
	RAIN	=	Mean annual rainfall for 1975 - 2006 (mm/yr)
	PERIMETER	=	Perimeter of entire upstream catchment (km)
	AREVAP_ANN	=	Mean annual areal actual evapotranspiration (mm)
	APEVAP_WIN	=	Winter areal potential evapotranspiration (mm) (winter taken as July to October)
	PCT_VEG89	=	Percentage of catchment area covered by woody vegetation as determined by AGO data from 1989
	ELEV_MN	=	Mean elevation of catchment area (m AHD)

Three gauged catchments were removed from the fitted regression equation: 609010 was removed as the SDL was zero, 609021 and 617002 were removed as these were identified as outliers to the fitted equation (both had low SDLs in relation to their catchment area).

Regression statistics were as follows:

- Number of observations (including outliers) = 142
- Number of observations (after excluding outliers) = 139
- Multiple R^2 on SDL per unit area (ML/km^2) = 0.819
- Multiple R^2 on SDL (ML) = 0.903
- Standard error of estimate in logarithmic domain on SDL = 8.0%

For the 139 gauged catchments, the SDL was computed using the regression equation and this was compared with the calculated value for each of the catchments. The resulting error in the prediction was calculated as the ratio of the value from the regression equation to the observed value. The purple line in Figure 5-5 shows the estimates of the ratio for the 139 gauged catchments, after ranking them from highest to lowest error. The olive coloured line shows the theoretical distribution of error that would result assuming that errors in the regression estimate are normally distributed in the logarithmic domain (a standard assumption in multiple linear regression analysis). From the theoretical distribution, for the middle 80% of catchments, the regression equation would produce an estimated SDL of between -52% and +106% of the observed value. This is similar to the level of error that is observed for the 139 gauged catchments used to derive the regression. The scatter plots below demonstrate that following implementation of the regression equation, the residuals are equally scattered without any appreciable trends with the values of any of the predictor variables.

The plot of the prediction equation results against the SDL calculated from observed data at the gauged catchments that were used to derive the equation is presented in Figure 5-6. The plot indicates a reasonably uniform distribution of residuals about the fitted regression equation. Plots of residuals are provided in Appendix D.

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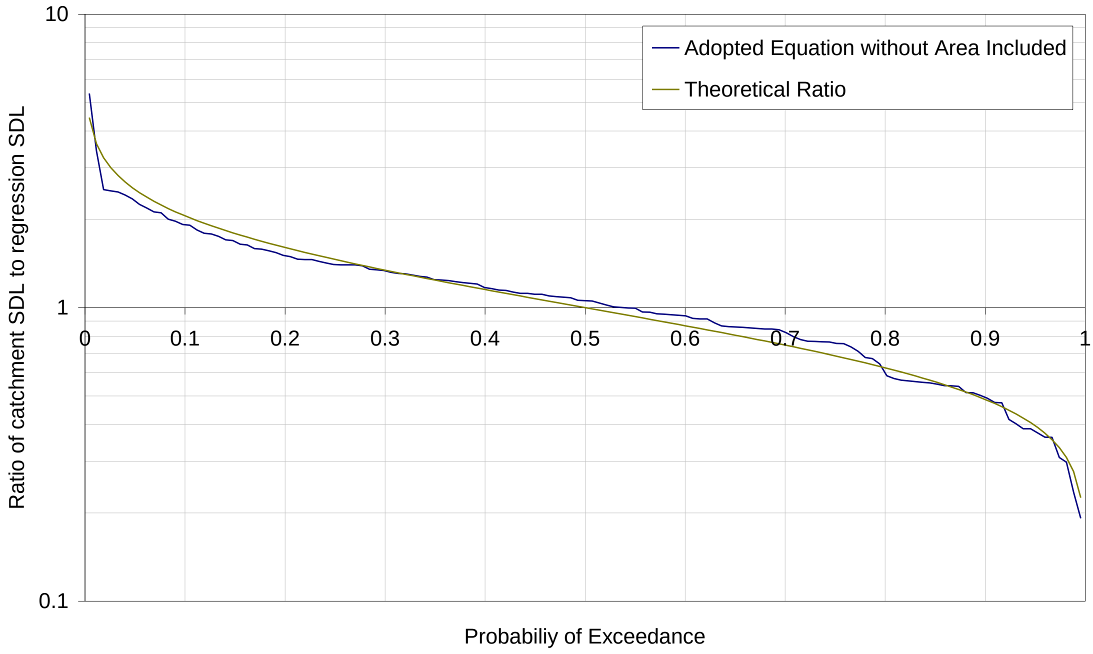
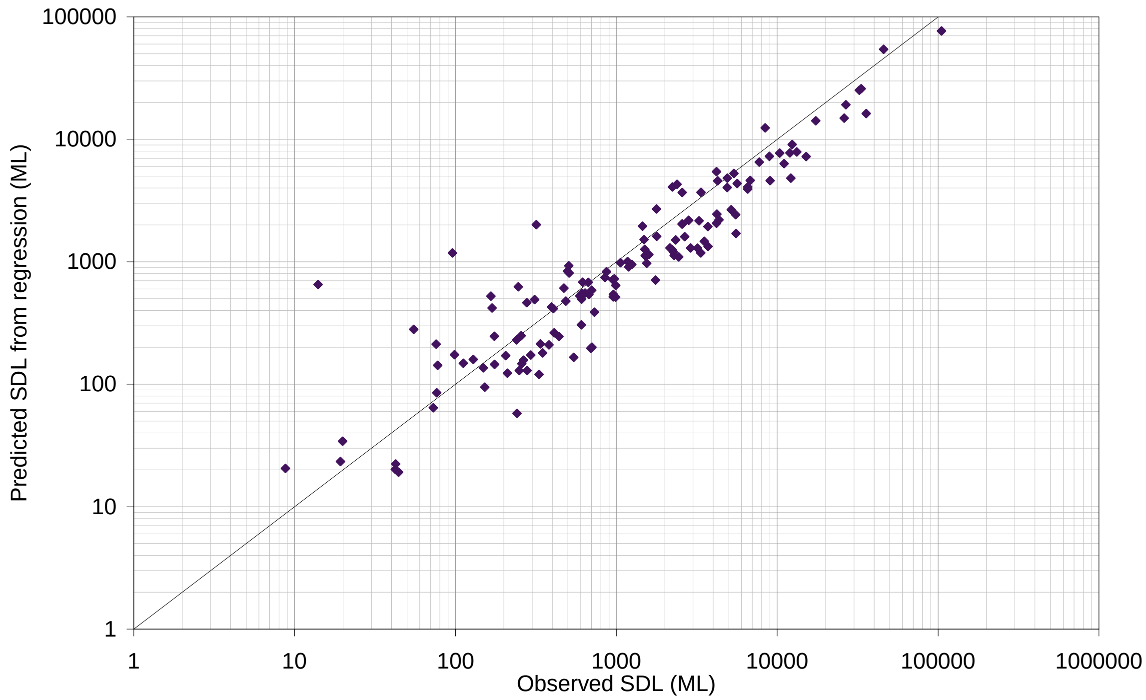


▪ **Figure 5-5 Ratio of sustainable diversion limit estimated from the regression equation to the observed value for gauged catchments**



▪ **Figure 5-6 Comparison between sustainable diversion limit predicted by regression equation and calculated from observed data for gauged catchments**

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5.4 SDL calculation methods for sub-catchments

Values for Sustainable Diversion Limits (SDLs) were calculated directly from recorded data for gauged catchments in the study area. Alternative methods were required to estimate the SDL in ungauged catchments. This section discusses these methods, and also explains the manner in which calculated SDL volumes for gauged catchments were apportioned internally between constituent sub-catchments.

The SDL of a sub-catchment was derived by applying one of the methods listed below:

Method Group 1		**SDL is calculated from gauged streamflow data**
	Method 1a	Gauge applies to single SDL sub-catchment
	Method 1b	Gauge applies to multiple sub-catchments and SDL is internally apportioned, according to the pattern of the Regional Prediction Equation estimates for individual subcatchments
	Method 1c	Nested gauges exist and SDL is apportioned as in (b) after subtracting the upstream SDL
Method Group 2		**SDL is estimated using Regional Prediction Equation**
	Method 2a	Direct application to single sub-catchment
	Method 2b	Application to an area of multiple sub-catchments, then SDLs assigned to ensure internal balancing of SDLs within the area.
Method Group 3		**SDL is assigned manually**

The sections below describe each of these methods in more detail. Also below are some examples showing the spatial distribution of each of the methods in two catchments.

Method 1a) SDL is calculated from streamflow data for a single sub-catchment

This method applies when the sub-catchment is gauged and the gauge applies to a single sub-catchment only. The SDL calculated from the gauged streamflow is assigned directly to the sub-catchment. This method accounted for 61 of 1966 SDL sub-catchments.

Method 1b) SDL is calculated from streamflow data then apportioned between sub-catchments

This method is applicable when the catchment of a gauge contains multiple SDL sub-catchments. For each gauged catchment, the process is as follows. First, the SDL is estimated using the Regional Prediction Equation for each sub-catchment within the gauged catchment. Then, these individual sub-catchment SDL estimates are summed, and the total is compared to the SDL derived from the gauged data. Then, all individual estimates are scaled up or down by the same factor, to ensure that the SDL for the entire catchment is equal to the sum of its parts.

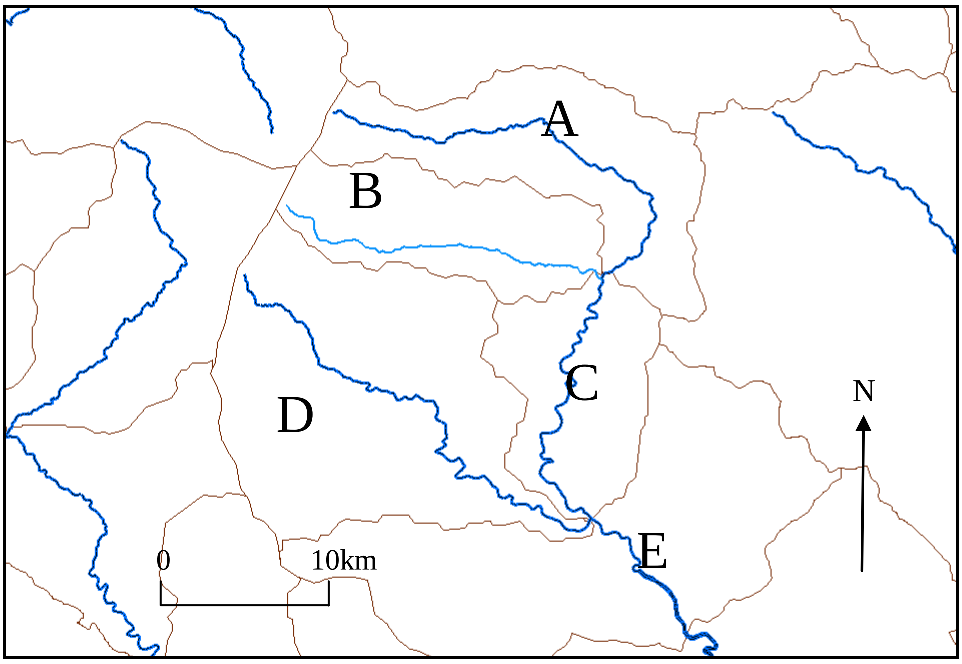
Essentially, this method takes the SDL calculated from gauged data and apportions it according to the *pattern* derived from the Regional Prediction Equation. This method accounted for 199 of 1966 SDL sub-catchments.

Method 1c) SDL is calculated from streamflow, then apportioned, taking account of nested gauges

This method applies to SDL subcatchments that lie within a gauged catchment, which itself contains "nested" gauged catchment(s) upstream. Each nested gauged catchment will have a fixed SDL under Methods 1a or 1b, but the remaining SDL is apportioned between the remaining SDL sub-catchments in a similar fashion to 1b. This method accounted for 193 of 1966 SDL sub-catchments.

Method 2a) SDL is estimated using the Regional Regression Equation for a single sub-catchment

This method applies the Regional Regression Equation using the catchment characteristics of a single SDL sub-catchment, to estimate the SDL for that sub-catchment. This method accounted for 1055 of 1966 SDL sub-catchments.



- **Figure 5-7 Section of the Oldfield River Catchment. Method 2a is used to calculate SDLs for A, B and D but Method 2b can be used for sub-catchments C and E.**

Method 2b) SDL is estimated using Regional Regression Equation over multiple sub-catchments

This method works by applying the Regional Regression Equation over areas of different sizes, and balancing the results.

To illustrate, please refer to the section of the Oldfield River (ungauged) Catchment shown in Figure 5-7 above. Sub-catchments A and B flow into Sub-catchment C. Applying the Regional Regression Equation we obtain:

SDL_A = 28.56 ML; SDL_B = 22.54 ML; $SDL_{A,B \text{ and } C \text{ combined}}$ = 84.53 ML.

The SDL for Sub-catchment C is then assigned as 84.53 – 28.56 – 22.54 = 33.43ML

In a similar way, SDL_E could be calculated by applying the regression to the combined area of A, B, C, D and E, then subtracting the individual SDLs of A, B, C, and D.

Method 2b only applies where the combined area is less than 2000km^2. To explain this limit, consider the following points:

- The regression is based on linear averages of catchment characteristics;
- Runoff (and thus, SDL) generally displays a non-linear response to catchment characteristics (eg such as rainfall and elevation);
- Larger catchments generally display greater variation in catchment characteristics. Therefore, linear averages are less likely to produce representative results in larger catchments.

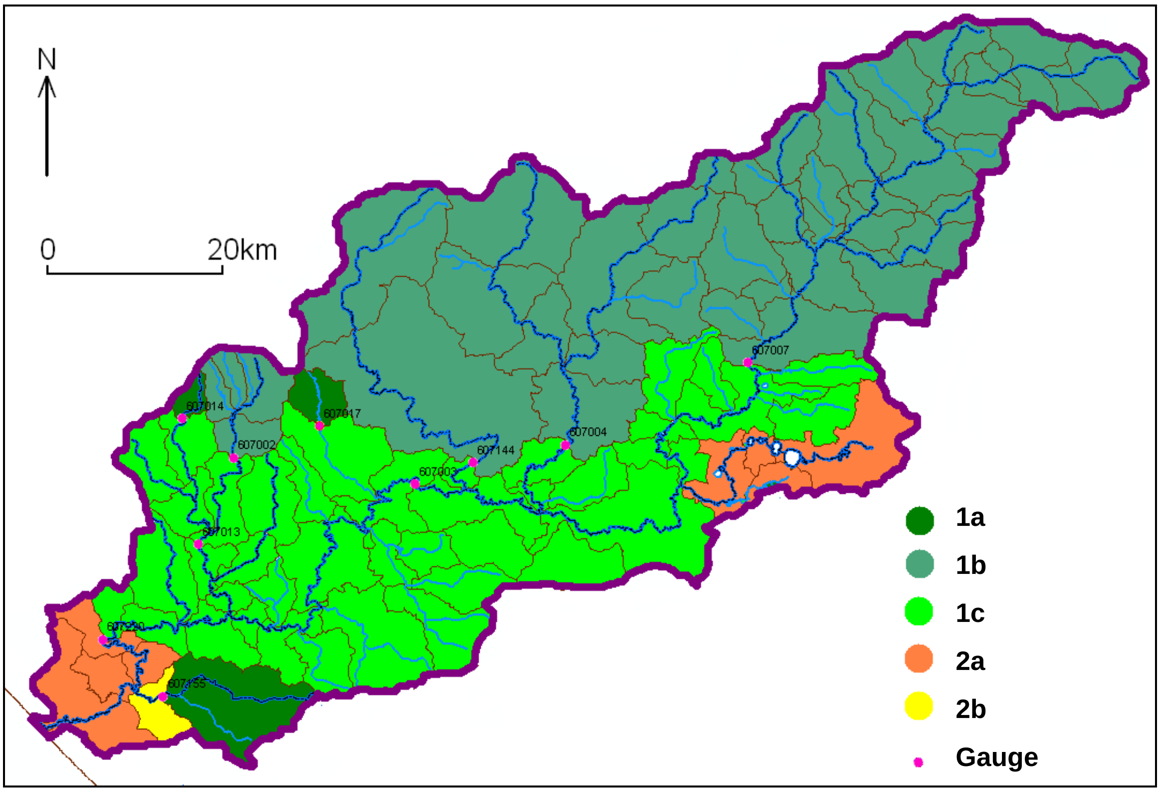
Taken together, these points indicate the need to limit the size of catchments where the Regional Regression Equation is used. For this project, a limit of 2000km^2 was adopted.

All SDLs calculated by Method 2b were subjected to a manual check. In a small proportion of cases, this method can produce large errors, particularly when the area of the sub-catchment is very small compared to its upstream area (and thus, anomalies in the upstream SDL values are concentrated onto the small sub-catchment through the balancing process). Fifty-two sub-catchments were manually changed during this process. The SDL values for these catchments were manually reassigned to the estimate that would have been produced from Method 2a.

Method 2b accounts for 458 of 1966 SDL sub-catchments.

Method 3) SDL is manually assigned.

Quality assurance checks on Sub-Catchment SDL values were completed after Methods 1a – 2b had been applied. For a more detailed description of these checks, see Appendix C. In most cases, any apparently large changes in SDL could be attributed directly to significant changes in catchment characteristics between adjacent catchments or by the differences in the method used to calculate the SDL – switching between an SDL calculated using the Regional Prediction Equation and an SDL calculated using gauged streamflow data. However, out of the 1966 SDL sub-catchments, there were 20 instances where specific anomalies were revealed that required adjustment. For a full list, please refer to Appendix C.



▪ **Figure 5-8 SDL Calculation methods employed in the Warren River Catchment.**

5.4.1 Example: Warren River Catchment

Figure 5-8 shows the distribution of SDL calculation methods used within the Warren River catchment. As the catchment contains many gauges, most of the catchment is under Methods 1a, 1b or 1c. The following points can be made on the spatial distribution of the different methods in the Warren River:

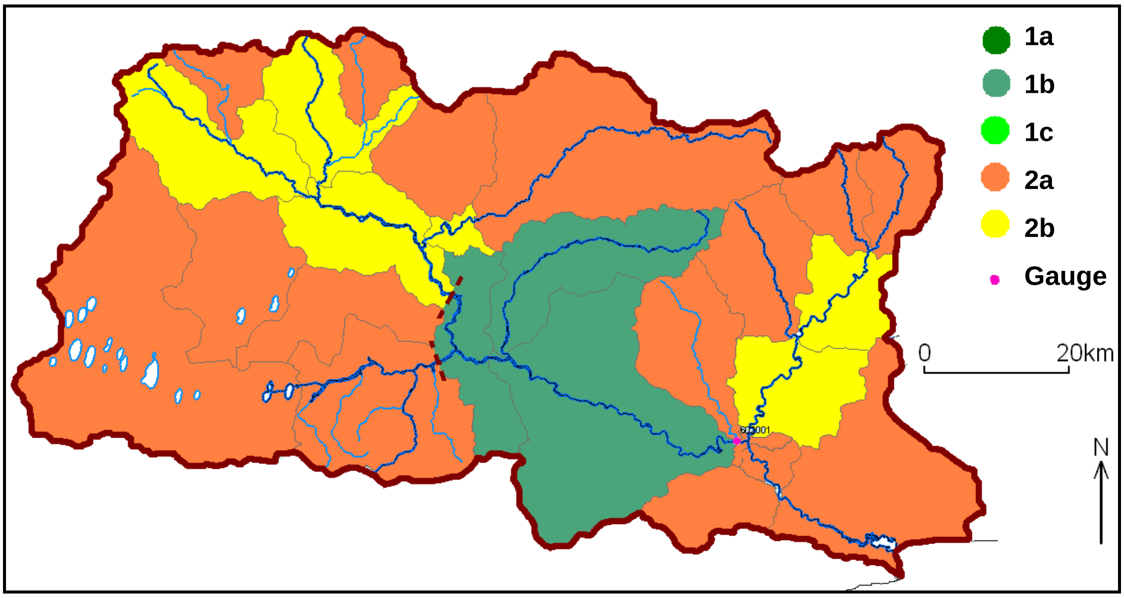
1) **Method 1a (direct application of Gauge SDL):** There are only 3 cases of Method 1a (Dark Green). This is because there are only 3 gauges in the Warren River catchment that contain only 1 SDL sub-catchment. Generally, Method 1a catchments often occur close to a major watershed, as they are the furthest catchment upstream in a particular tributary.
2) **Method 1b and 1c (apportioning of Gauge SDL):** Both methods apportion the SDL of a gauge between multiple sub-catchments, but Method 1b generally occurs further upstream in the catchment than Method 1c, because Method 1c deals with "nested" gauges.
3) **Method 2a and 2b (estimation by Regional Prediction Equation):** There are two areas where Methods 2a and 2b are applied in the Warren River Catchment:
    a. at the "bottom" of the catchment (near the mouth), these methods must be applied downstream of the "lowest" gauges, due to the lack of gauged data there. Method 2b (yellow) is applied only if upstream area <2000km^2.

b. Sub-catchments containing "terminal lakes" (located south of gauge 607007). These lakes are on a list (provided by the client) of lakes that overflow so seldom that their catchments can be considered hydrologically disconnected from downstream reaches (thus, their inclusion in the "Warren River Catchment" is debatable, but they are shown here for illustration). Thus, the areas upstream of the lakes are considered as "ungauged" and are calculated using Method 2a.

5.4.2 Example: Pallinup River Catchment

Figure 5-9 below shows the distribution of methods used within the Pallinup River catchment. This catchment is drier than the Warren River and contains only one SDL gauge. The following points can be made on the spatial distribution of the different methods in the Pallinup River:

1) **Method 1b (apportioning of gauge SDL):** The gauge in the Pallinup River catchment (602001) has numerous SDL sub-catchments upstream of it. Therefore, the SDL that was calculated from the gauged data is apportioned between these sub-catchments using the pattern of the SDL Regional Prediction Equation (Method 1b). **Note**: topographically, the gauge 602001 has 15 sub-catchments upstream. However, some of these catchments were flagged by the client as containing "terminal" lakes in the same way as described in the Warren River catchment. This effectively breaks the catchment up, with only 3 sub-catchments (shown in green) sharing the SDL from the gauge 602001, and the remainder being calculated under Methods 2a or 2b (see below).
2) **Method 2a (estimation using regional prediction equation):** This method (orange) applied to sub-catchments that are not within a gauged catchment and do not have any other sub-catchments upstream. In the Pallinup River, this includes sub-catchments located on tributaries not within the catchment of gauge 602001, and also sub-catchments that are topographically within this catchment but are upstream of "terminal" lakes (as defined by DoW).
3) **Method 2b (estimation using regional prediction equation over multiple sub-catchments):** This method (yellow) applied to sub-catchments that are not within the catchment of gauge 602001 (as defined in 2a above), and have one or more sub-catchments upstream. As shown in the figure, Method 2b (yellow) sub-catchments occur downstream of one or more Method 2a (orange) sub-catchments.



- **Figure 5-9: SDL Calculation methods employed in the Pallinup River Catchment. "Terminal" Lakes in this catchment mean that the sub-catchments are modelled as hydrologically disconnected along the dotted lines shown.**

5.5 Anomalies in application of SDL for two gauged catchments

- Gauge 616027 was taken out of the analysis and the SDL value calculated for this gauge was not used directly for the subcatchments upstream of it. This is because this gauge is downstream of a reservoir, and the flows that the SDL is based on are influenced by human regulation. This means that the flows through Gauge 616027 are often less than the sum of 2 gauges which are upstream (616065 and 616026). If this gauge were to be used in the analysis, it would have caused errors in calculations of SDL values for intermediate subcatchments.
- Gauge 616092 was taken out of the analysis and the SDL value calculated for this gauge was not used directly for the subcatchments upstream of it. This is because of problems of concurrency of records between this gauge and the gauges immediately upstream (616023, 616041, and 616 021). Generally speaking, the upstream gauges have longer records, whereas the record for gauge 616092 is quite short (only the most recent 10 years). The period it covers is comparatively dry, so the resultant SDL reflects this. This leads to: SDL (616092) < Sum (SDLs for upstream gauges). Furthermore, one of the upstream gauges records has almost no concurrent record with the downstream gauge, so the analysis can not be rerun over a common period. The SDL calculated from this gauge was therefore discarded.

5.6 Method for Assigning the SDL

Principal component analysis was used to asses the similarity of catchments with regard to the catchment characteristics influencing the SDL per unit area. Two principal components were

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derived (for a detailed method, see Appendix B.4). The first and second principal components were derived using the equations below:

PC1 = -0.965 **ln**(RAIN)_*std* +0.362 PERIMETER_*std* -0.950 AREVAP_WIN_*std* +0.022 **ln**(APEVAP_ANN)_*std* -0.628 PCT_VEG89_*std* 0.787 ELEV_MN_*std*

PC2 = 0.082 **ln**(RAIN)_*std* -0.187 PERIMETER_*std* +0.056 AREVAP_WIN_*std* -0.910 **ln**(APEVAP_ANN)_*std* +0.369 PCT_VEG89_*std* + 0.299 ELEV_MN_*std*

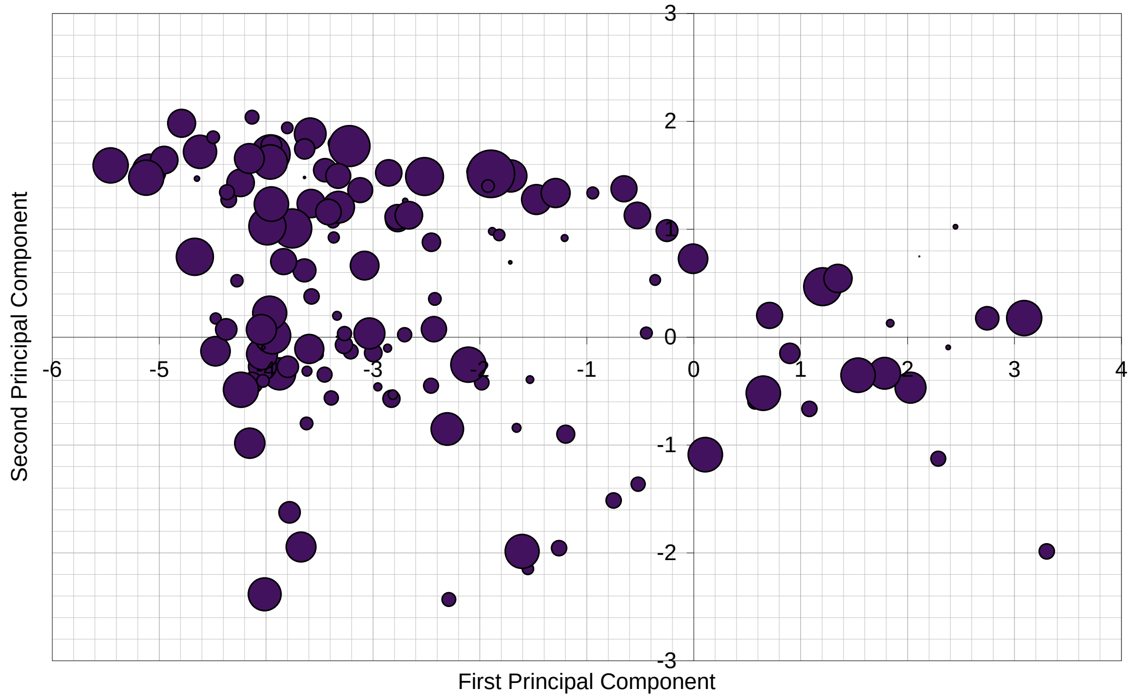
where

PC1	= First principal component
PC2	= Second principal component
ln(RAIN)_*std*	= Standardised natural log of mean annual rainfall in mm 1975-2005
PERIMETER_*std*	= Standardised perimeter of the total upstream catchment area in km
AREVAP_MN_*std*	= Standardised mean annual areal actual evapotranspiration in mm
ln(APEVAP_ANN)_*std*	= Standardised natural logarithm of annual average areal potential evapotranspiration in mm
PCT_VEG89_*std*	= Standardised percentage woody vegetation cover of the catchment in 1989
ELEV_MN_*std*	= Standardised mean catchment elevation (m AHD)

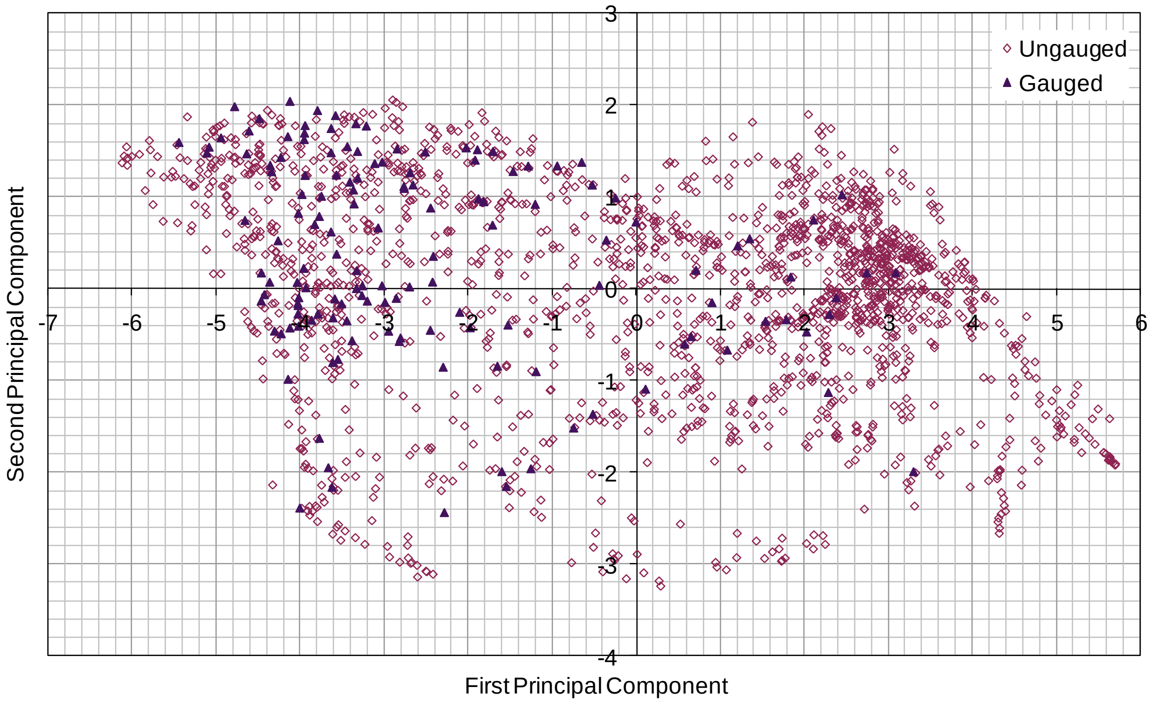
All variables were standardised so that the data set had a mean of zero and a standard deviation of one. The two principal components explain 68% of the variation between the catchments with respect to the six characteristics. The main influences on the first principal component are mean annual rainfall, areal actual evapotranspiration, the mean catchment elevation and vegetation cover. The main influences on the second principal component are potential evaporation, mean catchment elevation and vegetation cover.

Figure 5-10 demonstrates the relationship between SDL per unit area and the first and second principal components derived from catchment characteristics. This plot provided a means for assessing the degree of similarity across the 142 gauged SDL catchments. The distance between each plotted point is a measure of similarity of the catchments with respect to the specified catchment characteristics and hence the SDL.

In Figure 5-10 the actual SDL per unit area as calculated from the gauged data is shown by the size of the bubble. In general, it is seen that catchments with similar SDL are located close to one another. Principal components were calculated for all of the 1966 catchments.



- **Figure 5-10 Bubble plot of the influence of the first and second principal components (derived using catchment characteristics) on sustainable diversion limit per unit area for gauged SDL catchments**



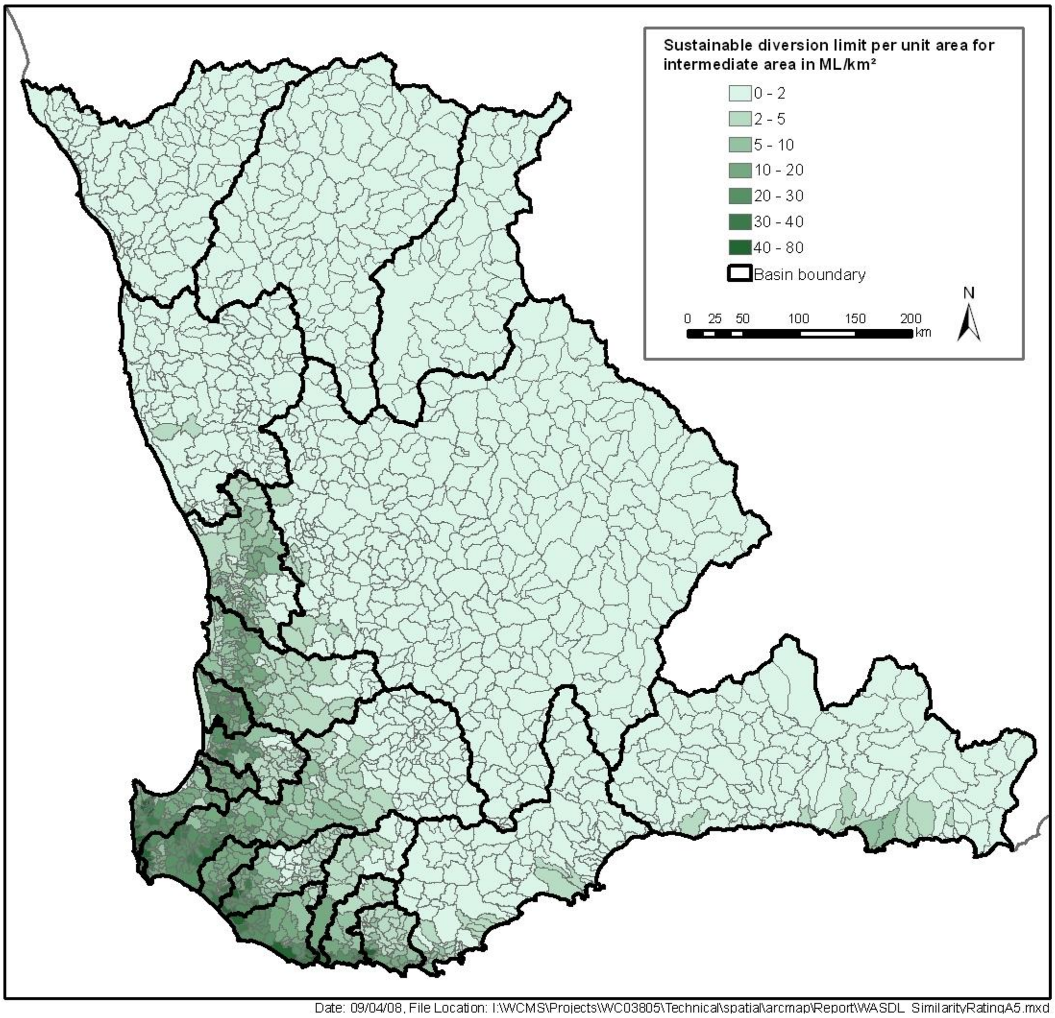
- **Figure 5-11 Scatter plot of the first and second principal components (derived using catchment characteristics) on sustainable diversion limit per unit area for gauged and ungauged SDL catchments**

Figure 5-11 compares the principal components from the gauged and ungauged catchments in the study area. It shows that the gauged catchments (represented by the solid purple triangles) are representative of the cloud of points for the ungauged catchments. This indicates that the regression equations developed for estimating the SDL for gauged catchments should be adequate for estimating SDL values for ungauged catchments across the study area.

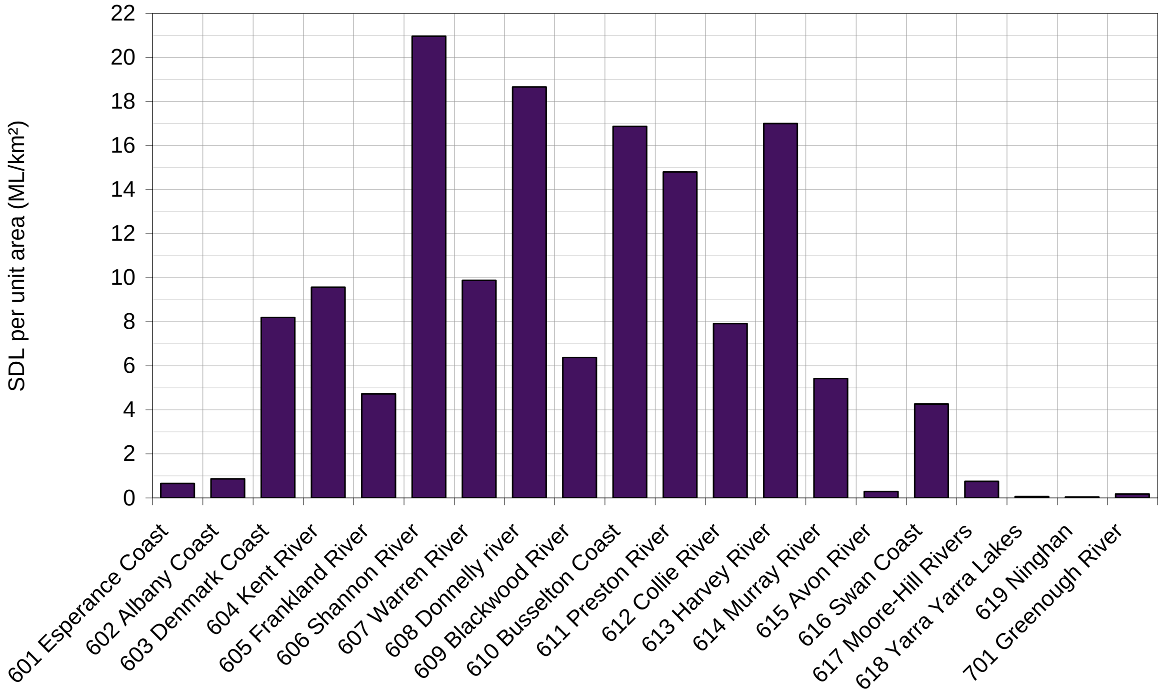
5.7 Variation of the Sustainable Diversion Limit

The SDL were calculated for the whole study area and were found to vary between 0.01 and 72.6 ML/km^2, as shown in Figure 5-12. The catchments with the highest SDL per unit area in the study region were located in high rainfall zones, very close to the south-western coast: in the lowest parts of the Denmark Coast, Kent River, Frankland River, Shannon River and Warren River Basins. Figure 5-13 reflects this with the highest basin average SDL per unit area values (exceeding 16 ML/km^2) recorded in the Shannon River, Donnelly River, Busselton Coast and Harvey River basins. Figure 5-13 also shows that SDL per unit catchment area declines moving further away from the Indian Ocean coastlines so that the lowest SDL values (less than 1 ML/km^2) are found in the low rainfall areas: the Esperance Coast, Albany Coast, Avon River, Moore-Hill Rivers, Yarra Yarra Lakes, Ninghan and Greenough River Basins. The average SDL across the study area was 1.85 ML/km^2.

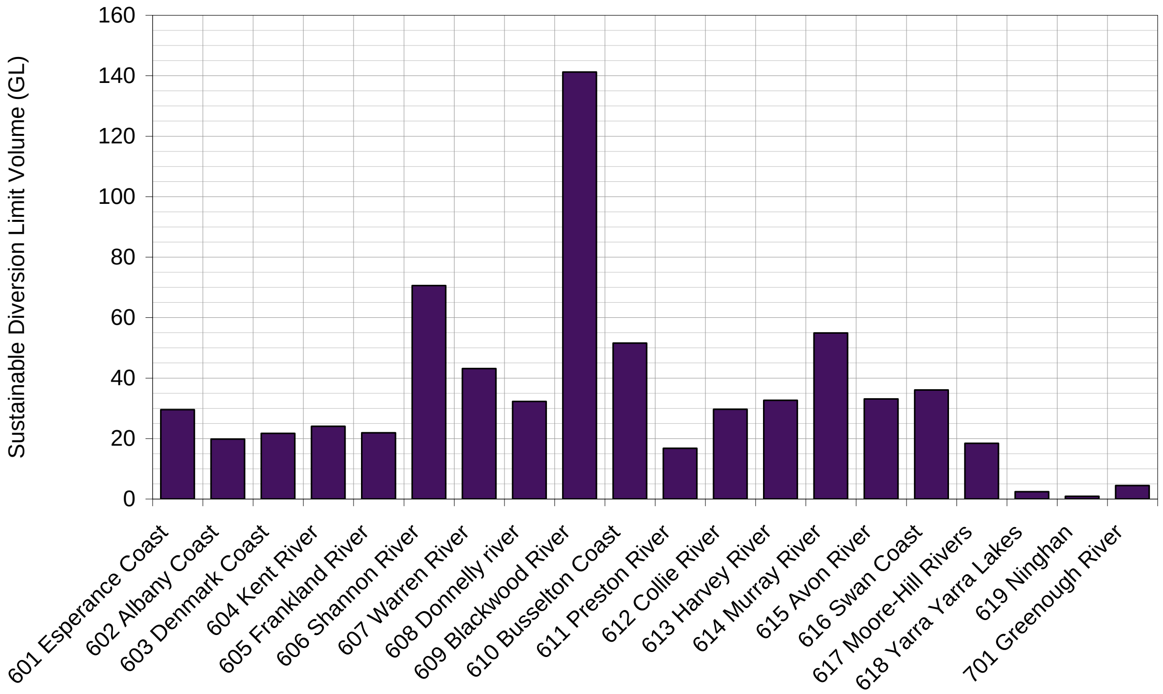
The total SDL volume for a basin is a product of the basin area and the SDL per unit area density. Figure 5-14 therefore shows that the Blackwood River basin has the highest volume of total SDL because it is has a large area and contains catchments with moderately high runoff and SDL contributions. Totals and averages for each AWRC Basin are tabulated in Table 5-1.



- **Figure 5-12 Geographic distribution of sustainable diversion limit per unit catchment area for all gauged and ungauged catchments**

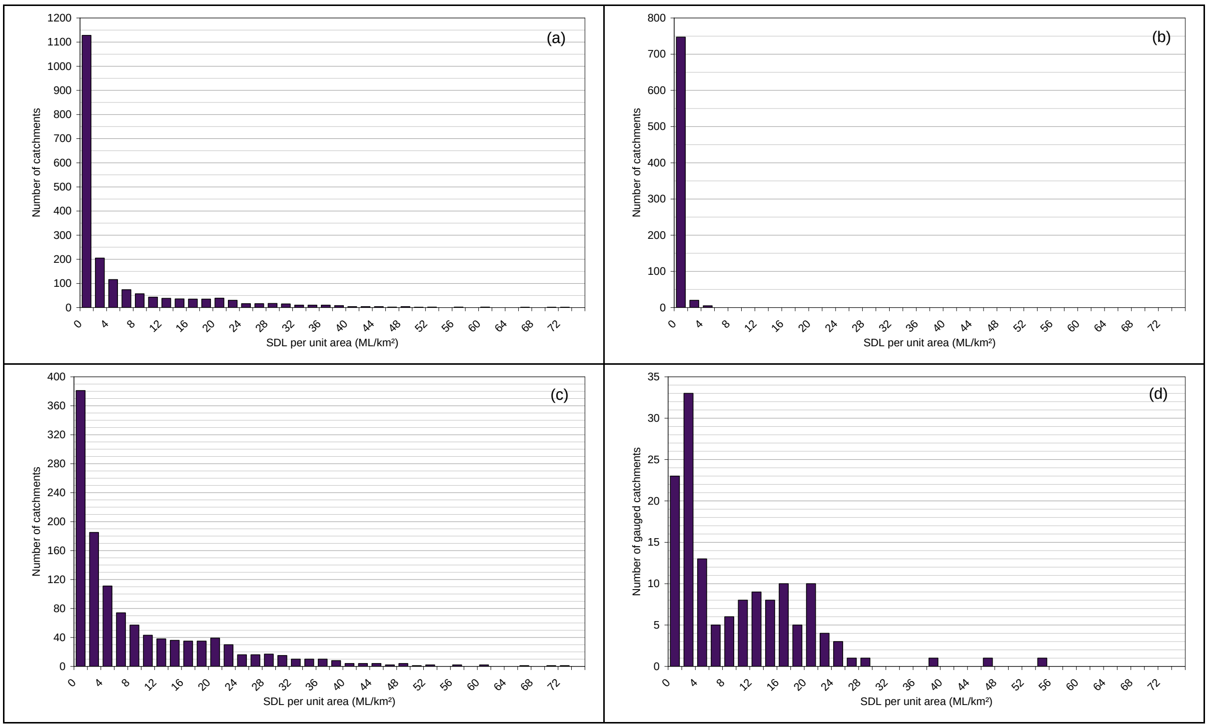


- **Figure 5-13 Sustainable diversion limit per unit area by AWRC Basin**

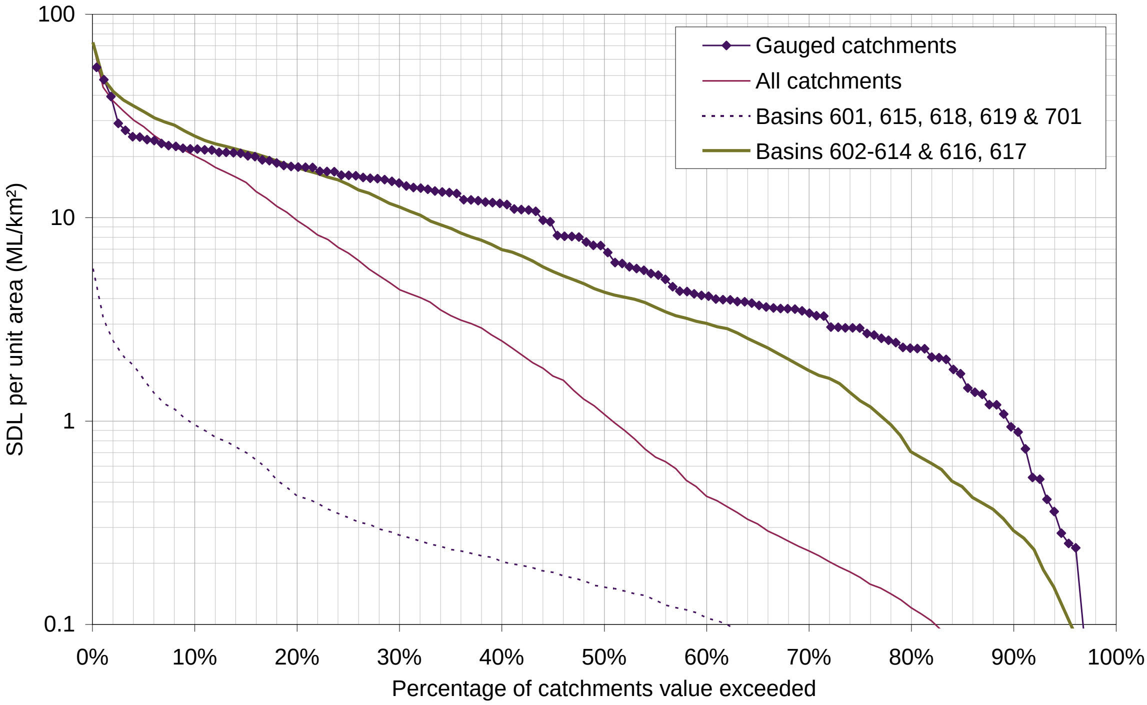


- **Figure 5-14 Total volume of sustainable diversion limit by AWRC Basin**

Histograms of SDL are provided in Figure 5-15 and the same information is re-shown as cumulative exceedance frequency curves in Figure 5-16. These plots compare the distributions of SDL of the gauged and ungauged catchments. Overall the SDL are higher for the gauged than the ungauged catchments because the gauged catchments are biased toward being located in the higher rainfall areas closer to the coast. Figure 5-15(d) shows that many of the gauged catchments have an SDL of between 4 and 24 ML/d but Figure 5-15(a) shows that it is relatively uncommon for an ungauged catchments to have an SDL per unit area in this range, with most ungauged catchments having an SDL less than 4 ML/km². The histogram for ungauged catchments in the south-western basins of the study area (basins 602 to 614, 616 and 617) in Figure 5-15(c) is much better represented by the gauged catchments. By contrast, virtually all of the ungauged catchments in the northern and eastern basins (basins 601, 615, 618, 619 and 701 in Figure 5-15(b)) have an SDL per unit area of less than 2 ML/km². Figure 5-16 shows that the cumulative exceedance plot for ungauged catchments in the south-western basins is well represented by the gauged catchments. Figure 5-16 alerts us that there is a lower level of confidence associated with SDL estimates for the drier catchments in the northern and eastern basins of the study area because the exceedance probability distribution for these catchments is very different to the gauged catchments that are predominantly located to the south-west.



- **Figure 5-15 Histograms of sustainable diversion limit per unit area for (a) all of the 1966 catchments; (b) for the 772 catchments located in AWRC basins 601, 615, 618, 619 and 701; (c) for the 1194 catchments located in AWRC basins 602 to 614, 616 and 617; and (d) for the subset of 142 gauged catchments**



- **Figure 5-16 Cumulative probability distributions of sustainable diversion limit per unit area for the same four groups of catchments used in Figure 5-15**

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- **Table 5-1 Volume of sustainable diversion limit available from each AWRC basin in the study area**

Basin Number	Basin Name	Number of catchments	Total SDL (GL)	Total Area (km^2)	SDL / Area (ML/km^2)
601	Esperance Coast	136	29.6	45444	0.65
602	Albany Coast	119	19.8	22986	0.86
603	Denmark Coast	53	21.7	2651	8.19
604	Kent River	24	24.0	2511	9.57
605	Frankland River	27	21.9	4639	4.72
606	Shannon River	48	70.6	3366	20.96
607	Warren River	96	43.1	4364	9.88
608	Donnelly river	29	32.2	1727	18.66
609	Blackwood River	232	141.2	22143	6.38
610	Busselton Coast	69	51.6	3056	16.87
611	Preston River	31	16.8	1134	14.80
612	Collie River	74	29.6	3743	7.92
613	Harvey River	45	32.6	1919	17.00
614	Murray River	102	54.9	10137	5.42
615	Avon River	366	33.1	116231	0.28
616	Swan Coast	104	36.0	8465	4.26
617	Moore-Hill Rivers	141	18.4	24654	0.75
618	Yarra Yarra Lakes	111	2.4	41792	0.06
619	Ninghan	50	0.9	24256	0.04
701	Greenough River	109	4.4	25244	0.18
Total		1966	684.7	370462	1.85

5.8 Summary

The SDLs were calculated from gauged data as per the method presented in Sinclair Knight Merz (2007) and Lang *et al*. (2008). The values ranged between 0 ML/km² and 39.4 ML/km² with an average of 9.9 ML/km². The values ranged considerably across the study area due to different climatic and physiographic characteristics.

The results for the 142 gauged catchments were used with the physiographic characteristics of their catchments to develop regional prediction equations using multiple linear regression. The model had a R^2 of 0.90 and a standard error equal to 8% of the mean SDL.

The regional prediction equation was used to assign SDL values to all ungauged catchments. Where the equation was not applicable the SDL was assigned using values from surrounding catchments weighted by their similarity.

The SDL volumes for the ungauged catchments ranged between 0.01 ML/km² and 72.6 ML/km² with an average of 1.85 ML/km². The catchments with the highest SDL per unit area in the study region were located in high rainfall zones, closest to the southern and western coastlines. The SDL per unit catchment area declines moving further away from the coastlines so that the lowest SDL values (less than 1 ML/km²) are found in the low rainfall areas: the Esperance Coast, Albany Coast, Avon River, Moore-Hill Rivers, Yarra Yarra Lakes, Ninghan and Greenough River Basins. There is a lower level of confidence associated with SDL estimates for the drier catchments in the northern and eastern basins of the study area because all of the gauged catchments were located in the southern and western basins.

6. Maximum Extraction Rate

6.1 Introduction

The maximum extraction rate (MER) is the total volume of water that can be extracted from the SDL catchment within one day. This volume needs to be estimated for ungauged catchments across the study area. Department of Water may use this volume to specify maximum diversion rates for individual licences, specify maximum pump sizes or develop scheduling of diversions across a catchment.

This chapter outlines the method used to calculate the MER for gauged catchment, the development of a regional prediction equation and application to ungauged catchments.

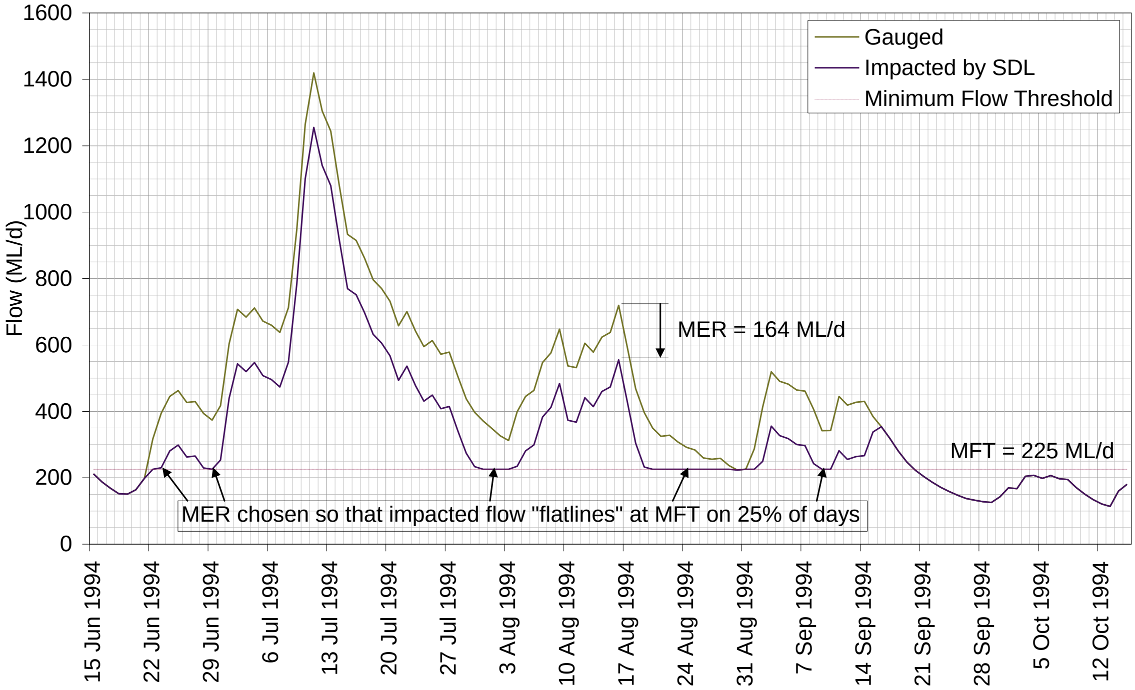
6.2 Gauged Catchments

The maximum extraction rate (MER) was calculated for the 142 selected gauged catchments using the prepared streamflow data. The maximum extraction rate is calculated as the difference between the flow that is exceeded on 75% of days that exceed the minimum flow threshold (MFT) and the minimum flow threshold itself. In other words, the MER is set so that if it were applied, the impacted flow time series would "flat line" at the MFT on 25% of days during the winterfill period of 15 July through 15 October. For further details on the methodology see Sinclair Knight Merz (2007).

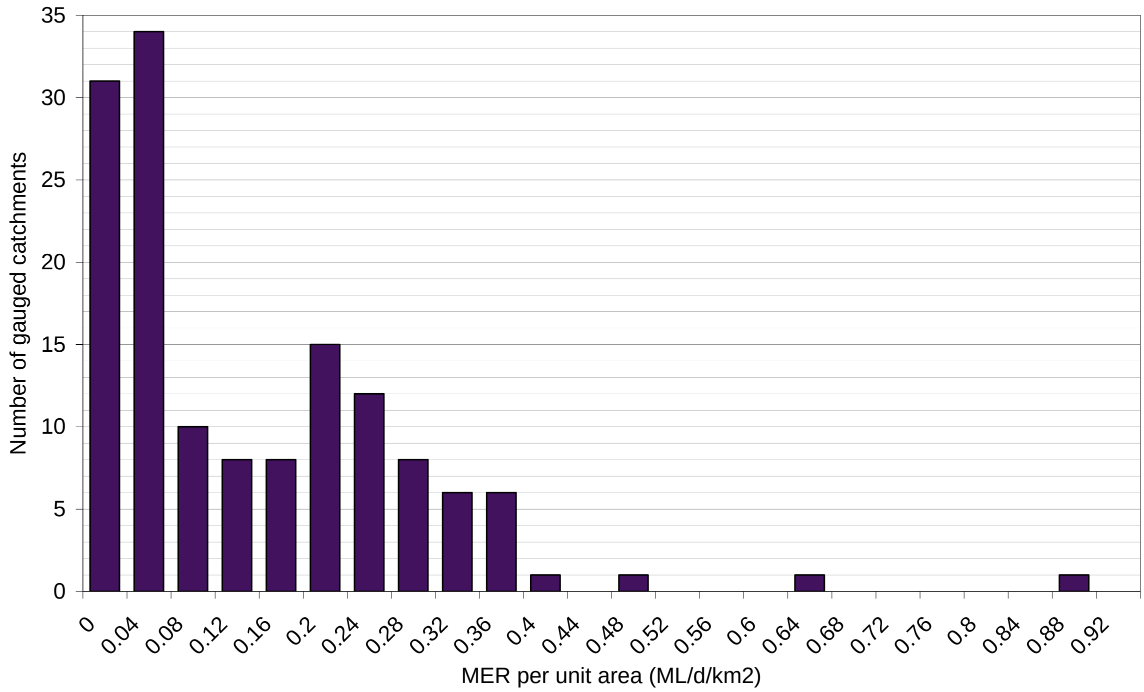
Figure 6-1 shows an example of implementation of the MER rules for the Donnnelly River at Strickland for the 1994 winterfill period. For this gauged catchment the MFT is 225 ML/d. The MER calculated for this catchment from the flow timeseries is 164 ML/d. Figure 6-1 shows that the impacted flow timeseries would "flatline" at the MFT value on 20 days in the 1994 winterfill period. On average across all of the gauged years analysed for this catchment (1975 through 2005) the impacted flow series would flatline at the MFT on 25% of the days that the gauged flow timeseries exceeds the MFT.

The calculated MER per km² for the 142 gauged catchments varied between 0.001 ML/d/km² and 0.91 ML/d/km² with an average of 0.15 ML/d/km². A histogram plot is presented in Figure 6-2.

The spatial distributions of the standardised MER volumes for all available 142 sites are shown in Figure 6-3. It is evident that in general the larger MER volumes (ML/d/km²) occur in catchments with higher mean annual rainfall, closest to the southern and western coastlines of the study area.



- **Figure 6-1 Daily flow time series for the 1994 winterfill period for the Donnelly River at Strickland showing the gauged flow timeseries and a timeseries impacted by implementation of the SDL rules.**



- **Figure 6-2 Histogram of maximum extraction rate per unit catchment area for gauged catchments**

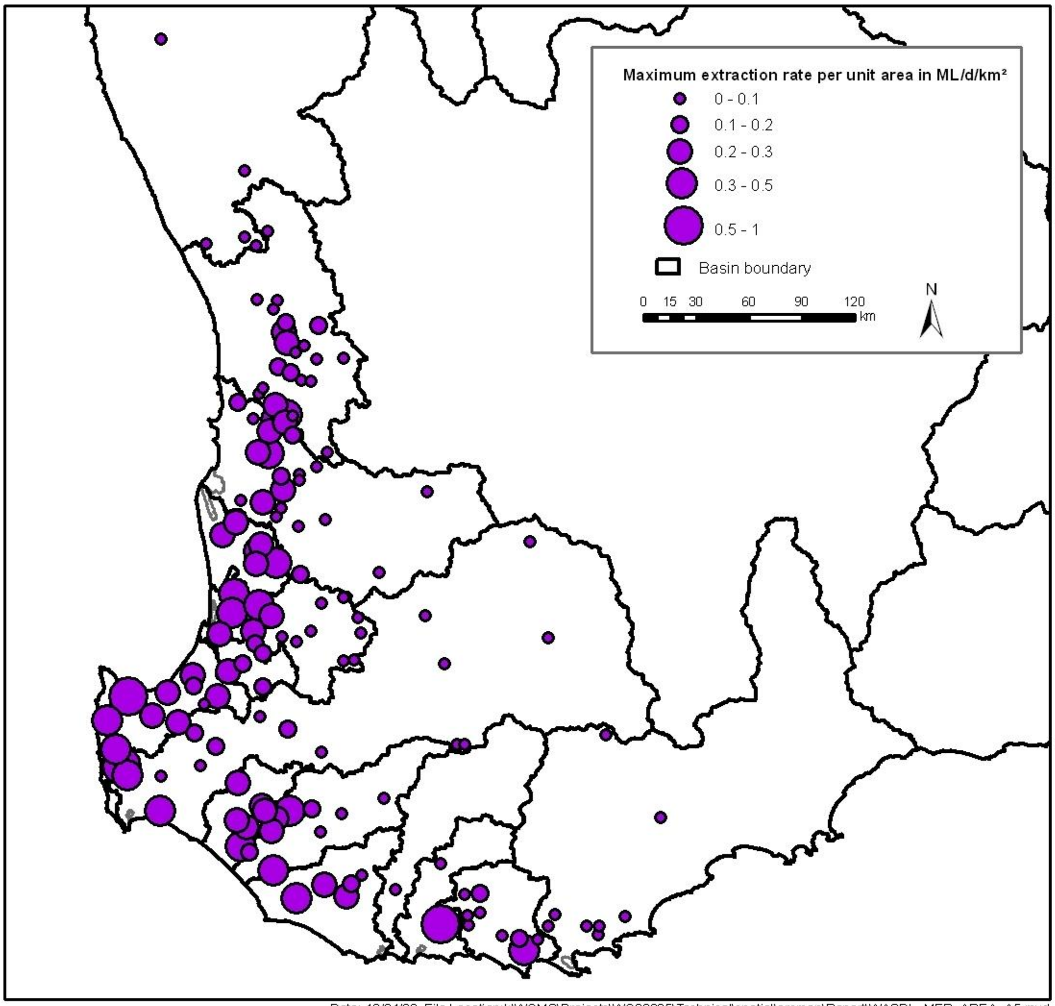


Figure 6-3 Geographic distribution of maximum extraction rate per unit catchment area (ML/d/km²)

6.3 Ratio of Sustainable Diversion Limit to Maximum Extraction Rate

The spatial distribution of the MER is similar to that of the SDL (Figure 5-3) because both factors are influenced by the persistence in streamflows. The MER is higher in catchments with high streamflow persistence, where the flows vary only gradually from one day to the next. This has resulted in the MER and the SDL being very highly correlated (R^2 = 0.972) as illustrated in Figure 6-4.

The ratio of the SDL to the MER provides the number of days over which diversion at the maximum extraction rate would be required to divert the full volume of the SDL in the winterfill season. It represents the minimum number of days of the winterfill period that would be required from the start of the season on 15 June to divert the full SDL volume in each catchment. In some years however, more days would need to elapse after the 15 June to divert the full SDL volume because diversion can only occur on days when the minimum flow threshold is exceeded. Even on days when the MFT is exceeded, diversions should be limited to the difference between the gauged flow and the MFT, which on some days may be less than the MER.

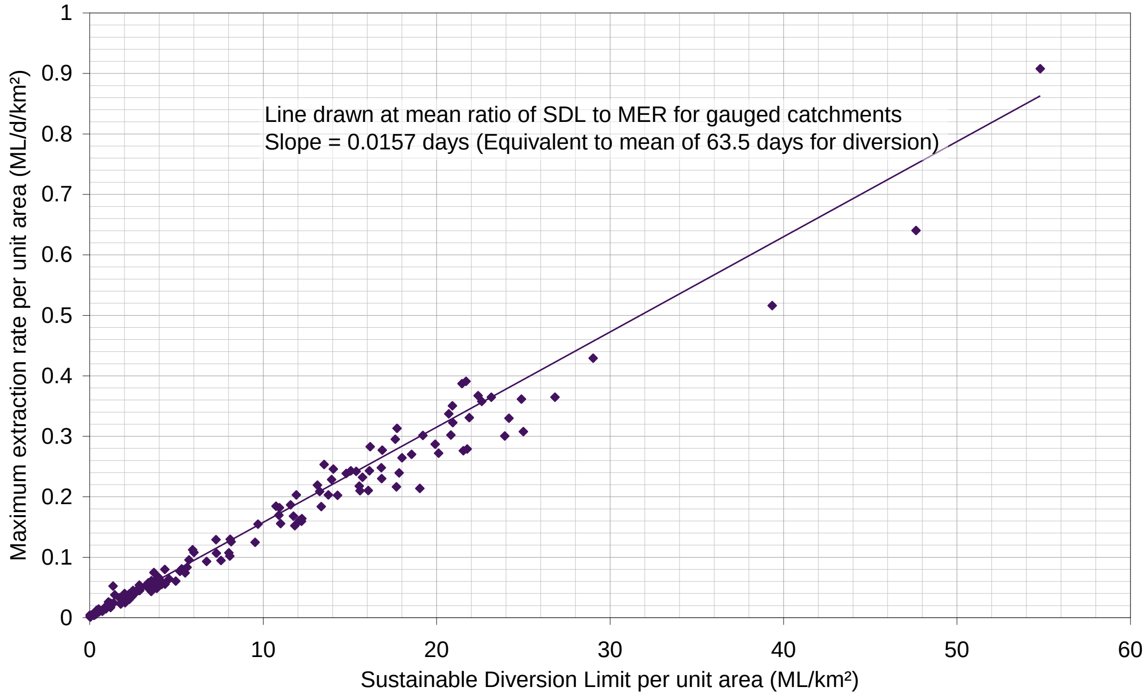
The SDL to MER ratio was computed for the 142 gauged catchments and a histogram of values is shown in Figure 6-5. The bulk of the catchments form a Gaussian (normal) distribution with a mean of 63.5 days and a reasonably tight standard deviation of 13.9 days. Since the winterfill period (15 June through 15 October) is 123 days long, for the average gauged catchment diversion would be required on about half of the days of the winterfill period at the MER to divert the full SDL volume. The line in Figure 6-4 is drawn at a slope of 63.5 days, which is the mean ratio of the SDL to MER ratio for the gauged catchments. As expected, it runs through the middle of the scatter of points for the gauged catchments.

The maximum possible ratio of SDL to MER is 92 days (75% of 123 days), since the MER is defined as the flow that is exceeded on 25% of days that exceed the MFT during the winterfill period. The gauged catchment with the highest SDL to MER ratio is Four Mile Brook at Netic Road (607014), which has a ratio of 89 days and is therefore close to the theoretical maximum. In applying the estimation of MER to ungauged catchments, the MER was restricted so that the maximum SDL to MER ratio was kept at the theoretical maximum value of 92 days.

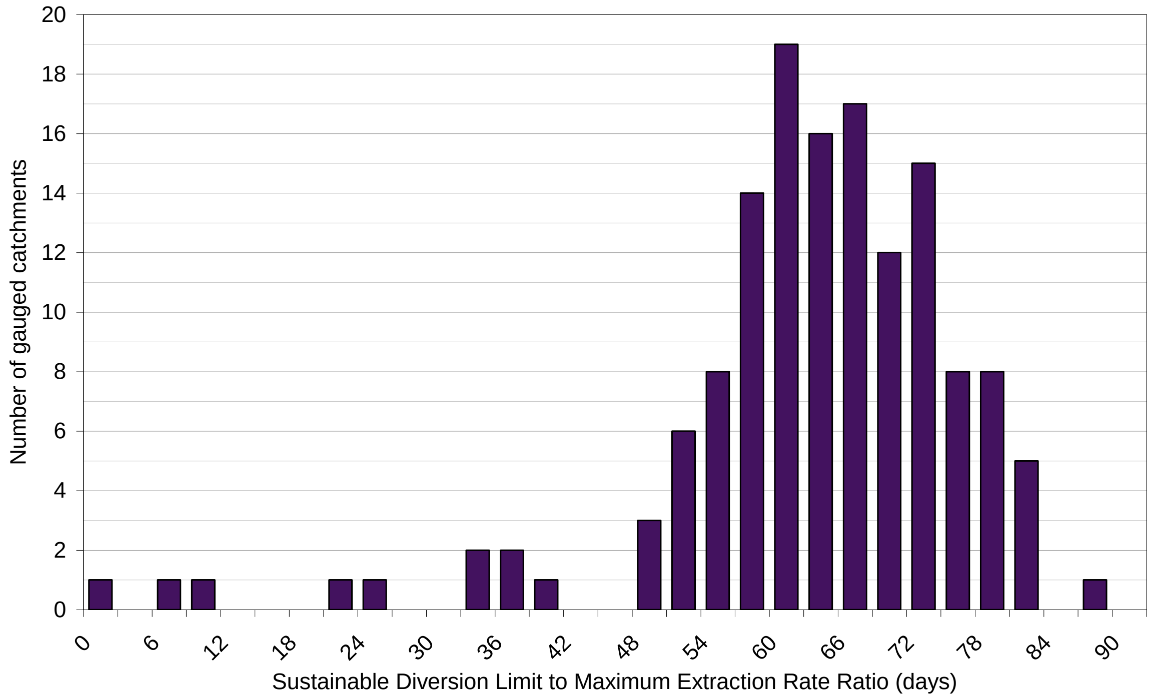
There are about ten catchments that have relatively low values of the SDL to MER ratio, as listed in Table 6-1. These catchments have relatively intermittent flow patterns and therefore have both a relatively low number of days in each winterfill period that exceed the MFT and relatively low values of SDL per unit catchment area. In fact:

- the four lowest ranked gauged catchments for SDL to MER ratio are in the lowest five ranked catchments for SDL per unit area and
- the ten lowest ranked gauged catchments for SDL to MER ratio are in the twenty-one lowest ranked catchments for SDL per unit area.

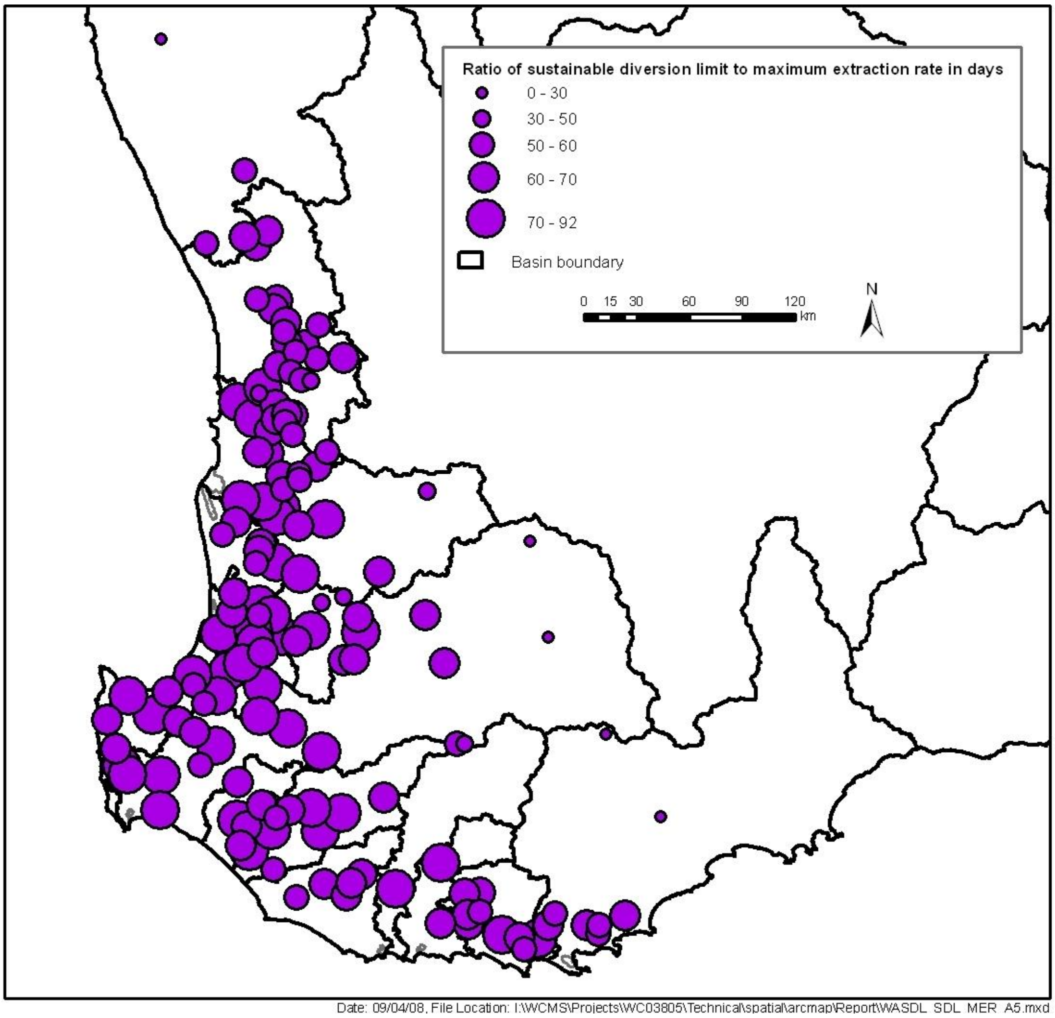
In intermittent catchments with low SDL values, relatively large pump capacities are required (compared to the SDL value) to opportunistically capture flows from streams on the few days each winterfill period when they exceed the MFT. Apart from catchment 609010, which has an SDL of zero and therefore has the trivial SDL to MER ratio of 0 days, the lowest ratio of SDL to MER for the gauged catchments was 7.8 days. In applying the estimation of MER to ungauged catchments, the MER was restricted so that the SDL to MER ratio was kept at a minimum value of 7 days.



- **Figure 6-4 Scatter plot of sustainable diversion limit and maximum extraction rate per unit catchment area for the 142 gauged catchments**



- **Figure 6-5 Histogram of the ratio of the sustainable diversion limit to maximum extraction rate ratio (in days) for the 142 gauged catchments**



- **Figure 6-6 Geographic distribution of the ratio of sustainable diversion limit to maximum extraction rate (in days) for the selected gauged catchments**

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- **Table 6-1 Sustainable Diversion Limit to Maximum Extraction Rate Ratios for the ten gauged catchments with the lowest value of this ratio**

Gauge Number	Gauge Name	SDL / MER Ratio (days)	Rank SDL / MER (1 = Low)	SDL / Area (ML/km²)	Rank SDL / Area (1 = Low)	MER/Area (ML/d/km²)
609010	Northern Arthur River @ Lake Toolibin Inflow	0.0	1	0.000	1	0.004
617002	Hill River @ Hill River Springs	7.8	2	0.015	2	0.002
609021	Coblinine River @ Bibikin Road Bridge	10.1	3	0.016	3	0.002
602003	Jackitup Creek @ Wellards	21.9	4	0.100	5	0.005
602001	Pallinup River @ Bull Crossing	25.9	5	1.352	19	0.052
612021	Bingham River @ Stenwood	33.2	6	0.412	10	0.012
616002	Darkin River @ Pine Plantation	34.0	7	0.250	7	0.007
614105	Hotham River @ Pumphrey's Bridge	36.7	8	0.518	11	0.014
609006	Weenup Creek @ Balgarup	38.5	9	1.451	21	0.038
612014	Bingham River @ Palmer	41.6	10	1.080	16	0.026

6.4 Regional Prediction Equation

In order to estimate the maximum extraction rate in ungauged catchments, a prediction equation was developed using catchment characteristics and the sustainable diversion limit. The SDL was used as a predictor variable because it had a very high correlation with MER and assisted in providing consistency between the two parameters across the study area. The equation found to provide the best prediction of the MER was:

$$\mathbf{ln}(\mathrm{MER}) = 0.802\,\mathbf{ln}(\mathrm{SDL}) + 0.170\,\mathbf{ln}(\mathrm{AREA}) + 0.00075\,\mathrm{RAIN} - 0.0026\,\mathrm{PCT\_VEG05} - 4.10$$

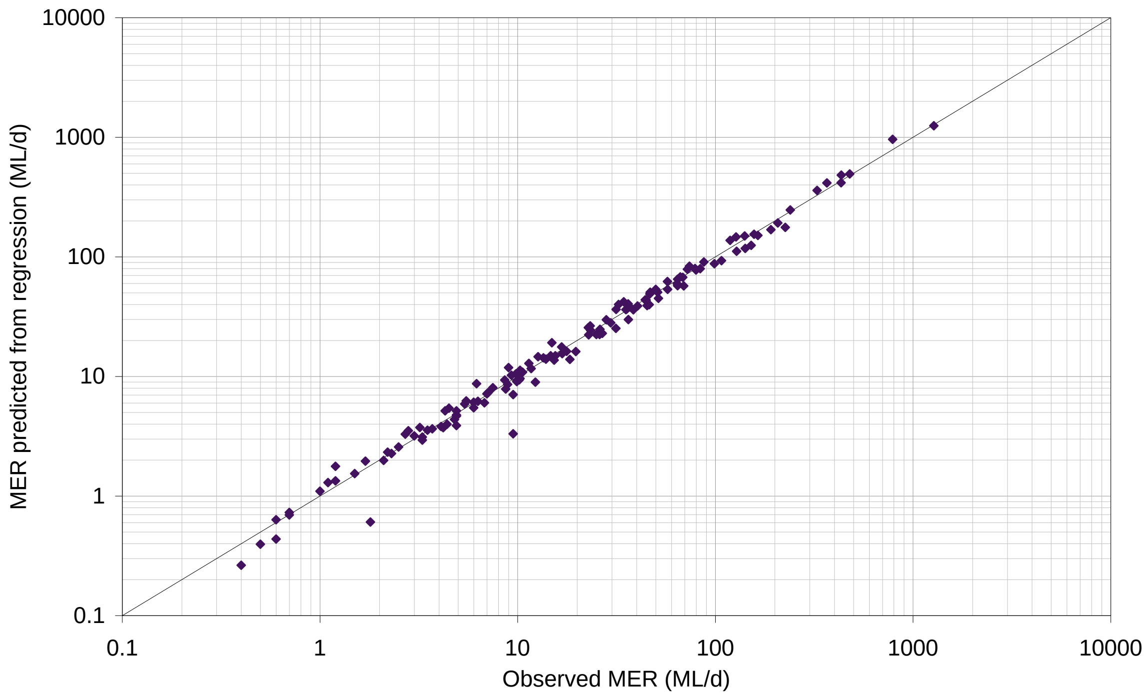
Where:	MER	=	Maximum extraction rate (ML/d)
	SDL	=	Sustainable diversion limit volume (ML)
	AREA	=	Area of entire upstream catchment (km)
	RAIN	=	Mean annual rainfall for 1975 - 2006 (mm/yr) (winter taken as July to October)
	PCT_VEG05	=	Percentage of catchment area covered by woody vegetation as determined by AGO data from 2005

Three gauged catchments were removed from the fitted regression equation: one gauge was removed as the SDL was zero (609010), and two outliers to the equation were removed (609021 and 617002). These were the same catchments that were removed from the SDL regression equation.

Regression statistics were as follows:

- Number of observations (including outliers) = 142
- Number of observations (after excluding outliers) = 139
- Multiple R^2 = 0.994
- Standard error of estimate in logarithmic domain on MER = 4.7%

The plot of the prediction equation results against the MER calculated from observed data at the gauged catchments that were used to derive the equation is presented in Figure 6-7. The plot indicates a reasonably uniform distribution of residuals about the fitted regression equation. Plots of residuals are provided in Appendix D.



- **Figure 6-7 Comparison between maximum extraction rate predicted by regression equation and calculated from observed data for gauged catchments**

A regression equation including the SDL as a predictor variable was adopted because it ensured that there was consistency between the MER and SDL across the study area. It should be noted that the standard error of 4.7% is not the true error of predicting the maximum extraction rate, but rather is the error that is conditional upon the SDL value used. In this context it is important that the maximum extraction rate (and the minimum flow threshold) are not estimated independently of the

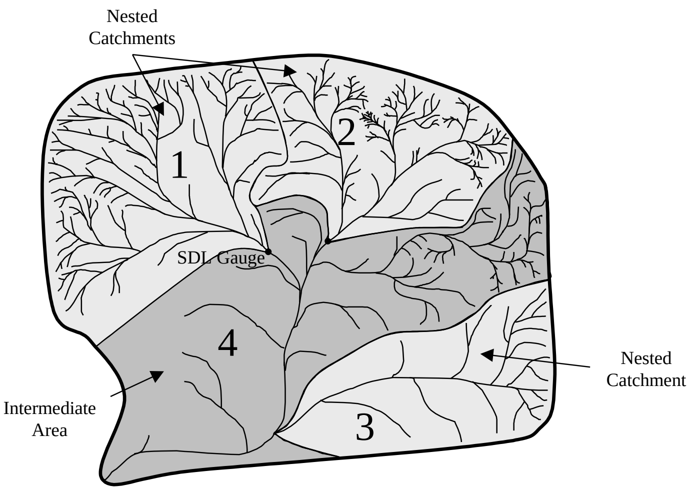
SDL volume but they should be linked to the annual licensed volume to ensure that any prediction errors are not propagated in a nonsensical fashion.

6.5 Application to Ungauged Catchments

The maximum diversion rate was calculated for each catchment using the prediction equation derived in the previous section. For catchments with nested catchments the MER was estimated for the intermediate area, and the MER for the entire catchment was estimated by adding the value of all nested catchments to the MER of the intermediate area.

For example, the MER would have been calculated individually for each of the four catchments in Figure 6-8. The MER for catchment number four would have been calculated for only the dark grey area. Assuming that the MER for catchments 1, 2, 3 and 4 are 20 ML/day, 20 ML/day, 10 ML/day and 15 ML/day respectively, then the MER for the entire catchment would be 65 ML/day.

The MER to SDL ratio was computed for all of the 1966 catchments. The MER was restricted for all of the ungauged catchments so that the ratio of MER to SDL was between 7 and 92 days (See Section 6.3 for a discussion of the permissible range of MER to SDL values). The restriction in the range of MER values only modified the MER for 28 (or just over 1%) of the catchments.



- **Figure 6-8 Illustration of nested catchments and intermediate areas.**

The maximum extraction rate ranges between 0.0001 and 0.996 ML/d/km² and has an average of 0.086 ML/d/km². A histogram is provided in Figure 6-9. Another way of thinking about the variability in MER is as the ratio of SDL to MER. Figure 6-10 shows histograms of this ratio for catchments in different parts of the study area.. Figure 6-10(b) and (c) show that the mean SDL to MER ratio is much shorter for catchments in the northern and eastern basins of the study area (41 days) than for the south-western basins (61 days). Catchments closer to the southern and western coasts have higher rainfall, higher SDL and more reliable streamflow. More days are available for extraction when the flow exceeds the MFT in the catchments in the south-western part of the study area and they therefore have a higher ratio of SDL to MER than catchments to the north and east. The histogram for the whole study area (Figure 6-10(a)) is bimodal, reflecting the combination of the distributions from both parts of the study area. Figure 6-10(d) shows that both the mean value (63 days) and the shape of the distribution for the gauged catchments is similar to the distribution for catchments in the south-western basins because the gauged catchments form a subset of catchments from these basins.

Figure 6-11 confirms that the geographical distribution of MER per unit catchment area is highly correlated with the spatial distribution of SDL per unit catchment area. Figure 6-12 confirms that the SDL to MER ratio is higher in catchments that are closer to the south-western corner of the study area, where rainfall and streamflow is more consistent throughout the winterfill period.

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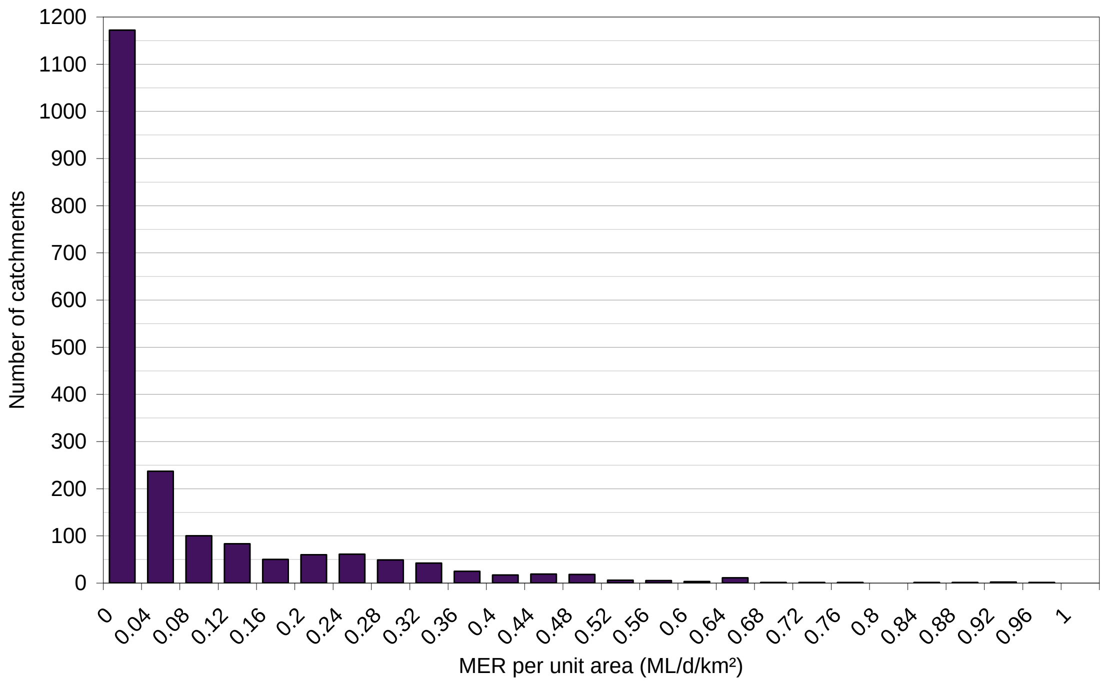
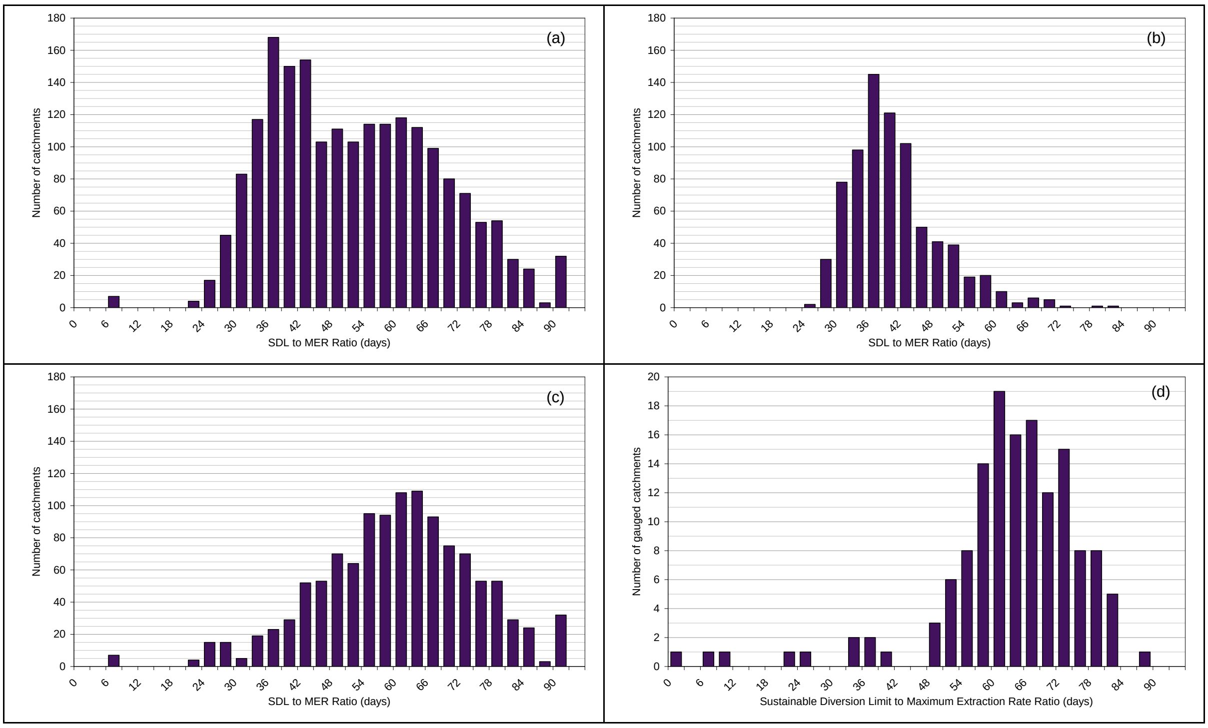
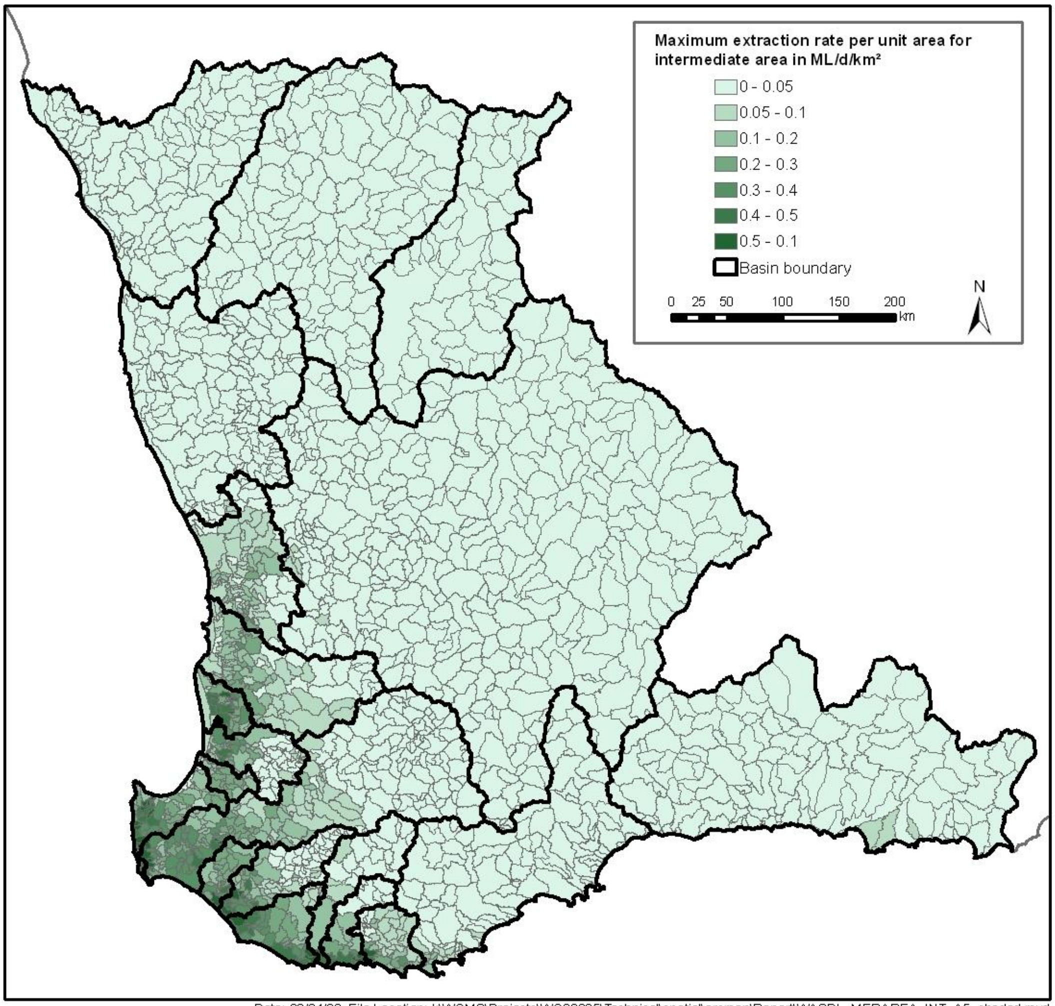


- **Figure 6-9 Histogram of maximum extraction rate per unit area for all of the 1966 catchments**



- **Figure 6-10 Histograms of sustainable diversion limit to maximum extraction rate ratio (a) all of the 1966 catchments; (b) for the 772 catchments located in AWRC basins 601, 615, 618, 619 and 701; (c) for the 1194 catchments located in AWRC basins 602 to 614, 616 and 617; and (d) for the subset of 142 gauged catchments**



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- **Figure 6-11 Geographic distribution of maximum extraction rate per unit catchment area for all 1966 catchments (ML/d/km²)**

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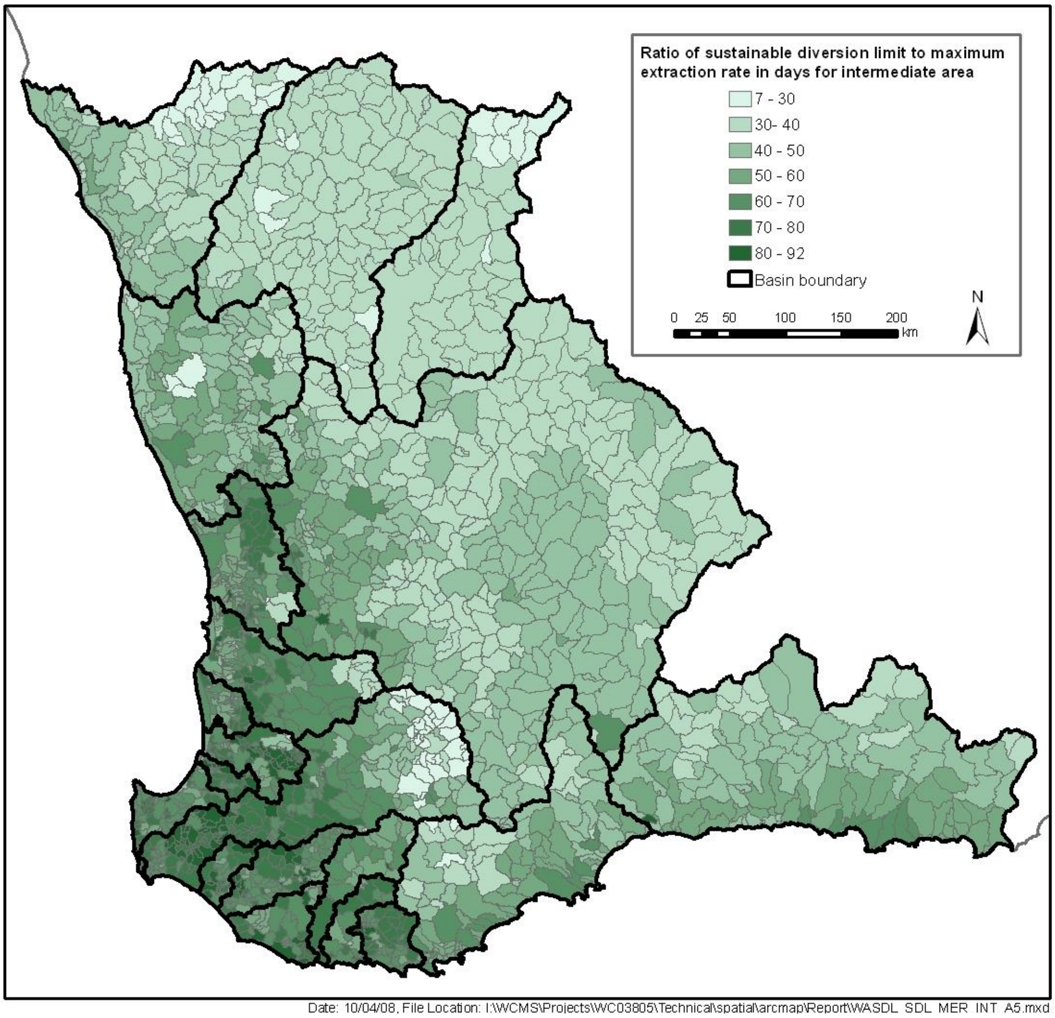

- **Figure 6-12 Geographic distribution of ratio of sustainable diversion limit to maximum extraction rate for all 1966 catchments (days)**

6.6 Summary

For the 142 gauged catchments the maximum extraction rates were calculated from flow data using the method in Sinclair Knight Merz (2007). The MER was highly correlated with the SDL. Values for the MER ranged between 0.001 and 0.91 ML/d/km² and had an average of 0.15 ML/d/km² for the gauged catchments.

The results for 142 gauged catchments were used with the SDL and physiographic catchment characteristics to develop a regional prediction equation using multiple linear regression. The model had an R^2 of 0.994 and a standard error equal to 4.7% in the logarithmic domain. The regional prediction equation was used to assign MER values to all catchments. The MER ranges between 0.0001 and 0.996 ML/d/km² and has an average of 0.086 ML/d/km² across the study area.

7. Minimum Flow Threshold

7.1 Introduction

The minimum flow threshold (MFT) is the lower limit below which the flow should not fall below as a result of diversions. This threshold can be estimated for every catchment. However the daily flow is not measured for each of the 1966 catchments in the study area and it will not be known when the flow has fallen below the minimum flow threshold. Each catchment will need to be assigned to a gauge, referred to as the indicator gauge. When the flow at this gauge falls below its minimum flow threshold, diversions in all its associated catchments should cease.

In this chapter the minimum flow threshold is calculated for 142 gauged catchments and a regional prediction equation is developed. In practice this will be required only to estimate the MFT for the indicator gauges for which the SDL cannot be calculated. For completeness the MFT has been estimated for all of the 1966 catchments in south west Western Australia. The method used to assign catchments to indicator gauges is provided in Chapter 8.

7.2 Gauged Catchments

The minimum flow threshold (MFT) was calculated for the 142 selected gauged catchments using the prepared streamflow data. The minimum flow threshold is the maximum of:

- The median flow observed over the winterfill period (15 June through 15 October) that is exceeded in 95% of years; and,
- 30% of the mean annual flow (per day).

Details of the method are provided in Sinclair Knight Merz (2007).

For example, the median flow observed between 15 June and 15 October that is exceeded in 95% of years for the Donnelly River at Strickland is 225 ML and 30% of the mean annual flow is 82 ML/day. Hence the minimum daily flow allocated to the Donnelly River is 225 ML per day (see Figure 6-1 for a sample of the time series of flow).

The calculated MFT per km² for the 142 gauged catchments varied between 0.01 ML/day/km² and 1.16 ML/day/km² with an average of 0.22 ML/km². A frequency exceedance plot is presented in Figure 7-1.

The spatial distributions of the standardised MFT volumes for all available 142 selected sites are shown in Figure 7-3. It is evident that higher minimum flows are required in the higher rainfall areas closer to the southern and western coastlines. This is consistent with high streamflow persistence and the pattern exhibited by the SDL and MER. Figure 7-2 illustrates the correlation between SDL and MFT for gauged catchments ($r^2 = 0.72$).

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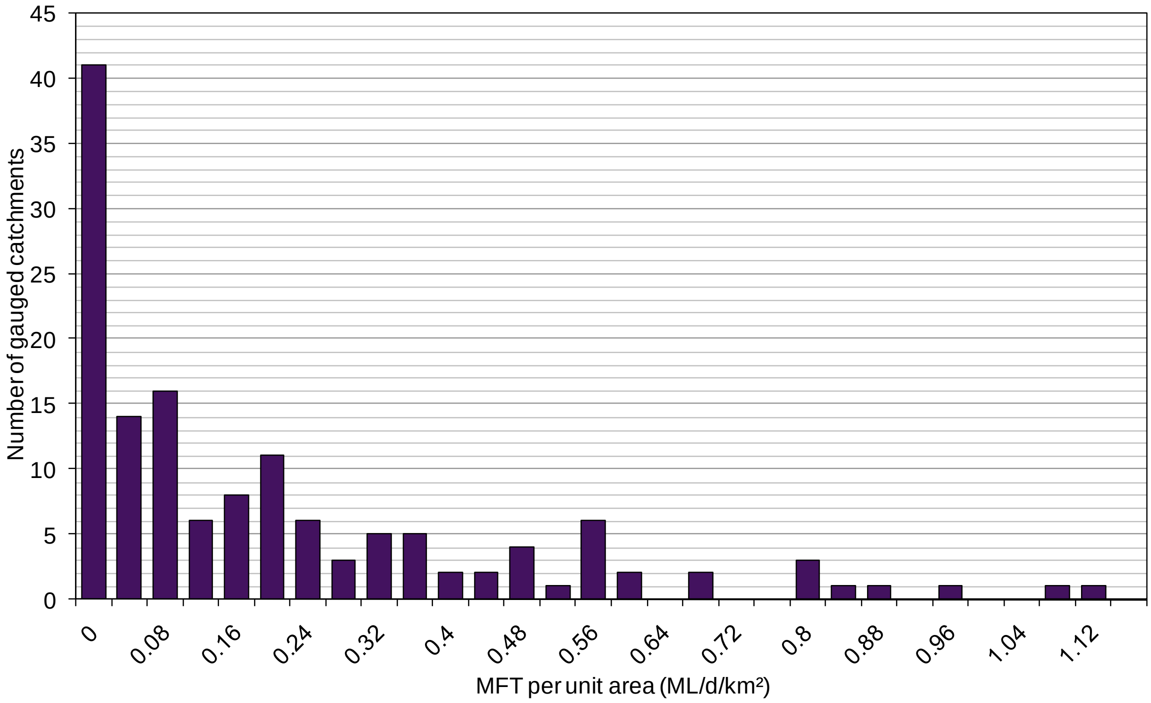

Figure 7-1 Frequency exceedance plot of the minimum flow threshold per square kilometre for all 142 gauged catchments.

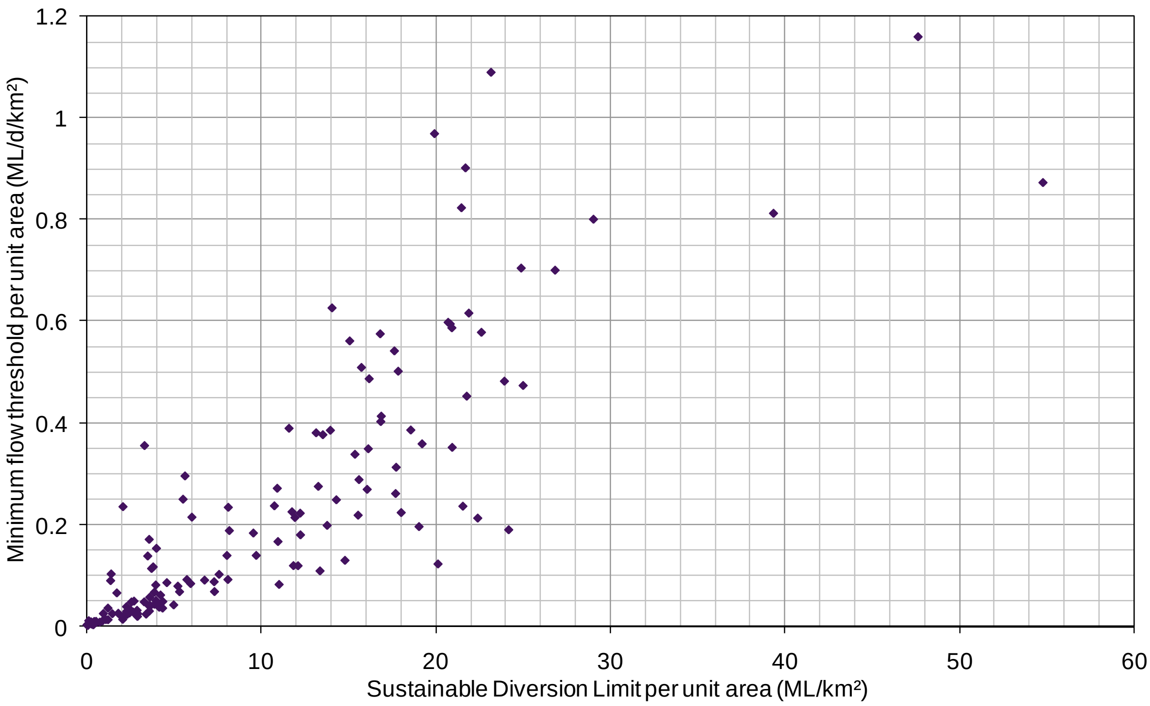

Figure 7-2 Scatter plot of SDL and MFT for the 142 gauged catchments.

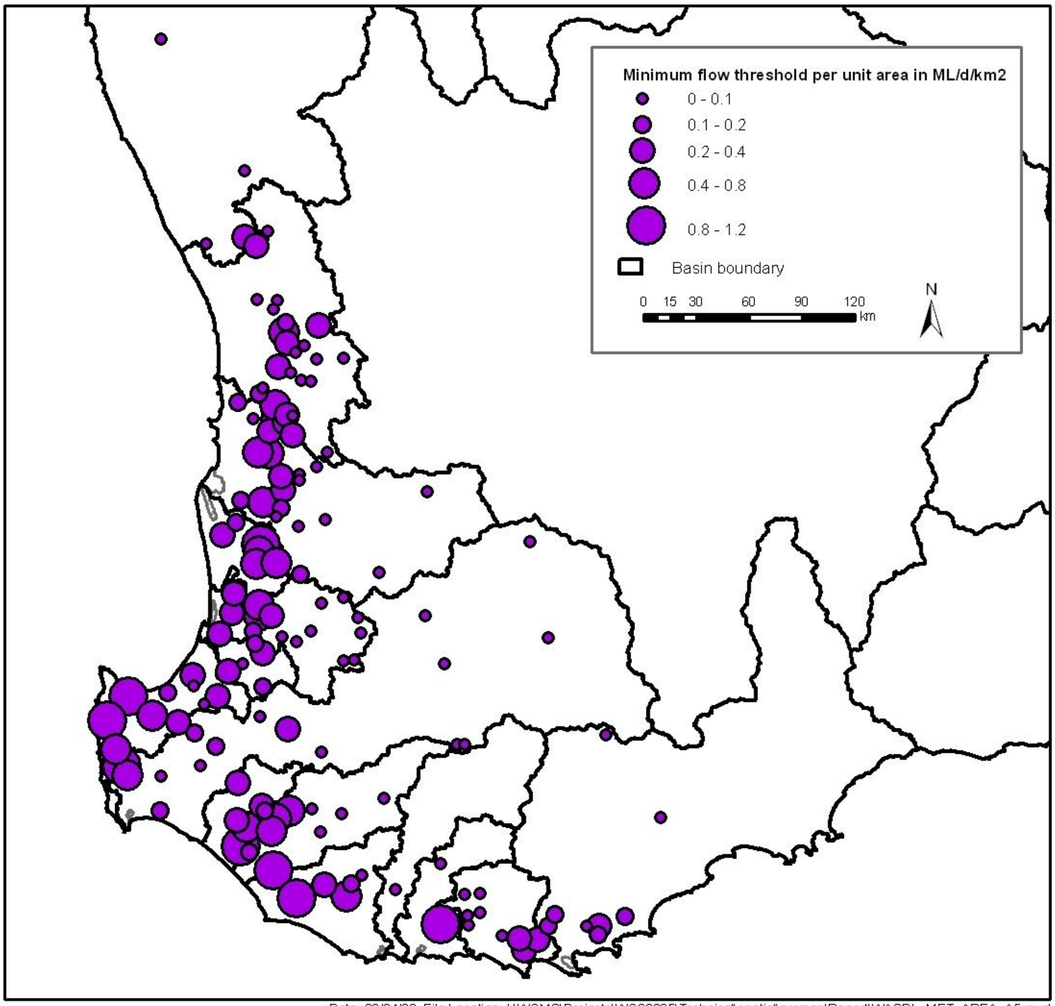

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Figure 7-3 Geographical distribution of MFT per unit catchment area (ML/km²/day). Large symbols indicate a high MFT and small symbols a low MFT.

7.3 Regional Prediction Equation

A regional prediction equation was developed to estimate the minimum flow threshold for ungauged catchments using the SDL and physiographic characteristics. The equation may also be used in the future to estimate the minimum flow threshold at an indicator gauge for which the minimum flow threshold cannot be calculated. This situation may arise if an indicator gauge is chosen that is newly established or the historical record is highly influenced by diversions.

The equation found to provide the best prediction of the MFT is:

$$\mathbf{ln(}\mathrm{MFT}\mathbf{)} = 0.653\ \mathbf{ln(}\mathrm{SDL}\mathbf{)} + 0.298\ \mathbf{ln(}\mathrm{AREA}) + 0.00233\ \mathrm{RAIN} - 0.0111\ \mathrm{PCT\_VEG05} - 44.2\ \mathrm{SFREQ} - 0.00188\ \mathrm{ELEV\_MIN} - 3.99$$

where:	MFT	=	Minimum flow threshold (ML/day)
	ln(SDL)	=	Natural logarithm of the SDL in ML
	ln(AREA)	=	Natural logarithm of total upstream catchment area (km^2)
	RAIN	=	Mean annual rainfall for 1975 - 2006 (mm/yr)
	PCT_VEG05	=	Percentage of catchment area covered by woody vegetation as determined by AGO data from 2005
	SFREQ	=	Frequency of stream junctions per unit area of catchment (number per km^2)
	ELEV_MIN	=	Elevation at the catchment outlet (m AHD)

In formulating the regression equation one gauge was removed as the SDL was zero (609010).

Regression statistics were as follows:

- Number of observations (including outliers) = 142
- Number of observations (after excluding outliers) = 141
- Multiple R^2 = 0.919
- Standard error of estimate in logarithmic domain = 2.4%

The plot of the prediction equation results against the observed results that were used to derive the equation is presented in Figure 7-4. This plot indicates a reasonably uniform distribution of residuals about the fitted line. Plots of the residuals are provided in Appendix D.

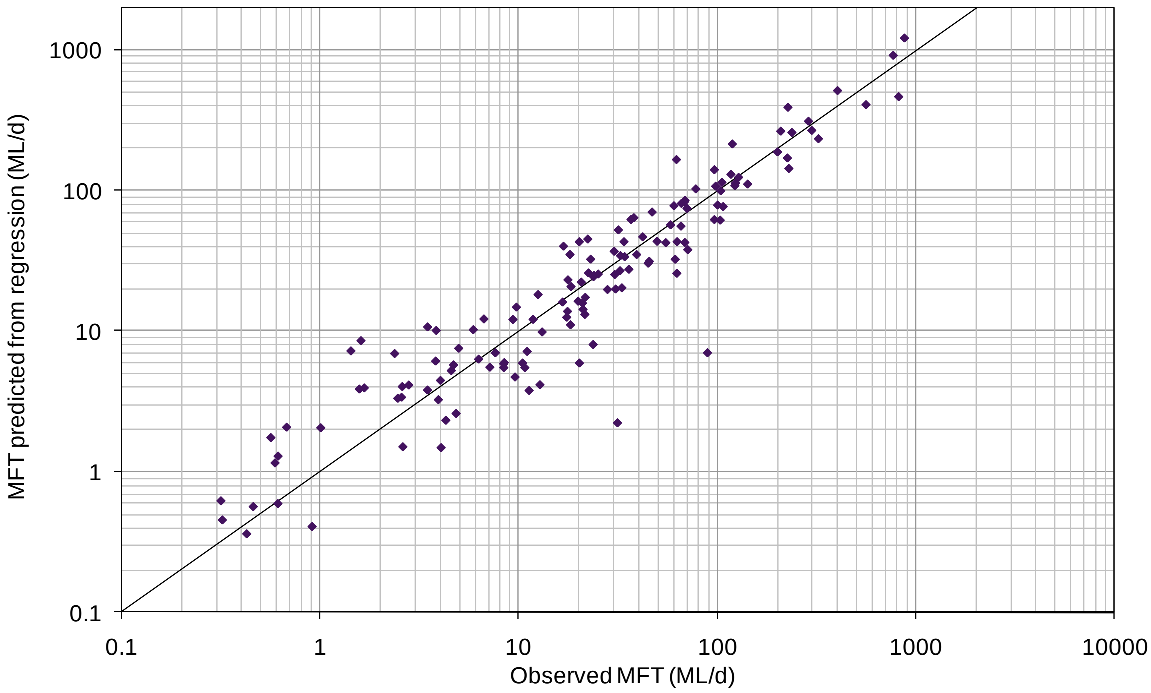


Figure 7-4 Predicted versus calculated minimum flow threshold.

7.4 Application to Ungauged Catchments

The minimum flow threshold was calculated for each catchment using the prediction equation derived in section 7.3. The MFT was only estimated for the total upstream area of each catchment (ie. including any nested catchments).

The values ranged between 0 ML/day/km² and 2.35 ML/day/km² with an average of 0.13 ML/day/km². A frequency exceedance plot is provided in Figure 7-5. The gauged catchments exhibit higher values because they are located in the wetter basins near the southern and western coastlines of the study area.

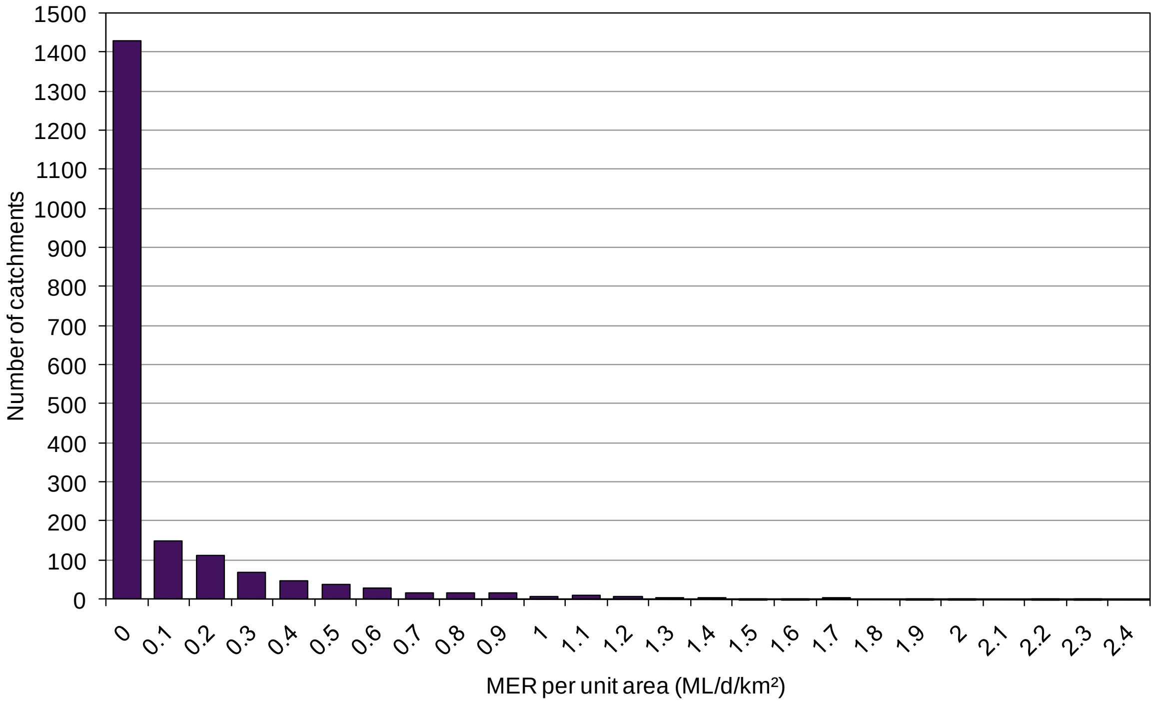


Figure 7-5 Histogram of the Minimum Flow Threshold per unit area for all of the 1966 catchments.

7.5 Summary

For 142 gauged catchments the minimum flow thresholds were calculated from flow data as per the method presented in Sinclair Knight Merz (2007). The values ranged between 0.01 ML/day/km² and 1.16 ML/day/km² with an average of 0.22 ML/km². The values ranged considerably across the study area consistently with the SDL.

The results for the 142 gauged catchments were used with the SDL and physiographic characteristics of their catchments to develop regional prediction equations using multiple linear regression. The model had a R^2 of 0.92 and a standard error equal to 2.4% of the mean.

The regional prediction equation was used to assign MFT values to all catchments. The MFT ranges between 0 ML/day/km² and 2.35 ML/day/km² and had an average of 0.13 ML/day/km².

The minimum flow threshold cannot be monitored for each catchment because the majority of them are ungauged. Hence each ungauged catchment needs to be assigned to a gauged catchment to enable licensing authorities to cease diversions during low flow conditions. This work is explained in chapter 8.

8. Minimum Flow Indicator Gauge Allocation

8.1 Introduction

The minimum flow threshold (MFT) is the lower limit below which the flow should not fall below as a result of diversions. This threshold can be estimated for every catchment. However the daily flow is not measured for each of the 1966 catchments in the study area and it will not be known when the flow has fallen below the minimum flow threshold. In order to implement the MFT it is necessary to know when the flow in the stream falls below the MFT so the licensing authorities will be able to stop diversions. Each catchment will need to be assigned to a gauge, referred to as the indicator gauge. When the flow at this gauge falls below its minimum flow threshold, diversions in all its associated catchments should cease.

This chapter firstly describes the development of the method to allocate a catchment to an indicator gauge based on the 142 gauged catchments that were selected to calculate the SDL (See Section 2.2). A simple way to allocate catchments would be to allocate a catchment to the nearest gauge. However catchments located next to each other can behave very differently during low flow conditions. Hence the allocation to a gauge needed to be based on proximity and hydrological similarity. This involved identifying the characteristics that influence MFT using multiple linear regression, defining hydrological similarity using principal component analysis and then allocating a catchment to a gauge based on hydrological similarity and proximity. Secondly the selection of indicator gauges and the allocation of catchments to these gauges is described.

8.2 Development of Method to Assign Catchments to Indicator Gauges

A method of assigning catchments to indicator gauges was developed using the 142 gauged catchments that were selected to calculate the SDL. The allocation of assigning catchments to indicator gauges was based on:

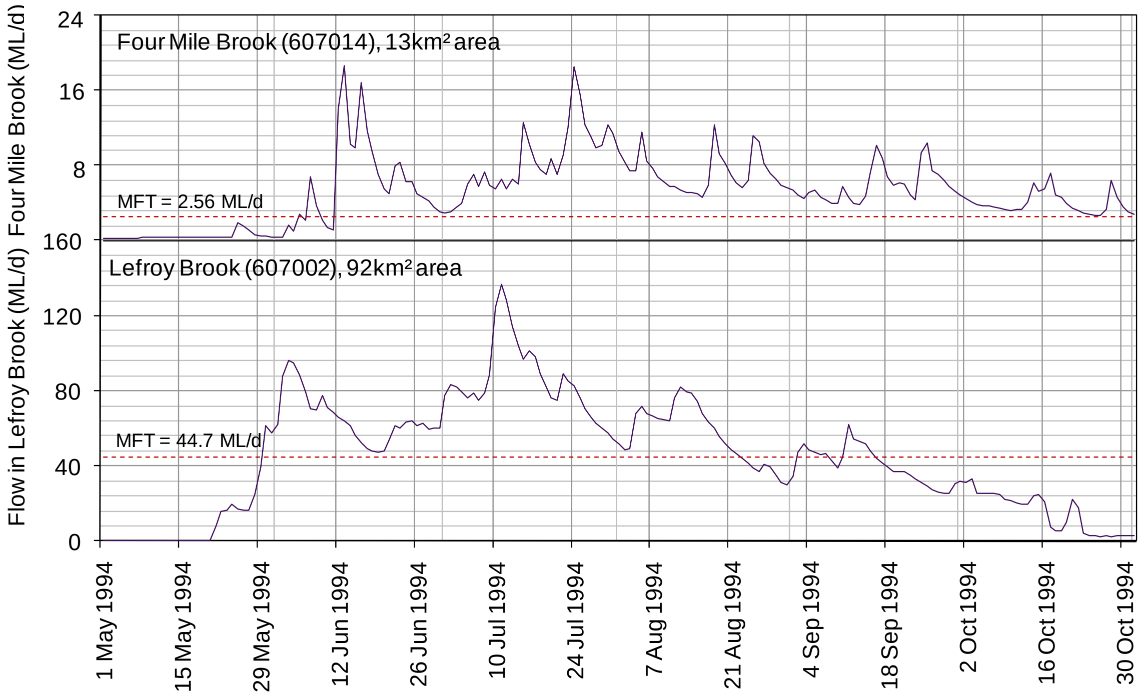
- the proximity of the catchment to each gauge; and,
- the minimum flow similarity of the catchments.

Neither of these factors alone can adequately assign catchments to indicator gauges.

8.2.1 Proximity

Comparing the distance between the centroid of the ungauged catchment and the centroids of the gauged catchments can easily identify the indicator gauge with the closest proximity. However the low flow conditions of a catchment are dependent on the underlying regolith and geology of a catchment. Two adjacent catchments may respond markedly different to drought conditions even though they are nearby.

For example if the selection of an indicator gauge for Lefroy Brook at Channybearup (607002) was based purely on location (distance between catchment centroids) the gauge selected would be Four Mile Brook at Netic Road (607014). The minimum flow threshold for Lefroy Brook is 0.49 ML/day/km², much more than the 0.20 ML/day/km² for Four Mile Brook. Figure 8-1 shows the hydrograph of both Lefroy and Four Mile Brooks for the winterfill period of 1994. The hydrograph indicates that Lefroy Brook, being a much larger catchment and with more catchment storage responds in a more attenuated manner to rainfall events, having a slower baseflow recession and less variability in streamflow on a daily basis than Lefroy Brook. The periods when the streamflows fall below the minimum flow thresholds therefore do not correspond very well. Four Mile Brook would not be a suitable indicator gauge for Lefroy Brook.



- **Figure 8-1 Hydrograph of Lefroy Brook (607002) and the catchment of closest proximity. The red dotted lines indicate the minimum flow threshold.**

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8.2.2 Hydrological Similarity

The similarity of minimum flow between catchments cannot be based on gauged information, as the majority of catchments will be ungauged. Rather it needs to be based on the similarity of the catchment characteristics that influence the minimum flow behaviour. Multiple linear regression was used to identify the variables that influence the minimum flow behaviour of the catchment. Principal component analysis was then used to assess the similarity of catchments with regards to these factors.

Regional Prediction Equation

A regional prediction equation was developed to estimate the minimum flow threshold in megalitres per square kilometre for ungauged catchments using catchment characteristics. This equation was used to identify the catchment characteristics that influence the minimum flow. It should be stressed that here we are interested in examining those characteristics that govern hydrologic similarity, which are not necessarily the same as those most suited to volumetric prediction.

The equation found to provide the best prediction of the MFT per unit catchment area is:

$$\mathbf{ln(}\mathrm{MFT/km^2}\mathbf{)} = -\,0.602\ \mathbf{ln(}\mathrm{SDL}\mathbf{)} + 0.00306\ \mathrm{RAIN} - 0.0104\ \mathrm{PCT\_VEG89} - 1.14\ \mathbf{ln}(\mathrm{PERIMETER}) - 0.00167\ \mathrm{ELEV\_MIN} - 3.14$$

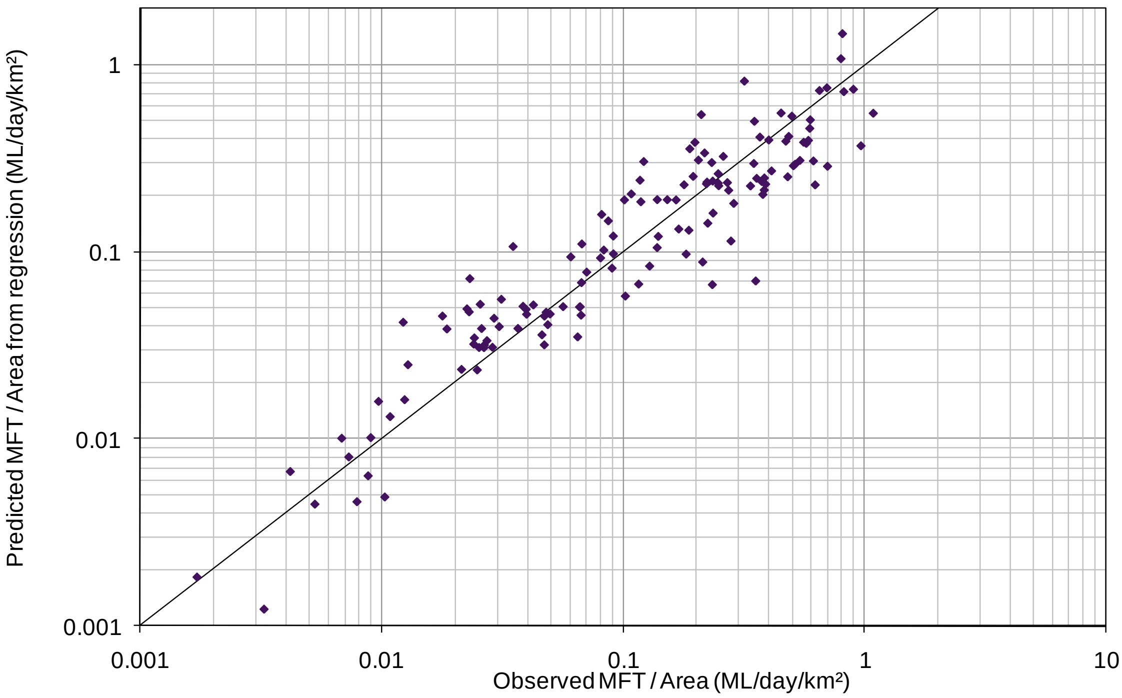
where:	MFT/km^2	=	Minimum flow threshold per area ($ML/day/km^2$)
	ln(SDL)	=	Natural logarithm of the SDL in ML
	RAIN	=	Mean annual rainfall for 1975 - 2006 (mm/yr)
	PCT_VEG89	=	Percentage of catchment area covered by woody vegetation as determined by AGO data from 1989
	ln(PERIMETER)	=	Natural logarithm of the perimeter of entire catchment (km)
	ELEV_MIN	=	Elevation at the catchment outlet (m AHD)

Two outliers were identified and removed from the sample.

Regression statistics were as follows:

- Number of observations (including outliers) = 142
- Number of observations (after excluding outliers) = 140
- Multiple R^2 = 0.878

The plot of the prediction equation results against the observed results that were used to derive the equation is presented in Figure 8-2. This plot indicates a reasonably uniform distribution of the residuals about the fitted line. Plots of the residuals are provided in Appendix E.



- **Figure 8-2 Predicted versus calculated minimum flow threshold per square kilometre.**

The use of multiple linear regression has indicated that the SDL, vegetation cover, elevation of the catchment outlet, catchment perimeter and mean annual rainfall are the five physiographic characteristics that influence the minimum flow threshold in ML/day/km².

Principal Component Analysis

The development of the regional prediction equation identified that the minimum flow threshold is influenced by the SDL volume, catchment perimeter, average annual rainfall, elevation at the gauge location and percentage vegetation cover in 1989. Therefore if two catchments are very similar with regards to these catchment characteristics it can be assumed that they have a similar minimum flow threshold per square kilometre.

Principal component analysis was used to asses the similarity of catchments with regard to the catchment characteristics influencing the SDL per unit area. Two principal components were derived (for a detailed method, see Appendix B.4). The first and second principal components were derived using the equations below:

$$PC1 = 0.895\ \mathbf{ln}(SDL)\_\mathit{std} - 0.042\ \mathbf{ln}(PERIMETER)\_\mathit{std} + 0.837\ RAIN\_\mathit{std} \\ + 0.498\ PCT\_VEG89\_\mathit{std}\ \ 0.734\ ELEV\_MIN\_\mathit{std}$$

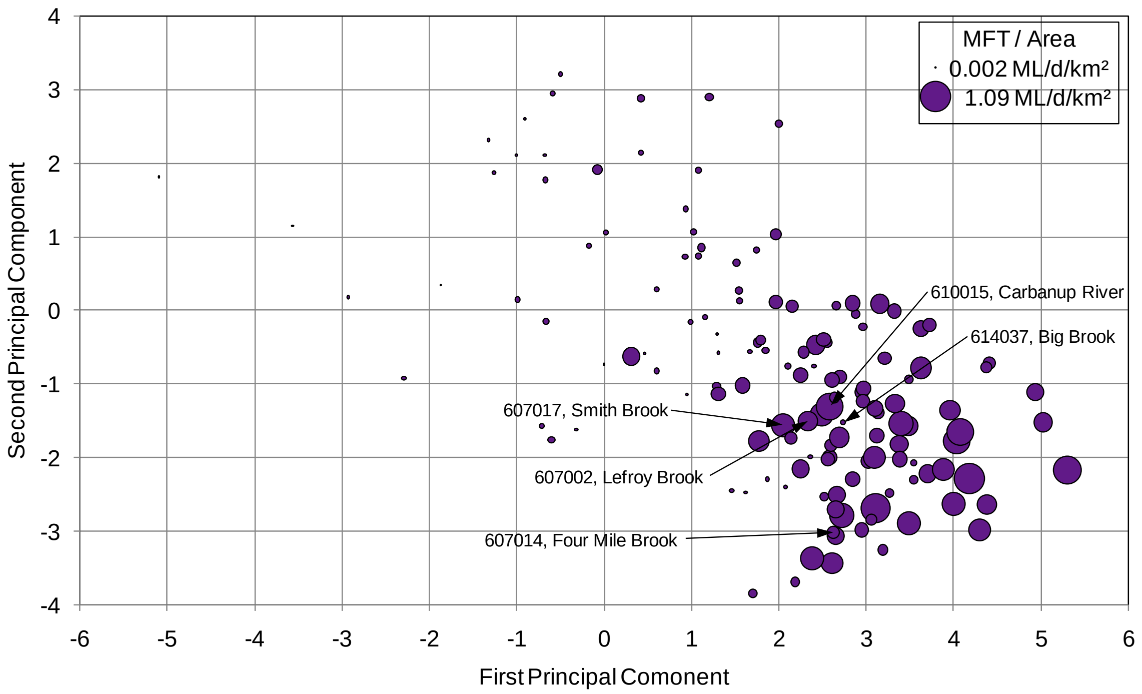
$$PC2 = 0.206\ \mathbf{ln}(SDL)\_\mathit{std} + 0.930\ \mathbf{ln}(PERIMETER)\_\mathit{std} - 0.452\ RAIN\_\mathit{std} \\ - 0.473\ PCT\_VEG89\_\mathit{std} + 0.324\ ELEV\_MIN\_\mathit{std}$$

where	PC1	= First principal component
	PC2	= Second principal component
	ln(SDL)_*std*	= Standardised natural logarithm of the SDL in ML
	ln(PERIMETER)_*std*	= Standardised natural logarithm of the catchment perimeter in km
	RAIN_*std*	= Standardised mean annual rainfall in mm for 1975-2005
	PCT_VEG89_*std*	= Percentage woody vegetation cover of the catchment in 1989
	ELEV_MIN_*std*	= Standardised elevation at the catchment outlet

All variables were standardised so that the data set had a mean of zero and a standard deviation of one. The two principal components explain 75% of the variation between the catchments with respect to the seven characteristics (The first principal component explains 46%, the second 29%). The main influences on the first principal component are the SDL volume, mean annual rainfall, and the elevation of the catchment outlet. The main influences on the second principal component are the length of the catchment perimeter, mean annual rainfall and vegetation cover.

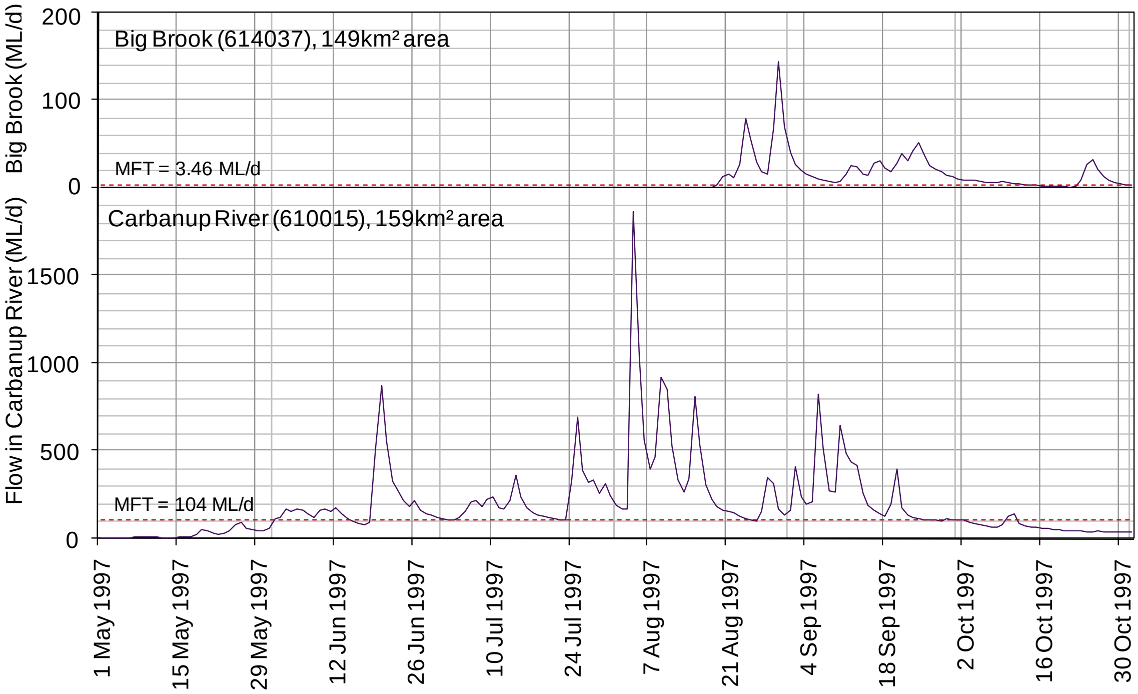
Figure 8-3 is a scatter plot of the two principal components. This plot provided a means for assessing the degree of similarity across all 142 catchments considered. The distance between each plotted point is a measure of the similarity of the catchments with regards to the specified catchment characteristics (SDL, perimeter, mean annual rainfall, vegetation cover and elevation at the catchment outlet) and hence the minimum flow threshold. For example the catchment of Lefroy Brook at Channybearup (607002) is most hydrologically similar to Smith Brook at Middlesex (607017). These two catchments are labelled in Figure 8-3.

In Figure 8-3 the actual minimum flow threshold as calculated from gauged data is demonstrated by the size of the symbol. For example, catchments attributed with the largest symbol have a MFT of 1.09 ML/day/km². Although there is some overlap between the various ranges it is generally evident that the minimum flow threshold increases towards the lower right hand corner of the plot.



▪ **Figure 8-3 Scatter plot of principal components derived using catchment characteristics that influence the minimum flow threshold. The size of the dots represents the size of the minimum flow threshold as calculated from gauged data.**

Continuing with the example of the previous section, Figure 8-3 indicates that if the selection of the indicator gauge for Big Brook at O'Neil Road (614037) was to be based solely on hydrological similarity the Carbanup River at Lennox Vineyard (610015, located 160 km away) would be selected. The minimum flow threshold of these two catchments are 0.023 ML/day/km² and 0.65 ML/day/km² respectively. Figure 8-4 shows the hydrograph of both Big Brook and Carbanup River for the winterfill period of 1997. The hydrograph indicates that these rivers are not experiencing the same climatic events as the flow peaks do not correspond and the periods where the flow falls below the minimum flow thresholds do not correspond. Clearly the Carbanup River would not act as a suitable indicator gauge to Big Brook even though it is similar with respect to the catchment characteristics that influence the minimum flow threshold.



- **Figure 8-4 Hydrograph of Big Brook at O'Neil Road and the catchment with the highest hydrological similarity (Carbanup River at Lennox Vineyard). The red dotted lines indicate the minimum flow threshold.**

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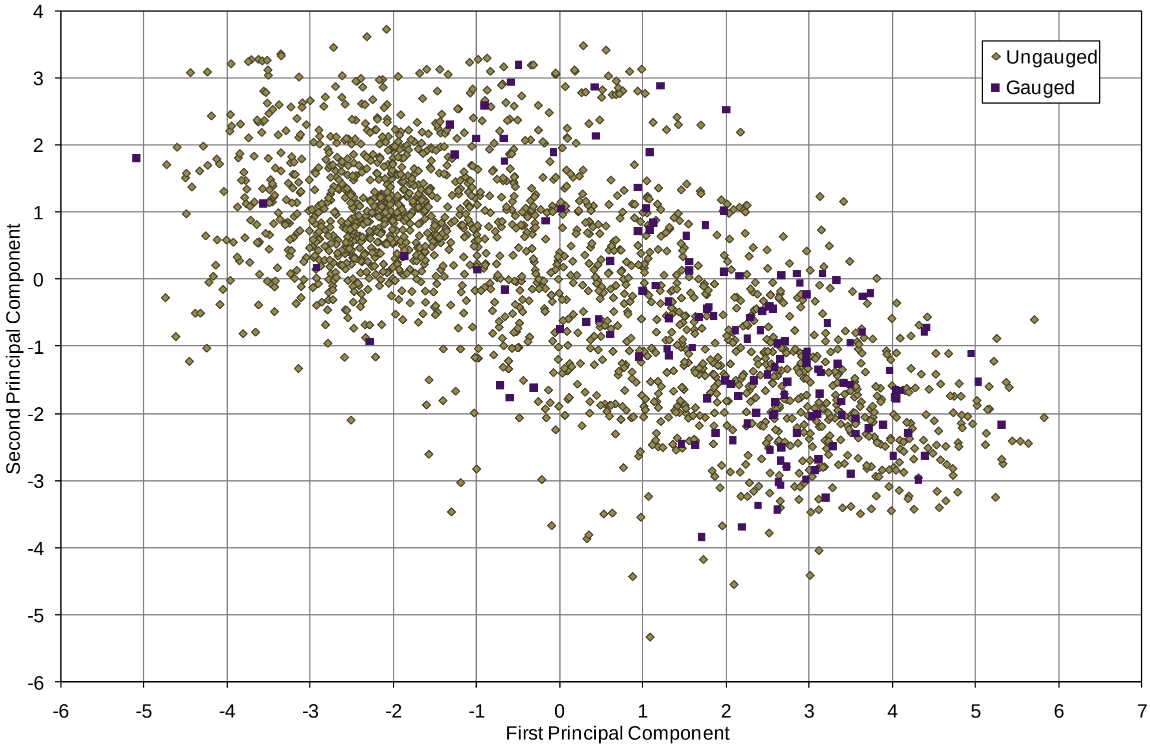
The assessment of minimum flow similarity was based on 142 selected catchments, but it was applied to 1966 catchments in the study area. Figure 8-5 plots the principal components for the 142 selected catchments in dark purple and the principal components for the 1966 SDL catchments in olive. The figure shows that the selected catchments are a fair representation of the SDL catchments with respect to the range of characteristics that influence the minimum flow threshold.



- **Figure 8-5 Scatterplot of principal components for all SDL catchments.**

8.2.3 Overall Similarity

The most suitable indicator gauge will be one that is in a catchment that experiences the same hydrological conditions and is hydrologically similar such that the overall similarity can be defined as:

$$\textit{Overall similarity} = \alpha(\textit{Hydrological similarity}) + (1-\alpha)(\textit{Proximity Similarity})$$

The hydrological similarity refers to the distance between the two catchments as plotted in Figure 8-5 and the proximity similarity is the distance between the catchment centroid of two stations calculated from standardised eastings and northings (ie the mean is zero and the standard deviation equals one). A small value indicates that two catchments are similar. Alpha (α) influences the weighting that is given to the hydrological and proximity similarity. So if α equals one the overall similarity is based solely on the hydrological similarity, and if α equals zero the overall similarity will be based on the proximity of the gauge.

The indicator gauge can be chosen for a given catchment by calculating the overall similarity for each possible indicator gauge and choosing the gauge that has the lowest overall similarity rating. The gauge selected depends on the α chosen.

The value of α was selected using all 142 sites. A range of α values were trialed and the indicator gauge for each of the 142 sites selected. The adequacy of the α selection was measured by the sum of the squared differences between each of the minimum flow thresholds of each catchment and its indicator gauge. The results for a range of α values are presented in Figure 8-6. The similarity between the minimum flow thresholds is poor when proximity (ie $\alpha = 0$) is used to select the indicator gauge. The least difference occurs when α equals 0.1, although the overall performance is fairly similar for all α values between 0 and 0.5. For the study region, although hydrological similarity has some importance in defining the indicator gauge, physical proximity is still the dominant effect. This was probably because many of the key drivers of hydrological similarity (mean annual rainfall, vegetation cover and SDL) are spatially correlated and proximity and hydrological similarity cannot therefore be neatly separated. A plot of the minimum flow threshold of the catchments versus the indicator gauge is provided in Figure 8-7.

The indicator gauge selected for Lefroy Brook at Channybearup (using $\alpha = 0.10$) was the gauge on Smith Brook at Middlesex (607017). The minimum flow threshold of this gauge is 0.60 ML/day/km^2 and a comparison of the hydrographs for the winterfill period of 1994 are provided in Figure 8-8. The baseflow response of these catchments match better than the closest gauge, providing a better correspondence for periods above the MFT.

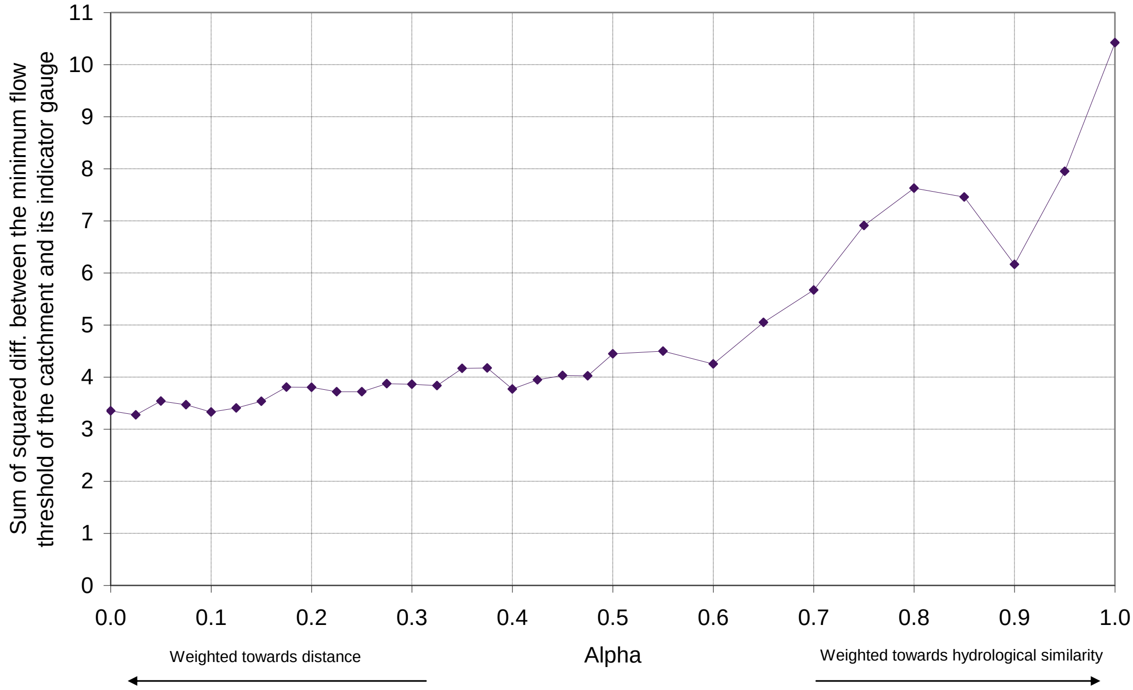
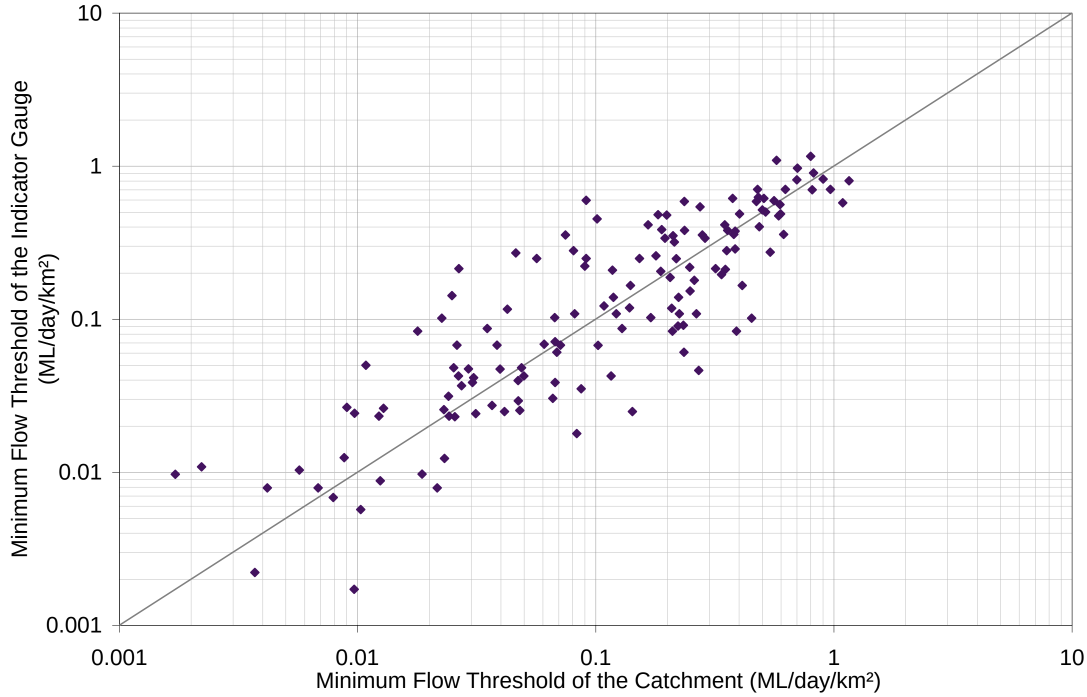
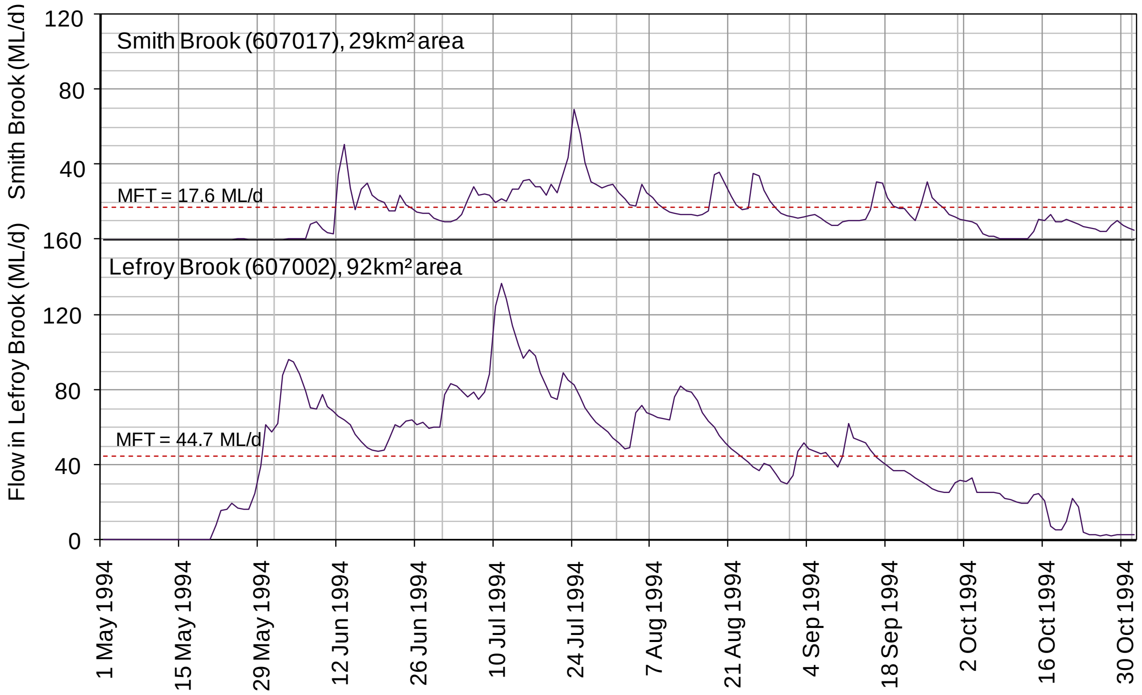


Figure 8-6 The sum of squared differences between the minimum flow threshold of the catchment and its indicator gauge for a range of alpha values.



- **Figure 8-7 Plot of the minimum flow threshold of the catchment versus the minimum flow threshold of the indicator gauge when the indicator gauge is selected using the overall similarity with alpha equal to 0.10**



- **Figure 8-8 Hydrograph of Lefroy Brook (607017) and the catchment with the best overall similarity (Smith Brook, 607017). The red dotted lines indicate the minimum flow threshold.**

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8.2.4 Selection of Indicator gauges

A set of streamflow gauges in the study area that can be used as indicator gauges for the minimum flow threshold was identified. The gauges selected needed to be:

- associated with an SDL catchment to allow the minimum flow threshold of the gauge to be estimated; and,
- still active.

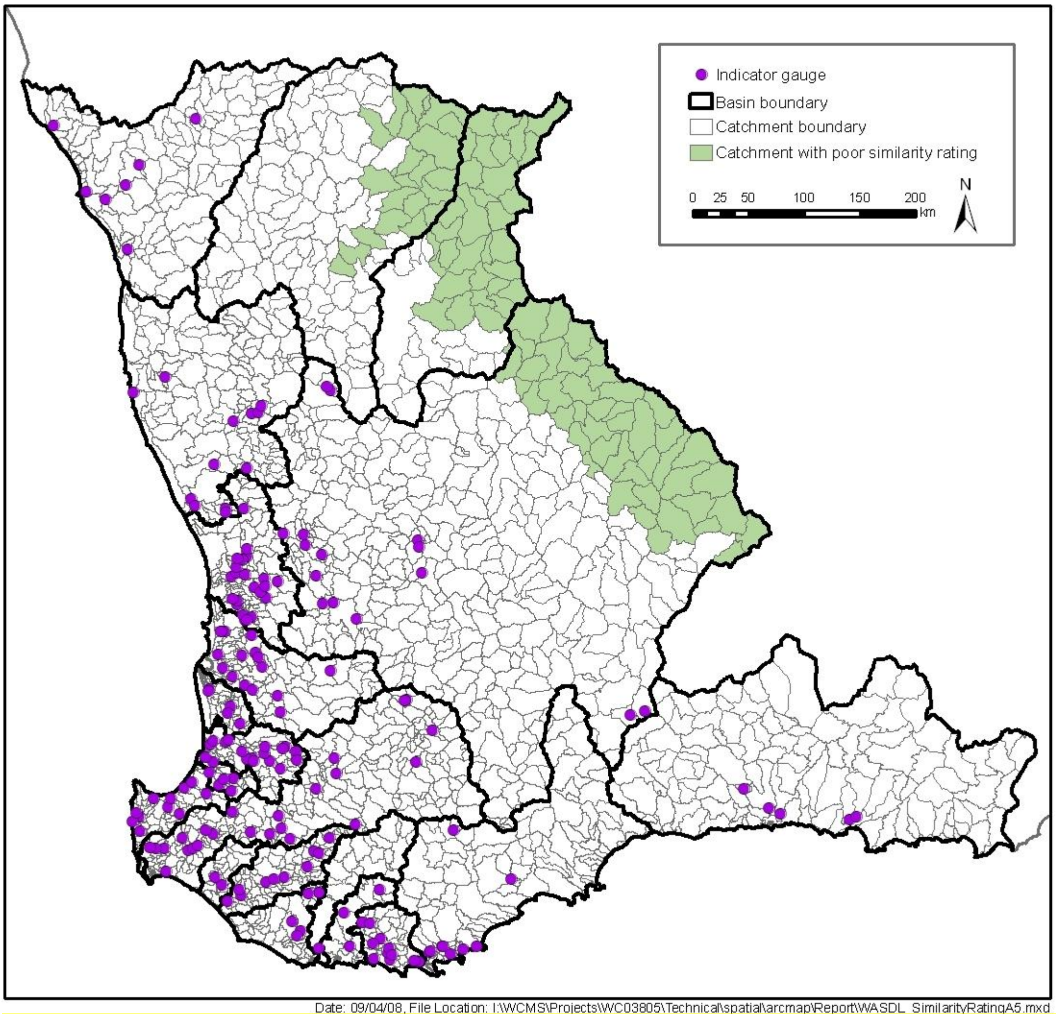
The gauges that correspond to SDL catchments comprise of:

- the 142 gauges for which the SDL was calculated (for details of their selection see section 2.2); and,
- the 307 other gauges associated with the downstream point of a SDL catchment.

There are 449 gauges associated with SDL catchments. These gauges were assessed as either active or closed according to information provided by Department of Water. In total 180 gauges were assessed as active (106 SDL gauges and 74 non-SDL gauges). In the selection process no consideration was given to the level of diversions or any regulation upstream of these gauges.

The streamflow timeseries were visually examined from all of the non-SDL gauges that were used as indicator gauges. In the visual examination, an assessment was made of whether the MFT calculated from the regression equation for the indicator gauge was representative of an MFT that would have been estimated directly from the timeseries had this gauge been included in the SDL data set. The non-SDL indicator gauges were assessed as being either “good quality” or “lower quality” for the purposes of acting as an indicator gauge for minimum flow exceedance. Of the 74 non-SDL gauges, 45 were assessed as “good quality” and 29 were assessed as “lower quality”. All of the 106 SDL gauges that were still open were automatically defined as “good quality” since the MFT is directly estimated from the streamflow timeseries for these gauges and it is not allocated using a regression.

In total 180 sites were selected. A listing of these sites is provided in Appendix F. Figure 8-9 illustrates the distribution of these gauges across the study area. There is a good coverage of indicator gauges across most of the study area, with the exception being the northern and eastern parts of the Avon, Yarra Yarra Lakes and Ninghan Basins.



- **Figure 8-9 Location of indicator gauges and catchments with a poor relative similarity rating (ie. a relative similarity rating in the bottom 5% of the study area catchments)**

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8.2.5 Allocation to Indicator Gauges

The method outlined in section 8.2.3 was used to allocate each of the 1966 SDL catchments to one of the indicator gauges selected in section 8.2.4. The hydrological similarity was based on data standardised using the mean and standard deviation of the 142 gauged SDL catchments*. In order to provide the licensing authorities with greater flexibility the second and third most appropriate gauges were also identified. The second and third most appropriate gauges provided alternates should a streamflow gauge be closed or otherwise temporarily unavailable in future. Catchments that contained an indicator gauge were assigned directly to that gauge, with the second and third most appropriate gauges provided should the gauge for that catchment be unavailable in future.

For example the SDL catchment 607_1_3_2, located in the Warren River and Tributaries SWMSA in the Warren River Basin, was allocated to three catchments as outlined in Table 8-1. The proximity measure suggests that gauge 609064 is closer than gauge 607024 to this catchment, but the gauge on Chowerup Brook (607024) was selected because it was hydrologically more similar and therefore had a lower overall similarity score.

- **Table 8-1 Proximity measure, hydrological similarity and overall similarity of the three indicator gauges allocated to the catchment 607_1_3_2 in the Warren River SWMSA.**

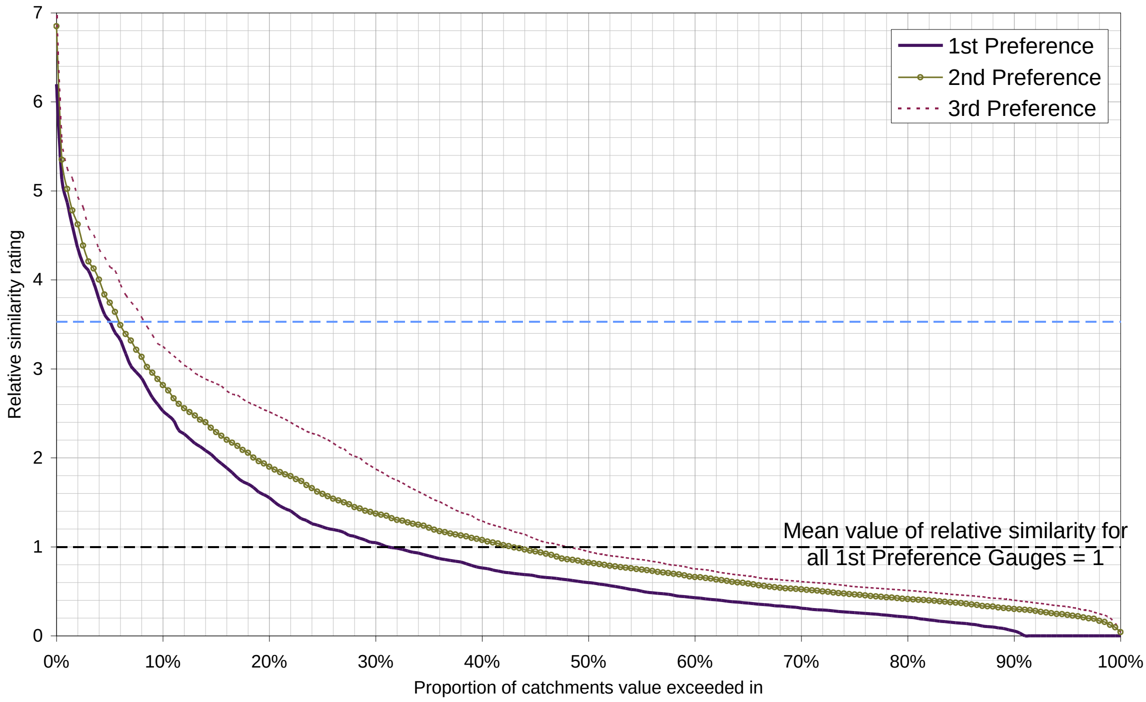
Site Num.	Site Name	MFT for Indicator Gauge (ML/d)	Similarity Scores			Similarity Rating
			Hydrological	Proximity	Overall	
607024	Chowerup Brook @ Stretch's Tree Farm	8.85	0.378	0.080	0.110	0.36
609064	Tweed River @ Rylington	2.49	0.553	0.078	0.126	0.41
607004	Perup River @ Quabicup Hill	16.59	0.484	0.115	0.151	0.49

A similarity rating was assigned to each of the selected gauges that would allow comparison of the overall similarity of indicator gauges. The weighting was calculated as the overall similarity score of the indicator gauge and the catchment divided by the average overall similarity weighting of all 1st preference indicator gauges (which equals 0.306). So for example the allocation of the gauge 607024 to the catchment 607_1_3_2 has a similarity rating of 0.36 (=0.110/0.306). This indicates that the overall similarity is better than average. A weighting of one would show that the overall similarity was average and a weighting higher than one would indicate that it was worse.

* The 142 SDL gauged catchments were used to derive the approach for assessing indicator gauge similarity, even though some of these gauges have since been closed and were not subsequently available as indicator gauges in the application phase of the method.

The weightings also allow comparison between the three indicator gauges. In Table 8-1 all three gauges are better than average and it can be seen that gauge one is appreciably better than the other gauges.

Figure 8-10 is a plot of similarity ratings assigned to all indicator gauge allocations. The thick purple line shows the similarity ratings of all first preference gauges. The olive line shows the similarity ratings of all second preference gauges and the dashed red line for all third preference gauges. It is seen that the similarity ratings increase for the second and third preference gauge allocations. The horizontal dashed blue, indicating a similarity rating of 3.53, is defined at the similarity rating above which 5% of the 1st preference gauges lie. A flag was assigned to an indicator gauge allocation if the similarity rating was greater than 3.53. Catchments thus flagged indicate that the reliability of any available indicator gauge is very poor compared to the rest of the study area.



- **Figure 8-10 Exceedance frequency curve of indicator gauge weightings (the blue line indicates the weighting corresponding to the 5% most unreliable of first preferences gauges).**

8.3 Summary

A method is required to assign all ungauged catchments to an indicator gauge to enable the licensing authorities to monitor the minimum flow threshold and cease diversions in catchments when necessary.

The method of assigning catchments to indicator gauges was developed using 142 gauged catchments. The overall similarity of two catchments is based on the proximity and hydrological similarity of the catchments with respect to minimum flow behaviour.

A set of 180 gauges across the study area were selected for use as indicator gauges. These gauges correspond to defined SDL catchments and are still active. Ungauged catchments were assigned to these gauges using the developed method.

9. Catchment Dams

9.1 Introduction

The proposed process for determining SDL extractions were based on the assumption that all extractions were obtained by pumped diversions. However, some proportion of current level of diversions and, presumably additional development in the future, will be harvested by catchment dams.

While pumped diversions can abide by the minimum flow threshold and the maximum extraction rate and the total volume diverted can be easily monitored, farm dams cannot. Farm dams are most easily licensed according to their capacity. However the capacity of a dam does not always correspond to the total volume harvested over the winterfill period because the harvested volume depends on the level of demand and the effect of rainfall and evaporation. Additionally, farm dams may have a larger impact on the flow regime at the start of the winter period (the second half of June, July and the start of August) as they refill after summer.

To ensure that the impact of a farm dam is not greater than pumped diversions an equivalent volume of farm dams can be determined so that:

- the volume of water harvested over the winterfill period does not exceed the SDL; and,
- the average volume extracted over the first half of the winterfill period (between 15 June and 15 August) does not exceed the volume available for pumped diversions.

A relationship between licensed diversions and total farm dam volume that “add up” to the SDL can be developed for each catchment similar to the example shown in Figure 9-1. For example, if the SDL volume is calculated to be 1,000 ML and if only pumped diversions occur in the catchment, the volume available for licences is 1,000 ML. However, if all the diversions are farm dams, then in this catchment only 840 ML of licences can be issued because this volume of farm dams will have same impact as 1,000 ML of pumped diversion.

In this chapter the ratio of pumped diversions and farm dams that can be licensed to fill the SDL has been calculated for 142 gauged catchments (section 9.2) and a method was investigated to estimate the ratio for ungauged catchments.

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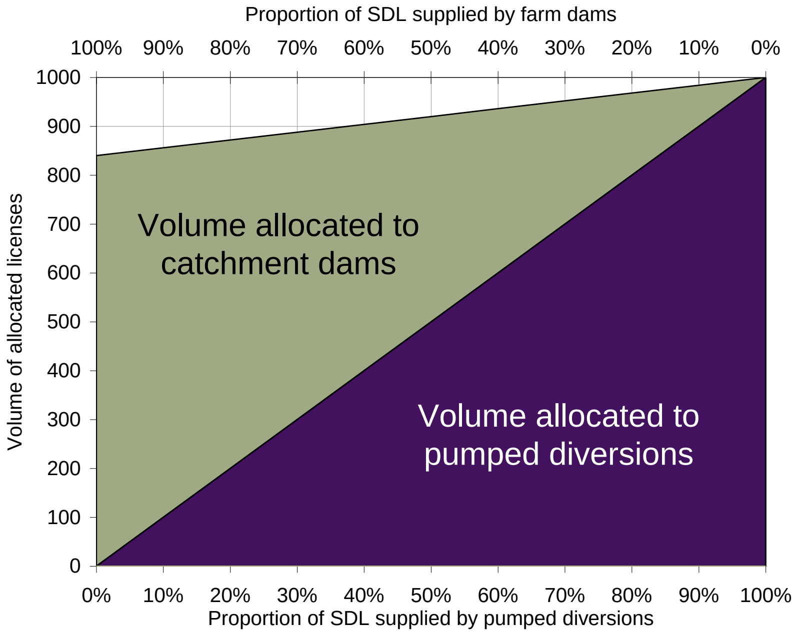


- **Figure 9-1 Hypothetical relationship between volume of an SDL of 1,000 ML distributed between pumped diversions and farm dams.**

9.2 Gauged Catchments

All of the 142 gauged catchments were used to calculate the volume of farm dams that have the equivalent annual impact on the flow regime equal to the SDL volume. Relationships derived for each catchment were used to derive the slope of the 'total allocation' line illustrated in Figure 9-1. A simulation model called CHEAT (Nathan et al., 2005) was used to model the impact of farm dams on the streamflow and determine the volume of farm dams that would fully satisfy the SDL (ie point where the 'total allocation' line crosses the vertical axis on the left side of Figure 9-1). The inputs required for each catchment in the CHEAT model are listed in Table 9-1 along with the source of each input.

An annual demand factor of one was adopted, that is, the annual demand is equal to the volume of farm dams within the catchment. Farm dam modelling is sensitive to changes in the annual demand factor (Lowe and Nathan, 2008) and hence a conservatively high factor was selected.

The adopted distribution of dam sizes was obtained by analysing the distribution of dam sizes observed from seven catchments in the south-west of the study area. Individual catchment dams were digitised from satellite and aerial photography imagery from the catchments of the Lower Collie River, Capel River, Wilyabrup Brook, Cowaramup Brook, Margaret River, Chapman Brook and Lefroy Brook (Sinclair Knight Merz, 2008). An average distribution was obtained from the seven catchments and this was assumed to be representative of potential future farm dam development across the study region. The distribution adopted is shown by volume of dams in Figure 9-2 and by number of dams in Figure 9-3. Seventy-eight percent of the dams observed in these seven catchments store less than 2 ML in volume, but due to their small size contribute only 14% to the total volume of storage in these catchments. Most of the dam storage volume (just over 50%) is taken up by dams between 10 and 100 ML in storage volume but these dams only make up around 7% of the total number of dams. There is a “tail” of a very small number of dams with volumes exceeding 150 ML in size that do not contribute greatly to the total volume of dams (less than 10%). In applying the model, CHEAT randomly samples from the size distribution until the volume of dams sampled meets the required total volume of dams to be modelled.

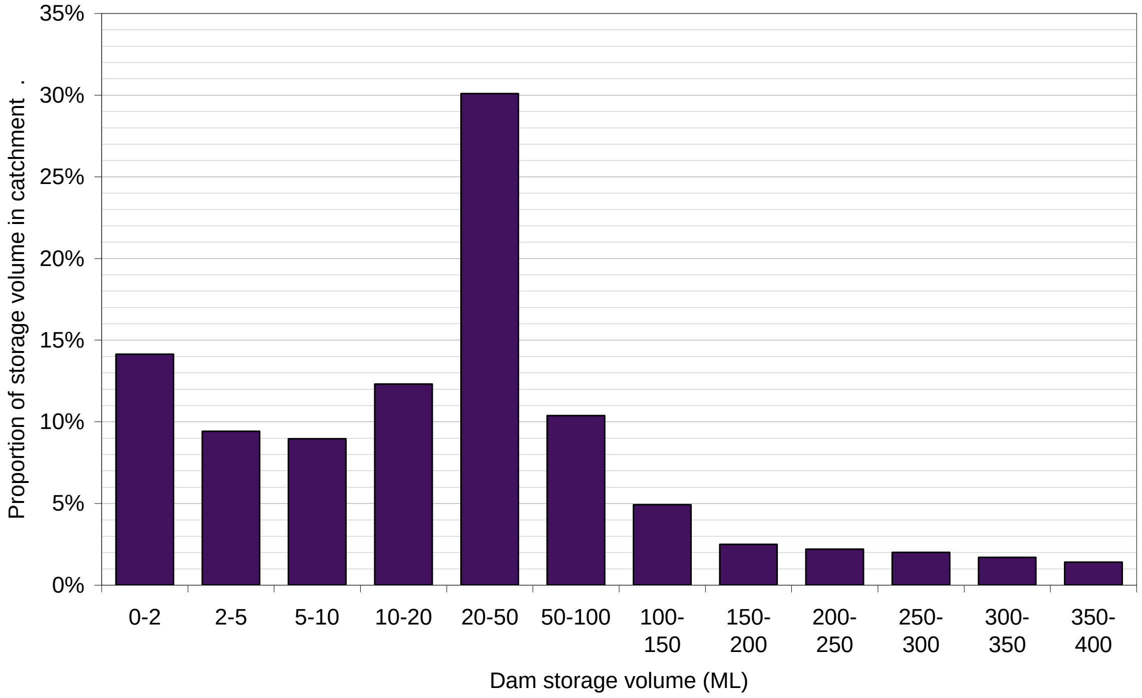
Figure 9-4 shows the relationship between dam storage volume and catchment area adopted for this study. This was the same relationship adopted for farm dam modelling for five of the seven catchments in the south-west of WA by Sinclair Knight Merz (2008).

A power-law relationship was adopted from Department of Water (2006) to estimate the relationship between the storage volume of each dam (V) and its surface area (A):

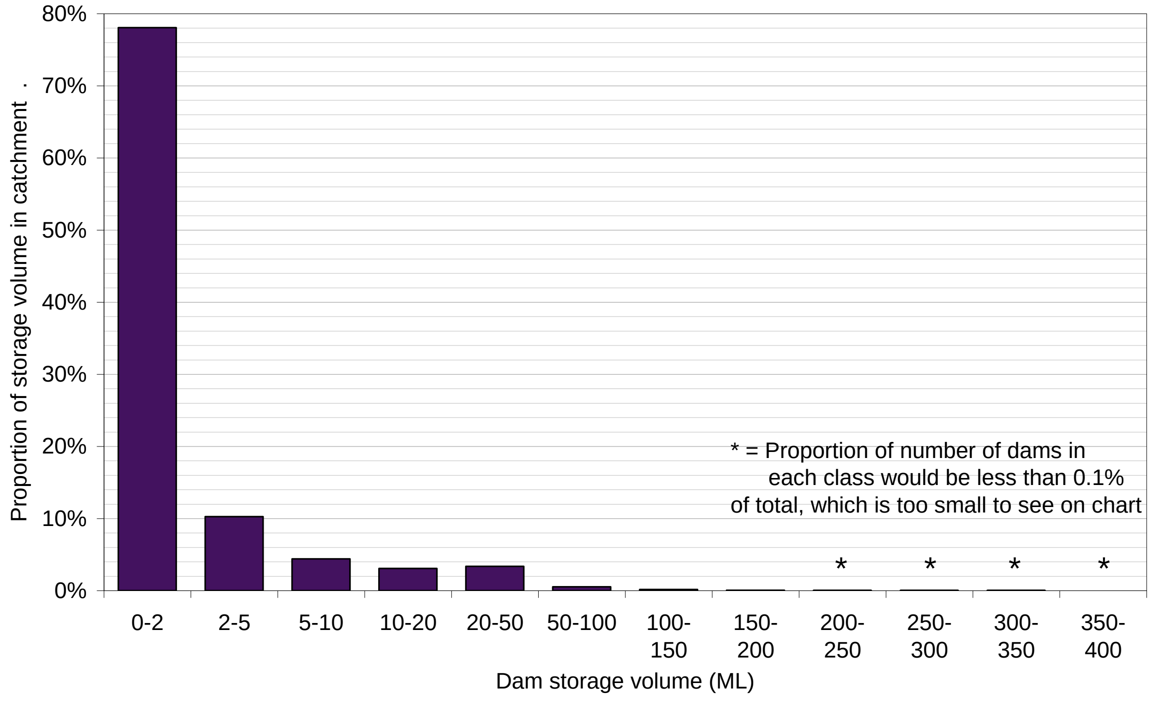
$$V = 0.0007\ A^{1.0709}$$

Table 9-1 Inputs required for the farm dams simulation model.

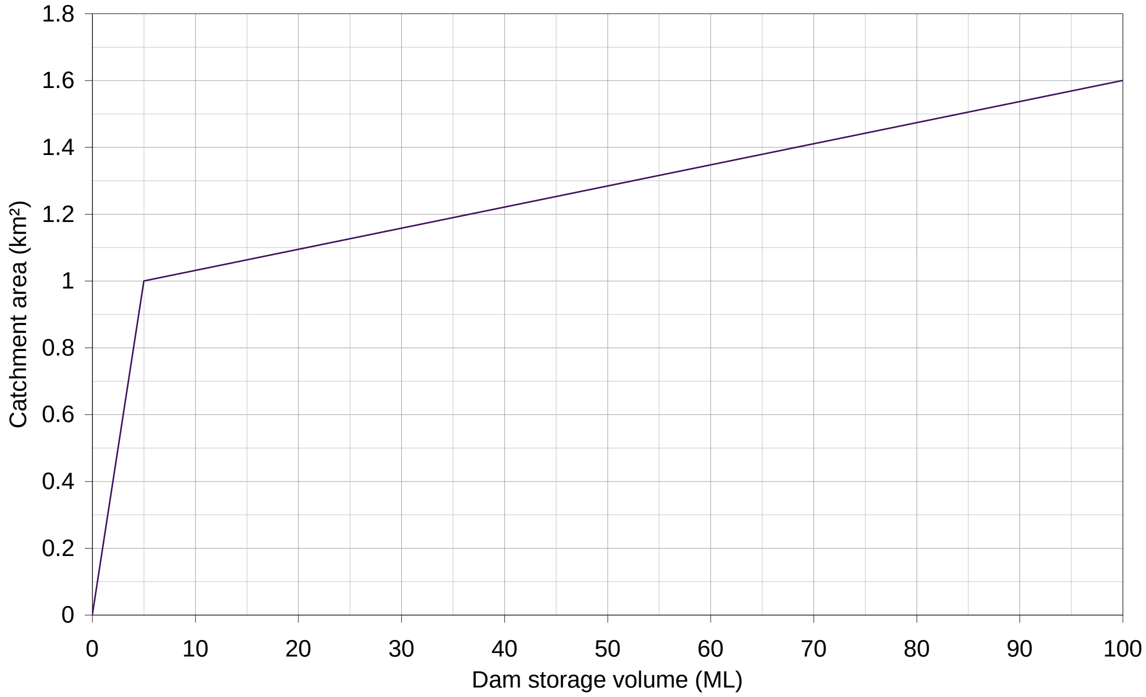
Input	Source of Information
Daily flow data	Aggregated from daily data supplied by Department of Water and prepared in section 2.2
Catchment area	Supplied by Department of Water (2006)
Total volume of existing catchment dams	For the purpose of the modelling the volume was allocated as zero.
Maximum volume of a stock and domestic dam	Assumed to be 5 ML
Monthly demand pattern for stock and domestic dams (< 5 ML volume)	Uniformly distributed throughout year
Monthly demand pattern for irrigation dams (>5 ML storage volume)	Same monthly distribution as mean monthly actual evaporation.
Annual demand volume	Assumed to be equal to dam volume
Distribution of existing catchment dam sizes	Not applicable
Distribution of additional catchment dam sizes.	Sampled from the distribution shown in Figure 9-2, which was obtained by averaging observed data on dam sizes from seven catchments in the south-west of WA
Relationship between dam surface area and dam storage volume	$V = 0.0007\ A^{1.0709}$ Department of Water (2006)
Relationship between dam storage volume and dam catchment area	Two-part linear relationship, shown in Figure 9-4
Daily rainfall	Data for the nearest rainfall site to the catchment centroid was obtained from the Bureau of Meteorology
Average monthly point potential evaporation	Bureau of Meteorology (2000)



▪ **Figure 9-2 Assumed distribution of sizes of farm dams by dam volume**



▪ **Figure 9-3 Assumed distribution of sizes of farm dams by number of dams**



- **Figure 9-4 Assumed relationship between dam storage volume and its catchment area for catchment dams in this study**

Using trial and error the volume of additional catchment dams was found such that both:

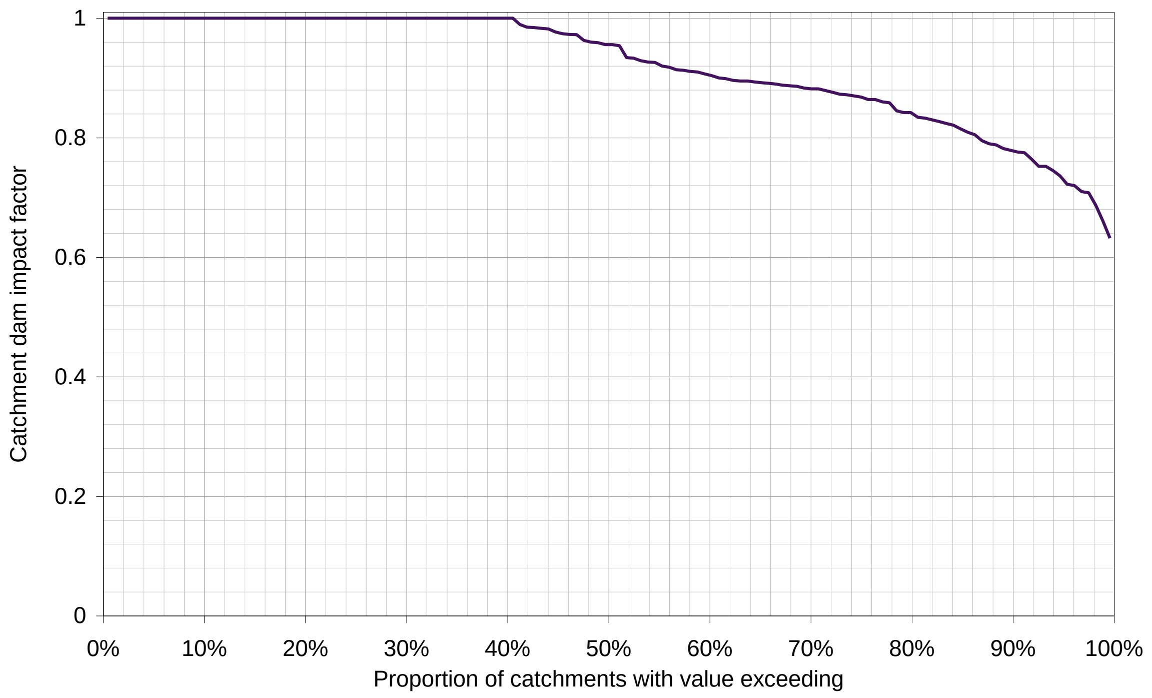
1) the volume of water harvested over the year did not exceed the SDL; and
2) the average extractions between 15 June and 15 August did not exceed the volume available for pumped diversions.

The ratio of the additional farm dams to the sustainable diversion limit was calculated for each of the 142 gauged catchments that were used to determine the SDL and was found to range between 0.63 and 1.00. A frequency exceedance plot is provided in Figure 9-5.

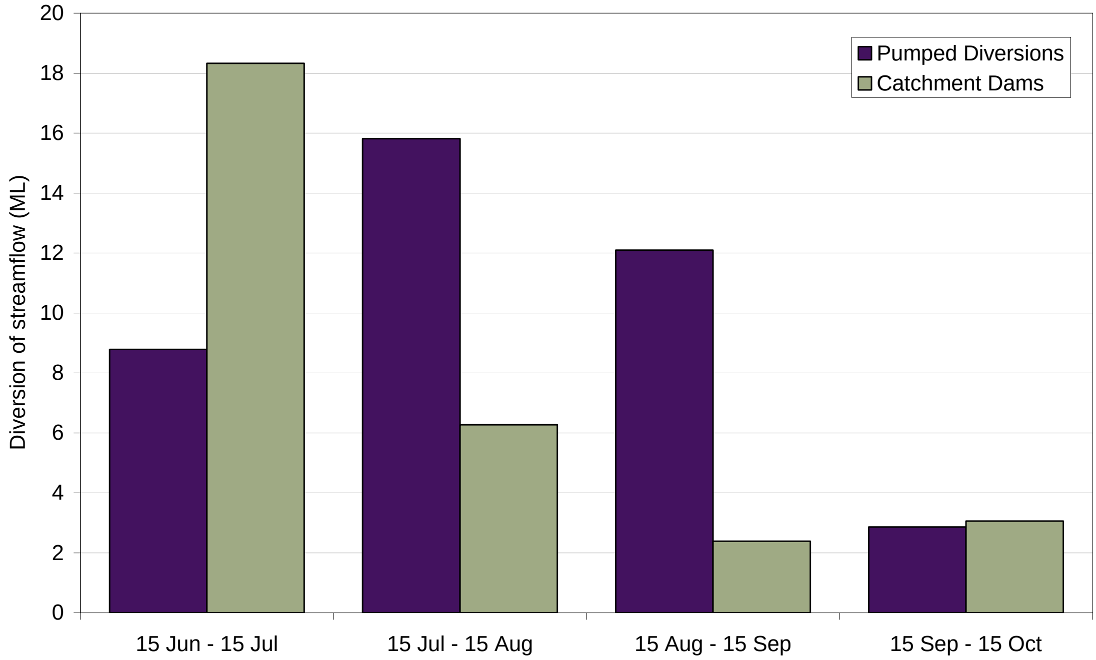
The nature of the relationship between the impact of farm dams and the SDL is illustrated by reference to two example catchments, Coolingutup Brook and the Bingham River.

In Coolingutup Brook at Pesconeri’s Farm (611221) the volume of catchment dams that could be added to the catchment was restricted by the impact that the catchment dams had between 15 June and 15 August. The SDL for this catchment is 42.5 ML but the volume of additional dams is only 36.5 ML (86% of the SDL). The majority of the SDL is extracted in the first two months of the winterfill period by farm dams with average diversions approximately 24.6 ML, while the volume extracted over the entire winterfill period (with a reliability of 80%) is only 36.5 ML. The mean monthly pattern of extractions for the winterfill period is illustrated in Figure 9-6 for both pumping and catchment dams.

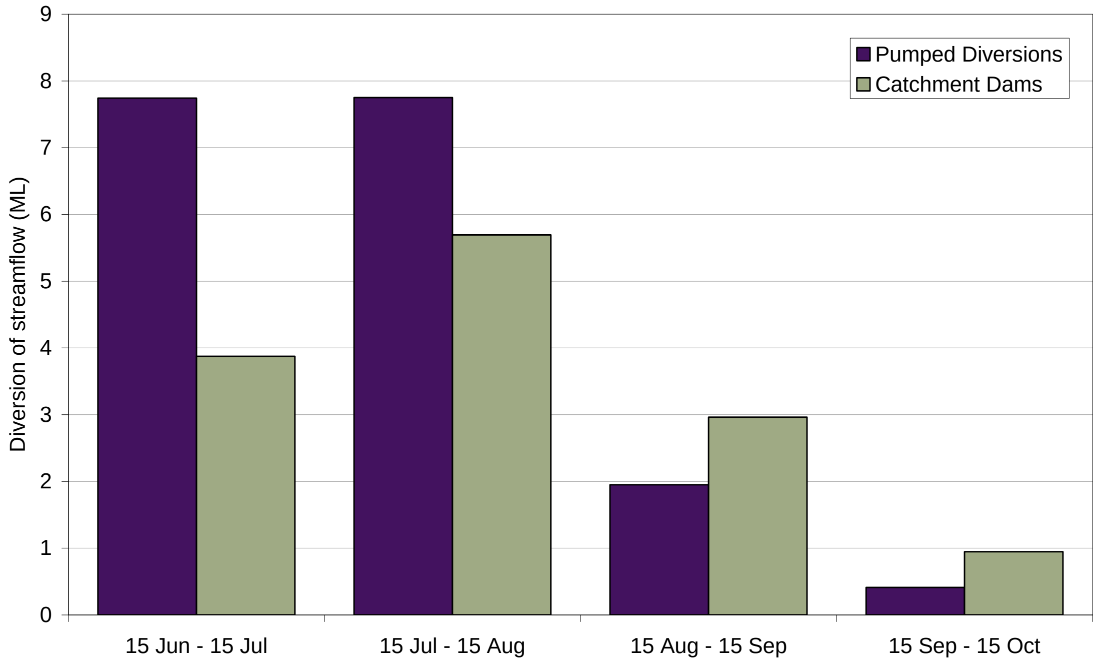
In the Bingham River at Stenwood (612021) the volume of catchment dams that could be added to the catchment was restricted by the impact that the catchment dams had over the entire year. The SDL for this catchment is 19.9 ML and the volume of additional dams that harvests this volume over the year is also 19.9 ML. The mean monthly pattern of extractions for the winterfill period is illustrated in Figure 9-7 for both pumping and catchment dams. The average impact of farm dams between 15 June and 15 August is 9.6 ML, which is less than the 15.5 ML caused by pumped diversions. Early season streamflows are sufficiently high in this catchment that farm dams would be typically near to full by 15 June (the start of the winterfill period) and extractions from farm dams are therefore more evenly spread across the winterfill period. High early season streamflows in this catchment also therefore mean that the pumped diversion SDL with 80% reliability is met in the first few months of the winterfill period and relatively few diversions are required after 15 August.



- **Figure 9-5 Frequency exceedance plot of the volume of farm dam and pumped diversion with an equivalent impact for 142 gauged catchments**



- **Figure 9-6 Comparison of reductions in flow caused by pumped diversions and catchment dams for the winterfill period on a mean monthly basis for Coolingutup Brook at Pesconeri's Farm (611221)**

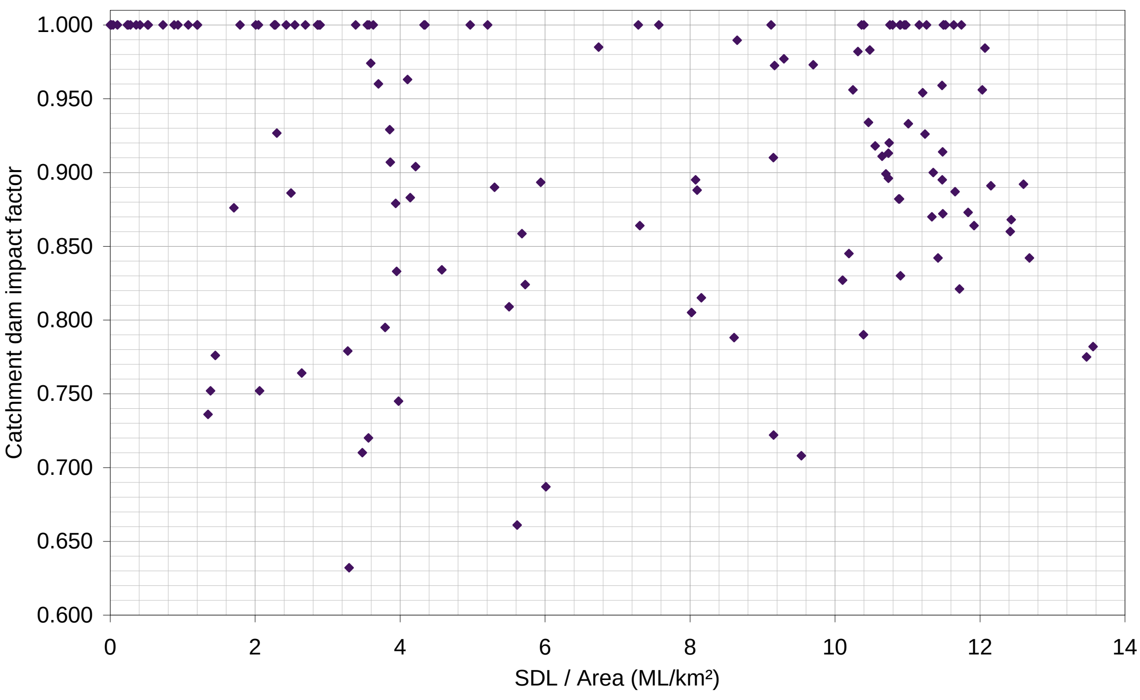


- **Figure 9-7 Comparison of reductions in flow caused by pumped diversions and catchment dams for the winterfill period on a mean monthly basis for Bingham River at Stenwood (612021)**

In reality the relationship between the proportion of diversions harvested by farm dams and that by pumped diversions is not as simple as derived in this analysis. The impact of farm dams – and hence the equivalence with pumped diversions – depends on the pattern and magnitude of demands, the size and distribution of farm dams, and other site-specific factors. In this study we have adopted the same assumptions regarding the demand factors and the distribution of farm dam sizes for all catchments considered. In reality the ratio will vary depending on the development proposals for each catchment.

9.3 Ungauged Catchments

Given the range of variation in the volume of farm dam and pumped diversion with an equivalent impact (Figure 9-5), an investigation was undertaken to determine whether a proportion of this variation could be explained by catchment characteristics. Predictive relationships were explored using multiple regression models using available catchment characteristics (section 4.2). However the results of all models trialed were poor, as shown in Table 9-2. For example, Figure 9-8 shows that there is no relationship between the catchment dam impact factor and the sustainable diversion limit. It was found that the equivalence factor could not be estimated with confidence from catchment characteristics.



- **Figure 9-8 Scatter plot of catchment dam impact factor and sustainable diversion limit per unit catchment area.**

- **Table 9-2 Correlation between catchment dam impact factor and catchment characteristics for gauged catchments**

Catchment characteristic	r^2
SDL / Area (ML/km²)	0.020
SDL Volume (ML)	0.010
Adopted catchment area (km²)	0.020
Vegetation cover in 2005 (%)	0.015
Soil Permeability index	0.038
Mean catchment elevation (m AHD)	0.021
Mean annual rainfall (1975-2005) (mm/year)	0.00003

While it is possible that further work could yield a more useful outcome, in the interim it appears reasonable to adopt a single value within the range of results obtained for the 142 gauged catchments. If a precautionary approach is taken, then it would be reasonable to adopt a ratio that is lower than that found for the majority of catchments. Ratios for different degrees of conservatism are provided in Table 9-3. For example if a ratio of 0.88 is adopted (i.e. a 0.88 ML farm dam has the same impact as 1 ML of pumped diversion) then it may be assumed that only 30% of catchments are likely to have a ratio less than this value.

In the absence of any other information and adopting a precautionary approach, it is considered reasonable to adopt a fixed ratio of 84%. Thus, 1.0 ML of pumped diversions can be assumed to have the same impact as 0.84 ML of farm dams; in other words, every one megalitre of farm dams is equivalent to 1.19 ML of SDL. In the minority of catchments (around 20%) it is likely that farm dams have a greater impact, however given the range of variation this degree of conservatism appears appropriate.

- **Table 9-3 Catchment dam impact factors for given probabilities of exceedance**

Exceedance probability	Catchment dam impact factor
50%	0.96
60%	0.90
70%	0.88
80%	0.84
90%	0.78
95%	0.73

9.4 Summary

The proposed process for determining SDL extractions were based on the assumption that all extractions were obtained by pumped diversions. However, some proportion of current diversions and presumably that of additional development will be harvested by catchment dams. Pumped diversions and those harvested by catchment dams effect the streamflow regime in separate ways.

An investigation was undertaken into the volume of farm dams that had an equivalent impact on streamflows as pumped diversions, though a suitable prediction model for use with ungauged catchments could not be derived.

It is suggested that an equivalence ratio of 84% be adopted. Thus, 0.84 ML of farm dams can be assumed to have the same impact as 1.0 ML of pumped diversions or 1.0 ML of catchment dams can be assumed to have the same impact as 1.19 ML of pumped diversions. In the minority of catchments (around 20%) it is likely that farm dams have a greater impact, however given the range of variation this degree of conservatism appears appropriate.

10. Conclusions

Estimates of the Sustainable Diversion Limit (SDL) parameters were derived for 142 gauged catchments across South West Western Australia. These flow parameters represent pre-development conditions, ie the sustainable limits on diversions given existing land-use. The criteria used to select the gauged data were reasonably comprehensive, though it is possible that some estimates are biased by the presence of farm dams and different climatic conditions. The influence of long-term climate variability was minimised by restricting the analysis to streamflow data from the period post-1975, corresponding with an acknowledged shift toward lower rainfall in the study region.

Regional equations were developed that relate SDL flow parameters to hydroclimatic and physiographic characteristics. The final predictions equations are based on characteristics that are hydrologically meaningful, and a good standard of accuracy was achieved; the proportion of variance explained (R^2) ranges between 90% and 99%, and the standard errors are around 5% to 8%.

The study area was divided into 1966 catchments, and SDL parameters were estimated for each catchment using the derived equations. The individual catchments typically range in size between 10 km^2 and 1000 km^2, and around 850 catchments include other catchments nested upstream of them. When estimating the parameters for all catchments across the study area the predicted estimates were combined with estimates based on gauged data where suitable. A minor degree of smoothing was incorporated to ensure consistency between nested and gauged estimates.

Prediction equations were also derived to provide objective measures of catchment similarity. These measures were used to help identify indicator gauges that can be used to represent low flow conditions in ungauged catchments, and also for the identification of streamflow gauges most suited to transposition to ungauged locations. The objective similarity measures and the accuracy of the relevant prediction equations are considered to provide a robust and defensible basis for transposing historic and current streamflows.

An investigation was undertaken into the volume of farm dams that had an equivalent impact on streamflows as pumped diversions, though a suitable prediction model for use with ungauged catchments could not be derived. A precautionary approach is recommended in which every one megalitre of farm dams is assumed equal to 1.19 ML of SDL

11. References

Bureau of Meteorology (BoM, 2001a): *Climatic Atlas of Australian Rainfall*.

Bureau of Meteorology (BoM, 2001b): *Climatic Atlas of Australian Evapotranspiration*.

Department of Water, Government of Western Australia (2006): *Farm Dam Capture Project – Part 1 – Wilyabrup Brook Catchment*, Development and Case Study Application.

Lang, S., Jordan, P., Durrant, J. and Nathan, R. (2008): Defining sustainable diversion limits in unregulated south-west Western Australian catchments, *Proc. Water Down Under 2008*, Adelaide, 15-17 April, pp. 145-156.

Lowe, L. and Nathan, R. (2008): Consideration of uncertainty in the estimation of farm dam impacts, *Proc. Water Down Under 2008*, Adelaide, 15-17 April.

McKenzie, N.J., D.W. Jacquier, L.J. Ashton and H.P. Cresswell (2000): *Estimation of Soil Properties Using the Atlas of Australian Soils*, CSIRO Land and Water Technical Report 11/00, Canberra.

Nathan, R.J. and McMahon, T.A. (1990): Evaluation of automated techniques for base flow and recession analyses. *Water Resources Research*, **26**(7), pp. 1465-1473.

Nathan, R.J., Jordan, P. and Morden, R. (2005): Assessing the impact of farm dams on streamflows, Part I: Development of simulation tools, *Australian J. Water Resources*, **9**(1), pp. 1-12

Northcote, K.H. (1979): *A Factual Key for the Recognition of Australian Soils, 4th Edition*, Adelaide, 124pp.

Sinclair Knight Merz (2007): *Approach for Determining Sustainable Diversion Limits for South West Western Australia*, Report for Department of Water, October 2007.

Sinclair Knight Merz (2008): *Estimation of Impact of Farm Dams on Runoff for Seven Catchments in South West Western Australia*, Report for Department of Water, In preparation.

Appendix A Selected Streamflow gauges

Site Number	Stream Name	Site Name	Catchm't Area (km^2)	Post-75 Record (years)	Start Date	End Date	SDL 80% reliability (ML)
602001	Pallinup River	Bull Crossing	3926.4	30.4	01/01/1975	10/05/2005	319
602003	Jackitup Creek	Wellards	88.0	27.0	16/05/1979	03/05/2006	9
602004	Kalgan River	Stevens Farm	2179.8	29.7	04/03/1976	24/10/2005	2231
602005	Chelgiup Creek	Anderson Farm	48.0	28.9	23/12/1976	24/10/2005	99
602014	King River	Billa Boya Reserve	155.6	13.6	02/01/1992	10/08/2005	619
602015	Mill Brook	Warren Road	177.8	12.5	07/05/1992	14/11/2004	246
602031	Waychinicup River	Cheynes Beach Road	238.3	30.4	01/01/1975	12/05/2005	278
602199	Goodga River	Black Cat	49.2	30.4	01/01/1975	08/05/2005	175
603001	Marbellup Brook	Elleker	121.9	31.8	01/01/1975	05/10/2006	671
603002	Denmark River	Lindesay Gorge	443.8	12.3	01/01/1975	14/04/1987	1594
603003	Denmark River	Kompup	241.9	30.9	01/01/1975	07/11/2005	992
603004	Hay River	Sunny Glen	1210.6	21.8	02/01/1984	17/10/2005	5393
603005	Mitchell River	Beigpiegup	51.4	19.8	02/01/1986	17/10/2005	294
603007	Sleeman River	Sleeman Road Bridge	75.7	20.5	13/04/1985	17/10/2005	612
603012	Torbay Main Drain	Meenwood Road	53.7	9.8	13/06/1989	24/03/1999	951
603136	Denmark River	Mt Lindesay	502.4	30.9	01/01/1975	15/11/2005	2663
603190	Yate Flat Creek	Woonanup	56.3	30.9	01/01/1975	07/11/2005	411
604001	Kent River	Rocky Glen	1069.9	26.6	22/03/1979	01/11/2005	2560
604053	Kent River	Styx Junction	1806.0	30.9	01/01/1975	15/11/2005	7746
605012	Frankland River	Mount Frankland	4508.9	29.1	01/01/1975	14/01/2004	17384
606001	Deep River	Teds Pool	467.8	29.5	16/05/1975	25/10/2004	4355
606002	Weld River	Wattle Block	24.2	23.6	10/07/1982	15/02/2006	265
606185	Shannon River	Dog Pool	407.6	24.4	01/01/1975	11/05/1999	6568
606195	Weld River	Ordnance Road Crossing	250.2	28.9	01/01/1975	03/12/2003	4216
606218	Gardner River	Baldania Creek Conflu	392.4	24.4	01/01/1975	10/05/1999	8417
607002	Lefroy Brook	Channybearup	92.1	24.2	01/01/1975	25/03/1999	1488
607003	Warren River	Wheatley Farm	2821.1	31.3	01/01/1975	11/04/2006	10393
607004	Perup River	Quabicup Hill	666.7	31.5	01/01/1975	26/06/2006	1194
607007	Tone River	Bullilup	983.1	28.1	22/04/1978	17/05/2006	2817
607013	Lefroy Brook	Rainbow Trail	249.4	27.1	18/04/1979	10/05/2006	4197
607014	Four Mile Brook	Netic Road	13.1	19.7	18/05/1979	10/02/1999	249
607017	Smith Brook	Middlesex	29.4	9.9	28/05/1988	15/04/1998	608
607144	Wilgarup River	Quintarrup	460.5	31.3	01/01/1975	11/04/2006	3717
607155	Dombakup Brook	Malimup Track	118.5	25.2	01/01/1975	28/02/2000	2570
607220	Warren River	Barker Rd Crossing	3933.7	31.2	01/01/1975	20/03/2006	32411
608001	Barlee Brook	Upper Iffley	159.1	25.2	01/01/1975	14/03/2000	2219
608002	Carey Brook	Staircase Road	30.3	31.0	23/04/1975	29/03/2006	509
608007	Record Brook	Boundary Road	24.8	12.8	09/05/1987	14/02/2000	381
608151	Donnelly River	Strickland	782.1	31.3	01/01/1975	27/03/2006	12187
608171	Fly Brook	Boat Landing Road	62.9	24.2	01/01/1975	25/03/1999	1455

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Site Number	Stream Name	Site Name	Catchm't Area (km^2)	Post-75 Record (years)	Start Date	End Date	SDL 80% reliability (ML)
609002	Scott River	Brennans Ford	627.7	31.4	01/01/1975	14/05/2006	15167
609003	St Paul Brook	Cambray	161.6	25.2	01/01/1975	07/03/2000	1567
609005	Balgarup River	Mandelup Pool	82.4	31.1	11/04/1975	03/05/2006	206
609006	Weenup Creek	Balgarup	13.3	25.2	10/04/1975	30/05/2000	19
609010	Northern Arthur River	Lake Toolibin Inflow	438.5	27.8	10/08/1978	22/05/2006	0
609012	Blackwood River	Winnejup	8729.5	25.6	24/09/1980	10/04/2006	35826
609014	Arthur River	Mount Brown	2117.6	23.0	17/02/1983	08/02/2006	2267
609015	Beaufort River	Manywaters	1565.2	22.8	14/04/1983	08/02/2006	3355
609016	Hester Brook	Hester Hill	176.6	22.4	29/03/1983	01/08/2005	2156
609017	Balingup Brook	Brooklands	548.9	23.1	13/04/1983	08/05/2006	3711
609018	St John Brook	Barrabup Pool	552.3	23.1	07/04/1983	26/04/2006	6807
609019	Blackwood River	Hut Pool	12372.2	22.9	30/03/1983	02/03/2006	105082
609021	Coblinine River	Bibikin Road Bridge	3915.2	9.9	12/06/1996	22/05/2006	96
609022	Chapman Brook	White Elephant Bridge	180.0	11.0	27/05/1995	30/05/2006	4897
609023	Chapman Brook	Forest Grove	45.2	11.1	12/05/1995	30/05/2006	1777
609025	Blackwood River	Darradup	11593.0	24.5	01/01/1975	04/07/1999	45864
610001	Margaret River	Willmots Farm	443.0	31.4	01/01/1975	02/05/2006	8957
610003	Vasse River	Chapman Hill	47.7	31.4	01/01/1975	02/05/2006	850
610005	Ludlow River	Happy Valley	109.2	24.2	01/01/1975	11/03/1999	473
610006	Wilyabrup Brook	Woodlands	82.3	31.4	01/01/1975	02/05/2006	2388
610008	Margaret River North	Whicher Range	15.5	22.6	06/05/1977	29/11/1999	279
610009	Ludlow River	Ludlow	207.8	15.4	30/05/1991	23/10/2006	1514
610010	Capel River	Capel Railway Bridge	394.7	13.0	18/05/1993	30/04/2006	5639
610014	Vasse Diversion Drain	Downstream Hill Road	265.4	11.1	14/04/1995	02/05/2006	3199
610015	Carbunup	Lennox Vineyard	159.4	11.0	21/04/1995	02/05/2006	4270
610219	Capel River	Yates Bridge	315.1	10.0	17/05/1996	30/04/2006	4895
611004	Preston River	Boyanup Bridge	808.4	26.1	01/05/1980	18/05/2006	11994
611007	Ferguson River	Southwest Hwy Ferguson	144.9	15.1	12/04/1991	30/04/2006	2576
611111	Thomson Brook	Woodperry Homestead	102.1	31.6	01/01/1975	15/08/2006	1249
611221	Coolingutup Brook	Pesconeris Farm	3.9	31.4	01/01/1975	18/05/2006	42
612001	Collie River East	Coolangatta Farm	1345.3	31.4	01/01/1975	03/05/2006	3268
612002	Collie River	Mungalup Tower	2546.2	31.4	01/01/1975	03/05/2006	11051
612004	Hamilton River	Worsley	32.3	31.1	01/01/1975	13/02/2006	695
612005	Stones Brook	Mast View	12.9	24.2	01/01/1975	14/03/1999	259
612012	Falcon Brook	Falcon Road	5.5	22.0	01/01/1975	09/12/1996	73
612014	Bingham River	Palmer	366.1	30.9	28/03/1975	13/02/2006	395
612016	Batalling Creek	Maxon Farm	16.8	30.4	21/01/1976	11/06/2006	44
612019	Bussell Brook	Duces Farm	37.5	22.0	09/03/1977	10/03/1999	441
612021	Bingham River	Stenwood	48.4	20.7	06/07/1978	23/03/1999	20
612022	Brunswick River	Sandalwood	116.2	26.0	25/04/1980	01/05/2006	2902

Site Number	Stream Name	Site Name	Catchm't Area (km^2)	Post-75 Record (years)	Start Date	End Date	SDL 80% reliability (ML)
612023	Lunenburgh River	Silver Springs	56.3	18.9	08/05/1980	16/03/1999	1177
612025	Camballan Creek	James Well	170.0	24.0	12/06/1982	06/06/2006	607
612026	Mairdebing Creek	Maringee	12.9	16.9	20/05/1982	24/03/1999	42
612032	Brunswick River	Cross Farm	509.4	15.9	01/06/1990	01/05/2006	12416
612034	Collie River	South Branch	661.6	31.1	01/01/1975	13/02/2006	1782
612039	Wellesley River	Juegenup Wellesley	209.0	15.9	01/06/1990	01/05/2006	6560
612230	Collie River East Trib	James Crossing	170.6	31.4	01/01/1975	06/06/2006	706
613002	Harvey River	Dingo Road	147.2	31.6	01/01/1975	23/07/2006	3520
613007	Bancell Brook	Waterous	13.6	31.6	01/01/1975	23/07/2006	338
613018	Mcknoes Brook	Urquharts	24.4	22.0	29/12/1979	07/01/2002	486
613031	Mayfield Drain	Old Bunbury Road	112.4	11.0	07/03/1991	04/03/2002	1546
613052	Harvey River	Clifton Park	573.0	23.1	31/03/1983	15/05/2006	13252
613146	Clarke Brook	Hillview Farm	17.1	31.3	01/01/1975	25/04/2006	240
614003	Marrinup Brook	Brookdale Siding	45.6	31.3	01/01/1975	26/04/2006	991
614005	Dirk Brook	Kentish Farm	35.1	26.4	01/01/1975	27/05/2001	731
614006	Murray River	Baden Powell Wtr Spout	6757.6	31.3	01/01/1975	23/04/2006	26106
614013	Peel Drain	Hope Valley	10.4	24.9	16/06/1976	21/05/2001	241
614028	Dirk Brook	Hopelands Road	63.9	22.2	05/04/1979	29/05/2001	961
614030	Serpentine Drain	Dog Hill	469.7	27.2	22/02/1979	11/04/2006	5183
614031	39 Mile Brook	Jack Rocks	55.4	18.1	15/04/1981	06/05/1999	594
614035	Serpentine River	River Road	242.9	17.1	08/05/1982	24/05/1999	703
614036	North Dandalup River	North Road	79.7	16.3	04/03/1983	15/06/1999	869
614037	Big Brook	O'neil Road	149.4	23.5	09/04/1983	08/10/2006	506
614044	Yarragil Brook	Yarragil Formation	73.5	31.3	01/01/1975	23/04/2006	169
614047	Davis Brook	Murray Valley Plntn	65.7	27.0	01/01/1975	08/01/2002	497
614059	South Dandalup Trib	Skeleton Road	18.7	9.6	01/06/1988	21/01/1998	256
614065	Murray River	Pinjarra	7049.8	13.0	15/04/1993	25/04/2006	26719
614073	Gooralong Brook	Mundlimup	51.5	24.4	01/01/1975	06/05/1999	956
614093	Big Brook	Jayrup	45.5	10.8	11/05/1995	16/02/2006	55
614105	Hotham River	Pumphrey's Bridge	1036.4	9.9	08/06/1996	01/05/2006	676
614123	Chalk Brook	Quindanning Road	57.1	11.4	01/01/1975	16/05/1986	544
614196	Williams River	Saddleback Road Bridge	1408.3	31.4	01/01/1975	10/05/2006	5561
614224	Hotham River	Marradong Road Bridge	3967.1	31.1	09/04/1975	01/05/2006	9042
616001	Wooroloo Brook	Karls Ranch	514.7	31.5	01/01/1975	18/06/2006	4196
616002	Darkin River	Pine Plantation	665.3	31.1	01/01/1975	16/01/2006	166
616005	Wooroloo Brook	Noble Falls	291.8	19.0	29/05/1980	10/06/1999	1753
616006	Brockman River	Tanamerah	961.2	25.8	06/06/1980	22/03/2006	2449
616007	Rushy Creek	Byfield Road	39.2	24.3	01/01/1975	07/04/1999	112
616009	Pickering Brook	Slavery Lane	29.4	24.4	01/01/1975	03/06/1999	175
616010	Little Darkin River	Hairpin Bend Rd	37.8	24.4	01/01/1975	03/06/1999	76

SKM

Site Number	Stream Name	Site Name	Catchm't Area (km^2)	Post-75 Record (years)	Start Date	End Date	SDL 80% reliability (ML)
616011	Swan River	Walyunga	18633.2	31.6	01/01/1975	13/07/2006	33320
616012	Helena Brook	Trewd Road Gs	26.7	31.1	01/01/1975	16/01/2006	76
616013	Helena River	Ngangaguringuring	327.0	30.8	01/01/1975	17/10/2005	78
616014	Piesse Brook	Furfaros Orchard	55.2	24.4	01/01/1975	03/06/1999	639
616019	Brockman River	Yalliawirra	1521.9	30.9	09/04/1975	14/02/2006	5522
616021	Seldom Seen Creek	Travellers Arms	7.2	31.8	01/01/1975	08/10/2006	152
616023	Waterfall Gully	Mount Curtis	8.6	31.8	01/01/1975	08/10/2006	149
616026	31 Mile Brook	31 Mile Road	11.0	14.0	08/06/1985	18/05/1999	210
616027	Canning River	Seaforth	876.6	31.3	01/01/1975	19/04/2006	1073
616039	Canning River	Millars Road	146.6	13.9	21/06/1985	25/05/1999	129
616040	Susannah Brook	Gilmours Farm	23.1	20.1	23/05/1981	19/06/2001	406
616041	Wungong Brook	Vardi Road	80.8	25.4	02/05/1981	27/09/2006	1061
616065	Canning River	Glen Eagle	520.6	24.4	01/01/1975	18/05/1999	1503
616092	Southern River	Anaconda Drive	152.0	9.1	28/03/1997	19/04/2006	1037
616178	Jane Brook	National Park	73.4	31.3	01/01/1975	20/04/2006	973
616189	Ellen Brook	Railway Parade	581.5	31.3	01/01/1975	05/04/2006	2290
616216	Helena River	Poison Lease Gs	590.9	31.1	01/01/1975	16/01/2006	311
617001	Moore River	Quinns Ford	9828.8	27.1	07/09/1978	28/09/2005	3361
617002	Hill River	Hill River Springs	925.9	30.2	01/01/1975	16/03/2005	14
617003	Gingin Brook	Bookine Bookine	1370.7	30.9	01/01/1975	28/11/2005	2341
617058	Gingin Brook	Gingin	105.8	31.2	01/01/1975	20/03/2006	349
617165	Lennard Brook	Molecap Hill	59.1	26.9	01/01/1975	04/11/2001	331

Appendix B Statistical Methods Adopted

B.1 Introduction

The development of regional prediction equations and the application of the SDL parameters to ungauged catchments involved the use of several multivariate statistical procedures. These techniques were multiple linear regression, cluster analysis and principal component analysis.

The objective of this chapter is to provide a brief overview of the statistical methods used throughout the report. Detailed descriptions of these methods are available in most statistics textbooks.

B.2 Multiple Linear Regression

B.2.1 Introduction

Multiple linear regression is a statistical technique that allows one dependent variable to be predicted from a number of independent variables. In this report the dependant variables are the SDL parameters and the physiographic characteristics are the independent variables. Although the variables chosen are known to influence the streamflow regime within a catchment, the equations are based on a statistical model not a conceptual model of the catchment. Multiple linear regression is useful for predictions when the complexity and exact nature of a system is not known.

The equation is in the form:

$$Y = a_0 + a_1X_1 + a_2X_2 + \ldots + a_nX_n$$

The dependant variable is denoted by Y, a is a coefficient, X is an independent variable and n refers to the number of independent variables. In order to determine the coefficients (a) a data set is required for which all of the dependent and independent variables are known. A set of 142 catchments was available from the study area with calculated SDL parameters and physiographic catchment characteristics. The coefficients are determined using a method of least squares, that is, the coefficients are selected so that the sum of the squared residuals are minimised. A residual is the difference between an observation and its predicted value.

B.2.2 Goodness measures

Two measures are commonly used to assess the accuracy, or goodness, of the regression. These are the coefficient of determination (R^2) and the standard error (see). The R^2 measures the proportion of the total variation that is explained by the model. A large R^2 is associated with a good model or prediction equation. The standard error is an estimate of the standard deviation of the residuals, that is, it measures the degree of scatter of the observed data points around the regression line. Hence a small standard error is associated with a good model. The standard error has been expressed as a percentage of the mean of the observed transformed dependent variable in this report.

B.2.3 Assumptions of the Model

The assumptions made in fitting a multiple linear regression are that the residuals are random and therefore:

- have a mean of zero;
- are normally distributed;
- exhibit a constant variance; and,
- are not correlated.

These assumptions need to be considered during the selection of variables, exclusion of data points and the transformation of variables. The assumptions also need to be checked before a prediction equation is adopted. Tools used to assess the assumptions are plots of the residuals versus each variable and a plot of the observed values verses the predicted values.

B.2.4 Variable Selection

Up to 41 catchment characteristics were considered in the development of prediction equations. Stepwise multiple regression was used to select appropriate variables. The process was interactive, allowing variables to be added or removed from the model one at a time. Foremost the variables were selected based on their relationship with the important hydrological processes.

Spurious correlation, the increase of the R^2 term caused by the inclusion of a common variable in both the independent and dependent variables, was avoided. For example when the prediction equation was developed for the minimum flow threshold in megalitres per kilometre the catchment area could not be included as an independent variable.

The addition of a variable to the model was based on the F statistic. This is a measure of the amount of remaining variation (ie the variation not explained by variables already in the model) explained by the variable. Variables with an F-statistic less than 4 were not included in the model.

Multi-collinearly, the correlation of independent variables, was avoided. Initially a correlation matrix was used to identify which variables showed high levels of correlation. During the stepwise selection of variables the statistical measure of tolerance was used. Tolerance indicates the level of correlation that a variable has with other independent variables included in the model. Variables were not added to the model if they exhibited a low tolerance.

B.2.5 Transformations

Transformations of variables were used to improve the goodness of the model (section B.2.2) and help the model satisfy the assumptions of multiple linear regression (section B.2.3). A hydrological explanation was not always available for the transformations applied, rather they were based on statistical measures.

After the initial variable selection a transformation of the dependent variable was considered. The requirement for a transformation was assessed using a plot of the estimate against the residuals. Transformations were applied when this plot identified a non-constant variance in the residuals. In the majority of prediction equations the natural log of the dependant variable was used. Once the dependent variable had been transformed the variable selection was repeated.

The need for a transformation of dependent variables was identified in plots of the residuals and each variable. Transformations were applied when a plot identified a non-constant variance in the residuals. The transformations commonly trialed were raising the variable to a range of power values and the natural log transformation. The natural log transforms were found to be most effective.

B.2.6 Outliers

Outliers are defined as stations that have a residual larger than is expected by chance. The removal of these stations from the analysis needs to be considered as they can have a large effect on the model estimation.

During the development of each prediction equation outliers were identified using the standardised residual. The standardised residual is defined as the estimate divided by the standard error of the estimate. If the standardised residual was greater than two, the catchment was removed from the model. If the goodness of the model improved greatly the new model, without the outliers, was adopted.

B.3 Cluster Analysis

Cluster analysis is statistical method that identifies groups within a sample that are similar. In this study cluster analysis has been used to identify groups of catchments that have similar combinations of catchment characteristics that are known to influence the SDL. These variables were identified using multiple linear regression.

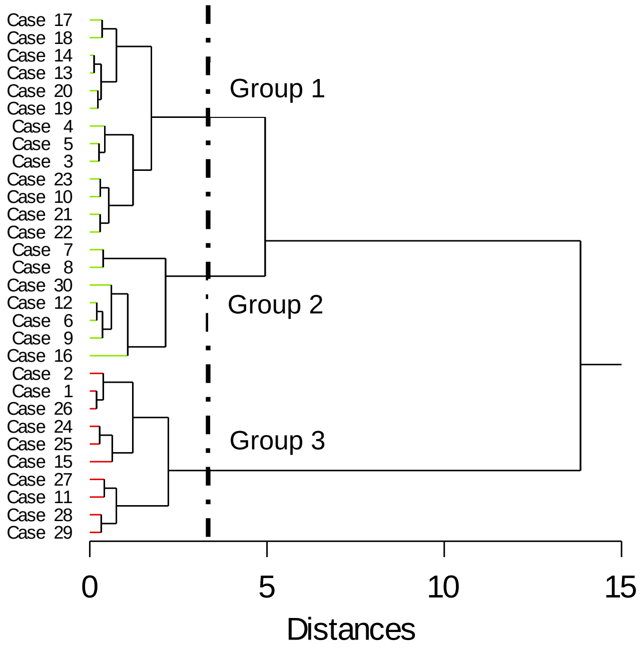
Before cluster analysis can be applied the data needed to be standardised in order to avoid scaling problems associated with arbitrary units of measurements. For example the results of a cluster analysis would differ if the units of rainfall were in metres rather than millimetres. The data was standardised so that each variable has a mean of zero and a standard deviation of one. Thus, the standardised variables (*VarStd*) are computed from the original variable (*VarOrig*) by:

$$VarStd = (VarOrig - average(VarOrig))/stdev(VarOrig).$$

Where *average(VarOrig)* denotes the arithmetic mean of the sample and *stdev(VarOrig)* denotes the standard deviation of the sample.

Hierarchical cluster was applied. There are a large variety of different clustering algorithms and distance measures available, and in many cases application of different combinations of methods and measures will yield different regional groupings. It is suggested that Ward's method in combination with Euclidean distance measure is most suited to hydrological problems, and thus this combination has been used.

The output obtained from cluster analysis is a set of groups containing catchments with a similar combination of characteristics. The groupings are shown in a classification tree (see Figure below), in which every horizontal branch is lined up such that the most similar catchments are closest to each other.



- **Example of the classification tree produced as an output of cluster analysis. This example shows that the cases could be reasonably split into three groups where the lines cross the vertical dashed lines and are labelled group 1, 2 and 3.**

B.4 Principal Component Analysis

Principal Component Analysis (PCA) is a tool used in this study to determine how similar one catchment is to another with respect to a set of defined characteristics. PCA reduces a set of correlated variables (that describe the behaviour of the catchment) to a smaller number of completely uncorrelated factors.

The number of components or uncorrelated factors generated using PCA varies. In all of the PCA undertaken as part of this study the number of factors was limited to two and are refereed to as the

1st principal component (or PC1) and the 2nd principal component (or PC2). This allows the similarity two catchments to be defined as the difference between their principal components.

For example, principal component analysis can be used to measure the similarity of catchments. Initially six correlated variables are used to describe these catchments. These variables may represent hydrological indices, climatic variables or physiographic characteristics. Using PCA two factors can be derived that describe the similarity of the catchments previously defined by six correlated variables.

In all PCAs of this study standardised data was used in order to avoid scaling problems associated with arbitrary units of measurements. These are calculated as per for cluster analysis (section B.3).

The standard outputs of PCA are:

- Latent roots (or eigenvalues);
- Component loadings;
- Variance explained by components; and,
- Coefficients of components.

The output provided for our example of the PCA of the six variables that describe a catchment is provided below:

Latent Roots (Eigenvalues)

1	2	3	4	5	6
2.3644	1.0891	0.9334	0.4622	0.3220	0.1089

Component loadings

	1	2
Variable 1	0.3081	0.7893
Variable 2	0.5371	-0.1768
Variable 3	0.3509	0.8325
Variable 4	-0.5931	0.6661
Variable 5	0.8633	-0.1177
Variable 6	0.8722	0.0646

Variance Explained by Components

1	2
2.3644	1.8091

Percent of Total Variance Explained

1	2
39.4065	30.1524

The first information provided is the Latent roots (or eigenvalues) of the generated factors. It is sufficient to understand that these reflect the variance explained by the different factors; an eigenvalue of less than unity represents less information that than contained by any single variable and is thus of no use. Eigenvalues greater than unity contain more information than a single variable and thus represent a reduction in the data. From the above, it is seen that the first two factors (shaded) have eigenvalues greater than unity.

The component loadings on the factors indicate the relative influence of each variable. Thus, for example, it is seen that the highest loadings on the first component are due to Variable 5 and Variable 6, and that those on the second are due to Variable 1 and Variable 3. While the extracted factors represent the fewest number of factors that explain the greatest amount of variance, they do not necessarily reflect the optimum combination of the smallest number of variables on each factor. It is possible to rotate the components, and while this does not noticeably alter the proportion of variance explained, it does sometimes allow easier physical interpretation of the results. There are a number of options for rotation, but experience has indicated that varimax rotation suits this type of data set. After rotation, the results are as follows:

Rotated Loading Matrix (VARIMAX)

	1	2
Variable 1	0.0529	0.8458
Variable 2	0.5658	-0.0042
Variable 3	0.0797	0.9000
Variable 4	-0.7682	0.4533
Variable 5	0.8581	0.1517
Variable 6	0.8108	0.3278

Variance Explained by Components

1	2
2.3644	1.8091

Percent of Total Variance Explained

1	2
39.4065	30.1524

It is seen that after rotation the highest loadings on the first component are now Variable 4, Variable 5 and Variable 6, and those on the second are due to Variable 1 and Variable 3.

The total variance explained by the variables can be represented as a percentage of the total variance for each variable. In our example the 1st principal component explained 40% of the variance and the 2nd principal component explained 30% of the variance, and the two principal components contain 70% of the information contained by the six correlated variables used to create them.

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The coefficients are used to calculate the factors. These coefficients should be applied to the data that has been standardised. Those for the example data set are provided below.

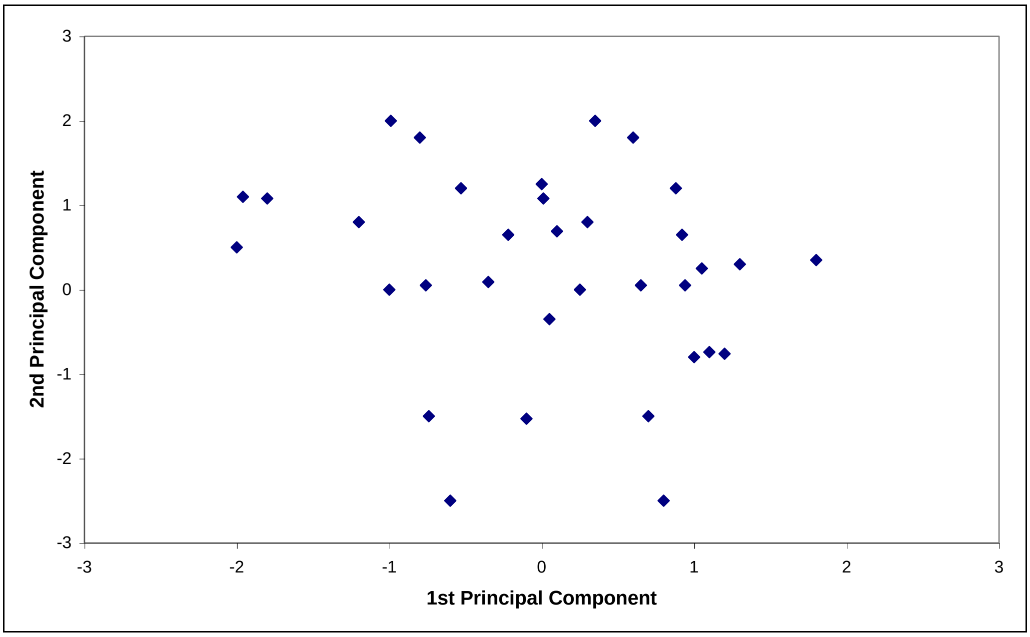
- **Table 11-1 Coefficients used to calculate principal components factors for the example PCA.**

Variable	1	2	3	4	5	6
1^{st} Principal Component	0.1307	0.2272	0.1485	-0.2506	0.3650	0.3688
2^{nd} Principal Component	0.4361	-0.0979	0.4601	0.3684	-0.0652	0.0354

Thus, for example, the first component is calculated as follows:

$$1^{st}\ \textit{Principal Component} = 0.1307x\textit{Variable\_1} + 0.2272x\textit{Variable\_2} + 0.1485x\textit{Variable\_3} - 0.2506x\textit{Variable\_4} + 0.3650x\textit{Variable\_5} + 0.3677x\textit{Variable\_6}$$

A plot of the two principal components can be created. The scatter plot for our example is provided in the figure shown below. The plot provides the basis for assessing similarity, the closer the points are the more similar the catchments, and the more distant the more dissimilar. In fact, when only considering two dimensions, the above scatter plot can be used to calculate the distance between points.



▪ **Example principal component scatter plot.**

B.5 Summary

A number of statistical techniques were used in this study. These included multiple linear regression, cluster analysis and principal component analysis. The brief description of these methods contained in this appendix is referred to throughout the report.

Appendix C Quality checking of SDL values

A quality assurance review of the draft SDL values layer for release to the client was made Philip Jordan on Tuesday 5 February 2008.

The review was undertaken by examining:

- An ArcReader project containing the draft SDL values for each of the 1900 or so SDL subcatchments. The ArcReader application contained the SDL catchments colour coded by ML/km² and colour coded by the ratio of SDL to annual rainfall.
- Spreadsheet for calculation of SDL inputs (D01_kf_SDLcalcs.xls).

The check involved panning around the ArcReader map, checking the SDL values (in ML and ML/km²) for each of the SDL catchments (all 1900), comparing them with SDL values for surrounding catchments. Particular attention was paid to where there were appreciable changes in SDL between catchments that were immediately upstream or downstream of one another or on adjacent tributaries.

In most cases, any apparently large changes in SDL could be attributed directly to significant changes in catchment characteristics between adjacent catchments or by the differences in the method used to calculate the SDL – switching between an SDL calculated using the regression equation and an SDL calculated using gauged streamflow data.

However, there were a few instances where specific anomalies were revealed that required more detailed investigation and possible adjustment. These anomalous SDL values and the conclusions that were made as to how they should be rectified are listed and discussed in the table below.

UFI numbers of SDL catchments	Nature of anomaly	Action taken to rectify anomaly
1319, 1228	SC 1319 (calculated using method 2b) has a much lower SDL/km² than SC 1228, which is immediately upstream (calculated using method 2a)	Manually redistribute total SDL of SC 1319 and 1228 according to ratio of respective method 2a estimates.
1606, 1557	SC 1606 (calculated by method 6) has much lower SDL/area than SC1557 (upstream) and SC 1607 (downstream)	No change required. Checked manually redistribution of total SDL of SC 1606 and 1557 according to ratio of respective method 2a estimates. However, on checking this made no difference.
1713, 1722, 17311	SC 1713 (method 2b) has apparently high SDL/area compared with downstream UFIs. Taking all of upstream SDL from method 2b after balancing with a streamflow gauge.	No change required. Already using Method 2a on all three SC. Much lower veg cover (46% versus 87%) for SC 1713 results in higher SDL estimate.
1531, 1541, 1543	Method 2b calculations of SDL values for three SC in series down the main stem of the Warren River. SDL/area anomalously decreases rapidly moving downstream.	Manually redistribute total SDL of SC 1531, 1541 and 1543 according to ratio of respective method 2a estimates.
1105, 1055	SC 1105 (method 2b) has much higher SDL/area value than immediately upstream SC 1055 (on same trib) and also much higher than SDL/area values for nearby SC on the mainstream that it joins.	Manually redistribute total SDL of SC 1105 and 1055 according to ratio of respective method 2a estimates.
1365, 13331	SC 1365 and SC 13331 (both method 2a) surrounded by SC with much higher SDL/area values.	Kier identified this as an issue caused by the fact that the surrounding subcatchments had been scaled up by a factor of 3 to reflect measured SDL at a downstream gauge, while the SC 1365 SDL value had been calculated using a regression and "cut off" by a small dam at its downstream boundary. Resolved to scale up SDL for SC 1365 by the appropriate scale factor.
1404, 1429, 1450, 14501	Large changes in SDL/area between adjacent SC surrounding a junction between streams and downstream of upstream gauges.	No change required. Already using Method 2a on all four SC. Much lower veg cover (23% versus between 85% and 99%) for SC 1450 results in higher SDL estimate.
1284, 1219	SC 1284 has much lower SDL/area than downstream SC 1219	No change required. SC 1284 has much higher veg cover (85%) than SC 1219 (22%).
10711, 1100,	SC 10711 has much lower SDL/area than surrounding SC	No change required. SC 10711 has much higher veg

UFI numbers of SDL catchments	Nature of anomaly	Action taken to rectify anomaly
1081	1100 and 1081	cover (91%) than SC 1081 and 1100 (42-54%).
1030, 10423	SC 10423 has much higher SDL/area than immediately US SC 1030 around the junction of streams.	Manually redistribute total SDL of SC 10423 and 1030 according to ratio of respective method 2a estimates.
1851	SC 1851 has much higher SDL/area than surrounding SC 1852, 1853, 755, 769, 782 and 793.	No change required. SC 1851 has slightly lower veg cover than most of surrounding catchments and most of the surrouding subcatchments are gauged, hence a different method required.
579, 592, 596, 600, 613, 606, 1841, 1843, 1844, 5741.	Large changes in SDL/area between adjacent SC surrounding a junction between streams and downstream of upstream gauges.	No change required. Method 2a values were checked and were consistent in the main with the applied SDL/area values. Therefore, no gain to be achieved by redistributing. SC 596 has a higher SDL/area than surrounding, but this can be explained by a higher mean annual rainfall.
915, 966, 975, 982, 995, 997, 1048	Large changes in SDL/area between adjacent SC surrounding a junction between streams and downstream of upstream gauges.	Manually redistribute total SDL of SC 915, 966, 975, 982, 995, 997 and 1048 according to ratio of respective method 2a estimates. This smoothes the changes in SDL/area over these subcatchments in a more uniform way and provides a better fit with surrounding subcatchments.
1553, 1585, 1587, 1602	Large changes in SDL/area between adjacent SC surrounding a junction between streams and downstream of upstream gauges.	No change required. Method 2a values were checked and were consistent in the main with the applied SDL/area values. Therefore, no gain to be achieved by redistributing. SC 1587 has a higher SDL/area than surrounding, but this can be explained by both higher mean annual rainfall and lower vegetation cover than the others.
1393	SC 1393 has higher SDL/area than surrounding SC.	Kier revealed that this should have been updated earlier with other subcatchments in area but was missed. New value of 432.87 ML, based on 3.5 times (gauge factor) the method 2a value.

Recalculation of SDL values for these manual changes are documented in the file D07_pwj_ManualEditsOfSDLValues.xls.

In summary, the following changes were required to SC as listed below:

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Summary of Manual Edits of SDL values during Review of Draft SDL values

UFI	Row of calc sheet	CATCHMENT_	Area (km²)	Pre-Review SDL value ML/km²	Pre-Review SDL value ML	Post-Review SDL value ML/km²	Post-Review SDL value ML	% change Post review to prereview
915	61	612_1_4_1	327.67	8.032	2631.91	9.593	3143.44	19%
966	62	612_1_5_1	21.42	6.217	133.18	7.425	159.06	19%
975	63	612_1_5_2	15.31	10.693	163.73	12.772	195.55	19%
982	64	612_1_5_3	17.59	12.363	217.48	9.354	164.53	-24%
995	65	612_1_6_1	72.98	23.734	1731.96	13.668	997.45	-42%
997	66	612_1_3_11	41.87	12.193	510.50	14.563	609.72	19%
1030	37	611_1_9_4	7.88	17.148	135.08	10.535	82.98	-39%
1048	67	612_1_6_2	42.10	14.544	612.32	17.371	731.33	19%
1055	20	609_1_2_26	270.20	2.617	707.09	2.842	767.92	9%
1105	19	609_1_2_27	27.74	5.266	146.09	3.073	85.25	-42%
1228	2	602_1_2_6	211.71	0.518	109.58	0.492	104.10	-5%
1319	1	602_1_2_7	51.44	0.047	2.42	0.153	7.89	227%
1365	76	609_3_2_1	15.07	6.970	105.01	24.388	367.43	250%
1393	78	609_3_1_4	11.90	51.771	616.28	36.364	432.88	-30%
1531	14	607_1_2_32	17.04	8.816	150.25	5.985	102.01	-32%
1541	15	607_1_2_33	16.46	4.844	79.71	4.815	79.24	-1%
1543	16	607_1_2_34	17.06	1.387	23.66	4.242	72.38	206%
5741	57	616_3_8_4	117.90	2.899	341.82	2.825	333.13	-3%
10423	36	611_1_9_3	12.82	2.229	28.57	6.293	80.67	182%
13331	80	609_2_5_1	1.86	2.938	5.47	10.279	19.13	250%

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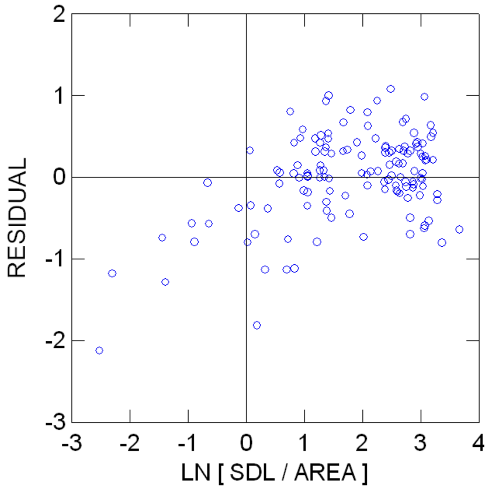
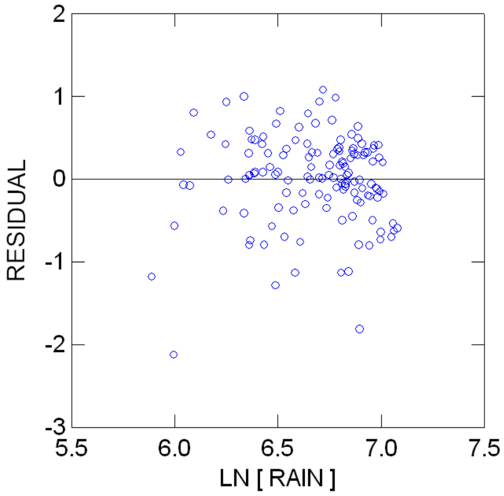
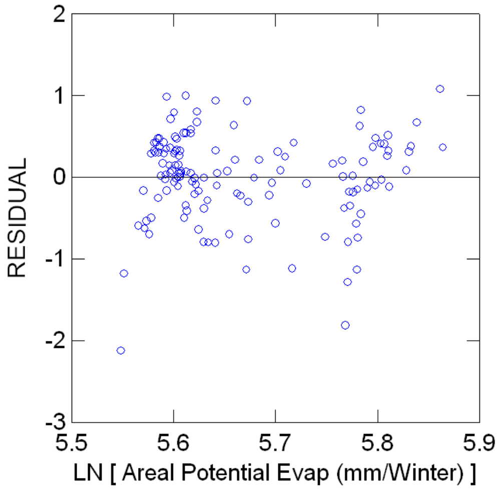
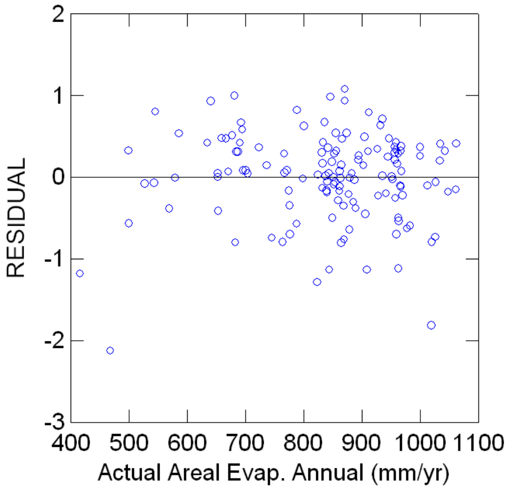
Appendix D Prediction Equation Residual Plots

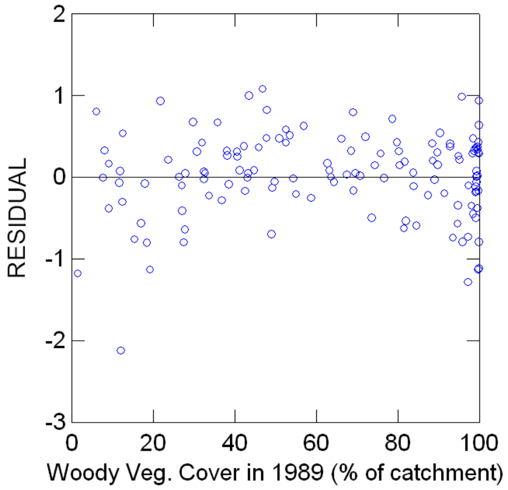
D.1 Sustainable Diversion Limit (ML)

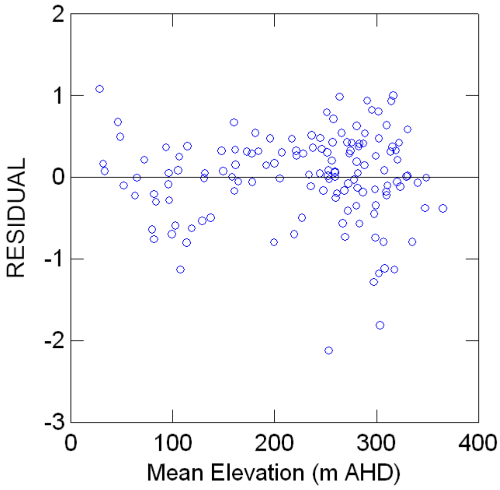


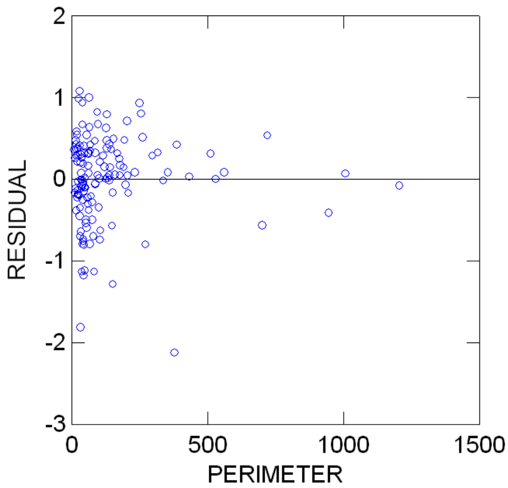







RESIDUAL
2
1
0
-1
-2
-3
0
20
40
60
80
100
Woody Veg. Cover in 1989 (% of catchment)


RESIDUAL
2
1
0
-1
-2
-3
0
100
200
300
400
Mean Elevation (m AHD)


RESIDUAL
2
1
0
-1
-2
-3
0
500
1000
1500
PERIMETER

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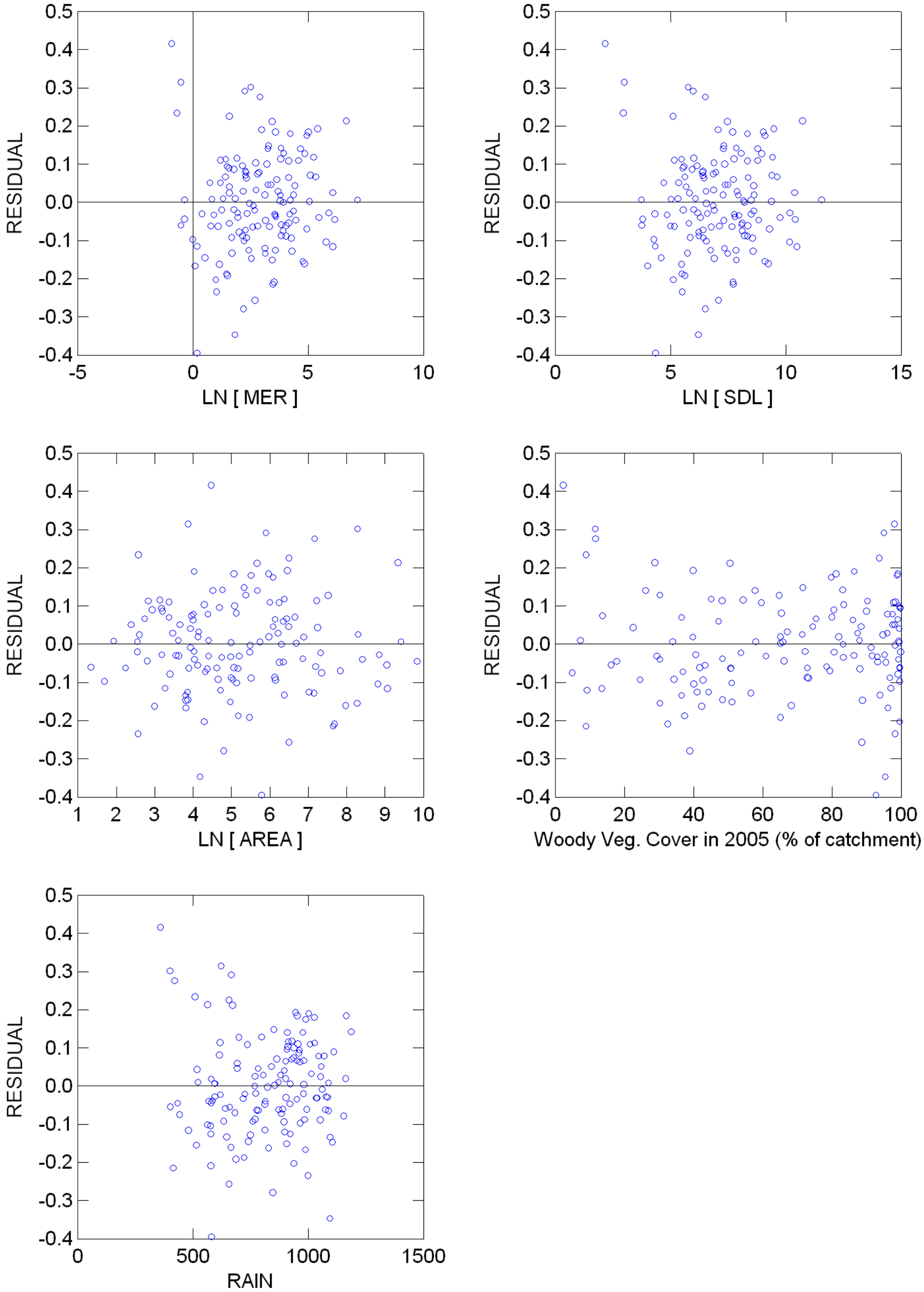
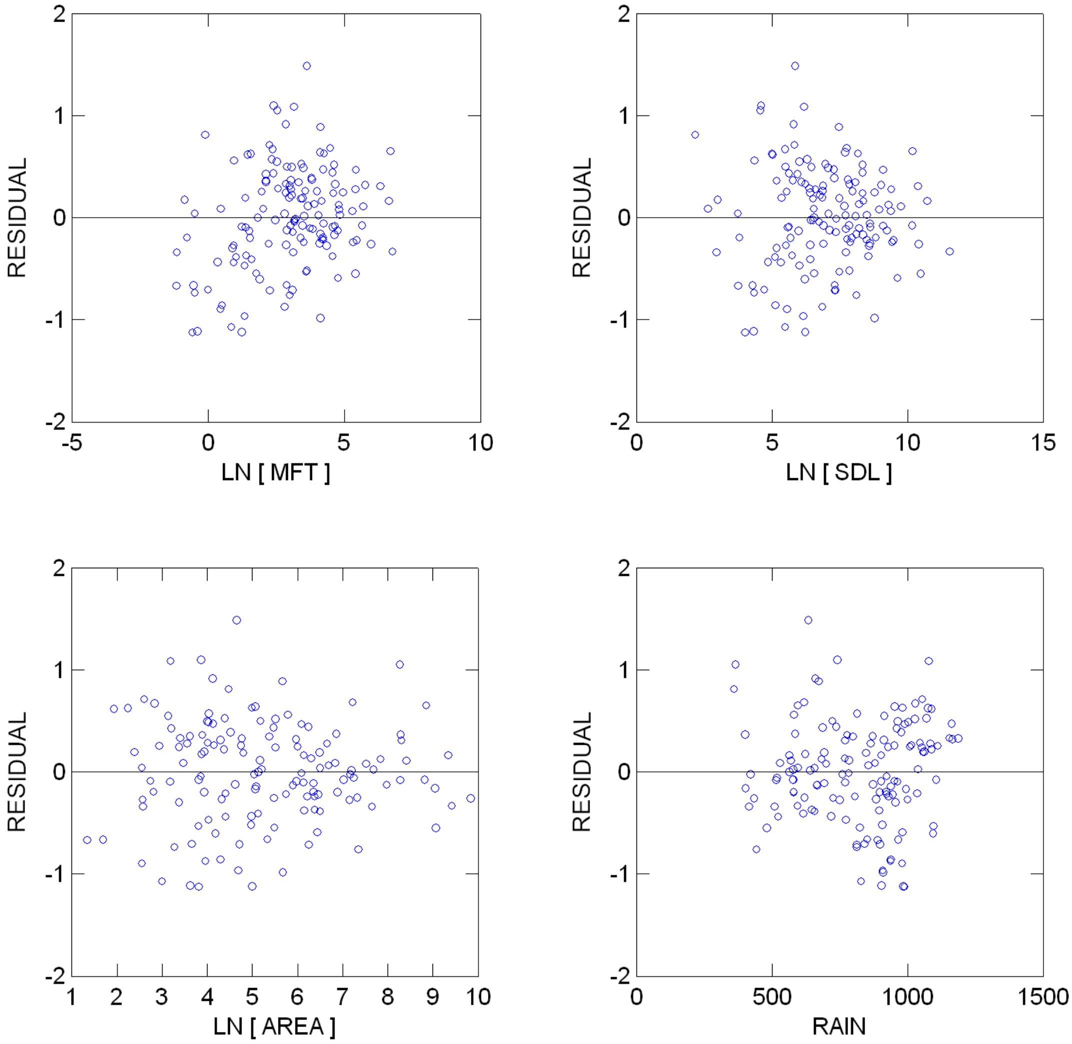
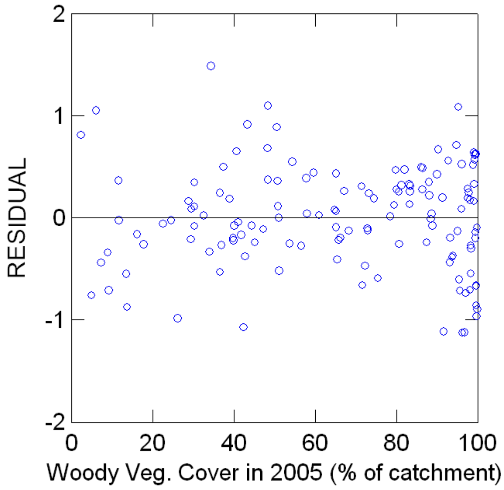
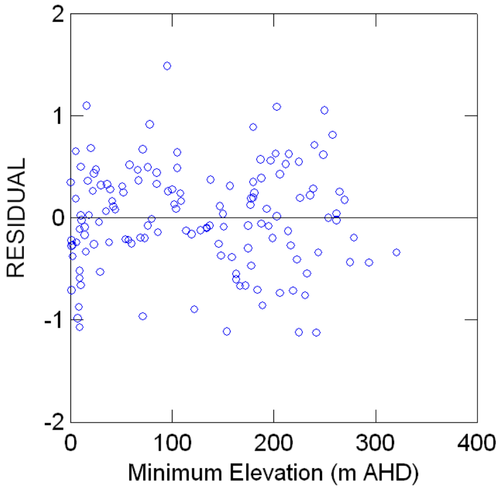
D.2 Maximum Extraction Rate (ML/day)

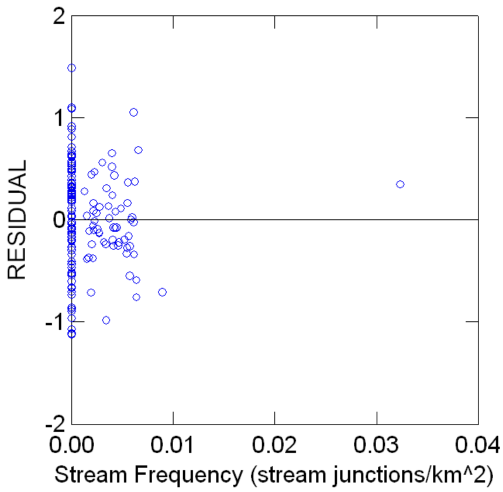


D.3 Minimum Flow Threshold (ML/day)



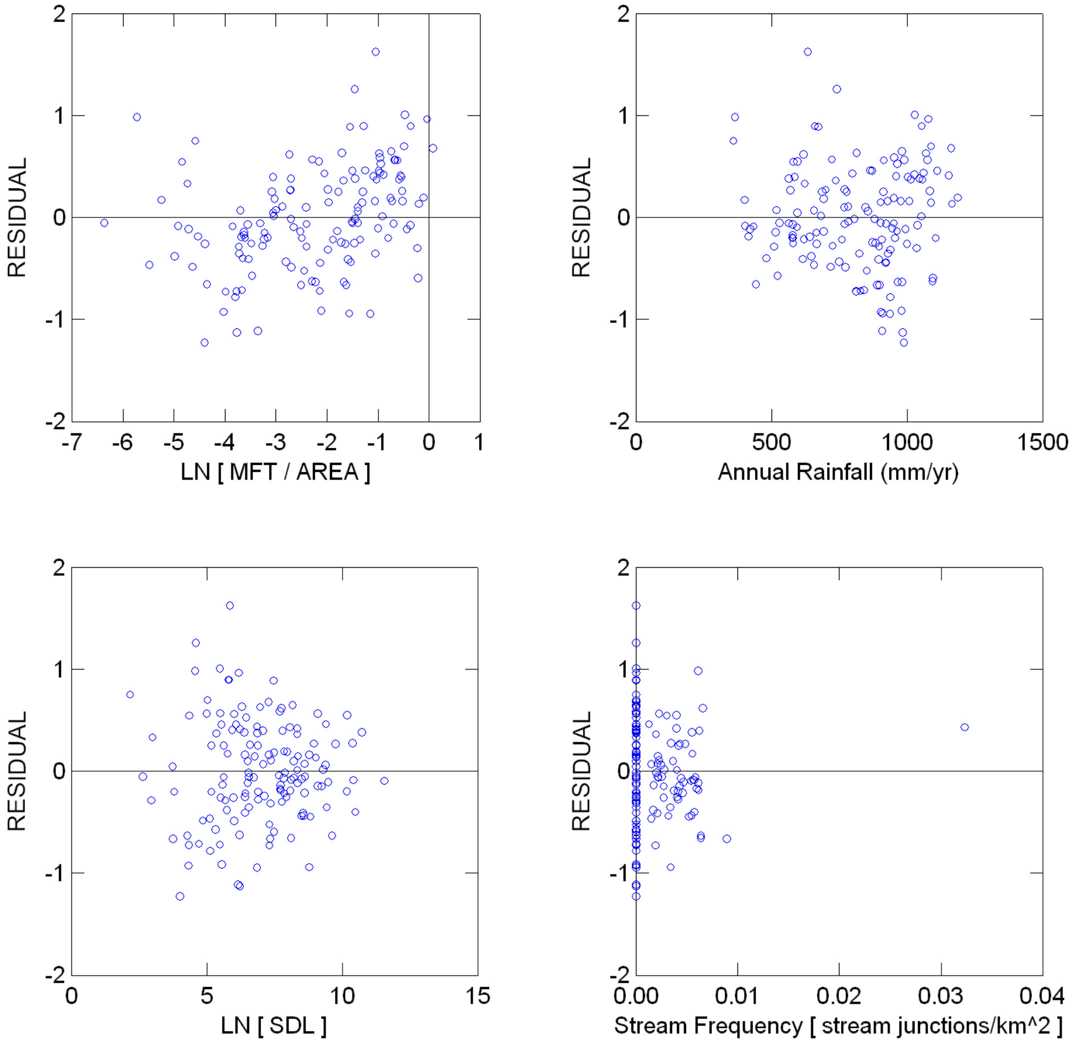

RESIDUAL
Woody Veg. Cover in 2005 (% of catchment)

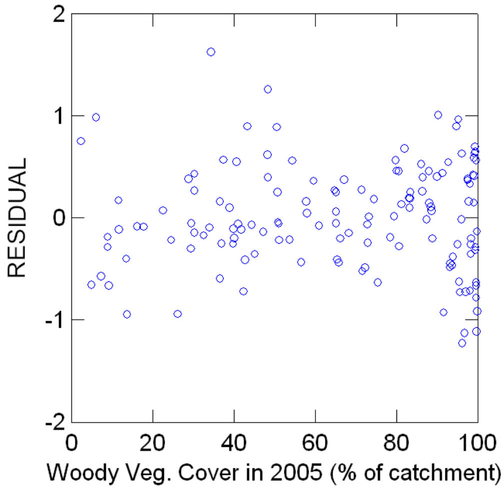

RESIDUAL
Minimum Elevation (m AHD)

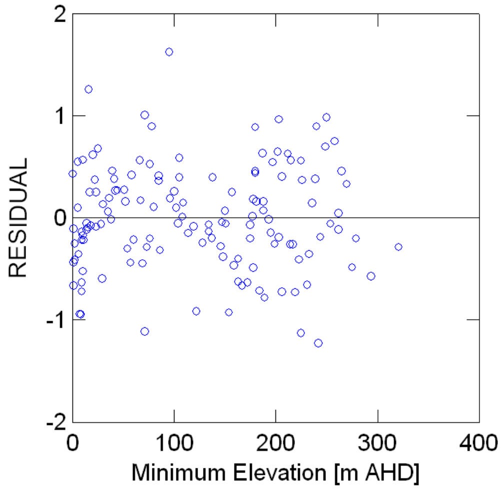

RESIDUAL
Stream Frequency (stream junctions/km^2)

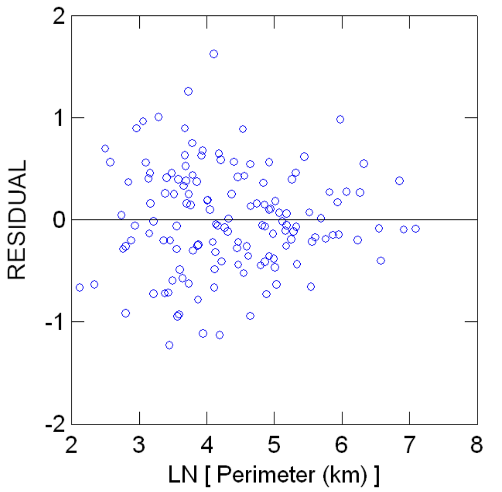
SKM

D.4 Minimum Flow Threshold per Unit Area (ML/km^2)




RESIDUAL
2
1
0
-1
-2
0
20
40
60
80
100
Woody Veg. Cover in 2005 (% of catchment)


RESIDUAL
2
1
0
-1
-2
0
100
200
300
400
Minimum Elevation [m AHD]


RESIDUAL
2
1
0
-1
-2
2
3
4
5
6
7
8
LN [Perimeter (km)]

SKM

Appendix E An Estimate of the Sustainable Diversion Limit as a Proportion of Mean Annual Flow

E.1 Proportion of Mean Annual Flow for Gauged Catchments

Previous attempts at defining the available water resources for catchments in unregulated streams in the study area have defined this as a fixed percentage of the estimated mean annual flow (MAF) for the catchment. In many areas, the available water resources have been set to 18% of the estimated MAF volume.

The SDL approach is based upon a more detailed consideration of the nature of the flow regime in South West Western Australian catchments. The SDL will therefore not represent a fixed proportion of the MAF but will vary from catchment to catchment according to the variability in observed streamflow regime. The SDL as a proportion of MAF can be directly calculated for the SDL gauged catchments.

On average for the gauged catchments, the SDL represents 9.2% of the MAF. The standard deviation of the SDL to MAF ratio represented 3.4% of the MAF. This variability represents observed variability in the streamflow regime across gauged catchments in the study area, as discussed in detail in Sinclair Knight Merz (2007). Catchments with a high SDL to MAF ratio tend to be catchments with regular flow regimes, as evidenced by high baseflow index (BFI) and low interannual coefficient of variability (CV). A high BFI and low CV indicate a catchment with persistent flows, a large component of which comes from groundwater stores.

E.2 Indicative estimated Proportion of Mean Annual Flow for Ungauged Catchments

Unlike the gauged catchments, it is not possible to directly estimate the SDL as a proportion of MAF for unguaged catchments because the MAF is not calculated as part of the application of the SDL. It would be possible but take considerable effort to estimate the MAF for the ungauged catchments (and consequently to estimate the SDL to MAF ratio) using a regression and application approach similar to that applied for the SDL.

However, it is possible to understand the uncertainty in estimation of the SDL to MAF ratio that would result from such a regression approach if it were to be applied. Using the 140 gauged catchments, a multiple linear regression model was applied to estimate the MAF from catchment characteristics. As with the SDL, the multiple linear regression model applied estimated the MAF per unit area (in ML/km^2) since the MAF was directly proportional to catchment area.

The equation found to provide the best prediction of the SDL per unit area is:

$$\ln(MAF/km^2) = 5.51 \ln(RAIN) - 2.08 \ln(AREAVP\_ANN) - 0.0181\, PCT\_VEG89 - 0.565 \ln(PCEAST) + 0.346 \ln(SLP\_MN) - 16.04$$

where;	MAF/km^2	=	Mean annual flow volume per area (ML/km^2)
	RAIN	=	Mean rainfall data from WA (1975-2006) (mm/yr)
	AREAVP_ANN	=	Mean annual areal actual evapotranspiration (mm)
	PCT_VEG89	=	Percentage of catchment area covered by woody vegetation as determined by AGO data from 1989 (%)
	PCEAST	=	Percentage of catchment area with an Easterly aspect (%)
	SLP_MN	=	Mean catchment slope (%)

Regression statistics were as follows:

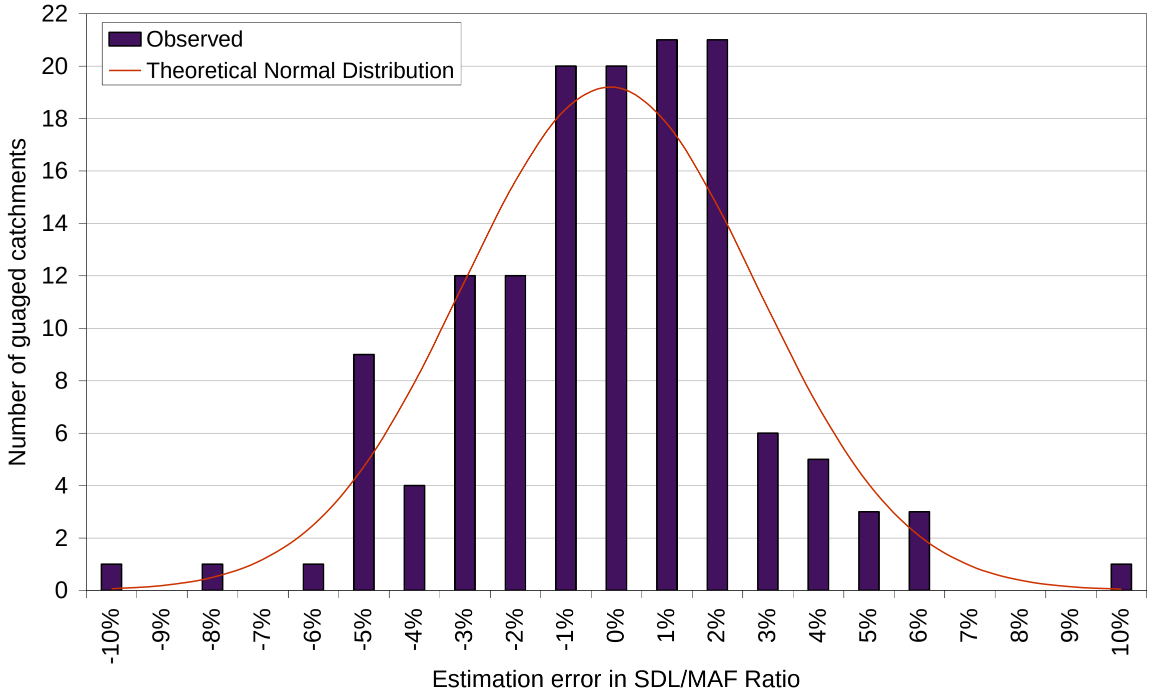
- Number of observations = 140
- Multiple R^2 on $MAF/km^2 = 0.830$
- Multiple R^2 on MAF = 0.924
- Standard error of estimate in logarithmic domain on MAF = 4.8%

It should be noted that mean annual rainfall (for 1975-2006), mean annual areal actual evapotranspiration and the percentage of woody vegetation as at 1989 were the three strongest predictor variables for both the SDL and the MAF regression equations. Regression based estimates for ungauged catchments for the SDL and the MAF would be expected to be highly correlated because both equations are strongly dependent upon the same catchment characteristics.

To test the uncertainty in SDL/MAF ratio estimates from adopting a regression approach, the adopted regression equations for both SDL and MAF were applied to the 140 gauged SDL catchments that were used to develop the regression equations. For each catchment, the actual SDL was divided by the actual MAF to estimate the SDL to MAF ratio. The respective regression equations were then applied to each gauged catchment to estimate the SDL to MAF ratio that would have been estimated from a regression approach. The difference between these two ratios was then computed for each of the 140 gauged SDL catchments.

Figure E-1 shows the histogram of the difference between the SDL to MAF ratio directly calculated from streamflow data and estimated using the two respective regression equations. The distribution of the uncertainty in the SDL to MAF ratio is approximated by a normal distribution with a mean value of -0.13% and a standard deviation of 2.89%. The normal distribution approximation is also shown on Figure E-1. The mean very close to 0% indicates that using a regression approach produces an unbiased estimate of the SDL to MAF ratio. On average therefore, applying a regression approach to estimate the SDL does not result either in systematic over- or under- estimation of the SDL as a proportion of MAF. Furthermore, the regression approach produces a reasonably tight level of uncertainty in the SDL to MAF ratio estimates. It is expected that the middle 80% of catchments would have an estimated SDL to MAF ratio within -3.8% to +3.6% of the true SDL to MAF ratio value.

Taking this analysis a step further, for a catchment with the average SDL to MAF ratio of the gauged catchment sample of 9.1%, there is an 80% chance that the SDL to MAF ratio estimated by application of the regression approach would lie within the range of 5.3% to 12.7%. Applying the regression equation to estimate the SDL therefore should estimate the true SDL to MAF ratio for 80% of catchments to within -42% to +39%.



- **Figure E-1 Histogram of estimation error in ratio of SDL to Mean Annual Flow resulting from application of regression equations to estimation of SDL and Mean Annual Flow for 140 gauged catchments**

Appendix F Indicator Gauges

Gauge Number	Stream Name	Site Name	Minimum Flow Threshold (ML/d)	Catchment Area (km²)
SDL Gauges still open – Good quality indicators for MFT				
602001	Pallinup River	Bull Crossing	21.02	3926.4
602003	Jackitup Creek	Wellards	0.91	88.0
602004	Kalgan River	Stevens Farm	58.07	2179.8
602005	Chelgiup Creek	Anderson Farm	11.25	48.0
602014	King River	Billa Boya Reserve	23.74	155.6
602015	Mill Brook	Warren Road	18.18	177.8
602031	Waychinicup River	Cheynes Beach Road	10.99	238.3
602199	Goodga River	Black Cat	8.37	49.2
603001	Marbellup Brook	Elleker	30.37	121.9
603003	Denmark River	Kompup	9.32	241.9
603004	Hay River	Sunny Glen	77.81	1210.6
603005	Mitchell River	Beigpiegup	4.68	51.4
603007	Sleeman River	Sleeman Road Bridge	17.65	75.7
603136	Denmark River	Mt Lindesay	33.81	502.4
603190	Yate Flat Creek	Woonanup	3.80	56.3
604001	Kent River	Rocky Glen	32.44	1069.9
604053	Kent River	Styx Junction	123.31	1806.0
605012	Frankland River	Mount Frankland	298.45	4508.9
606001	Deep River	Teds Pool	65.47	467.8
606002	Weld River	Wattle Block	4.02	24.2
606195	Weld River	Ordnance Road Crossing	103.17	250.2
607003	Warren River	Wheatley Farm	116.86	2821.1
607004	Perup River	Quabicup Hill	16.59	666.7
607007	Tone River	Bullilup	30.17	983.1
607013	Lefroy Brook	Rainbow Trail	100.21	249.4
607144	Wilgarup River	Quintarrup	42.03	460.5
607220	Warren River	Barker Rd Crossing	560.06	3933.7
608002	Carey Brook	Staircase Road	17.40	30.3
608151	Donnelly River	Strickland	225.01	782.1
609002	Scott River	Brennans Ford	118.74	627.7
609005	Balgarup River	Mandelup Pool	2.58	82.4
609010	Northern Arthur River	Lake Toolibin Inflow	0.97	438.5
609012	Blackwood River	Winnejup	226.51	8729.5
609014	Arthur River	Mount Brown	22.97	2117.6
609015	Beaufort River	Manywaters	20.12	1565.2
609017	Balingup Brook	Brooklands	49.62	548.9
609018	St John Brook	Barrabup Pool	68.24	552.3

Gauge Number	Stream Name	Site Name	Minimum Flow Threshold (ML/d)	Catchment Area (km²)
SDL Gauges still open – Good quality indicators for MFT				
609019	Blackwood River	Hut Pool	874.84	12372.2
609021	Coblinine River	Bibikin Road Bridge	12.75	3915.2
609022	Chapman Brook	White Elephant Bridge	127.74	180.0
609023	Chapman Brook	Forest Grove	36.67	45.2
609025	Blackwood River	Darradup	768.09	11593.0
610001	Margaret River	Willmots Farm	228.86	443.0
610003	Vasse River	Chapman Hill	23.88	47.7
610006	Wilyabrup Brook	Woodlands	65.82	82.3
610008	Margaret River North	Whicher Range	3.46	15.5
610009	Ludlow River	Ludlow	18.07	207.8
610010	Capel River	Capel Railway Bridge	97.91	394.7
610014	Vasse Diversion Drain	D-S Hill Road	27.92	265.4
610015	Carbunup	Lennox Vineyard	103.90	159.4
610219	Capel River	Yates Bridge	68.63	315.1
611004	Preston River	Boyanup Bridge	200.68	808.4
611007	Ferguson River	Sw Hwy Ferguson	37.92	144.9
611111	Thomson Brook	Woodperry Homestead	18.29	102.1
611221	Coolingutup Brook	Pesconeris Farm	0.32	3.9
612001	Collie River East	Coolangatta Farm	34.08	1345.3
612002	Collie River	Mungalup Tower	122.31	2546.2
612004	Hamilton River	Worsley	7.60	32.3
612014	Bingham River	Palmer	4.56	366.1
612016	Batalling Creek	Maxon Farm	0.46	16.8
612022	Brunswick River	Sandalwood	54.92	116.2
612025	Camballan Creek	James Well	4.97	170.0
612032	Brunswick River	Cross Farm	208.36	509.4
612034	Collie River	South Branch	32.28	661.6
612039	Wellesley River	Juegenup Wellesley	62.14	209.0
612230	Collie River East Trib	James Crossing	6.26	170.6
613002	Harvey River	Dingo Road	70.85	147.2
613007	Bancell Brook	Waterous	9.55	13.6
613031	Mayfield Drain	Old Bunbury Road	22.22	112.4
613052	Harvey River	Clifton Park	237.09	573.0
613146	Clarke Brook	Hillview Farm	10.70	17.1
614003	Marrinup Brook	Brookdale Siding	20.59	45.6
614006	Murray River	Baden Powell Water Spout	287.40	6757.6
614030	Serpentine Drain	Dog Hill	96.45	469.7
614031	39 Mile Brook	Jack Rocks	13.07	55.4
614036	North Dandalup River	North Road	21.58	79.7

Gauge Number	Stream Name	Site Name	Minimum Flow Threshold (ML/d)	Catchment Area (km²)
SDL Gauges still open – Good quality indicators for MFT				
614037	Big Brook	O'neil Road	3.47	149.4
614044	Yarragil Brook	Yarragil Formation	1.66	73.5
614065	Murray River	Pinjarra	818.44	7049.8
614093	Big Brook	Jayrup	0.56	45.5
614105	Hotham River	Pumphrey's Bridge	11.78	1036.4
614196	Williams River	Saddleback Road Bridge	70.23	1408.3
614224	Hotham River	Marradong Road Bridge	105.30	3967.1
616001	Wooroloo Brook	Karls Ranch	96.48	514.7
616002	Darkin River	Pine Plantation	2.79	665.3
616006	Brockman River	Tanamerah	45.32	961.2
616009	Pickering Brook	Slavery Lane	2.45	29.4
616010	Little Darkin River	Hairpin Bend Rd	0.68	37.8
616011	Swan River	Walyunga	402.58	18633.2
616012	Helena Brook	Trewd Road Gs	0.61	26.7
616013	Helena River	Ngangaguringuring	2.60	327.0
616019	Brockman River	Yalliawirra	60.36	1521.9
616021	Seldom Seen Creek	Travellers Arms	4.28	7.2
616023	Waterfall Gully	Mount Curtis	4.82	8.6
616026	31 Mile Brook	31 Mile Road	3.92	11.0
616027	Canning River	Seaforth	31.35	876.6
616041	Wungong Brook	Vardi Road	30.70	80.8
616092	Southern River	Anaconda Drive	31.66	152.0
616178	Jane Brook	National Park	20.14	73.4
616189	Ellen Brook	Railway Parade	46.83	581.5
616216	Helena River	Poison Lease Gs	4.05	590.9
617001	Moore River	Quinns Ford	62.59	9828.8
617002	Hill River	Hill River Springs	1.60	925.9
617003	Gingin Brook	Bookine Bookine	89.04	1370.7
617058	Gingin Brook	Gingin	37.52	105.8
617165	Lennard Brook	Molecap Hill	17.42	59.1
Non-SDL Gauges – Good quality indicators for MFT				
602018	Normans Creek	Duck Egg Downs	4.43	
603013	Cuppup River	Eden Road	15.32	61.1
603020	Little River	Ocean Beach Road	9.37	31.7
603022	Sunny Glen Creek	Girrawheen	8.52	35.4
603024	Seven Mile Creek	Wonton Hills Farm Road	6.38	27.9
606004	Noobijup Brook	Upstream Muir Highway	3.64	17.3
607022	Lefroy Brook	Cascades	33.53	344.6
607024	Chowerup Brook	Stretch's Tree Farm	8.85	82.7

SKM

Gauge Number	Stream Name	Site Name	Minimum Flow Threshold (ML/d)	Catchment Area (km²)
Non-SDL Gauges – Good quality indicators for MFT				
607027	Tone River	Hillier Road	12.32	232.2
607028	Mobrup Creek	Evans Farm	9.37	114.4
609001	Rosa Brook	Crouch Road	16.32	89.2
609028	Gnowergerup Brook	Jayes Rd	42.21	368.4
609039	Arthur River	Moodiarrup	30.71	5789.0
609040	Blackwood River	Bridgetown	62.74	9001.2
609058	Blackwood River	Old Nannup Caravan Park	83.24	10417.5
609059	Blackwood River	Boyup Brook Flax Mill	59.16	7800.9
609064	Tweed River	Rylington	2.49	
610029	Cowaramup Brook	Gracetown	9.97	21.5
611009	Preston River	Lowden Road Bridge	22.48	311.6
611017	Ferguson River	Doudell Road Bridge	14.97	114.5
612038	Collie River	Buckingham Mill	18.28	793.5
612047	Brunswick River	Beela	15.73	209.1
614063	Nambeelup Brook	Kielman	16.54	115.0
615012	Lockhart River	Kwolyn Hill	25.61	6050.0
615013	Mortlock River North	Frenches	14.99	2333.2
615015	Yilgarn River	Gairdners Xing	12.44	9771.5
615020	Mortlock River	Odriscolls Farm	28.26	5040.1
615024	Avon River	Balladong St - York	44.12	5929.9
615025	Avon River	Beverley Bridge	54.76	2975.8
615026	Avon River	Stirling Tce Toodyay	46.02	14872.1
615027	Dale River	Waterhatch Bridge	21.17	2007.1
615029	Avon River	Yenyening Confluence	30.95	1821.0
615062	Avon River	Northam Weir	40.87	6717.4
616088	Jane Brook	Great Northern Hwy - Road Bridge	12.21	138.1
616099	Susannah Brook	River Road	5.71	55.1
617009	Moore River East Branch	Woury Pool	28.60	1513.3
617010	Moore River North	Moora Caravan Park	18.19	1876.9
617017	Hill River	Ardross	29.27	3723.9
701002	Greenough River	Karlanew Peak	44.56	11736.5
701007	Chapman River	Utakarra	26.38	1578.5
701008	Greenough River	Pindarring Rocks	14.35	5668.0
701009	Irwin River	Mountain Bridge	22.98	5264.1
701010	Hutt River	Yerina	13.59	1078.4
701011	Greenough River	Eradu	29.84	10797.5
701012	Greenough River	Mitthutharra	12.23	10388.3

SKM

Gauge Number	Stream Name	Site Name	Minimum Flow Threshold (ML/d)	Catchment Area (km²)
Non-SDL Gauges – Lower quality indicators for MFT				
601001	Young River	Neds Corner	46.67	1893.3
601004	Lort River	Fairfield	60.14	2901.5
601006	Young River	Munglinup	1.70	11.5
601008	Coramup Creek	Myrup Road	27.11	318.9
601009	Bandy Creek	Fisheries Rd	32.82	545.0
604003	Kent River	Watterson Farm	17.22	249.1
606005	Lake Muir Inflow	Mulgarnup Bridge	11.26	146.2
609036	Dongolocking Creek	Cooks Farm	2.61	168.6
609038	Inflow Lake Toolibin	Calm Drain West	5.58	106.5
609041	Blackwood River	Gingilup	44.44	
609042	Milyeannup Brook	Milymily	27.00	
610028	Wilyabrup Brook	Juniper	18.20	43.6
611006	Preston River	Donnybrook	25.95	622.7
612007	Bingham River Tributary	Don's Catchment	1.23	3.5
612008	Bingham River Tributary	Ernie's Catchment	0.69	2.7
612035	Collie River	Central Collie	50.48	1842.4
614060	South Dandalup River Tributary	Gordon Catchment	8.95	2.1
614114	Serpentine River	Lowlands	6.30	182.9
615011	Mooranoppin Creek	Mooranoppin Rock	4.17	83.1
615016	Lake Ace Creek	Spencers Farm	15.15	489.5
615017	Lake Ace Creek	Hatters Hill	1.75	21.9
615044	Pithara	Pithara Upstream	3.11	
615045	Pithara	Pithara Downstream	3.81	125.0
616004	Swan River	Meadow Street Bridge	51.14	19574.5
616110	Canning River	Orlando Street	8.53	862.8
617011	Moore River North	Long Pool Bridge	20.42	1682.7
617012	Dungaroo Creek	Round Hill Bridge	8.79	145.5
617013	Moore River North	Nardy Road	19.99	1414.9
617015	Moore River	Waterville Rd	24.39	10498.0