Approach for Determining Sustainable Diversion Limits for South West Western Australia

- Final C
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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. Simon Lang conducted the majority of the technical analysis, and is the author of this document. Technical support was provided by Robert Morden, Heath Sommerville 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.

Contents

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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. 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.

An expert panel was assembled for this project. The panel was comprised of researchers and practitioners with knowledge of stream ecology, water quality, geomorphology, hydrology, wetlands and catchment management. Members of the panel had considerable experience in the development of environmental flow recommendations for Western Australian rivers. The expert team was advised and supported by a technical team from SKM. Members of this technical team had been involved in the derivation of SDLs for Victoria. Together, the expert panel and technical team comprised the study team which developed the rules used to define the SDLs for the unregulated rivers of south-west Western Australia.

The SDLs were established by trialling various rules on daily streamflow data obtained for 142 gauged sites from across south-west Western Australia. The suitability of different rules was tested by investigating their impacts on extraction volumes, and a range of hydrologic criteria, across all parts of the study area. Particular attention was given to investigating the impacts of extractions during drought periods.

Rules for defining the SDLs were based on a:

- Winterfill period over which extractions can occur;
- Minimum flow threshold (MFT), below which extractions should cease;
- Maximum extraction rate (MER); and a
- Annual licensed volume associated with a specified reliability of supply.

The winterfill period recommended is 15 June – 15 October inclusive. The recommended minimum flow threshold is the maximum of 0.3 times the mean daily flow, and the 95th exceedance percentile of the median winterfill period daily flow. The recommended maximum extraction rate is the 25th exceedance percentile of the difference between the daily flow and the MFT, for those days in the winterfill period when the MFT is exceeded. The impacts of these rules on the environment were tested assuming an annual reliability of supply of 80%.

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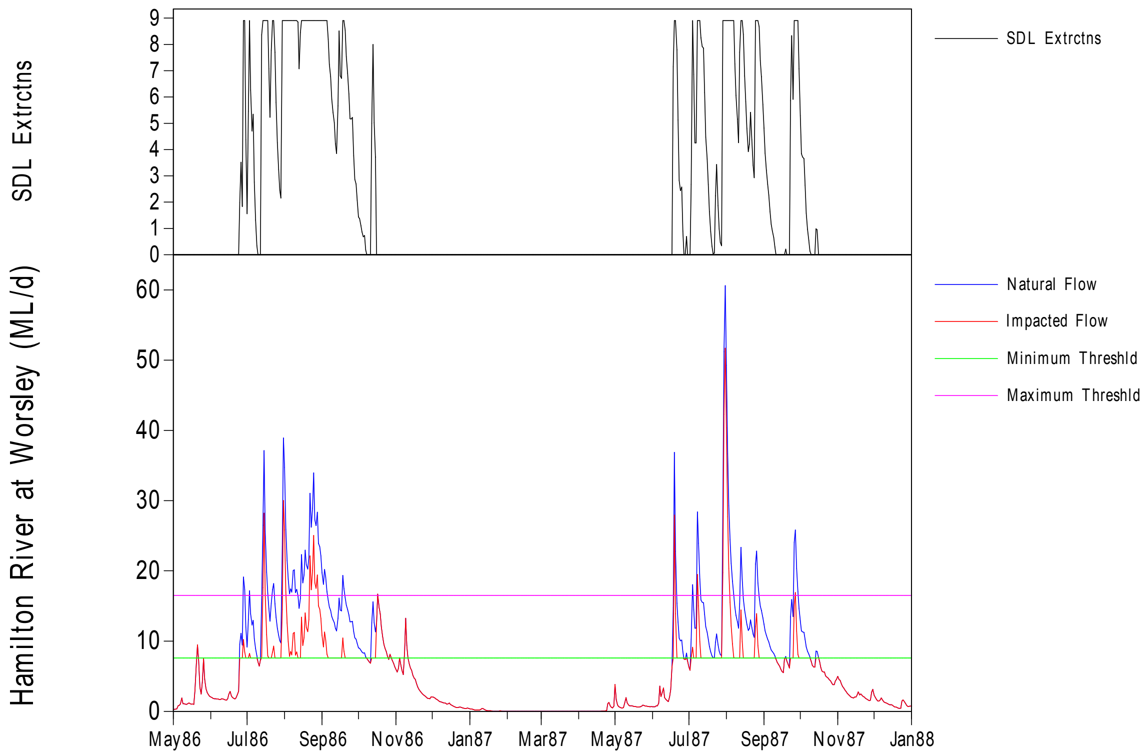
Figure E.1, an example time-series for the Hamilton River at Worsley (612004), illustrates the concepts of MFT, MER (i.e. the difference between the minimum and maximum flow thresholds), natural and impacted flow time-series, and SDL extractions.

Application of these four rules to the 142 selected gauge sites results in a median SDL of 11.0% of mean winterfill period streamflow. The SDL varies from catchment to catchment, but there is a strong correlation between the SDL and mean rainfall for the winterfill period. In addition, diversion potential is generally high for streams with a significant proportion of groundwater contribution, and is low for ephemeral streams which flow intermittently in direct response to rainfall.



- **Figure E.1: An example time-series plot showing a minimum flow threshold (MFT; green) and maximum flow threshold (purple) calculated for the Hamilton River at Worsley (612004), assuming a mid June-mid October winterfill period. The maximum extraction rate (MER) is the difference between the maximum and minimum flow thresholds. Also shown are the natural and impacted time-series, with the SDL extractions being the difference between the two.**

1. Introduction

1.1 Background

With increasing demand and competition for available water, there is a need to establish operational rules (where such rules are currently absent) for water sharing among users, including the environment.

In Western Australia, the Department of Water determines the water sharing arrangement in surface water systems. The Department does this by defining the sustainable yield of individual catchments. The sustainable yield is the maximum quantity of water available for abstraction from a surface water resource after environmental water requirements have been satisfied. In areas where the level of surface water use is minimal, estimates of sustainable yield are based on regional models. As the level of surface water use increases towards highly allocated systems, then so too does the intensity of investigations required to determine the sustainable yield.

Western Australia is the largest State in Australia, covering more than 2.5 million square kilometres, with climate zones ranging from tropical in the north with a wet summer, to temperate in the south, with a wet winter. In terms of water resource assessment, the south-west of Western Australia includes Australian Water Resources Council (AWRC) basins 601 to 619 in the South West Drainage Division, and AWRC basin 701 in the Indian Ocean Drainage Division (Figure 1.1).

Currently, the Department of Water uses an internally developed regional model to estimate annual sustainable yields for the majority of catchments in south-west Western Australia. Surface water licences are allocated up to the limit of the sustainable yield. Diverters are not allowed to abstract water during summer months, but may take water at any other time. However, these periods of no abstraction are neither specifically defined nor currently enforced by the Department.

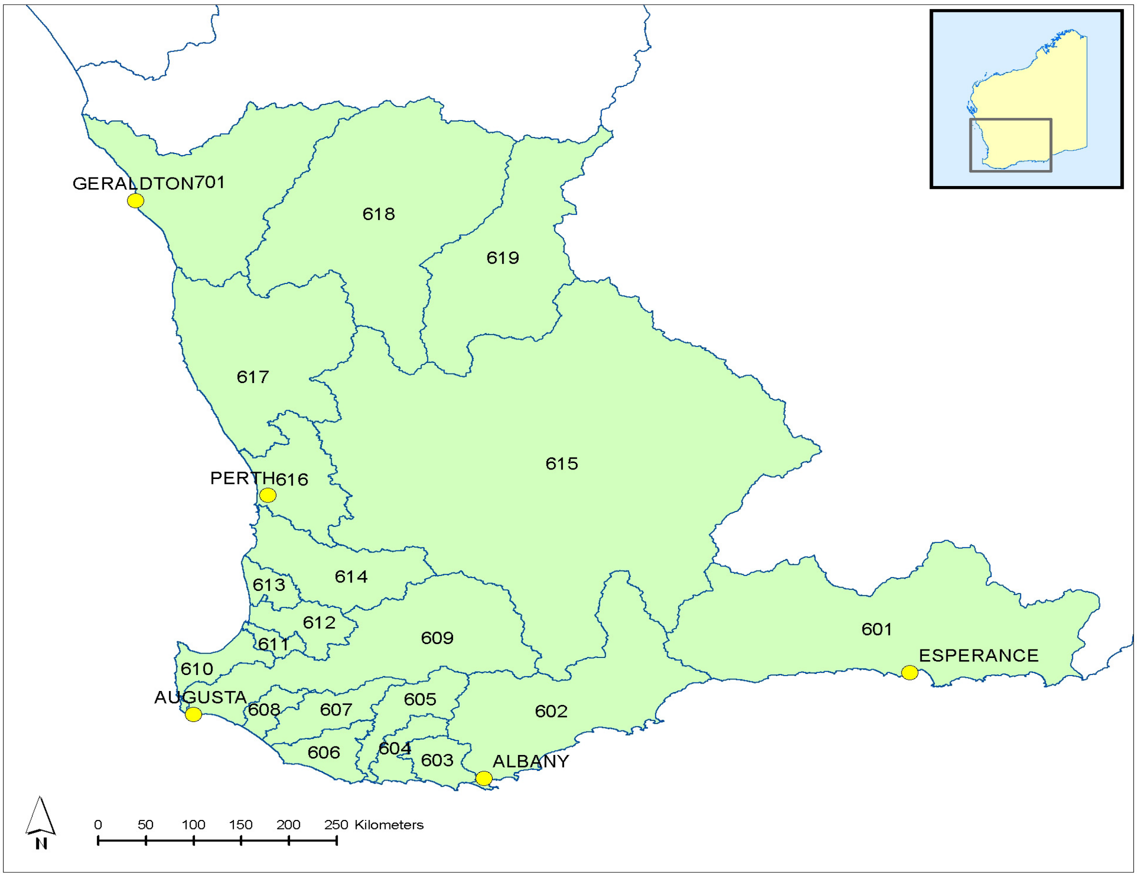
Because of an increasing demand for water, the Department of Water intends to replace this simple process with a more defensible framework which still provides quick and conservative estimates of sustainable yield. The Department also intends to resolve the ambiguity surrounding the period when diverters can abstract water.

To address these needs, the Department of Water initiated the 'Sustainable Diversion Limit' (SDL) project. The focus of this project was to develop the means to rapidly and conservatively estimate, for the catchments of south-west Western Australia, the potential to extract water from unregulated streams during a defined 'winterfill' period. The key outcome of this project is a method which allows SDLs to be determined using regional information, thus avoiding the need for site-specific assessments.

The term ‘winterfill’ here refers to the period in which diverters are permitted to abstract water from unregulated rivers. Prior to this project, the winterfill period in south-west Western Australia was March to November. However, this period was not explicitly defined. One outcome of this project therefore, is an explicitly defined winterfill period in which diversions from unregulated rivers are allowed.

The term ‘unregulated’ here refers to rivers that do not have dams that impound water for later release. These dams generally have outlet structures that can deliver individual components of defined environmental flow regimes. Therefore, it is not intended that the SDL approach be applied to regulated systems downstream of storages. However, river reaches upstream of storages may be included in the unregulated category, and limits for extractions from their catchments defined using the SDL approach.

Generally, diversions from unregulated rivers are either from direct pumping, or storage of streamflow in on-stream structures such as farm dams. One outcome of the SDL study will be a means to control these diversions. That is, the volume of water that diverters are licensed to extract each year can be capped by the SDL. However, because estimates of SDL are based on a regionalised set of inputs, SDLs are conservative, and should be applied for broad regional planning or preliminary design purposes only. That is, rather than being viewed as a fixed cap, the SDL should be regarded as a limit that cannot be exceeded unless more detailed investigations indicate that additional extractions from the unregulated system would not represent an unacceptable risk to the environment. These detailed investigations may take the form of local studies of an unregulated river’s Environmental Water Requirement.



- **Figure 1.1: South-west Western Australia. Basins 601, 615, 618, 619, 701 and half of 602 were excluded from the final study area.**

1.2 Overall Approach and Conduct of Study

A ‘scientific opinion’ process was used to develop the method for defining the SDL for catchments where streamflow data are available. The scientific panel consisted of eight specialists, with skills in the following areas:

- Knowledge of south-west Western Australian water courses;
- Ecological water requirements in unregulated catchments;
- Knowledge of the Western Australian framework for managing unregulated catchments.

This panel was advised and supported by a technical team from SKM that undertook the necessary technical analyses and reporting. Together, the expert panel and technical team comprised the study team which developed the rules used to define the SDLs for the unregulated rivers of south-west Western Australia. The study team met three times to discuss, and come to a consensus on the issues investigated.

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For the first meeting, the briefing material included an outline of the project background and objectives, an explanation of the rules used to define the SDL in Victorian catchments, and preliminary consideration of an appropriate winterfill period in south-west Western Australia. During the meeting, the process for defining the SDL rules was discussed. It was agreed the method for defining SDLs would apply to the whole of south-west Western Australia, excluding basins 601, 615, 618, 619, 701 and the eastern half of 602, and would be based on four rules:

- A winterfill period over which extractions could occur;
- A minimum flow threshold (MFT), below which extractions should cease;
- A maximum extraction rate (MER); and
- An annual licensed volume associated with a specified reliability of supply.

Another outcome from the first meeting was a list of 16 sites the study team wished to use for investigating the impact of SDL rules on the volume of water available to diverters, and the difference between natural and impacted streamflow time-series. These sites were selected by the panel based either on prior knowledge of their ecological water requirements, and/or availability of site-specific hydraulic and hydrological models. Results from these 16 sites (Table 1.1) formed a significant component of the written material provided for the second and third study team meetings.

- **Table 1.1: A list of the 16 sites selected by the study team.**

Site ID	River	Site Name	Catchment Area (km^2)	Post-1975 Record Length (years)	% Missing
607013	Lefroy Brook	Rainbow Trail	249.4	27.1	0.62
609022	Chapman Brook	White Elephant Bridge	180.0	11.0	-
609023	Chapman Brook	Forest Grove	45.2	11.1	-
610006	Wilyabrup Brook	Woodlands	82.3	31.4	0.38
610010	Capel River	Capel Railway Bridge	394.7	13.0	-
611111	Thomson Brook	Woodperry Homestead	102.1	31.6	0.35
612001	Collie River East	Coolangatta Farm	1345.3	31.4	0.34
612002	Collie River	Mungalup Tower	2546.2	31.4	0.14
612004	Hamilton River	Worsley	32.3	31.1	-
612014	Bingham River	Palmer	366.1	30.9	0.11
612032	Brunswick River	Cross Farm	509.4	15.9	-
616019	Brockman River	Yalliawirra	1521.9	30.9	0.40
616027	Canning River	Seaforth	876.6	31.3	2.36
617001	Moore River	Quinns Road	9828.8	27.1	2.25
617002	Hill River	Hill River Springs	925.9	30.2	-
617058	Gingin Brook	Gingin	105.8	31.2	1.94

At the second study team meeting, material arising from the first meeting was reviewed. The focus of discussions was on definition of the winterfill period and the minimum flow threshold. The winterfill period was defined as 15 June – 15 October (Section 4). The MFT was defined as the maximum of 0.3 times the mean daily flow and the 95th percentile of the median winterfill period daily flow (the same rule was used to set the MFT for unregulated rivers in Victoria, Section 5). However, the rule proposed for determining the maximum extraction rate (also based on the Victorian rule) was questioned.

The third and final meeting of the study team therefore focused on the appropriate definition of a MER for the unregulated rivers of south-west Western Australia. The agreed MER was set so that 25% of days above the MFT under natural conditions, 'flat-lined' at the MFT under impacted conditions (Section 6). All investigations were conducted assuming an 80% reliability of supply. The impact of the four SDL rules on streamflow time-series in drought periods, the variability in inter-annual flow duration curves, and the frequency and duration of spells above important thresholds were also examined at the third study team meeting.

Following the final meeting, the outcomes of the scientific opinion process were summarised and circulated to the study team. Therefore, the culmination of the study team's input to the SDL project are the recommendations contained within this report.

1.3 Streamflow Data Used

In addition to the 16 gauge sites selected by the study team, a further 126 sites were chosen from the Western Australia gauging station catalogue, to provide an adequate representation of the range of natural hydrological conditions across the unregulated catchments of south-west Western Australia.

The following criteria needed to be satisfied, before sites were selected:

- A catchment area greater than 10 km^2,
- A flow record of at least 10 years, post 1975,
- A minimal percentage of missing data, and
- No effects from reservoirs, drainage, and data inconsistencies.

To remove the effect of the well known post-1975 south-west Western Australia climate shift from the gauge records selected, only data post-1975 was used. Subsequent references in this report to the 'available record' mean the available record post-1975.

Given the criteria for selecting sites, it was assumed that streamflow at each of the 142 gauges represented streamflow under natural conditions. Of the 142 sites selected, 75 had post-1975 periods of record of 25 years or longer. Therefore, where appropriate, written material presented to the study team used results from either the 16 sites chosen by the panel, the 75 sites with periods of record 25 years or longer, or all 142 sites. Figure 1.2 maps the locations of the 142 selected gauges, while Appendix A contains details for each site.

1.4 Victorian SDL Project

The first state to initiate a 'Sustainable Diversions Limit' (SDL) project was Victoria in 2001-2002. The Department of Natural Resources and Environment engaged a consortium led by Sinclair Knight Merz to undertake the necessary scientific studies, and develop maps of SDL for 165 gauged and 1584 ungauged catchments. Findings and outcomes from the Victorian SDL project were published in two Government reports (NRE, 2002; NRE, 2003), and the Australian Journal of Water Resources (Nathan et al, 2002).

The south-west Western Australian SDL project employed a similar method to that used for the Victorian SDL project, i.e. the engagement of a study team to develop SDL 'rules' using data from gauged catchments, and the use of prediction equations to assign an SDL to ungauged catchments. However, for this project, the study team, streamflow data and subsequent considerations and investigations undertaken were unique to south-west Western Australia. Therefore, the recommendations for defining SDLs outlined in this report are developed specifically to suit the conditions found in south-west Western Australia.

1.5 Outline of Report

This report summarises the deliberations from the three study team meetings, and the final rules recommended for estimating the SDL of unregulated catchments where streamflow data are available. It represents the first formal output from the SDL project.

- Section 2 describes the conceptual framework underpinning the SDL rules,
- Section 3 describes the selection of the study area,
- Section 4 discusses the definition of a winterfill period for south-west Western Australia,
- Section 5 outlines the rule for determining minimum flow thresholds,
- Section 6 outlines the rules for determining maximum extraction rates,
- Section 7 explores the effect assumed reliability of supply has on SDL volumes,
- Section 8 describes some characteristics of SDL volumes across south-west Western Australia,
- Section 9 looks at the impacts of extractions on the natural flow regime
- Section 10 explores some important considerations regarding SDLs, and
- Section 11 contains a summary of the outcomes from this part of the SDL project.

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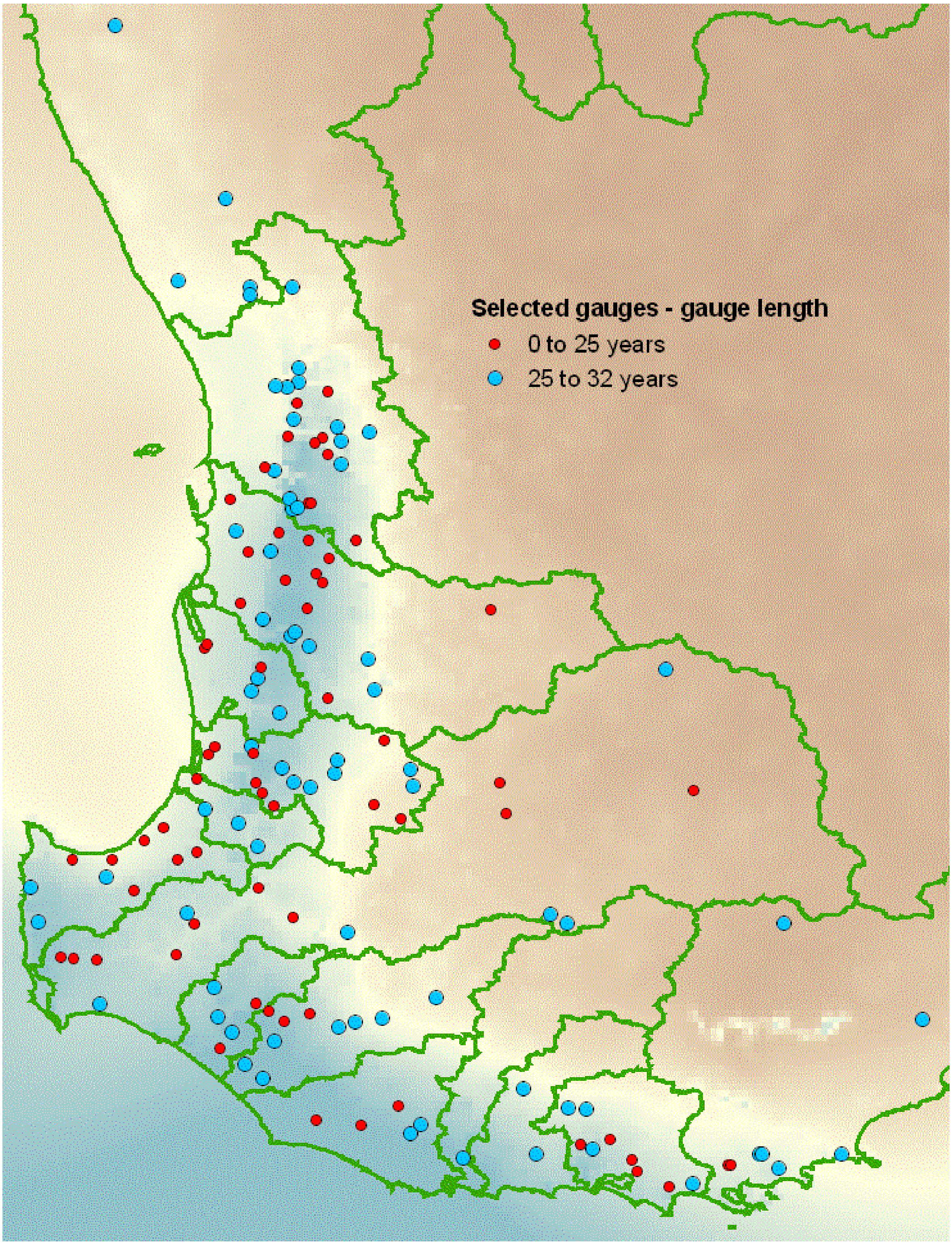


- **Figure 1.2: Selected gauge sites. The dot colour represents post-1975 record length, and the background colour rainfall contours (blue: high rainfall, red: low rainfall).**

2. Conceptual Framework for Winterfill Diversions

2.1 Introduction

In a regulated system, water for environmental maintenance can be deliberately released from the dam. Many techniques are available to estimate the Environmental Water Requirement (EWR) of downstream ecosystems (e.g. Arthington and Zalucki, 1998), so an environmental flow regime can be calculated and delivered.

However, for other generally smaller, unregulated streams, there are no similar methods by which an environmental flow can be specifically delivered. Rather, the only option in unregulated rivers is to limit the amount of water extracted. Essentially, the environmental component of the flow is the water that passes down the river without being diverted. The challenge in unregulated systems therefore is to ensure the water that remains in the system is sufficient to maintain or restore its environmental values.

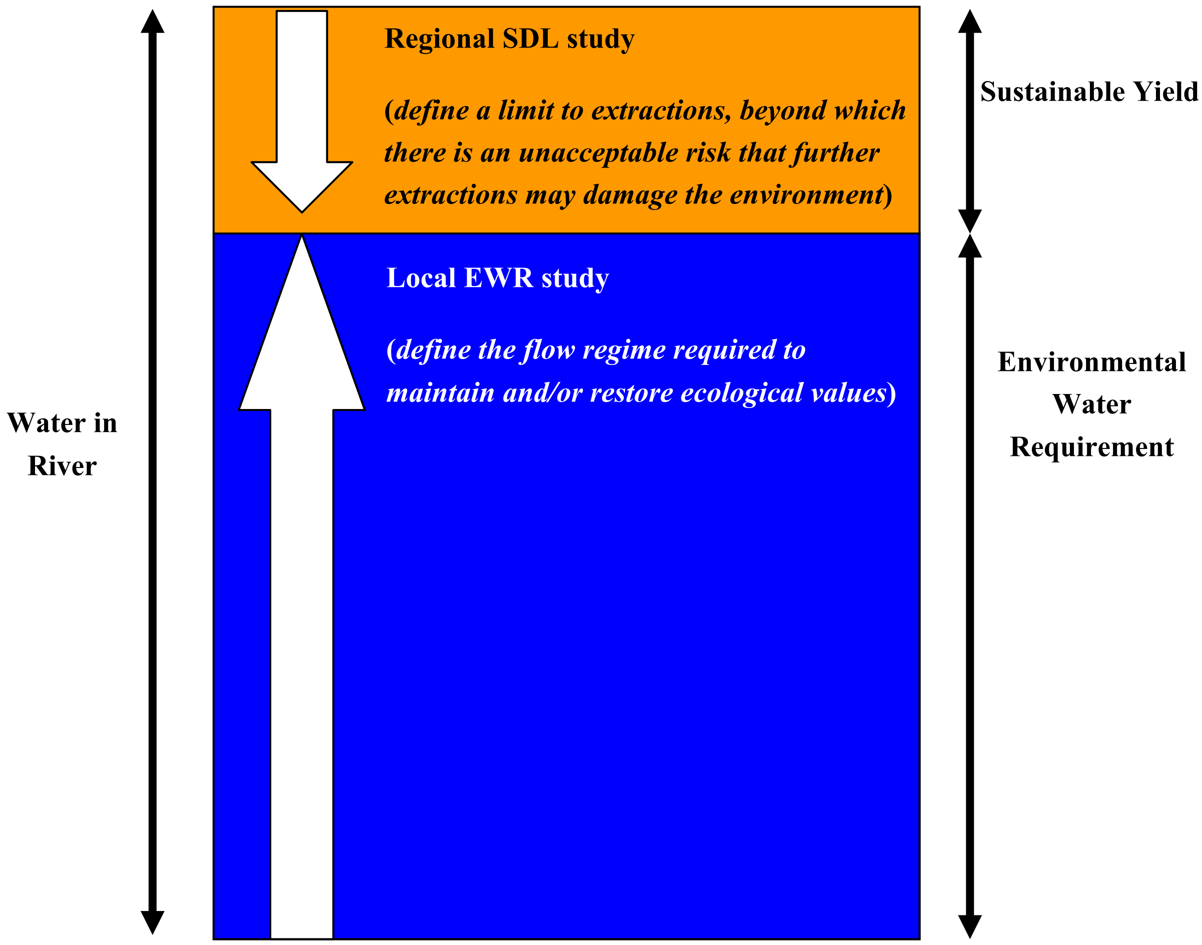
Many flows of ecological importance occur during the months which comprise a possible winterfill period for south-west Western Australia. For example:

- channel forming flows,
- flows that redistribute coarse sediments leading to riffle building that maintains the natural pool and riffle sequence,
- flows that redistribute large woody debris and particulate organic matter such as leaf litter,
- flows that scour solid surfaces, thus reducing algal build-up,
- flows that trigger seed germination and plant growth,
- flows that trigger fish migration or spawning, and
- flows that flood off-stream wetlands and connect the river to the floodplain.

Many methods for determining a river's EWR work on the principle of maintaining and protecting specific flow components such as these (e.g. the Building Block Method described by Arthington and Zalucki, 1998). Implicit in these methods is the concept that there are threshold flows which trigger events of ecological importance. During a detailed local EWR study of an individual river, important threshold flows can be identified from literature review, field examinations and modelling. Once the threshold flows are defined, environmental flow recommendations and sustainable yields can be defined to protect these flows.

A similar approach could be used to determine the sustainable yields for the unregulated catchments of south-west Western Australia. If a set of threshold flows that had ecological significance in all or most rivers could be identified, sustainable yields would be set to ensure the impact of extractions on threshold flows did not present an ecological risk. However, while in any given river it is possible to define threshold flows of ecological importance, defining such flows for the entire south-west of Western Australia, with its variety of stream sizes and types, would be a prohibitively costly and time-consuming task.

This project was therefore commissioned to address the challenge of developing a regional method for defining the sustainable yield, or Sustainable Diversion Limits (SDLs), of unregulated rivers. Defining sustainable yields using a regional method required a different conceptual approach to that adopted in local EWR studies. In local EWR studies, the flow regime required to maintain or restore ecological values is defined. That is, a bottom up approach is used. In contrast, the regional SDL method is by necessity a precautionary approach, and defines the limit beyond which there is an unacceptable risk that additional extractions may degrade the environment (Figure 2.1). The SDL method is therefore a top down approach.



- **Figure 2.1: A comparison of the regional Sustainable Diversion Limit and local Environmental Water Requirement approaches.**

2.2 Natural Variability

The conceptual framework adopted to underpin the derivation of rules which define SDLs for the unregulated catchments of south-west Western Australia, can be summarised by the following sentence.

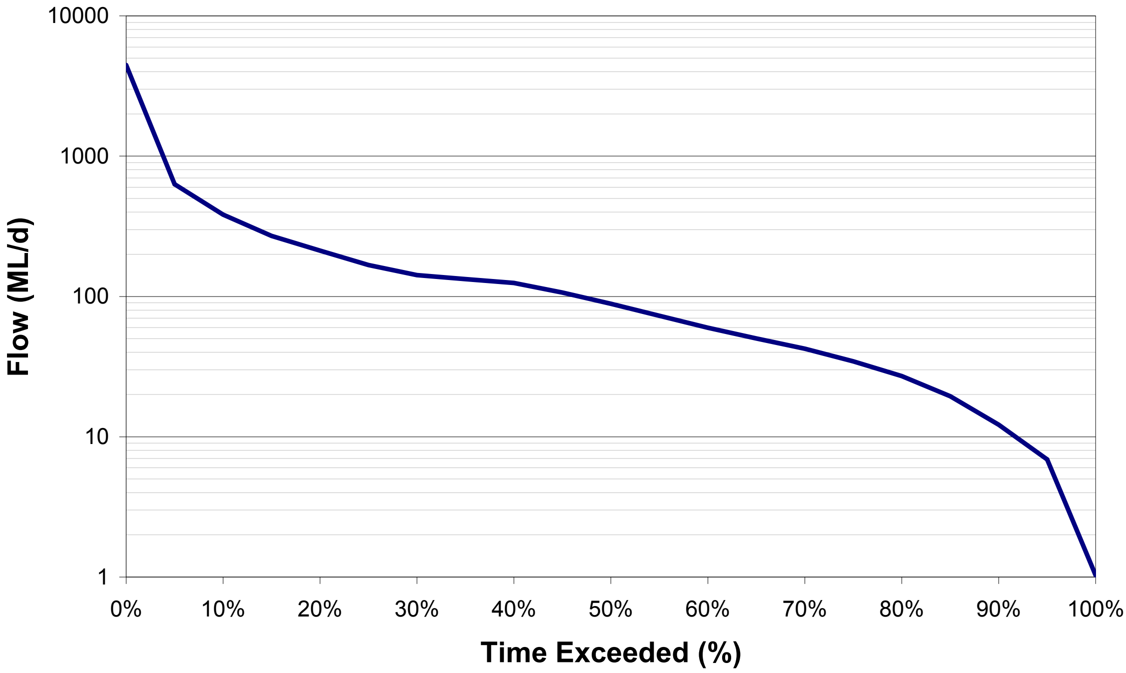
> *The winterfill period flow regime after extractions must be within the range of the natural (post 1975) winterfill period flow regime.*

It is assumed that, if the resulting flow regime is within the natural range, then key individual flow components in any individual river will be maintained within the natural range. If flow components are within their natural range, the thresholds flows which the ecological functions rely upon will also be within their natural range of frequency and duration.

The natural flow regime of any river is a complex mixture of variations in streamflow. Zero flows, periods of low, relatively constant flows, small freshes and large floods are all important components of the natural flow regime within a given year. Streamflows also vary from year to year, in accordance with low rainfall and high rainfall periods. All these variations need to be taken into account when defining the natural variability of the winterfill period flow regime.

Possibly, the simplest depiction of the variability of the flow regime during a hypothetical winterfill period is a flow duration curve. Figure 2.2 shows the flow duration curve for a period of June – October, for the Denmark River at Mt Lindesay, derived using daily data between 1975 and 2005. Natural flows during this period range from a high of 4450 ML/d in June 1988 to 1 ML/d in June 2002.

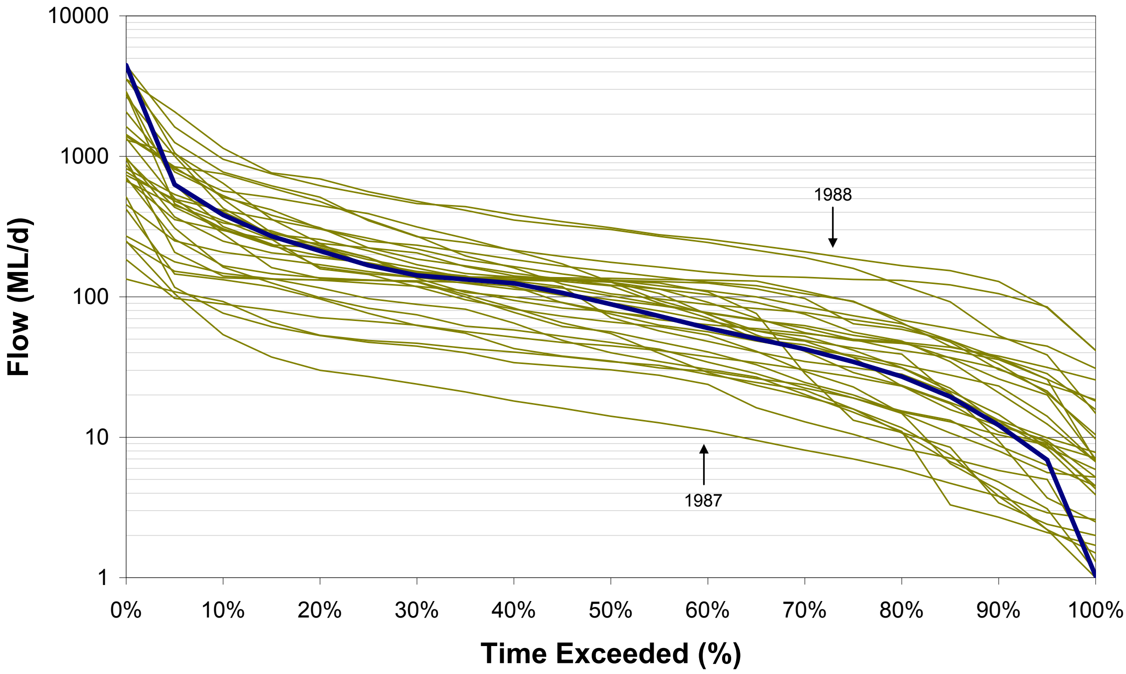
Flow duration curves also represent the proportion of time that flows of a given magnitude are exceeded. For example, it is common to characterise different aspects of the flow regime by percentiles of 'time exceeded'. 'Low flows' are often defined as flow exceeded 80% or 90% of the time and 'high flows' as flows exceeded 10% or 20% of the time. 'Typical flows' are best characterised by the median. While flow duration curves provide a simple means of describing the flow regime, they do not provide any indication of the sequence of events or the natural year to year variation in flows.



- **Figure 2.2: Flow duration curve of daily streamflow in the Denmark River at Mt Lindesay (603136), for the months June – October inclusive between 1975 and 2005.**

Figure 2.3 provides a better depiction of the variability of the winterfill period flow regime. Figure 2.3 contains flow duration curves of daily streamflow in the Denmark River at Mt Lindesay (603136) for each June – October period between 1975 and 2005. The 31 individual flow duration curves form an envelope around the overall flow duration curve (from Figure 2.2). The lower bound is predominately comprised of the flow duration curve for 1987, while the upper bound is predominately comprised of the flow duration curve for 1988.

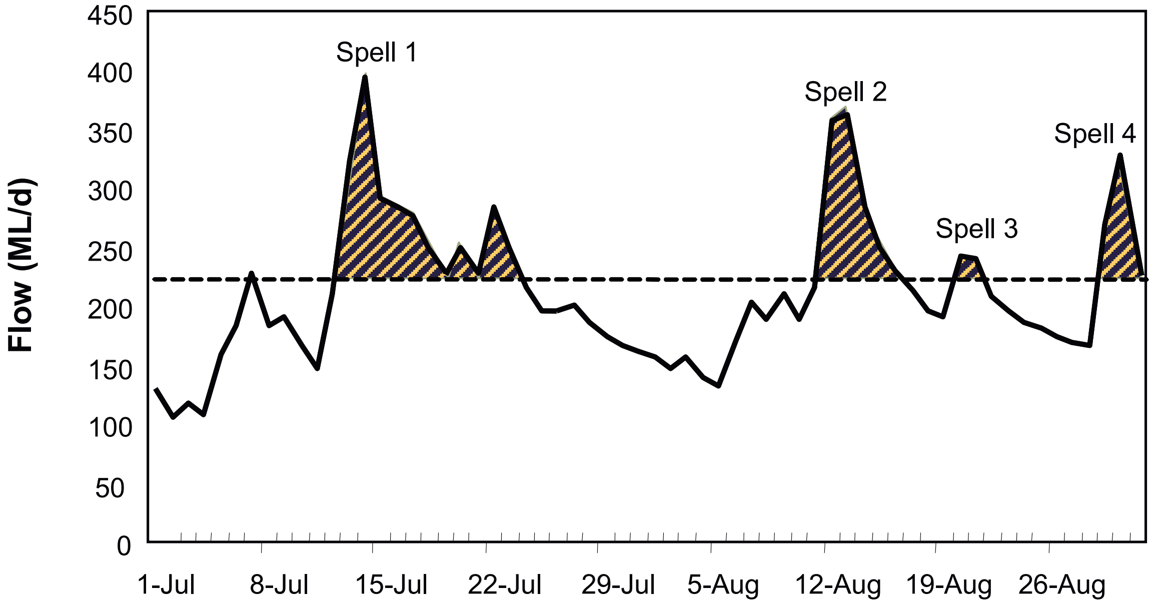
The envelope of flow duration curves represents the natural range of winterfill period flows (over the observed period 1975 – 2005). However, most curves form a cluster around the overall flow duration curve. That is, 1987 is somewhat separate from the main body of curves. Ecologically, 1987 would be considered a time of high environmental stress. Therefore, although the 1987 flow duration curve forms part of the natural range, it would be undesirable if the overall flow duration curve after extractions was too similar to a flow regime expected under extremely dry conditions.



- **Figure 2.3: Flow duration curves of daily streamflow in the Denmark River at Mt Lindesay (603136), for each June – October period between 1975 and 2005. The flow duration curve for all years (1975-2005), as shown in Figure 2.2 is shown in bold.**

Each annual flow duration curve is comprised of individual daily flows from that year's June – October period. A number of aspects of these individual flows also need to be taken into account, e.g. the frequency and duration of spells above flow thresholds of ecological importance (Figure 2.4). While maintaining the overall flow duration curve (after extractions) within the bounds of natural variability remains the objective in defining SDLs, it is also important to consider the impact of extractions on the frequency and duration of flows above thresholds of ecological importance.

Another significant issue in the natural variability of streamflow in the winterfill period is inter-annual sequencing. Droughts are followed by wetter years, wetter years by droughts, and so on. The ecological stress caused by droughts is relieved by wetter years. For example, for the Denmark River, the drought of 1986-87 was broken by the wet year of 1988 (Figure 2.3). Therefore, in maintaining the overall flow duration curve (after extractions) within the bounds of natural variability, it is also necessary to ensure the annual flow duration curves (after extractions) of wet years remain in the upper portion of the envelope of natural variability, so that periods of ecological stress are still relieved by wet years.

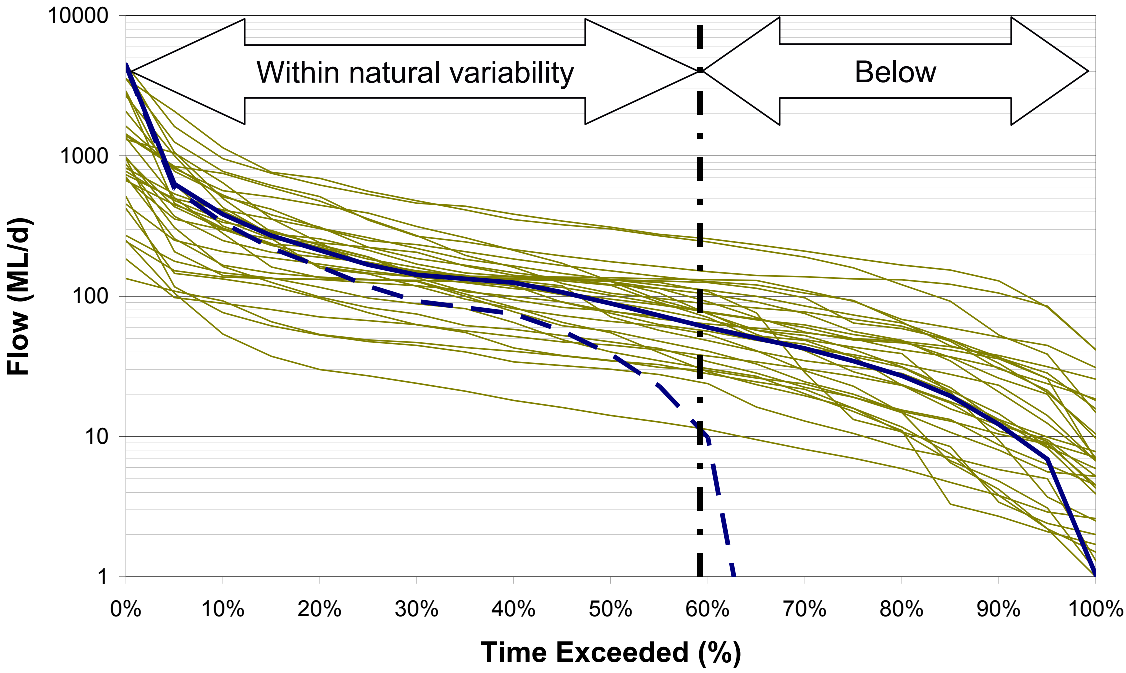


- **Figure 2.4: A schematic definition of spells above a flow threshold of 230 ML/d for a hypothetical stream.**

2.3 Impact of Diversions

The extraction of water from rivers can have a number of different impacts on the natural streamflow regime. For example, most farm dams capture the majority of inflows until the dam is full, reducing downstream flows and potentially eliminating small freshes while they fill. The impact of direct extractions varies according to the time that pumps operate. During low flow periods, direct extractions reduce the volume of flow, making low flows lower, but without changing the timing and shape of the hydrograph. When timed to coincide with freshes, direct extractions reduce the frequency and duration of those freshes.

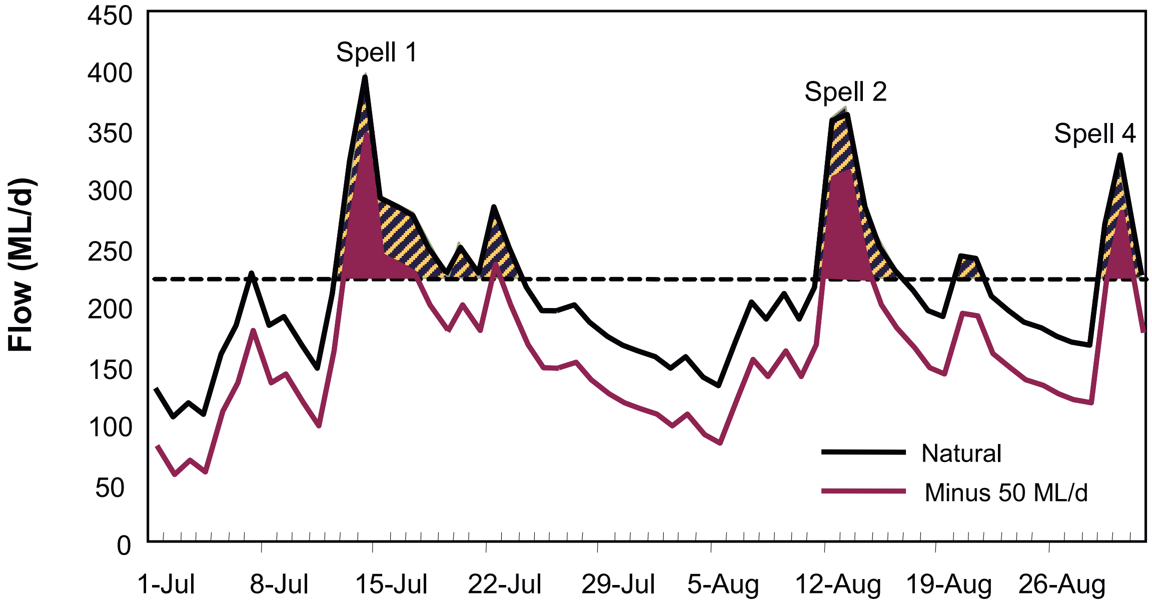
Assuming that all diversions from a river are via direct extractions with a constant extraction rate, the impact of diversions on the overall natural flow duration curve is to move the curve downwards by a volume equivalent to the extraction rate. For example, if 50 ML/d is diverted from the Denmark River at Mt Lindesay during the period June to October inclusive for all years between 1975 and 2000, any flow less than 50 ML/d becomes zero, and all other flows are reduced by 50 ML/d (Figure 2.5). The greater the extraction rate, the greater the shift of the flow duration curve downwards. What Figure 2.5 also shows, is that if a maximum extraction rate of 50 ML/d was set for the Denmark River at Mt Lindesay, without any other caveats, the resulting impacted flow duration curve would be outside the envelope of natural variability for 40% of the time.



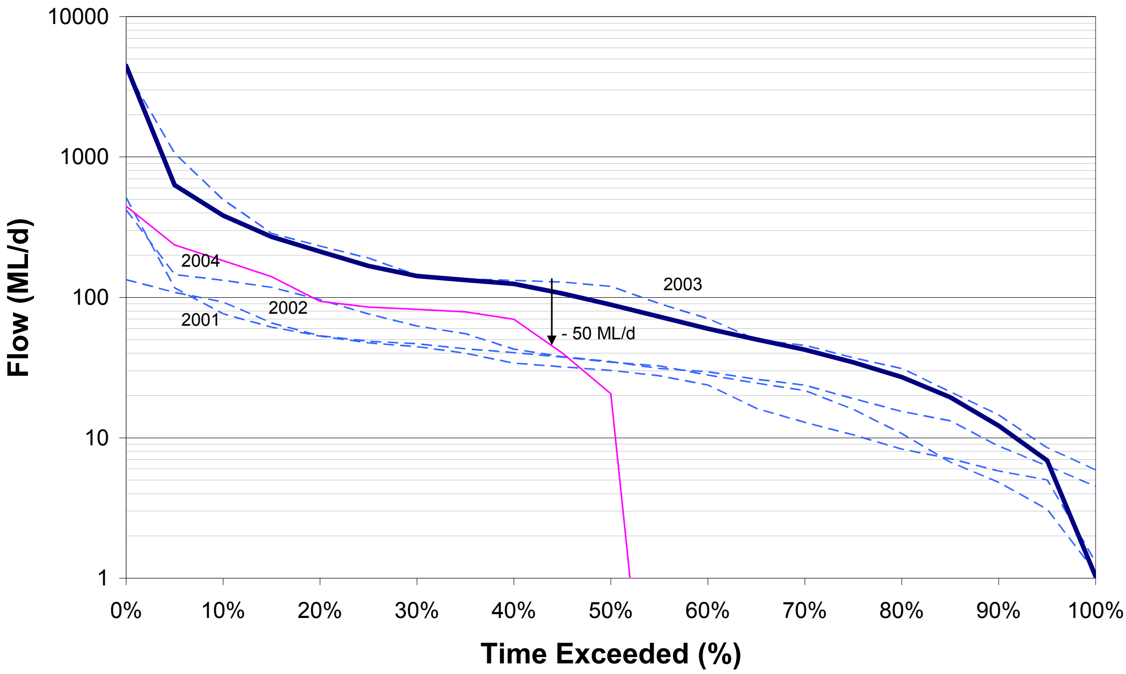
- **Figure 2.5: The dashed curve shows the flow duration curve in Figure 2.2 after extractions of 50 ML/d. For 40% of the time, the impacted flow duration curve is outside the envelope of variability experienced under natural conditions.**

As introduced in Section 2.2, extractions also have an impact on the frequency and duration of spells. For example, Figure 2.6 shows that if 50 ML/d is extracted from the hypothetical time-series of daily flows in Figure 2.4, the number of spells above the threshold of 230 ML/d reduces from four to three, and the duration of spells 1, 2 and 4 above the threshold is reduced. The greater the extraction rate, the greater the impact on the frequency and duration of spells above thresholds of ecological importance.

Extractions can also adversely alter the inter-annual sequence of wet and dry years. Following a drought of several years, it is likely that large volumes of water will be extracted to fill depleted off and on-stream storages once the drought broke. Unchecked extractions could, from the river's point of view, extend the dry period. For example, if 50 ML/d was taken from the Denmark River at Mt Lindesay from June to October in 2003, the resulting flow duration curve would resemble the 2001, 2002 and 2004 flow duration curves, thus extending the dry spell from three out of four years, to a sequence of four consecutive years.



- **Figure 2.6: Spells above 230 ML/d, after extractions of 50 ML/d, for a hypothetical stream.**



- **Figure 2.7: The flow duration curves for the period June – October in 2001, 2002, 2003 and 2004 under natural conditions (dashed lines), and for 2003 if 50 ML/d is extracted (solid line). The flow duration curve in Figure 2.2 is shown in bold.**

2.4 Components of the Sustainable Diversion Limit Rules

By defining the conceptual framework and overall objective underpinning the project, and by identifying components of the natural streamflow regime affected by extractions, the study team were able to develop a method that defined SDLs which were consistent with the overall objective, and limited the effect extractions had on spell frequency and duration and inter-annual sequencing.

The first deliberations of the study team were about the period over which extractions would be allowed, i.e. the winterfill period.

Subsequently, it became apparent that allowing diverters to extract water every day of a defined winterfill period, would move the impacted flow duration curve outside the envelope of natural variability at the low flow end of the streamflow regime, thereby increasing the frequency and duration of zero and low flow spells (Figure 2.5). To avoid this situation, a minimum flow threshold (MFT) became necessary. By stipulating that extractions must cease if streamflows fall below the MFT, the problem of impacted low flows being outside the envelope of natural variability is solved. Figure 2.8 shows the impacted flow duration curve for the Denmark River at Mt Lindesay if a MFT of 35 ML/d was adopted.

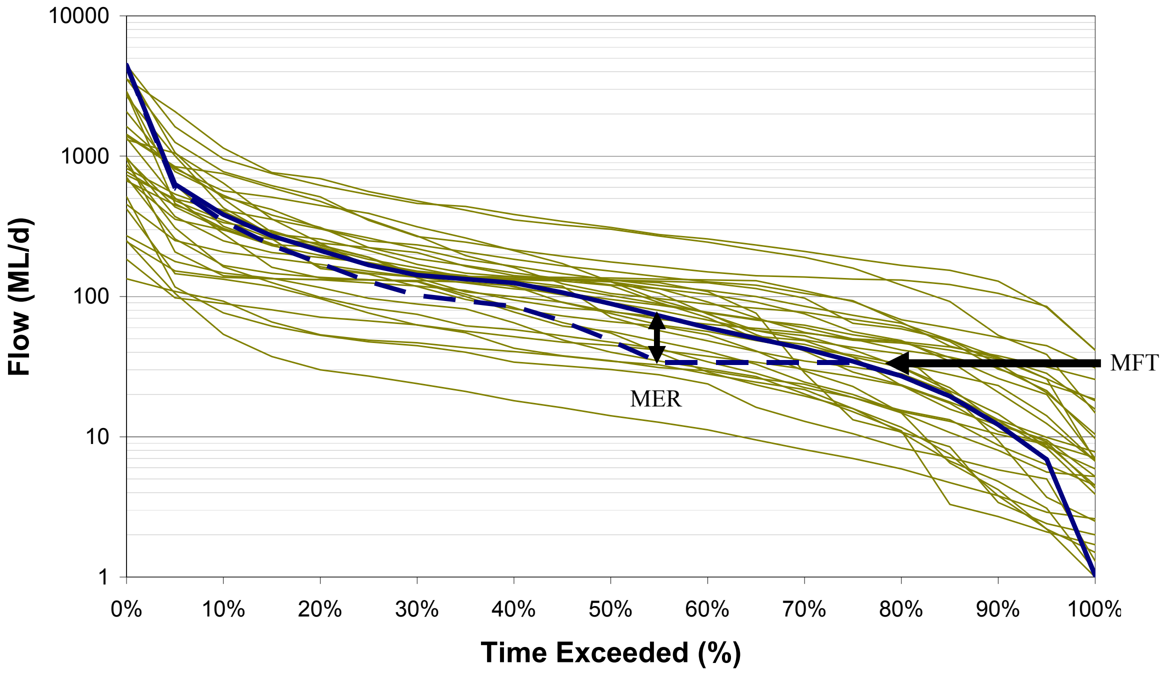
For flows above the MFT, unchecked extractions would ‘flat-line’ streamflows at the MFT for long periods of time. This situation would move the impacted flow duration curve outside the envelope of natural variability at the high flow end of the streamflow regime, remove spells above the MFT, and reduce the inter-annual variability of streamflows. Each of these problems is countered by setting a maximum extraction rate (MER), which limits the volume of water taken from the river on any given day. Figure 2.8 shows the impacted flow duration curve for the Denmark River at Mt Lindesay if a MER of 40 ML/d was adopted.

Therefore, the major rules which define the SDL for each catchment of south-west Western Australia became the:

- Winterfill period,
- Minimum flow threshold, and a
- Maximum extraction rate.

By employing these rules, it was possible to calculate the volume of water available for extraction each year. Based on these time-series of extractions, a seasonal limit was imposed that yielded a maximum diversion volume with an expected annual reliability of supply.

Each of these rules is discussed in detail, in the four chapters that follow.



- **Figure 2.8: The overall flow duration curve under natural (highlighted) and impacted (dashed) conditions, for the Denmark River at Mt Lindesay (603136), assuming a minimum flow threshold (MFT) of 35 ML/d and a maximum extraction rate (MER) of 40 ML/d.**

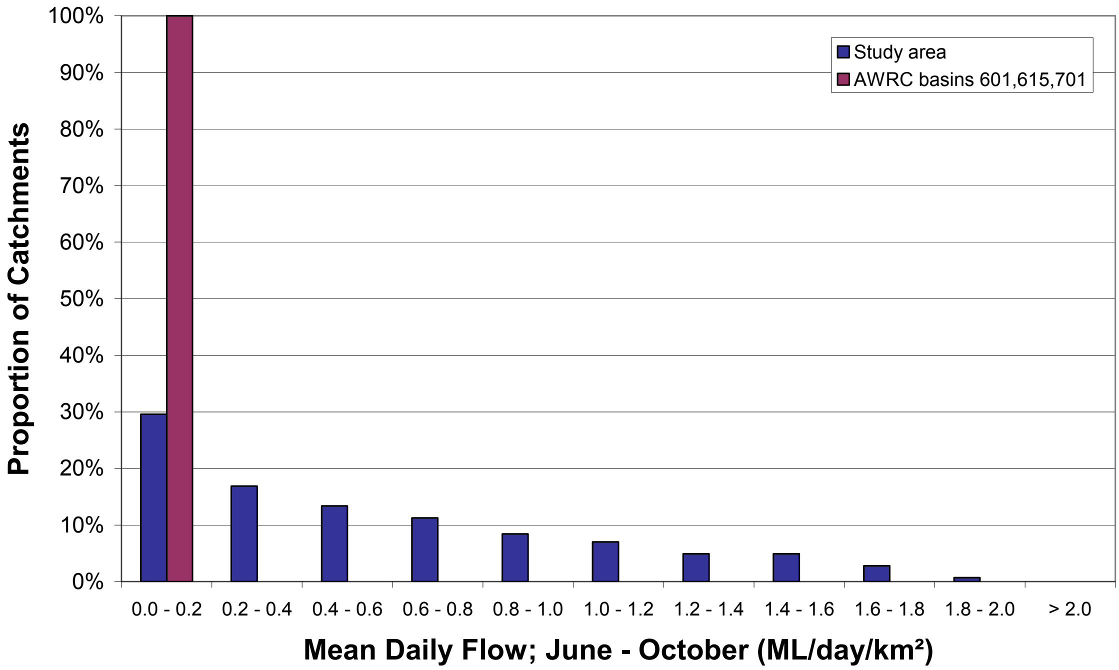
3. Refinement of Study Area

Before the rules which define the SDLs of unregulated catchments in south-west Western Australia were developed, the area to which these rules would apply was refined. Initially, it was thought the SDL rules would apply to the whole of south-west Western Australia (Figure 1.1). However, analysis of the streamflow data from AWRC basins 601, 615 and 701 showed the attributes of catchments at the northern and eastern extremities of the initial study area to be very different to the attributes of catchments in the remainder of the study area.

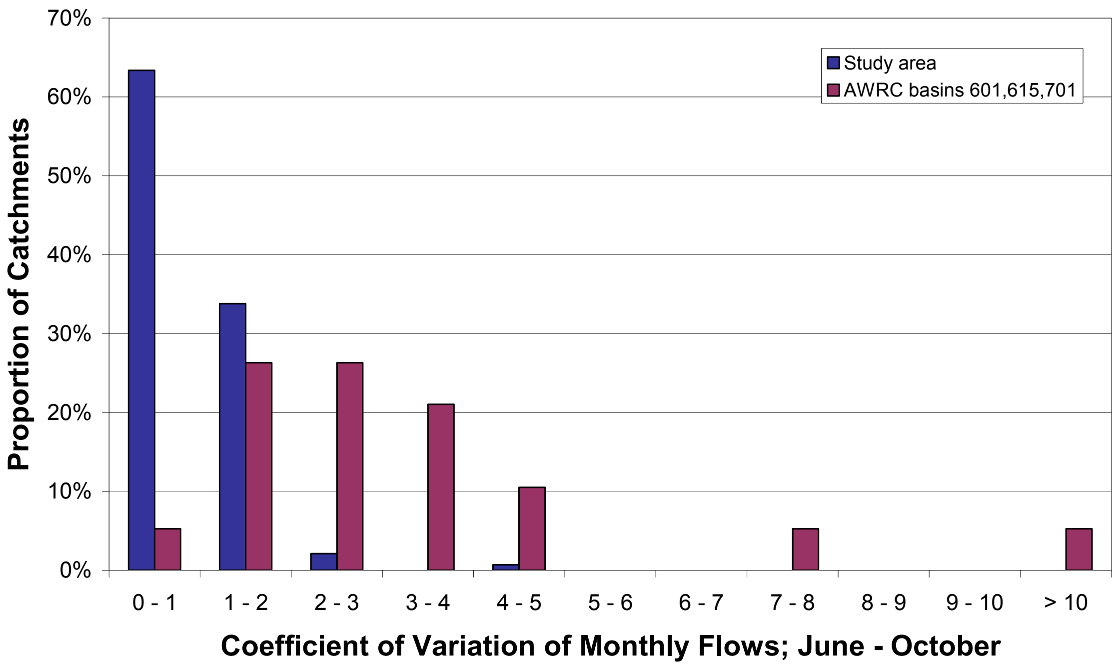
For example, from the streamflow records of 19 gauging sites in basins 601, 615 and 701, it was apparent that compared to the unregulated rivers in the remainder of the study area, rivers to the north and east have lower mean daily flows (Figure 3.1), greater variability in flows (Figure 3.2) and less contribution from baseflows (Figure 3.3) during months which were candidates for the winterfill period. The opinion of the study team was that the unregulated rivers with greatest potential for sustainable extractions would exhibit consistently high flows during the winter and spring months, underpinned by reasonable contributions of baseflow. The sites in basins 601, 615 or 701 did not demonstrate these attributes, and therefore it was decided by the study team to exclude these basins from the study area, on the assumption that the low and variable flows typical of these regions would restrict the industrial and agricultural use of surface water resources.

Basins 618, 619 and the eastern half of basin 602 were also excluded from the study area by the study team, because of their hydrologic similarity to basins 601, 615 and 701.

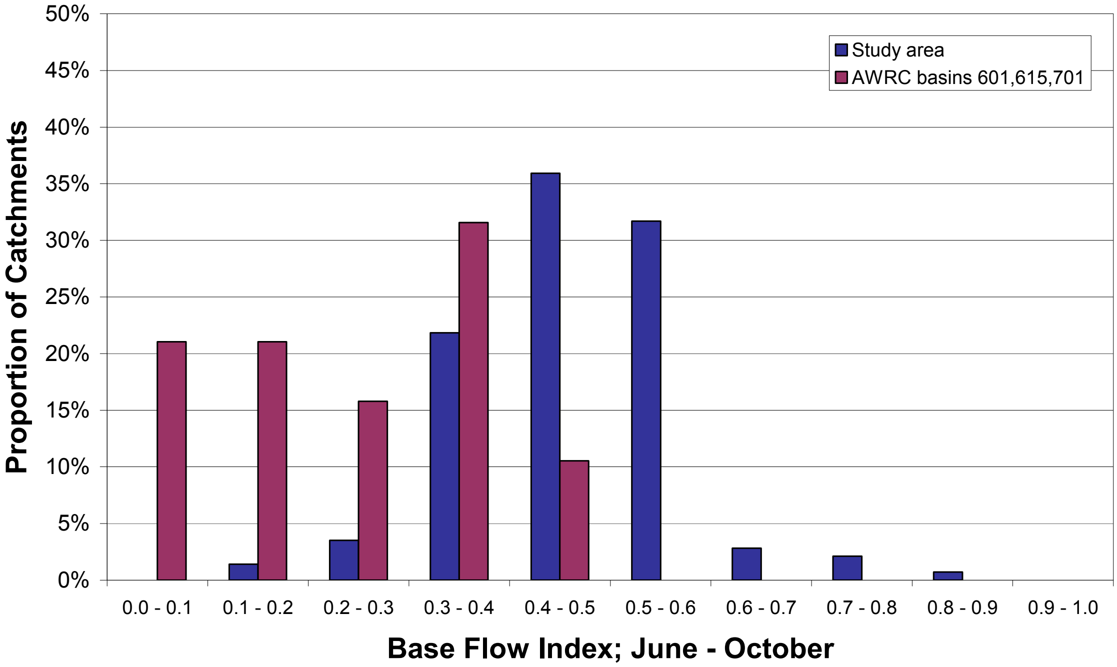
The final study area adopted is shown in Figure 3.4. All further references to ‘south-west Western Australia’ in this report refer to this study area.



- **Figure 3.1: Mean daily flow (in ML/day/km^2) for the months June – October, for 19 sites in AWRC basins 601, 615 and 701 versus 142 sites in the adopted study area. Mean daily flows outside the study area are much lower than within the study area.**



- **Figure 3.2: Monthly coefficients of variation for the months June – October, for 19 sites in AWRC basins 601, 615 and 701 versus 142 sites in the adopted study area. The variability in flows is much greater outside the study area than within the study area.**



- **Figure 3.3: Base flow index (estimated proportion of total streamflow that is derived from groundwater discharge) for the months June – October, for 19 sites in AWRC basins 601, 615 and 701 versus 142 sites in the adopted study area. The contribution of baseflow to streamflows is much less outside the study area than within the study area. The base flow index was calculated using a digital filter (Nathan and McMahon, 1990).**

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- **Figure 3.4: The adopted study area for the south-west Western Australian SDL project is shaded.**

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4. The Winterfill Period

4.1 Introduction

The first decision required when developing the SDL rules was to define the period over which extractions would be allowed (i.e. the winterfill period). Currently, diverters are not allowed to abstract water during summer months, but may take water at any other time. However, these periods of no abstraction are neither specifically defined nor currently enforced by the Department of Water. One of the key objectives of this study therefore, was to develop a rigorous and defensible definition of the winterfill period, when diversions would be allowed.

The transition between extended ‘dry’ and ‘wet’ periods (e.g. the transition from summer to winter and winter to summer) was identified by the study team as being particularly important in all catchments. The dry period of the year, characterised by low water levels and poorer water quality, can place a great amount of stress on river biota. These stresses are often exacerbated by extractions from the river to irrigate agriculture.

The first high flows of the wet period relieve the environmental stresses present during the dry period of the year, and act as triggers for a number of events of ecological significance, such as fish movement and preparation for breeding (Humphries, 1989). In ephemeral rivers, the first flows stimulate invertebrate production (Boulton and Lake, 1992).

The study team considered the transition from ‘wet’ to ‘dry’ to be of equal ecological importance to the transition from ‘dry’ to ‘wet’. For example, the final high flows in a given year can influence the survival of juvenile fish, the condition of biota in preparation for the upcoming dry period, and the distribution of aquatic species before river pools become isolated.

Diversion of the first and/or final high flows of the wet period of the year has the potential to extend the environmental stresses experienced by the biota, and interrupt the ecological events associated with the transition from ‘dry to wet’ and ‘wet to dry’ periods. Therefore, the key driver of the study team in defining a winterfill period for the south-west of Western Australia was protecting the months, or portions of months, which contained these initial transitional periods.

4.2 Approach

To inform the study team’s deliberations about the winterfill period, several criteria were used:

1) The wettest one month, two month and three month period within a year, based on mean daily flows (Section 4.3.1),
2) The probability of daily flows within given months exceeding a proportion of the mean daily flow (Section 4.3.2), and

3) The probability of daily flows within given months exceeding the median daily flow of the wettest three months (Section 4.3.3).

The first criterion is self-explanatory, while criteria 2 and 3 simply examined the probability of high flows occurring in different candidate months. For the purposes of defining the winterfill period, high flows were nominally defined as a fraction of mean daily flow (calculated over the whole year), and flows above the median flow of the three wettest months (which turned out to be July, August and September).

The overall approach used to define the winterfill period was to apply each criterion in turn, and examine the relative difference in results between months. Therefore, while the thresholds applied in criteria 2 and 3 were somewhat arbitrary, they remained independent of scale and location, and allowed the relative probabilities of ‘high’ flows occurring to be compared across months, using results from all catchments (i.e. regardless of size).

To further emphasise the validity of criteria 2 and 3, Section 4.3.4 examines the sensitivity of results to different thresholds which are also a function of mean or median flows. Section 4.3.4 shows that regardless of threshold, the relative difference in results between months remains constant.

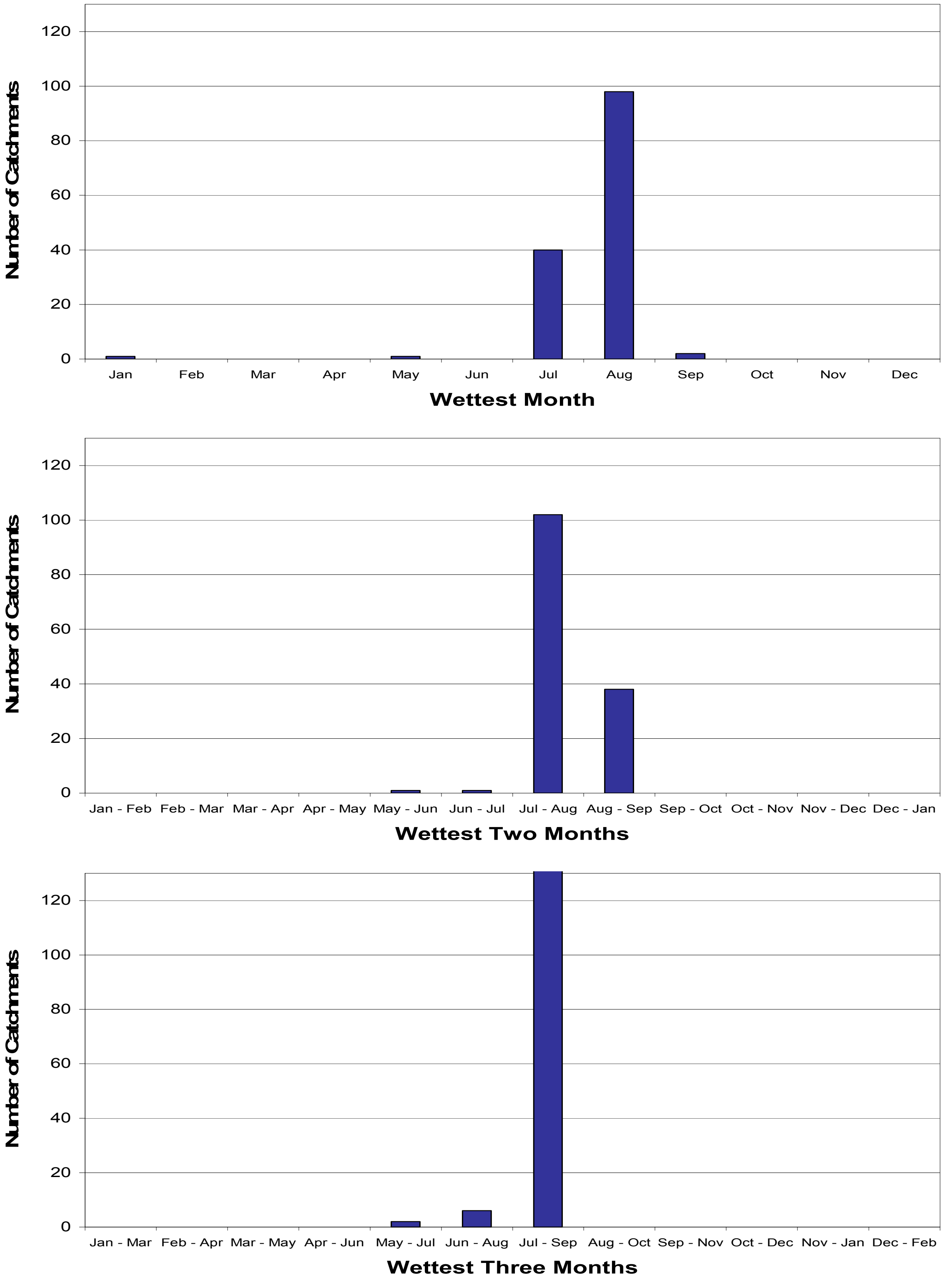
Section 4.4 summarises the conclusions of the study team with respect to the winterfill period, following their considerations of the results presented in Sections 4.3.1 – 4.3.4.

4.3 Evaluation of Candidate Months

4.3.1 Wettest Months

Figure 4.1 contains a count of the wettest one month, two month and three month period within a year for the 142 selected sites, based on mean daily flows. For example, for 98 of the 142 selected sites, August has the highest mean daily flow; for 102 of the 142 selected sites, the two month period with the highest mean daily flow is July-August; and for 134 of the 142 selected sites, the three month period with the highest mean daily flow is July-August-September.

Based on Figure 4.1, the logical conclusion made by the study team was that the winterfill period would include the months July – September. This conclusion is also supported by Section 4.3.2 and Section 4.3.3, which show that July, August and September are consistently the ‘wettest’ months. However, the inclusion or otherwise of other months in the winterfill period, such as June and October, was based on considerations of other criteria, such as those discussed in Section 4.3.2 and Section 4.3.3.



- **Figure 4.1: Counts for the start month with the highest mean daily flows over one, two, and three month periods.**

4.3.2 Threshold Based on a Proportion of the Mean Daily Flow

Figure 4.2 contains box plots of the probability of daily flows in the candidate winterfill period months (March – November) exceeding 0.4 of the mean daily flow (calculated over the whole year). 0.4 is an arbitrary threshold which is examined further in Section 4.3.4.

Figure 4.2 shows that based on results from the 142 selected sites, for 90% of sites, there is at least a ~60% chance that daily flows in July will exceed 0.4 of the mean daily flow. However, the two important conclusions drawn from Figure 4.2 were that:

- Daily flows in July, August and September have a much greater probability of exceeding 0.4 of the mean daily flow than daily flows in the other months analysed, and
- Daily flows in June and October have a much greater probability of exceeding 0.4 of the mean daily flow, than daily flows in March, April, May and November.

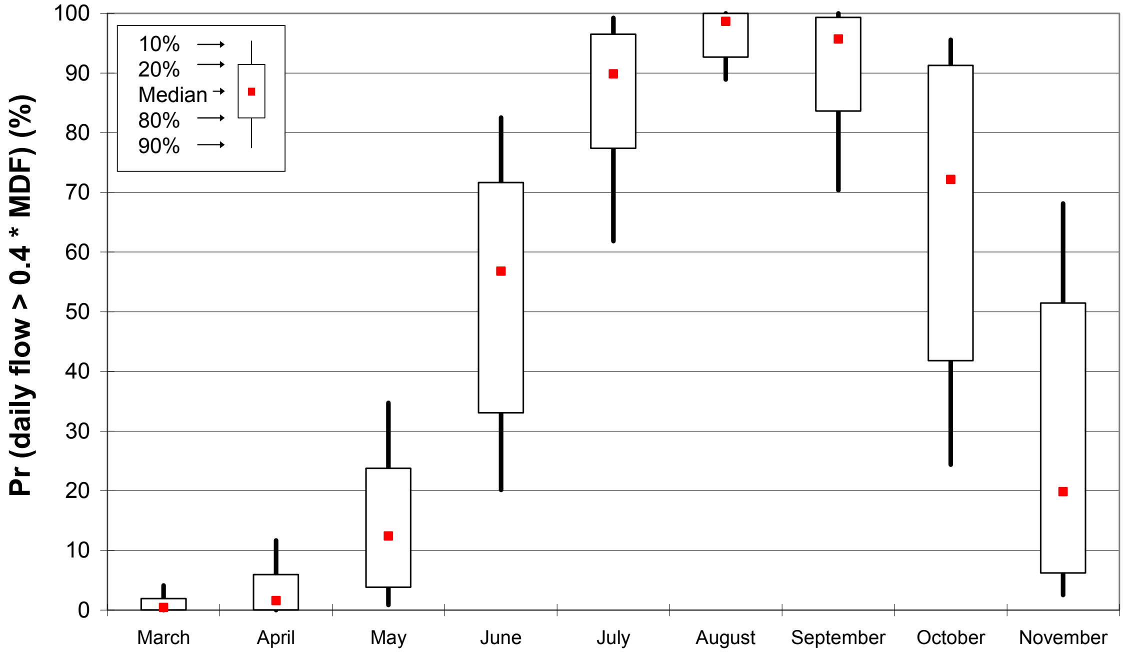
These results indicated that June and October, along with July-September were possible inclusions for the 'winterfill' period. To better understand the distribution of flows within June and October, it was decided by the study group to split these months in two (June 1st-14th and June 15th-30th, and October 1st-15th and October 16th-31st) and redo the threshold analysis (Figure 4.3).

Figure 4.3 shows a similar pattern to Figure 4.2. From Figure 4.3, the additional conclusions drawn were that in south-west Western Australia,

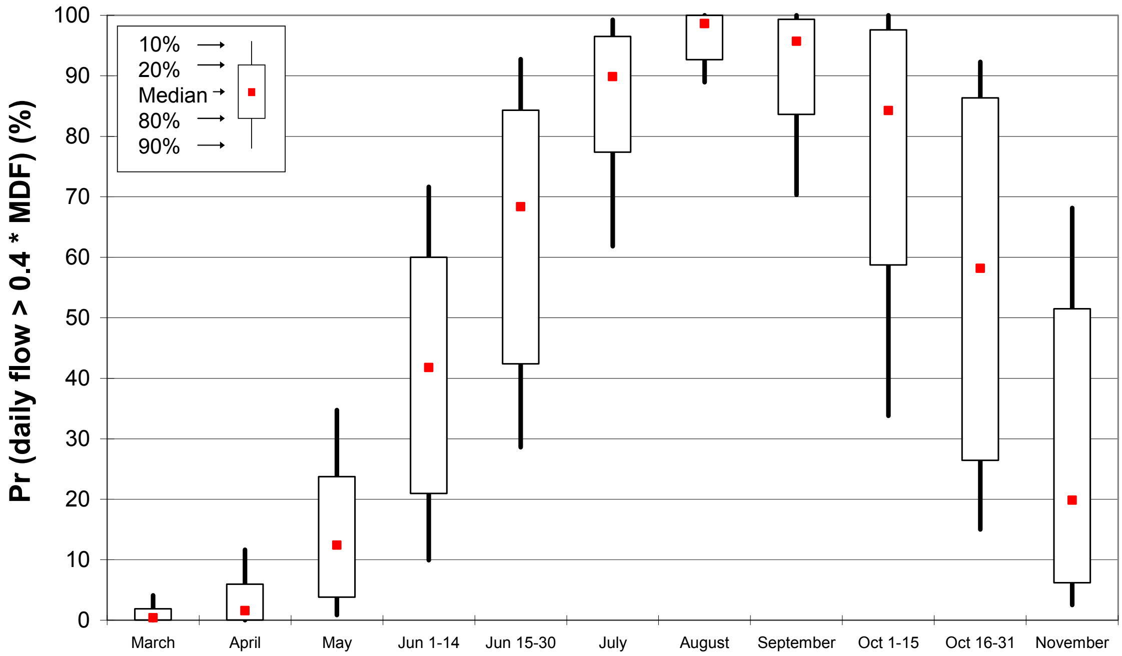
- the initial transition from 'dry' to 'wet' generally occurs in the first half of June,
- the transition from 'wet' to 'dry' generally occurs in the second half of October or during November, and
- in some years, the 'wet' period is shorter, and the transitions occur later or earlier (e.g. Figure 4.4).

With all this in mind, it was the opinion of the study team that it would be appropriate to extend the winterfill period to include the second half of June and first half of October,

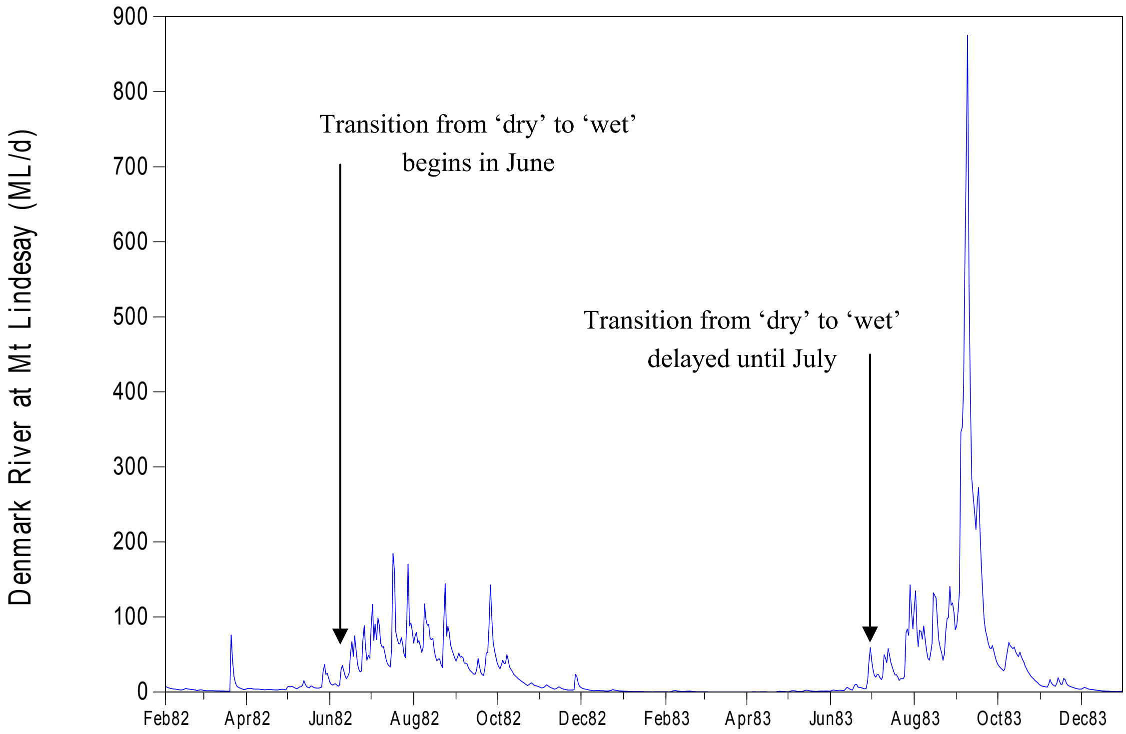
- provided the adopted minimum flow thresholds protected the ecologically important aspects of 'winter start' and 'winter end' streamflows, should they occur during the winterfill period, and
- because limiting the winterfill period to July – September would, in a number or years, deprive diverters the opportunity to extract water during high flow events which occurred in the second half of June or the first half of October.



- **Figure 4.2: Box plots of the probability that daily flows in March, April, May, June, July, August, September, October and November exceed 0.4 of the mean daily flow (calculated over the whole year).**



- **Figure 4.3: Box plots of the probability that daily flows in March, April, May, June 1st-14th, June 15th-30th, July, August, September, October 1st-15th, October 16th-31st and November exceed 0.4 of the mean daily flow (calculated over all the whole year).**

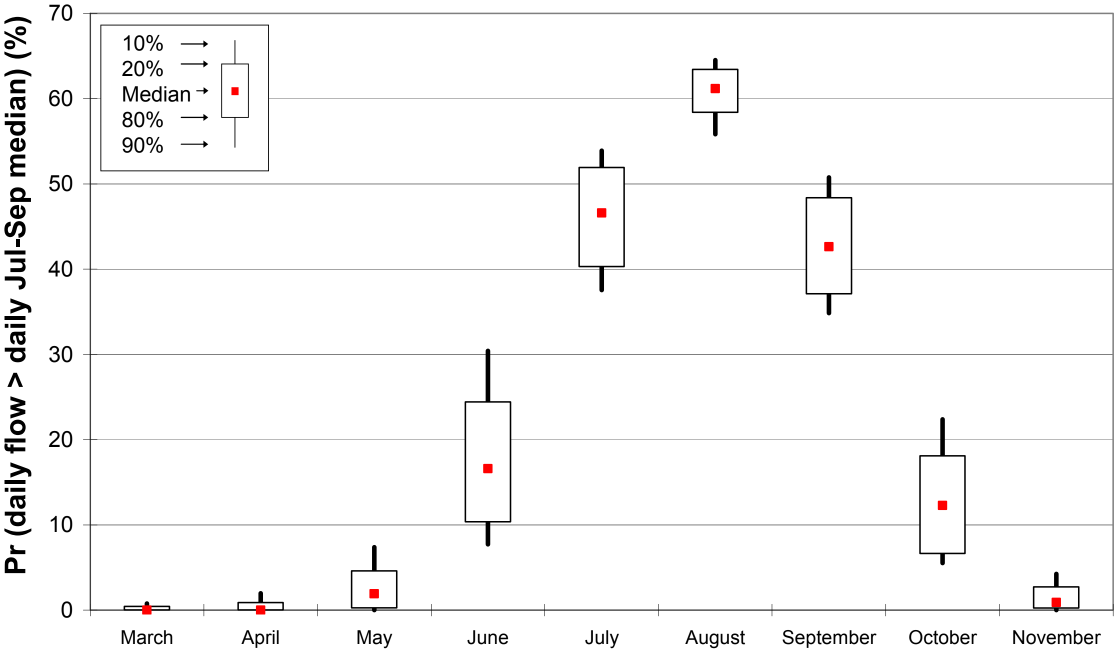


- **Figure 4.4: An example of the different year to year timing in transition flows. Generally in south-west Western Australia, transition from 'dry' to 'wet' occurs in the first half of June, and the transition from 'wet' to 'dry' in the second half of October.**

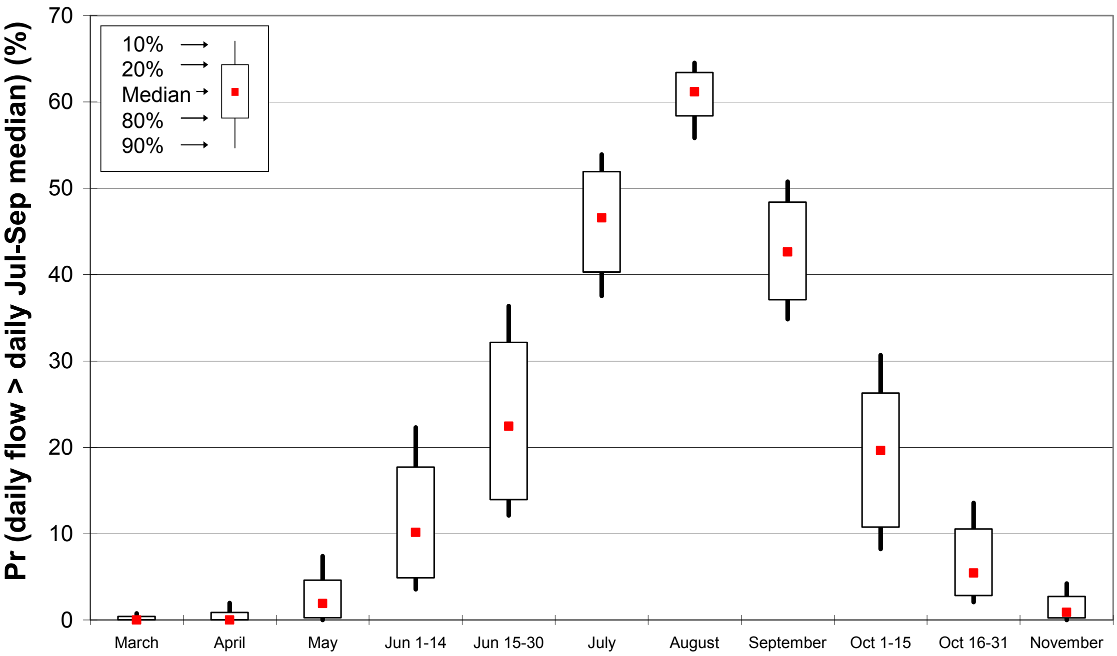
4.3.3 Threshold Based on the Median Jul-Sep Daily Flow

Given July-September formed part of the winterfill period as the three wettest months, when defining the whole winterfill period it became worth considering a threshold based on flows between July and September. Figure 4.5 contains box plots of the probability of daily flows in the candidate months exceeding the median Jul-Sep daily flow. For example, Figure 4.5 shows that based on results from the 142 selected sites, for 80% of sites, there is at least a ~10% chance that daily flows in June will exceed the median Jul-Sep daily flow. Again, the important aspect of Figure 4.5 is the difference in results for June and October, compared with the results for March, April, May and November. These results again indicated that June and October were transition months and therefore also candidate months for the winterfill period.

Again, to better understand the distribution of flows within June and October, it was decided to split these months in two, i.e. June 1st-14th and June 15th-30th, and October 1st-15th and October 16th-31st (Figure 4.6). Figure 4.6 gives the same insight as Figure 4.3, i.e. that it would be defensible to include June 15th-30th and October 1st-15th in the winterfill period, provided the adopted minimum flow thresholds protect the ecologically important aspects of 'winter start' and 'winter end' streamflows should they occur during the winterfill period.



- **Figure 4.5: Box plots of the probability that daily flows in March, April, May, June, October and November exceed the median Jul-Sep daily flow.**



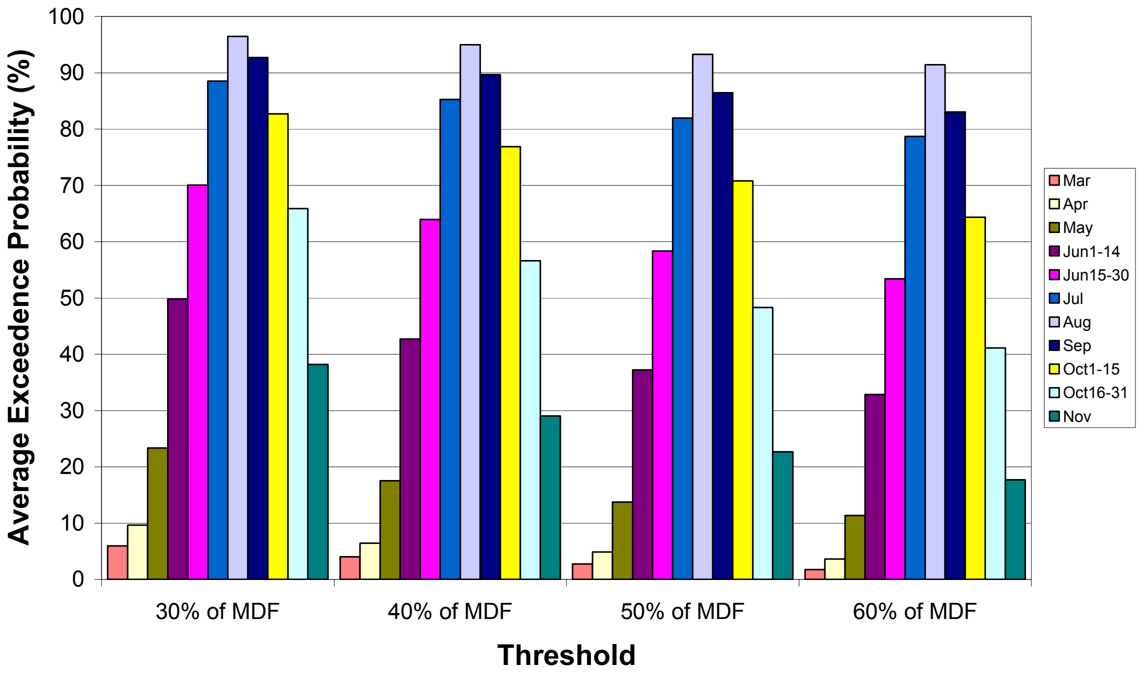
- **Figure 4.6: Box plots of the probability that daily flows in March, April, May, June 1st-14th, June 15th-30th, July, August, September, October 1st-15th, October 16th-31st and November exceed the median Jul-Sep daily flow.**

4.3.4 Comparison of Median and Mean Thresholds

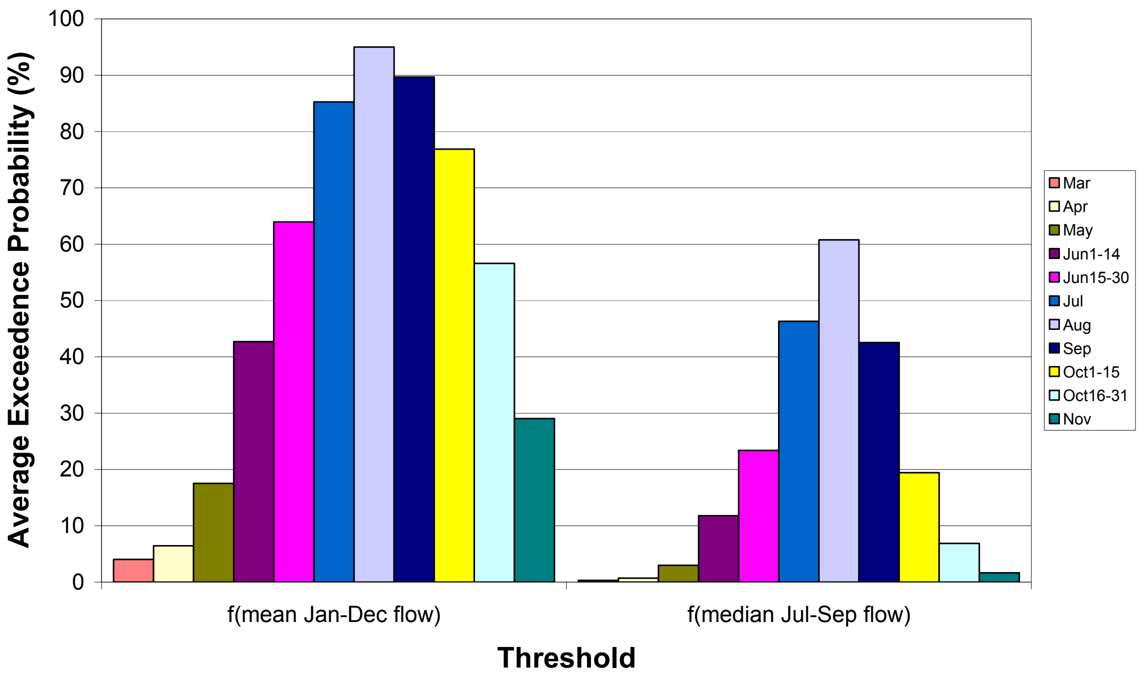
Given the thresholds in Section 4.3.2 and Section 4.3.3 were somewhat arbitrarily chosen, it was decided to examine the difference in results if other equally appropriate thresholds were chosen. Results from all 142 sites were used, and June and October were again split in two.

Figure 4.7 shows the average probability of flows in candidate months for the winterfill period exceeding thresholds which are 0.3, 0.4, 0.5 and 0.6 of the mean daily flow (calculated over the whole year). What is encouraging about Figure 4.7 is that regardless of the threshold chosen, the pattern of probabilities remains the same. That is, the relative difference in probabilities between months remains relatively constant across the four thresholds.

Figure 4.8 compares the probability of flows in candidate months exceeding a threshold which is 0.4 of the mean daily flow (calculated over the whole year), and a threshold which is the median Jul-Sep daily flow. Again, the relative difference in probabilities between months is similar for the two thresholds. Although October 1^{st}-15^{th} has a higher average exceedance probability than June15^{th}-30^{th} when the threshold is a function of mean flow, and June15^{th}-30^{th} has a higher average exceedance probability than October 1^{st}-15^{th} when the threshold is a function of median flow, the probabilities for these periods are significantly higher than the probabilities for other periods regardless of threshold. Figure 4.7 and Figure 4.8 therefore show that the study team's conclusions about the winterfill period were independent of the thresholds chosen in Sections 4.3.2 and 4.3.3.



- **Figure 4.7: A comparison of the average probabilities that daily flows in March, April, May, June 1st-14th, June 15th-30th, July, August, September, October 1st-15th, October 16th-31st and November exceed various proportions of the mean daily flow.**



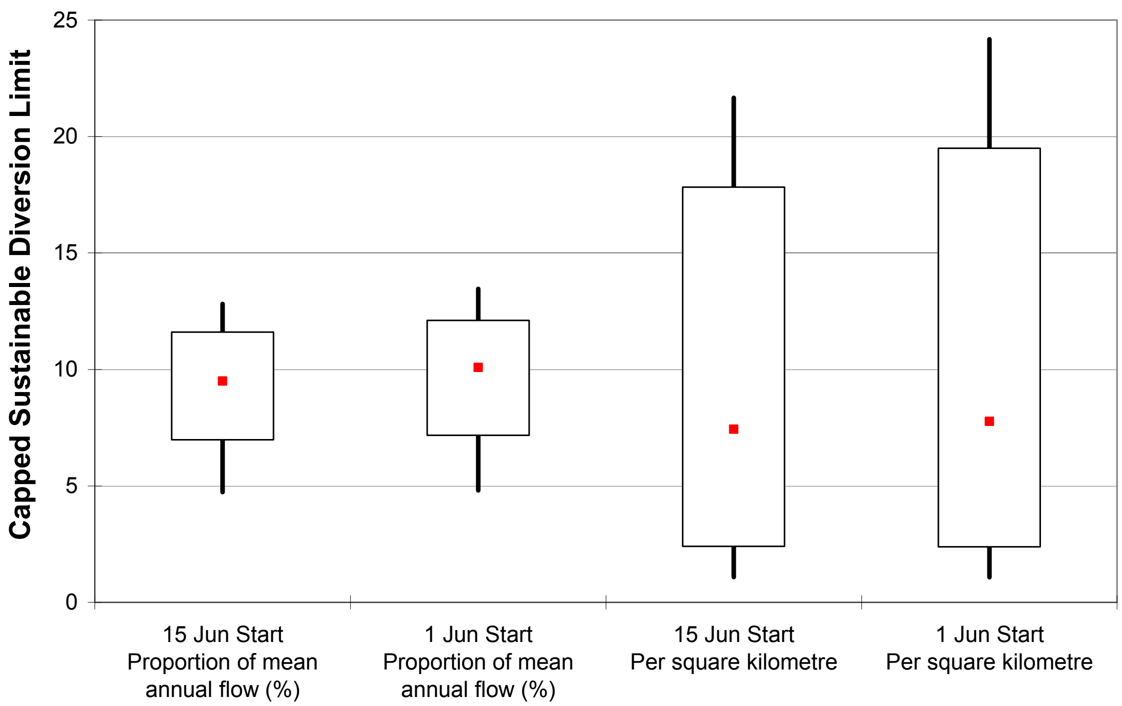
- **Figure 4.8: A comparison of the average probabilities that daily flows in March, April, May, June 1st-14th, June 15th-30th, July, August, September, October 1st-15th, October 16th-31st and November exceed 0.4 of the mean daily flow, or the median Jul-Sep daily flow.**

4.4 Sensitivity of Sustainable Diversion Limits to the Winterfill Period

In response to comments from the study team that adopting a winterfill period beginning on June 1st may be appropriate in the south-west corner of the study area, the sensitivity of SDL volumes to the winterfill period was investigated. Starting on June 1st would extend the duration of the winterfill period by 14 days, or 11%. While this investigation needed to wait until the remaining SDL rules were determined, it is logical to report the outcomes here.

Figure 4.9 shows that for the 142 gauged catchments selected, starting the winterfill period on June 1st would increase the median capped SDL from 9.5% of mean annual flow (MAF) to 10.1% of MAF. Figure 4.10 maps the percentage change in SDL. There is some spatial correlation in Figure 4.10, but the correlation is not strong. That is, it could be argued that extending the winterfill period is more likely to increase the SDL of catchments closer to the coast, and decrease the SDL of catchments further away from the coast, but the evidence is not convincing. Extending the winterfill period can decrease the SDL, because of the interdependence of the SDL rules.

With all this in mind, it was decided by the study team that for this project, the benefits of a consistent winterfill period for the study area outweighed the benefits of winterfill periods tailored to specific regions. Over time, it may be appropriate for the winterfill period of given regions to be refined following local EWR studies.



- **Figure 4.9: The distribution of standardised south-west Western Australia SDL volumes, capped at 80% reliability, for winterfill periods of 15 June – 15 October and 1 June – 15 October.**

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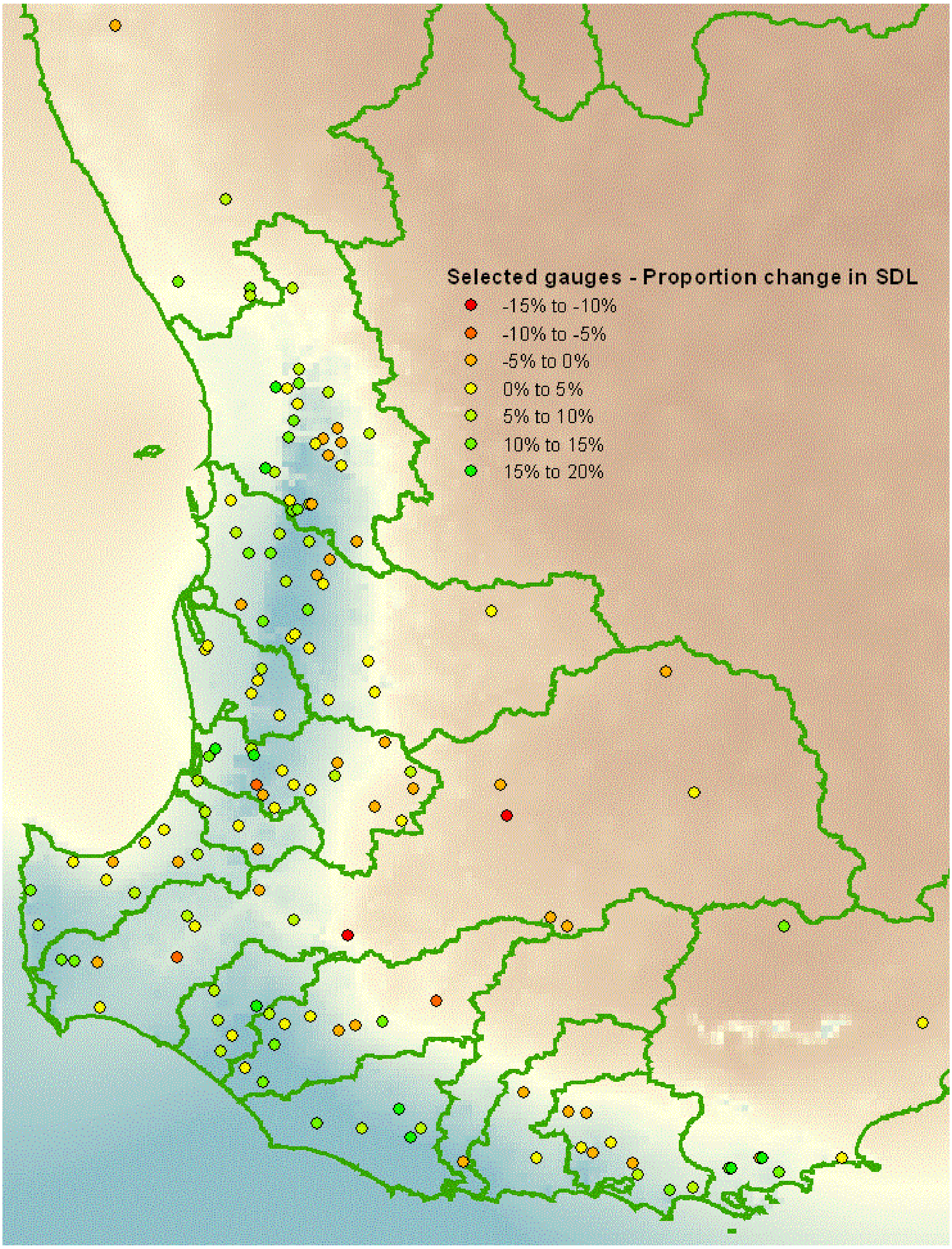


- **Figure 4.10: The proportion change in capped SDL volume, if moving from a winterfill period of June 15 – October 15 to 1 June – 15 October. The background colour represents rainfall contours (blue: high rainfall, red: low rainfall).**

4.5 Selection of the Winterfill Period

Based on the results presented in Sections 4.3.1 – 4.3.4, the study team made the following conclusions regarding the winterfill period for south-west Western Australia:

- July – September are winterfill months,
- January – May, and November – December are not winterfill months, and
- June 15th-30th and October 1st-15th can be included in the winterfill period, provided the agreed minimum flow threshold rule protects the ecologically important aspects of 'winter start' and 'winter end' streamflows should they occur within the winterfill period.

Therefore, the recommended winterfill period for south-west Western Australia is 15 June – 15 October.

5. The Minimum Flow Threshold

5.1 Introduction

As discussed in Section 2, allowing diversion of streamflows on all days of a defined winterfill period would extend the percentage of time a river experiences zero or low flows, and move the winterfill streamflow regime outside the bounds of variability experienced under natural conditions. The objective in defining SDLs, of maintaining the overall impacted flow duration curve within the envelope of natural variability, therefore lends itself to setting a minimum flow threshold (MFT) below which extractions should cease, and the streamflow be allowed to pass.

In practice, the adoption of a MFT will necessitate the selection and use of a 'reference' streamflow gauge to indicate when extractions are allowed or should cease. Although not discussed in detail here, previous experience (e.g. Nathan *et al*., 2000) has shown that this concept is feasible and practical. The use of streamflow gauging information to make operational decisions is already practiced by water authorities in Victoria.

It is also expected that operational rules developed to implement MFTs will need to account for appropriate lead times in implementing and lifting restrictions. Such issues are dependent on site-specific issues related to the density of diverters, the proximity of indicator gauges, and other organisational factors. However, the operational issues that require resolution were considered by the study team to be surmountable, and best solved by the Department of Water during implementation of the SDL rules. Therefore, the MFT should be thought of as a target, which the streamflow should not drop below because of extractions.

5.2 Approach

The overriding concern of the study team in establishing a MFT was to design a threshold that protected the low flow component of the winterfill period streamflow regime, and streamflows during the transition from 'dry' to 'wet' and 'wet' to 'dry' conditions, should those transitions occur in the winterfill period of 15 June – 15 October.

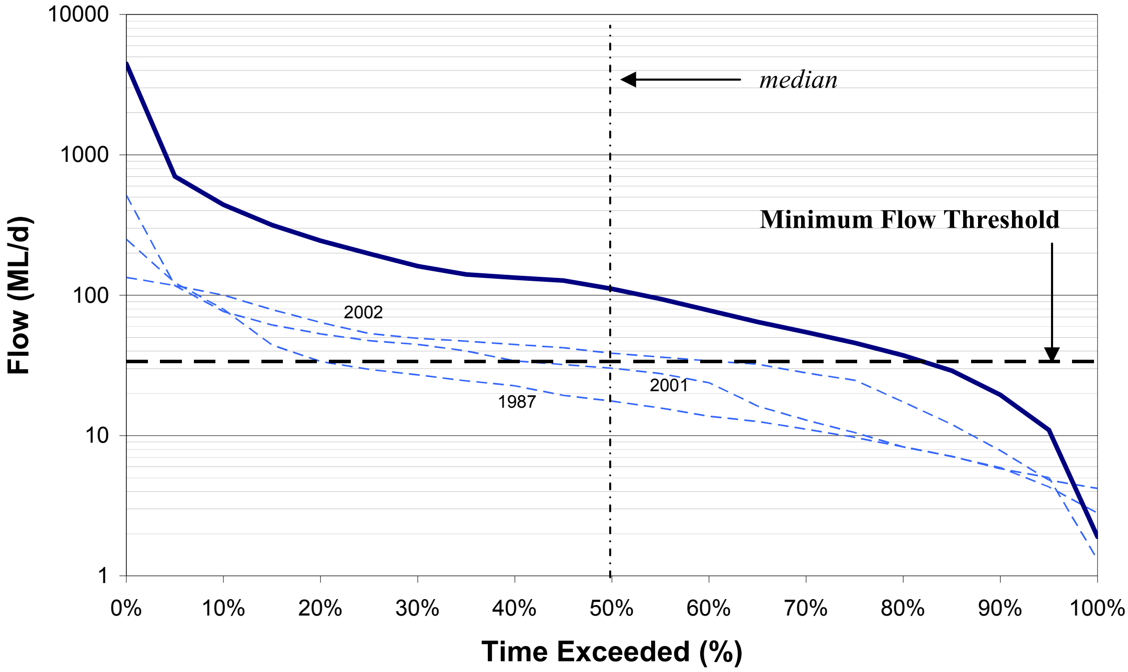
The options considered by the study team all involved the adoption of a fixed MFT below which diversions should cease. Given the rule which defined the MFT needed to be applicable across the whole south-west of Western Australia, but specific to the catchments contained therein, the rule was linked to streamflow characteristics.

The options considered in detail consisted of a MFT based on a specified:

- likelihood of exceedance over the winterfill period, and
- a proportion of the mean daily flow (calculated over all months).

To ensure that streamflows after diversions remain within the envelope of natural variability, the MFT must be equal to or greater than the flows experienced during the driest year on record (Figure 5.1). However, it was the opinion of the study team that basing the MFT on low flows experienced in extreme drought years (such as 1987 for the Denmark River), would be irresponsible, because years such as 1987 are extremes, and represent periods of great ecological stress. Implementing a MFT that enabled the impacted streamflow regime after extractions to mimic an extreme drought regime would be inconsistent with the precautionary approach adopted for defining SDLs. Therefore, the first MFT tested was the 95th exceedance percentile of the median winterfill period daily flow. That is, if the median daily flow of each winterfill period was calculated for a streamflow record spanning 100 years, the MFT would be the median daily flow in the fifth driest winterfill period.

From a diverter's point of view, adopting a MFT akin to the 95th percentile of the median winterfill period daily flow would mean that in 95% of years extractions would be allowed on more than half the days during the defined winterfill period. In the other 5% of years, extractions would be allowed on less than half the days.



- **Figure 5.1: The overall flow duration curve (highlighted) for the Denmark River at Mt Lindesay (603136) for the period 15 June – 15 October between 1975 and 2005, and the three driest years on record. The 95th percentile of the median winterfill period daily flow (dashed line) for the Mt Lindesay streamflow record is approximately half-way between the median daily flow for the second and third driest years of the thirty-one years of streamflow record.**

A preliminary analysis of the attributes of a MFT based on the 95th percentile of the median winterfill period daily flow showed that while it worked well for the majority of catchments, it was inappropriate for the handful of systems in the study area which had highly variable year-to-year flows. For example, if the 95th percentile of the median winterfill period daily flow was adopted as the MFT for the Bingham River at Palmer (612014), the MFT would be ~0 ML/d (Figure 5.2).

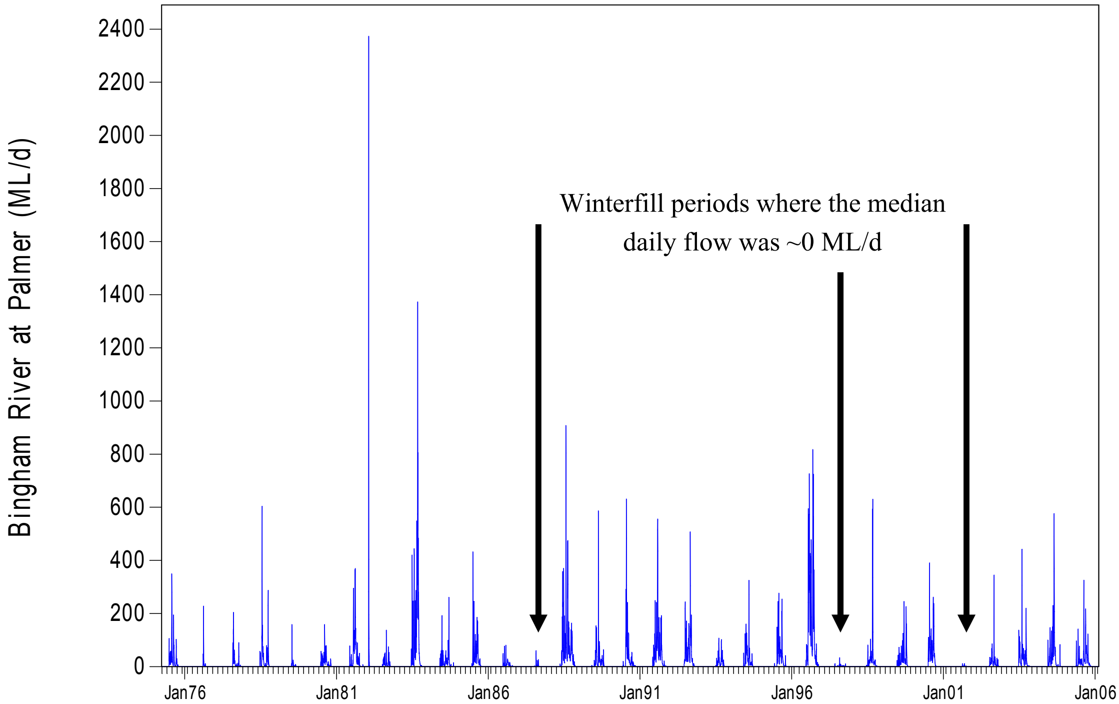
To overcome this situation, an additional threshold was added to the MFT rule, based on a percentage of the mean daily flow (calculated over all months). 0.3 of the mean daily flow (MDF) was initially chosen because it was successfully adopted as a component of the Victorian rule for defining the MFT, and recent research has identified 0.3 of MDF as a threshold of ecological importance (NRE, 2002; Stewardson, pers. comm., 2002).

Therefore, the starting point for analysis of the implications of the MFT, was with a MFT defined by the equation,

$$\max(0.3 \times MDF, \text{95\%ile of median winterfill period daily flow}),$$

▪ **Equation 1**

where *MDF* = mean daily flow, calculated over all months.



▪ **Figure 5.2: The time-series of natural flows for the Bingham River at Palmer (612014). In 1987 and 2001, the median daily flow during the winterfill period was ~0 ML/d.**

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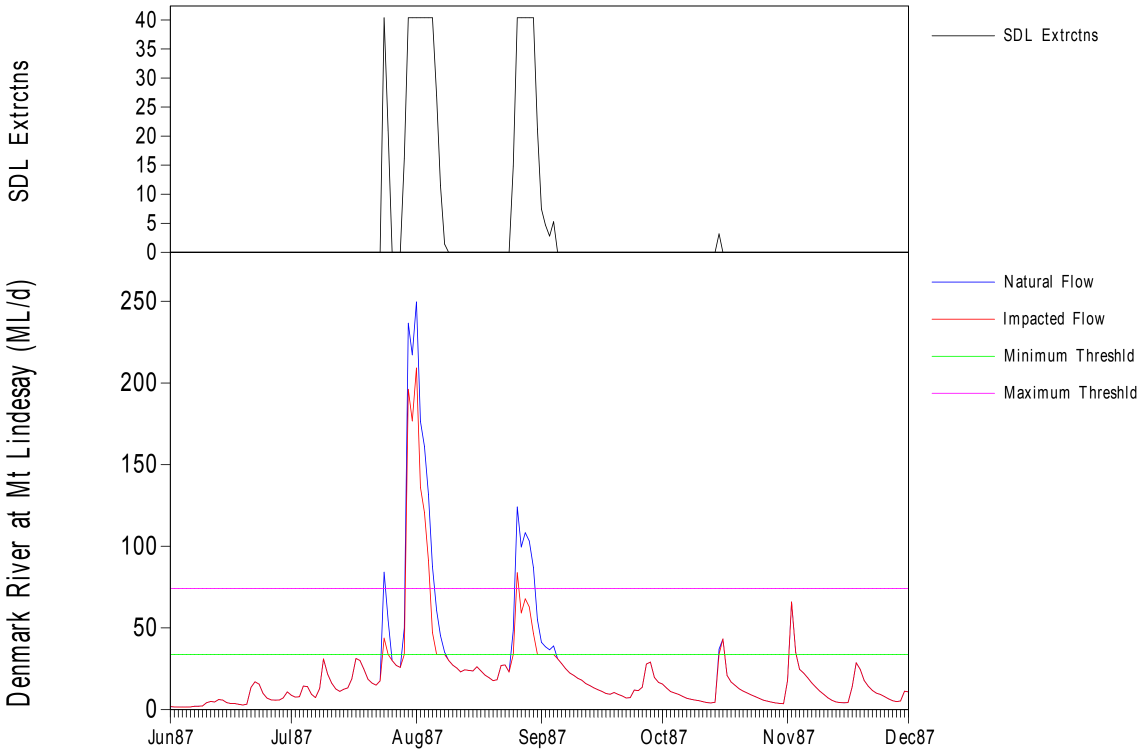
Figure 5.3 shows how the ‘ideal’ application of the MFT described by Equation 1 would impact the natural streamflow of the Denmark River at Mt Lindesay (603136), during the drought year of 1987, assuming a maximum extraction rate of 40 ML/d.



- **Figure 5.3: The time-series of natural and impacted flows for the Denmark River at Mt Lindesay (603136), during the drought year 1987, assuming a minimum flow threshold described by Equation 1, and a maximum extraction rate of 40 ML/d. The winterfill period is 15 June – 15 October.**

5.3 Evaluation of Candidate Criteria

To analyse the effect of increasing or decreasing the MFT, the initially proposed MFT was systematically increased and decreased from the base case (Equation 1). Reducing the MFT increases the number of days on which diverters can extract water from the river, and thus the proportion of water available for harvesting. Increasing the MFT has the opposite effect.

For example, for the Denmark River at Mt Lindesay, if a MFT based on Equation 1 was applied, extraction would be allowed on 25 days of the 15 June – 15 October winterfill period in 1987 (Figure 5.3). If a maximum extraction rate (MER) of 40 ML/d was adopted, 17% of the streamflow during the winterfill period of 1987 would be available to harvest. Increasing the MFT by 25% would decrease the number of days extractions occur from 25 to 19, and reduce the percentage of streamflow harvested from 17% to 15%.

Figure 5.4 and Figure 5.6 summarise the impacts (for the 75 sites with at least 25 years of record) of increasing or decreasing the MFT on the number of days on which extractions occur (Figure 5.4), and the proportion of flow harvested (Figure 5.6) in the three driest winterfill periods on record. Results in Figure 5.6 assume a MER as described in Section 6.

While not linked directly to measures of ecological significance, these criteria enabled the marginal benefits (or marginal disadvantages) to the environment of increasing (or decreasing) the MFT to be assessed. That is, while it was difficult for the study team to objectively assess the threat to the environment of one specific MFT over another, systematically increasing and decreasing the MFT from the base case did enable comparison of the relative effects of different MFTs.

Only results from the three driest years were examined because if SDLs are capped at 80% or 90% reliability (Section 7), it follows that the driest years on record directly influence a catchment's assigned SDL volumes. Also, if the adopted MFT protects the environment during dry extremes that perhaps occur once every 10 years, it follows the environment will also be protected during less ecologically stressful winterfill periods.

The patterns in Figure 5.4 and Figure 5.6 are somewhat similar; however it is worth making a comment on each:

- In Figure 5.4, for proportions close to 1.0 (i.e. from 0.8 – 1.25), the number of days on which extractions occur in the three driest winterfill periods responds in an almost 1:1 manner. That is, if the MFT is factored by 0.8, the number of days on which extractions occur at a 'typical' site increases by ~1.25 (the inverse of 0.8), and vice-versa (see Figure 5.5). However, as the proportions move further from 1.0, the response of the number of days on which extractions occur becomes increasingly amplified. The nature of this amplification depends on whether the proportions are less than or greater than 1.0. For example, if the MFT is halved, the number of days on which extractions occur increases by about 1.8 times (less than double), but if the MFT is doubled, the number of days on which extractions occur decreases to about one-third of the base case (i.e. to much less than half).

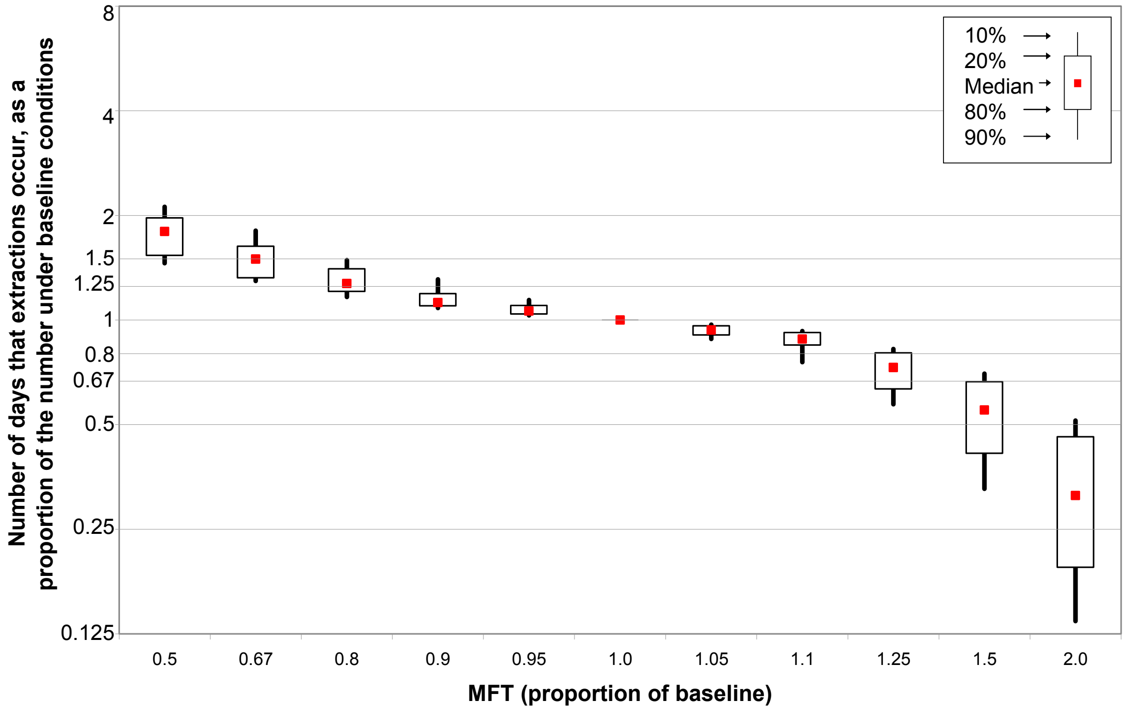
  This pattern indicated that once the MFT is below the baseflow component of streamflows, the number of days on which extractions are allowed becomes increasingly insensitive to reducing the MFT. In turn, once above the baseflow component of streamflows, the number of days on which extractions are allowed becomes increasingly sensitive to increasing the MFT.

- Like Figure 5.4, Figure 5.6 shows that increasing and decreasing the MFT have similarly large but opposite effects on the volume of flow harvested in the three driest winterfill periods for proportions of the MFT between 0.8 and 1.25. For example, going from 1.0 of MFT to 0.8 of MFT increases the proportion of water harvested at a 'typical' site in the three winterfill periods by 6.1%, while moving from 1.0 of MFT to 1.25 of MFT decreases the proportion of water harvested at a ‘typical’ site in the three driest winterfill periods by 5.4% (see Figure 5.7). However, as the proportions of MFT move further away from 1.0, the inferred benefit to the environment of raising the MFT (in terms of the volume of water left in the river) diminishes, while the benefit to diverters of lowering the MFT (in terms of the volume of water available for extraction) continues to rise in a linear fashion.

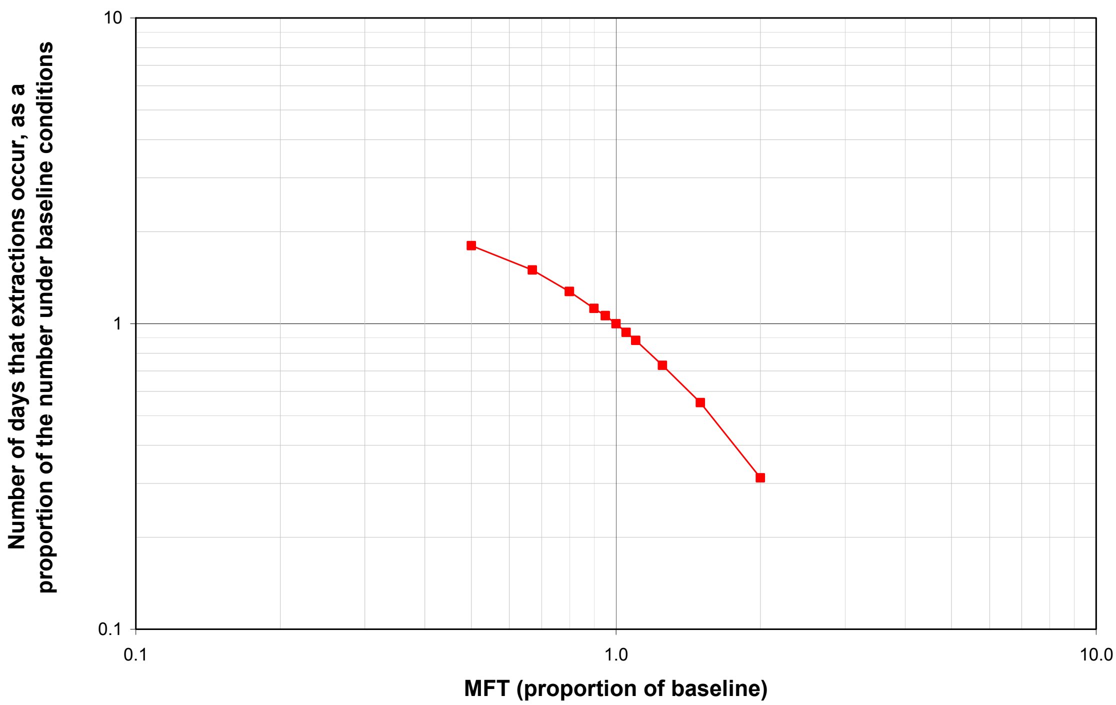
Again, this pattern was somewhat expected. Lowering the MFT exposes more and more of the baseflow component of streamflows, whereas raising the MFT protects higher and higher flow events, which do not occur with the regularity of baseflows.

Taken together, Figure 5.4 – Figure 5.7 demonstrated to the study team that Equation 1 represented a reasonable MFT. To confirm this, MFTs for the 16 sites selected by the study team were plotted against streamflow for various periods of the available records. Figure 5.8 and Figure 5.9 show site-specific MFTs versus streamflow for Chapman Brook at White Elephant Bridge (609022), Wilyabrup Brook at Woodlands (610006), Thomson Brook at Woodperry Homestead (611111), and the Collie River at Mugalup Tower (612002). From observation of time-series such as these, the study team were satisfied that the proposed MFTs provided sufficient protection of low flows during the winterfill period, and of streamflows during the transition from ‘dry’ to ‘wet’ and ‘wet’ to ‘dry’ conditions.

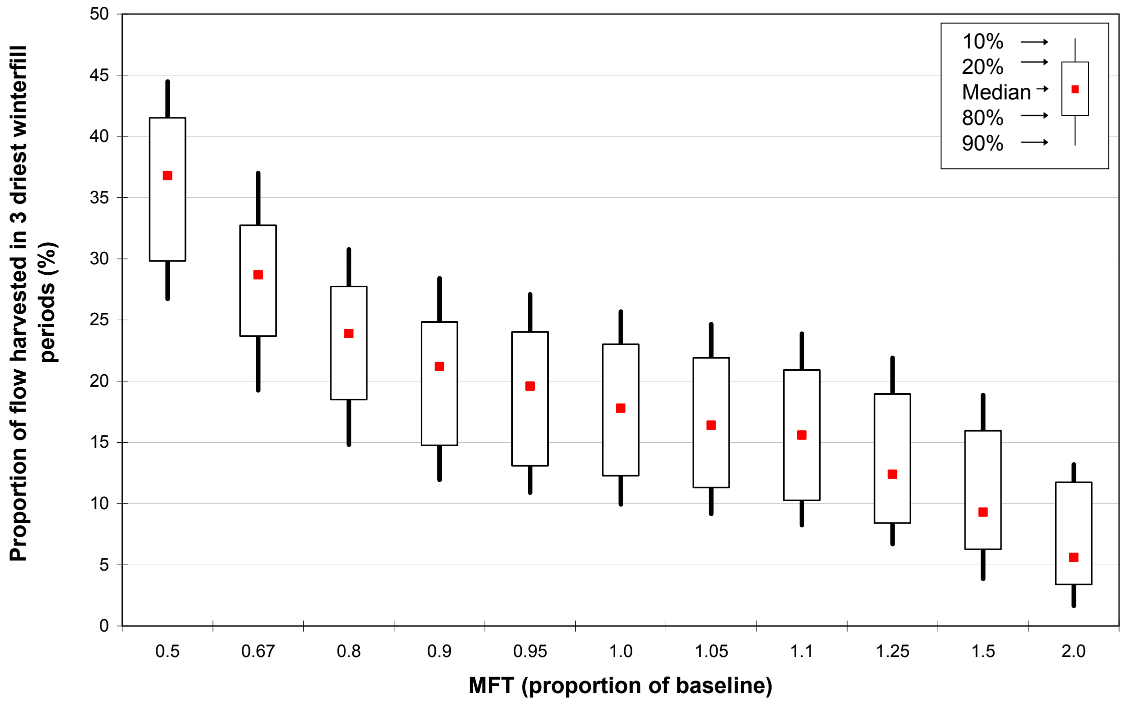
Multiplying the MFT computed from Equation 1 by proportions between 0.8 and 1.25 has an impact on diverters and the environment during the three driest winterfill periods which is linear in manner and similar in magnitude, indicating the recommended MFT stands in the middle of what could be considered a reasonable range. This is important; given Equation 1 is the recommended rule for defining MFTs for the entire study area, without consideration of site-specific issues.



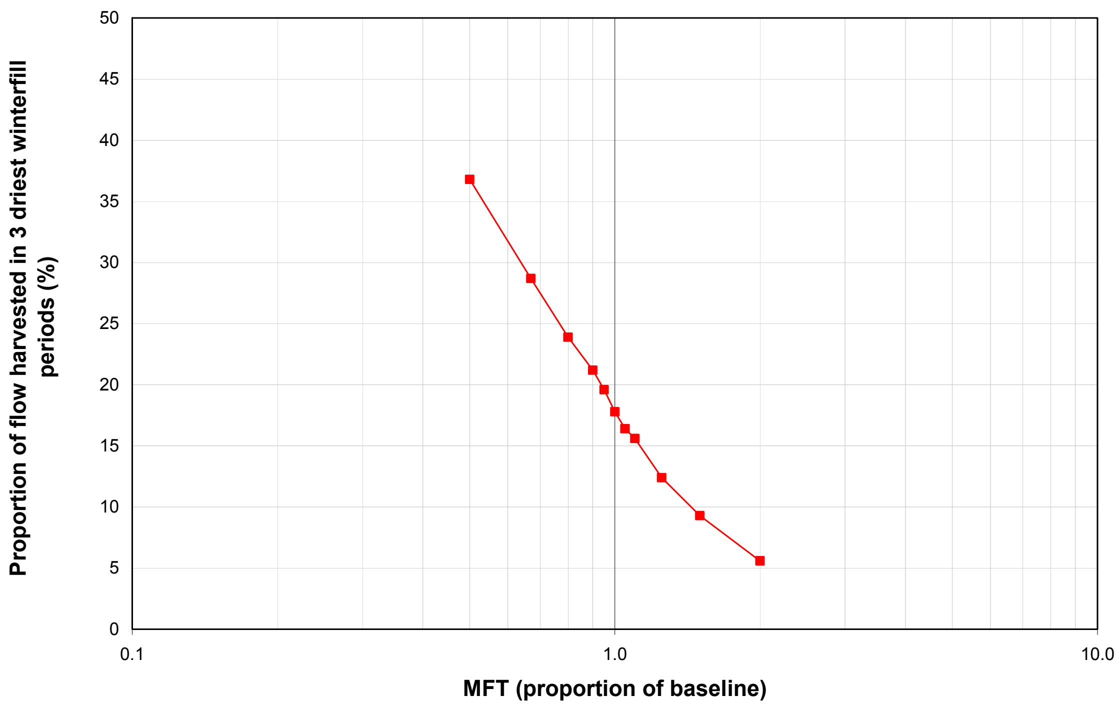
- **Figure 5.4: The impact of different MFTs on the number of days over which extractions occur in the three driest winterfill periods on record, for the 75 sites with at least 25 years of record.**



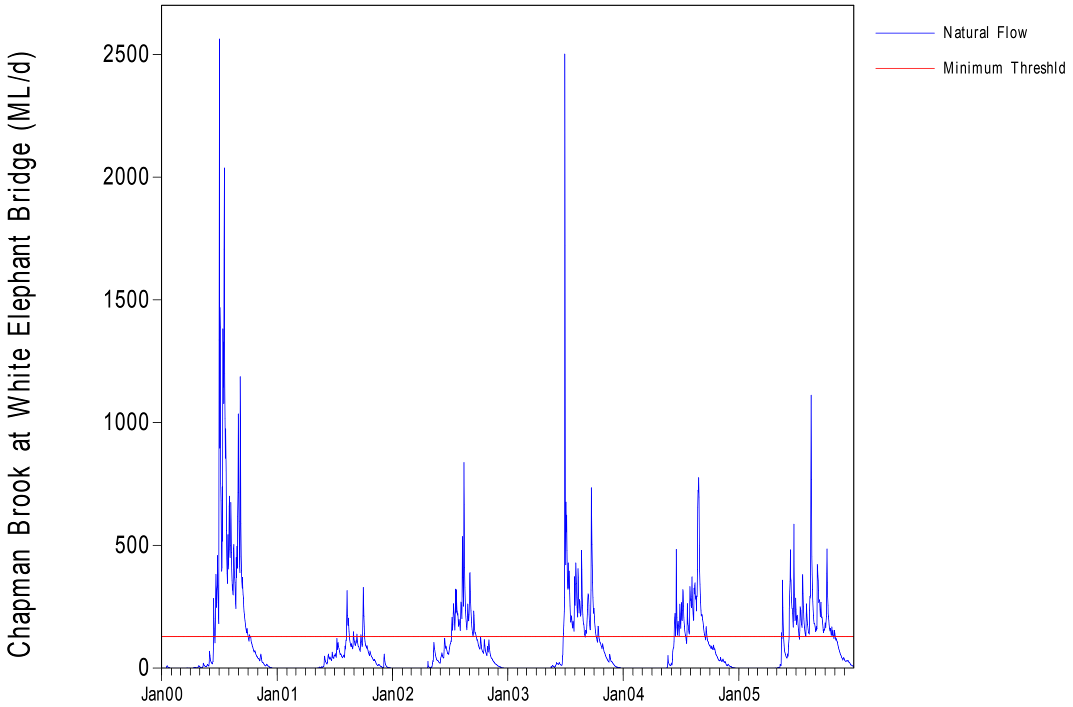
- **Figure 5.5: The median series from Figure 5.4, plotted on a log-log axis.**

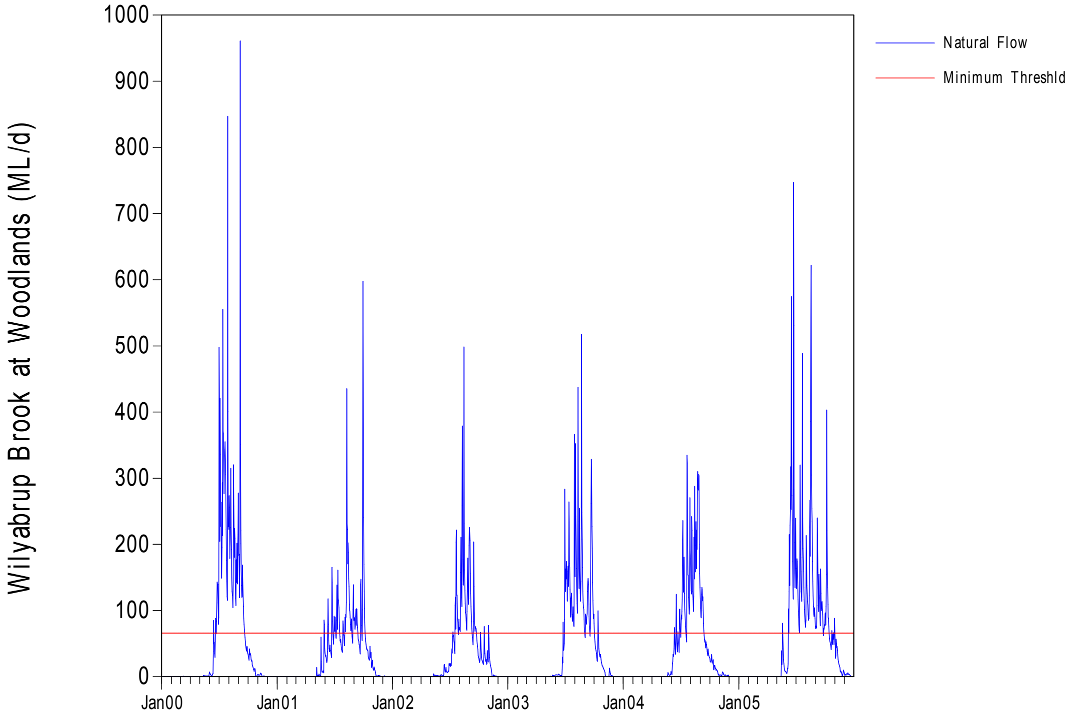


■ **Figure 5.6: The impact of different MFTs on the proportion of winter volume extracted in the three driest winterfill periods on record, for the 75 sites with at least 25 years of record (assuming a maximum extraction rate as described in Section 6).**

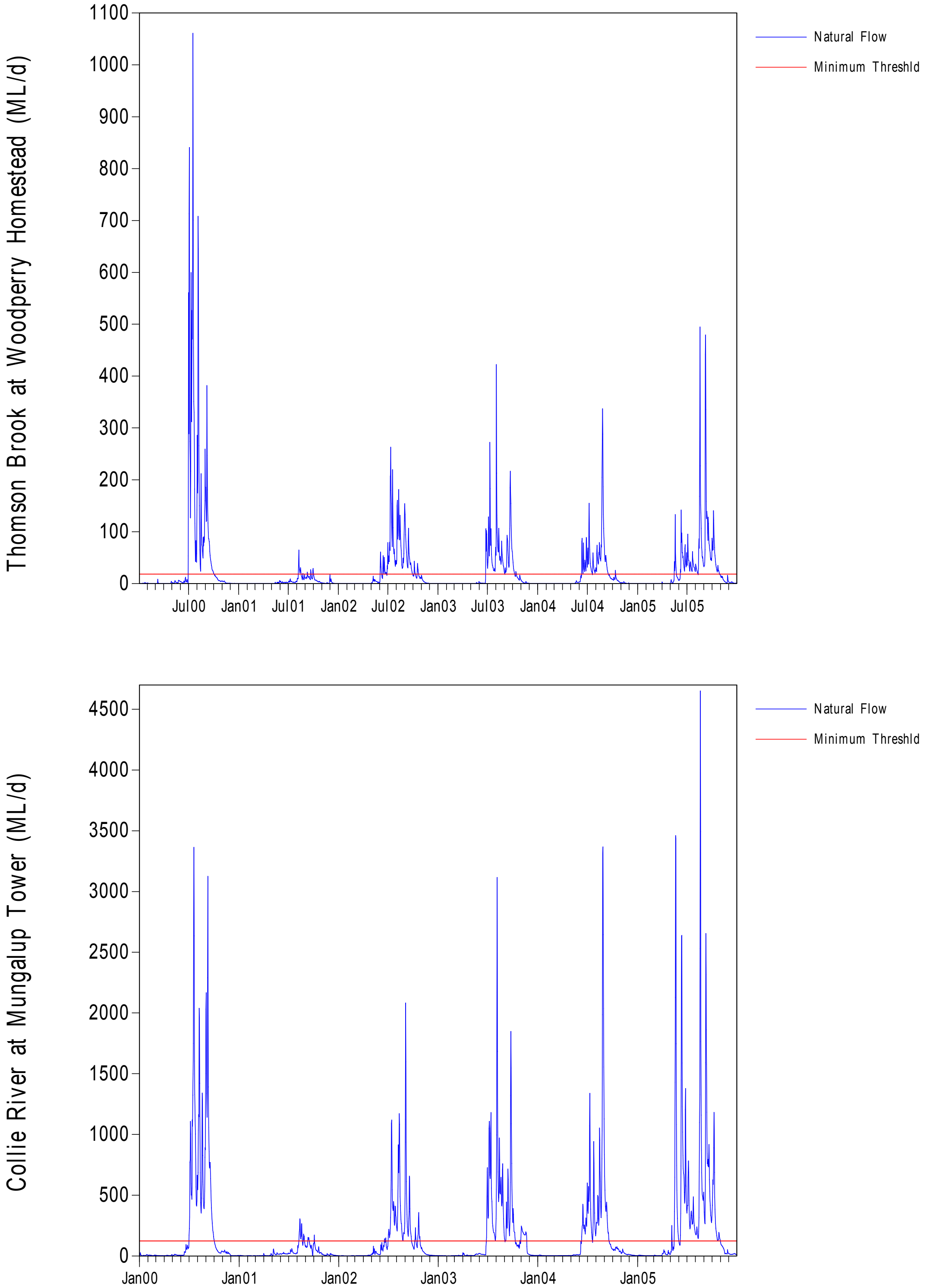


■ **Figure 5.7: The median series from Figure 5.6, plotted on log-linear axes.**





- **Figure 5.8: Example time-series for Chapman Brook at White Elephant Bridge (609022) and Wilyabrup Brook at Woodlands (610006), comparing the MFT to daily flows.**



- **Figure 5.9: Example time-series for Thomson Brook at Woodperry Homestead (611111) and the Collie River at Mugalup Tower (612002), comparing the MFT to daily flows.**

5.4 Selection of the Minimum Flow Threshold

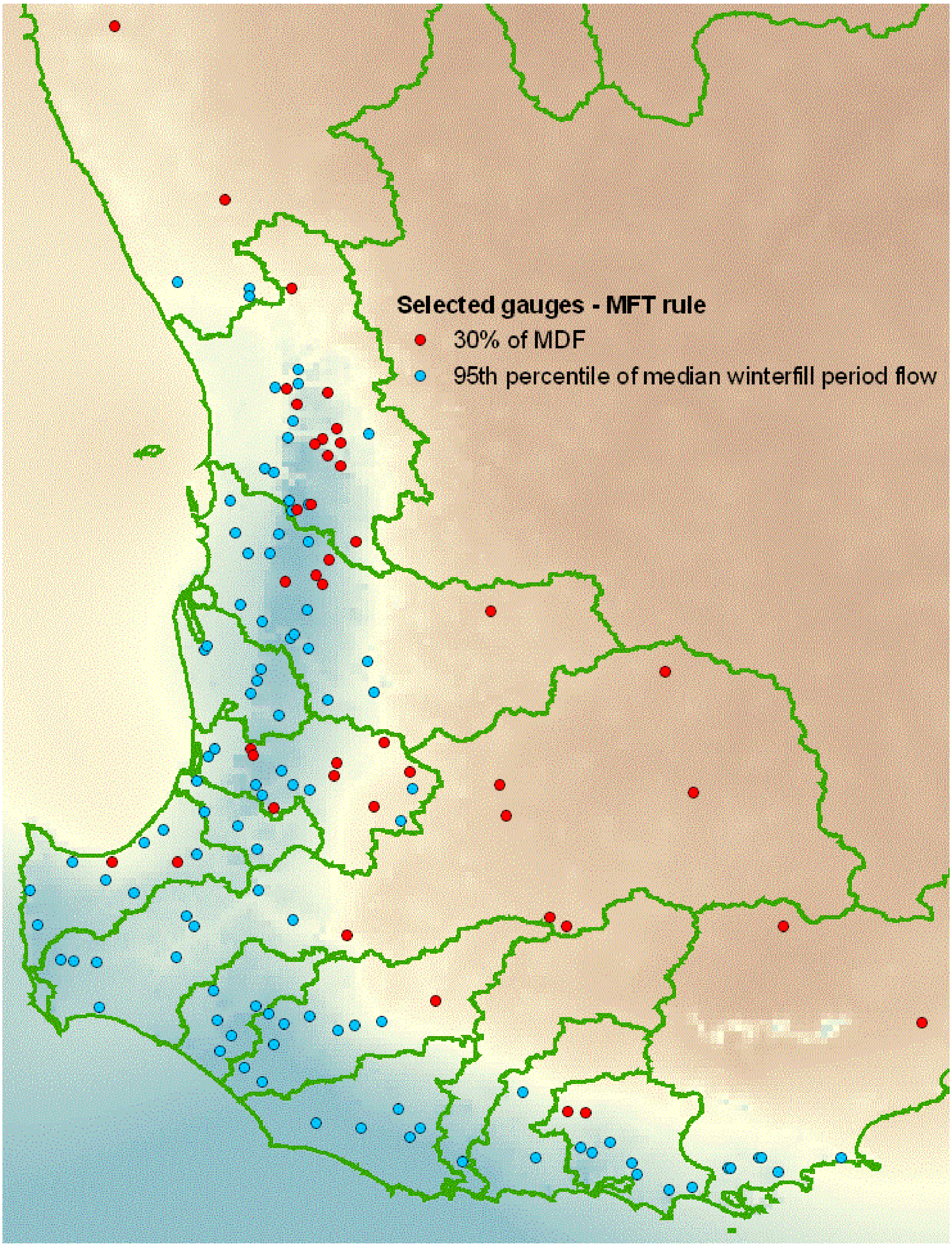
Based on the results presented in Section 5.3, and time-series for the 16 sites in Table 1.1, the study team made the following conclusions regarding the minimum flow threshold (MFT) for diversions from unregulated rivers in south-west Western Australia:

Equation 1, i.e.

$$\max(0.3 \times MDF, \text{95\%ile of median winterfill period daily flow}),$$

provides sufficient protection of the low flow component of the winterfill period streamflow regime, and streamflows during the transition from 'dry' to 'wet' and 'wet' to 'dry' conditions should those transitions occur within the winterfill period. The relative benefits to diverters or the environment are not sufficient to warrant lowering or raising the recommended MFT.

Figure 5.10 shows which component of Equation 1 determines the MFT for the 142 gauged sites.



- **Figure 5.10: Red dots show where 0.3 of mean daily flow is the component of Equation 1 that determines the minimum flow threshold (MFT), while the blue dots show where the 95th percentile of median winterfill period daily flow is the MFT.**

6. The Maximum Extraction Rate

6.1 Introduction

The maximum extraction rate (MER) limits the volume of water that can be extracted from the catchment on any one day. As explained in Section 2, allowing unchecked diversions of flows above the minimum flow threshold (MFT) would result in streamflows 'flat-lining' at the MFT for long periods of time. This situation would move the impacted flow duration curve outside the envelope of natural variability at the high flow end of the streamflow regime, remove spells above the MFT, and reduce the inter-annual variability of streamflows.

In practice, the adoption of a MER will require the Department of Water to regulate the total capacity of all pumps within a given catchment, so that if all diverters extract water simultaneously, the rate of extraction remains within the recommended MER. Alternatively, if the majority of diversions in a given catchment are farm dam diversions, the MER can be used (in conjunction with farm dam impact modelling) to control the volume and distribution of farm dams within a catchment. Again, the operational issues that require resolution were considered by the study team to be surmountable, and best solved by the Department of Water. Therefore, the MER should be thought of as a target, which extractions from the catchment should not exceed on any given day.

6.2 Approach

The overriding concern of the study team in establishing a MER, was to design a rate that limited the percent of time the impacted streamflow regime 'flat-lined' at the MFT during the winterfill period.

The options considered by the study team all involved the adoption of a fixed MER, which capped the rate of extraction on any given day. Given the rule which defined the MER, like the MFT, also needed to be applicable across the whole south-west of Western Australia, but specific to the catchments contained therein, the rule was linked to streamflow characteristics.

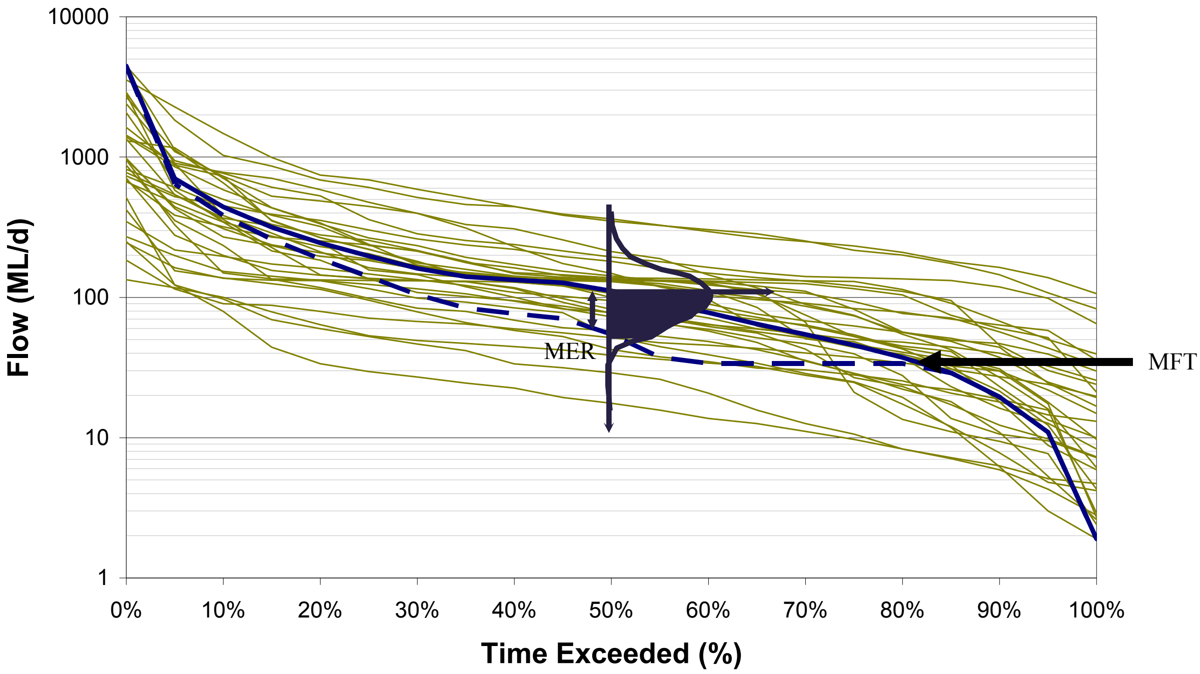
The options considered in detail consisted of a MER based on a specified:

- Difference between percentiles of median winterfill period daily flows, and a
- Percent of allowable time 'flat-lining' at the MFT.

As shown in Section 2, if all diversions from a river are via direct extractions with a constant extraction rate, the overall flow duration curve shifts downwards by a volume equivalent to the extraction rate. The greater the extraction rate, the greater the shift of the flow duration curve downwards. It is this shift that needs to be controlled, so that streamflows after diversions do not 'flat-line' at the MFT, and therefore move outside the envelope of natural variability.

The first MER trialled was the difference between the 50th and 80th percentile of the median winterfill period daily flow (Figure 6.1). By basing the MER on the distribution of annual median winterfill period daily flows, the downward shift of the flow duration curve is made to lie within the envelope of natural variability, provided a minimum flow threshold (MFT) is also implemented (Section 5).

However, this approach to determining the MER was not favoured by the study team. Setting the MER as the difference between percentiles of median winterfill period daily flows means in relative terms, the more reliable the stream (i.e. the closer together the annual flow duration curves), the lower the MER, and therefore SDL. This was contrary to expectations of the study team, i.e. that the SDL of more reliable streams would be higher (in relative terms) than the SDL of more variable streams.

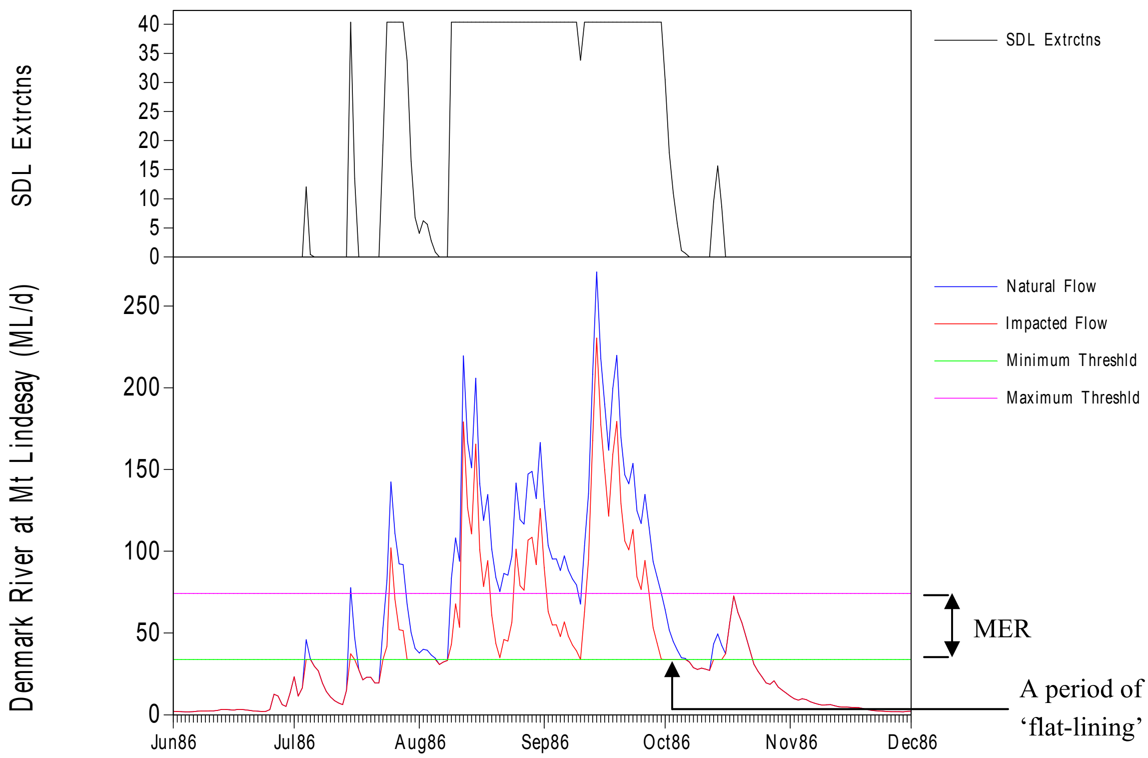


- **Figure 6.1: Defining the maximum extraction rate (MER) for the Denmark River at Mt Lindesay (603136) as the difference between the 50th and 80th percentile of median winterfill period daily flow. Each line shows a flow duration curve for a given winterfill period under natural conditions, while the highlighted line shows the flow duration curve for all winterfill periods. The dashed line shows the overall flow duration curve after extractions, assuming a minimum flow threshold (MFT) is also implemented.**

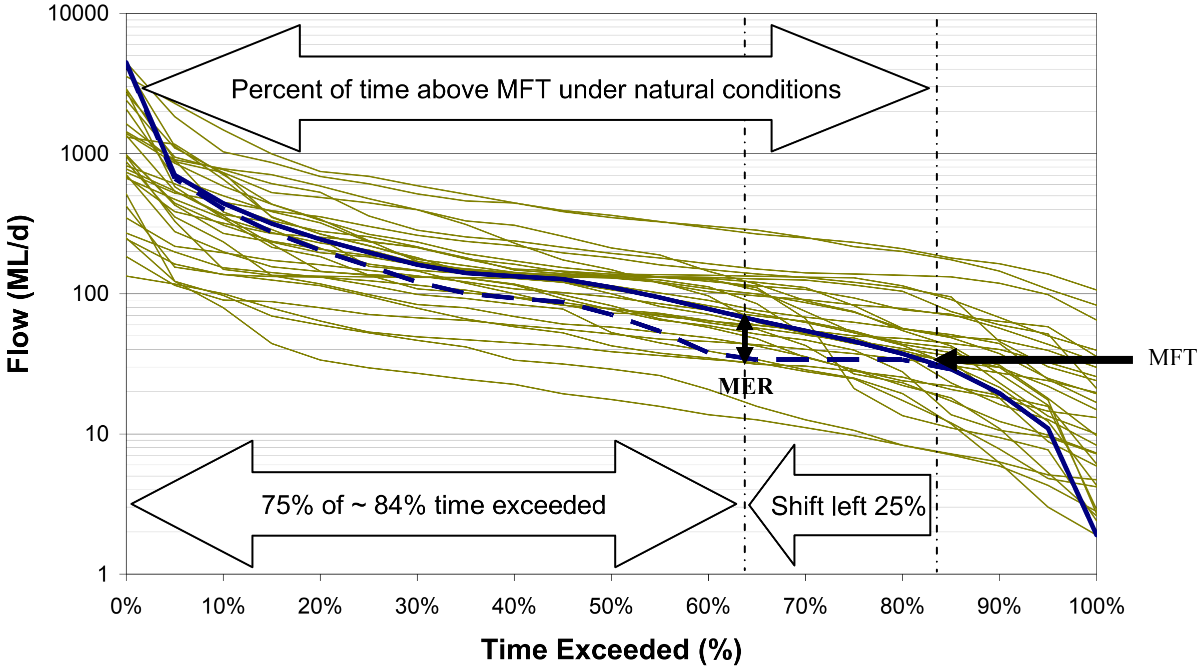
Therefore, a second MER rule was trialled. The MER was set as the 75th exceedance percentile of the difference between the natural flow and the MFT (in the winterfill period over the available record), for days when the MFT is exceeded under natural conditions. Therefore, on the 25% of days when the natural flow exceeds the MFT by less than the defined MER, the impacted flow 'flat-lines' at the MFT (Figure 6.2).

This second approach to defining the MER limits the extent to which the impacted flow duration curve moves towards the left of the plot. However, restricting the shift of the impacted flow duration curve leftwards, also limits the shift of the curve downwards (Figure 6.3). In addition, the benefit of this second approach is that more water is extracted from reliable streams than variable streams. Because reliable streams have more days above the MFT, when this rule is applied, the impacted flow duration curve moves further left and therefore further down the plot than for more variable streams, which have fewer days of streamflow above the MFT.

For the remainder of this document, the percent of days above the MFT under natural conditions that 'flat-line' under impacted conditions is used as the defining criteria for the MER.



- **Figure 6.2: Defining the maximum extraction rate (MER) as the percentage of time that the impacted time-series 'flat-lines'. Flat-lining under impacted conditions occurs when the MER equals or exceeds the available flow above the minimum flow threshold (MFT; green).**



- **Figure 6.3: Defining the maximum extraction rate (MER) as the percentage of time that the impacted time-series 'flat-lines'. Here, a MER based on 25% of days flat-lining under impacted conditions (dashed line) has been applied.**

6.3 Evaluation of Candidate Criteria

Other options for the MER were tested, using various percentiles of the difference between the natural flow and MFT (which result in different proportions of time that the impacted flow flat-lines). For example, using the 90th percentile results in 10% of days above the MFT under natural conditions flat-lining under impacted conditions (in the winterfill period over the available record). Increasing the percent of days that flat-line increases the proportion of water harvested and decreases the volume of water which passes downstream. Reducing the percent of days that flat-line has the opposite effect.

For example, for the Denmark River at Mt Lindesay, if a MER based on 25% of days above the MFT flat-lining under impacted conditions was adopted, 28.5% of streamflows in the 15 June – 15 October winterfill period of 1986 would be harvested (Figure 6.2). 34.5% of the streamflow in the winterfill period would be above the MFT, but unavailable to diverters, while 22 days would flat-line at the MFT. Increasing the MER, so that 35% of days above the MFT flat-lined under impacted conditions, would increase the proportion of water harvested to 41.8%, decrease the percent of water above the MFT but unavailable to diverters to 21.1%, and increase the number of days flat-lining to 43.

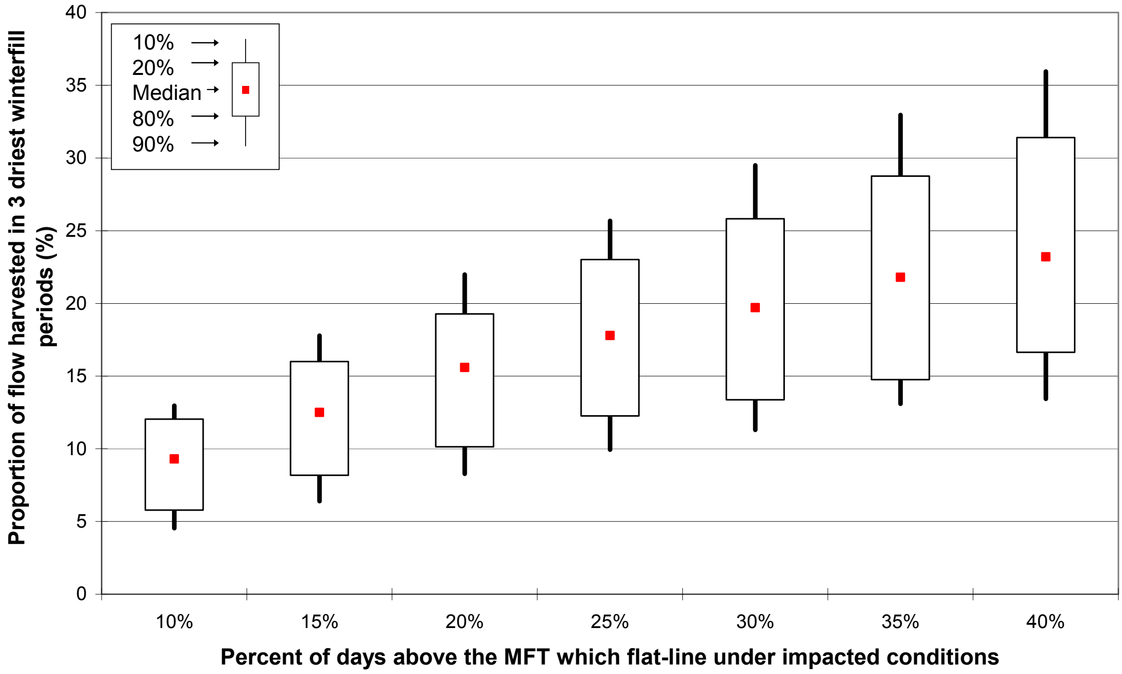
Figure 6.4 to Figure 6.7 summarise the impacts (for the 75 sites with at least 25 years of record) of increasing or decreasing the percentage of days above the MFT that flat-line under impacted conditions. Figure 6.4 shows how the proportion of water diverted in the three driest winterfill periods changes; Figure 6.5 shows how the percent of water above the MFT, but unavailable to diverters, alters; Figure 6.6 shows how the number of days which flat-line under impacted conditions during the three driest winterfill periods varies; while Figure 6.7 shows how calculated SDLs (capped at 80% reliability) change.

While not linked directly to measures of ecological significance, these criteria enabled the marginal benefits (or marginal disadvantages) to the environment of increasing (or decreasing) the MER to be assessed. That is, while it was difficult for the study team to objectively assess the threat to the environment of one specific MER over another, systematically increasing and decreasing the MER did enable comparison of the relative benefits of different MERs.

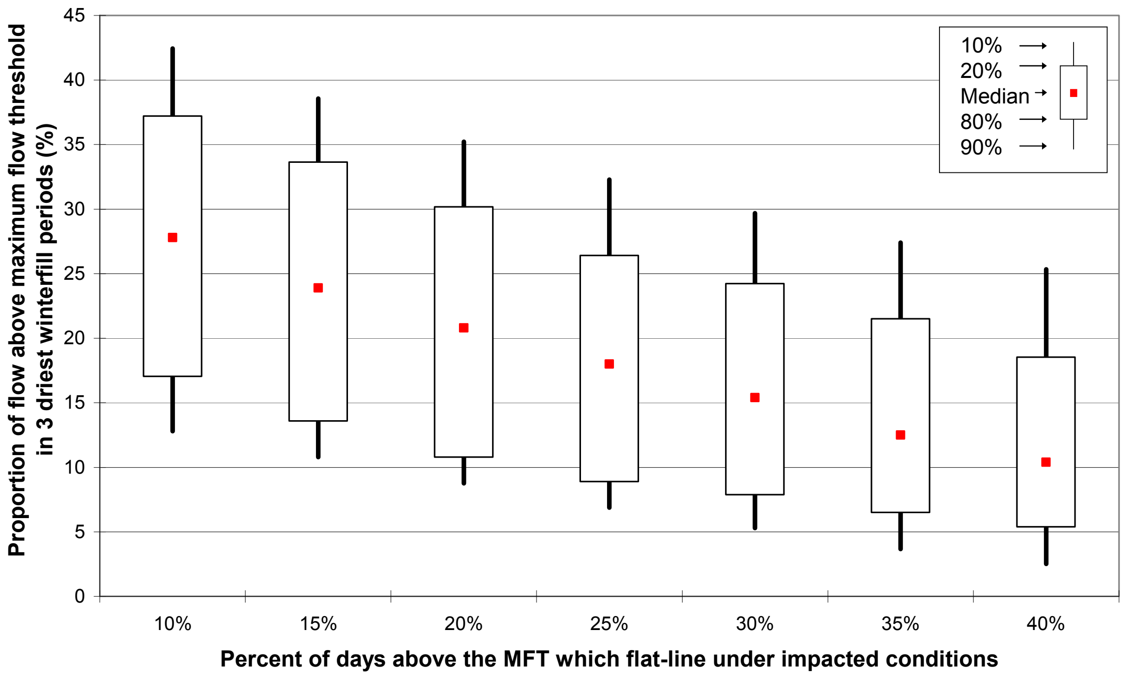
Only results from the three driest years were examined, because if SDLs are capped at 80% or 90% reliability (Section 7), it follows that the driest years on record directly influence a catchment's assigned SDL volumes. Also, if the MER adopted protects the environment during dry extremes that perhaps occur once every 10 years, it follows the environment will also be protected during less ecologically stressful winterfill periods.

Figure 6.4 shows that for the majority of sites, as the percent of days flat-lining increases past 25%, the rate of increase in the proportion of water diverted in the three driest winterfill periods diminishes slightly. The inverse of Figure 6.4 is Figure 6.5, which shows that as the percentage of days above the MFT that flat-line under impacted conditions increases, the volume of water in the three driest years above the MFT but unavailable to diverters decreases. Figure 6.5 in particular, appears to have a minor change of slope at 25%. That is, once above 25%, the rate of increase in the volume of water available to diverters in the three driest winterfill periods diminishes.

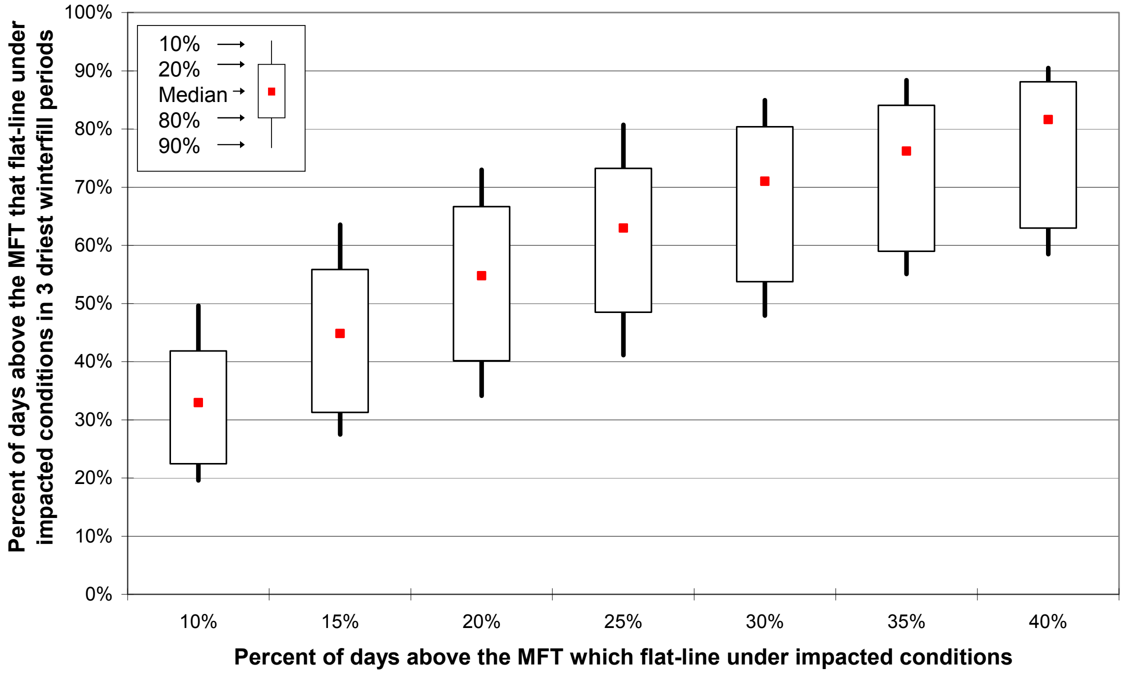
Figure 6.6 gives further weight to the choice of 25%. For percentages less than or equal to 25%, the number of days above the MFT that flat-line in the three driest winterfill periods appears normally distributed about the median. However, for percentages greater than 25%, the distribution becomes increasingly skewed, with high percentages (>70%) of days above the MFT flat-lining under impacted conditions in the three driest winterfill periods at the majority of sites. That is, the site-to-site distribution in days flat-lining in the three driest winterfill periods becomes skewed towards high percentages if MERs are based on more than 25% of days above the MFT flat-lining under impacted conditions.



- **Figure 6.4: The impact of different MERs on the proportion of flow harvested in the three driest winterfill periods on record, for the 75 sites with at least 25 years of record.**



- **Figure 6.5: The impact of different MERs on the proportion of flow above the maximum flow threshold in the three driest winterfill periods on record, for the 75 sites with at least 25 years of record.**

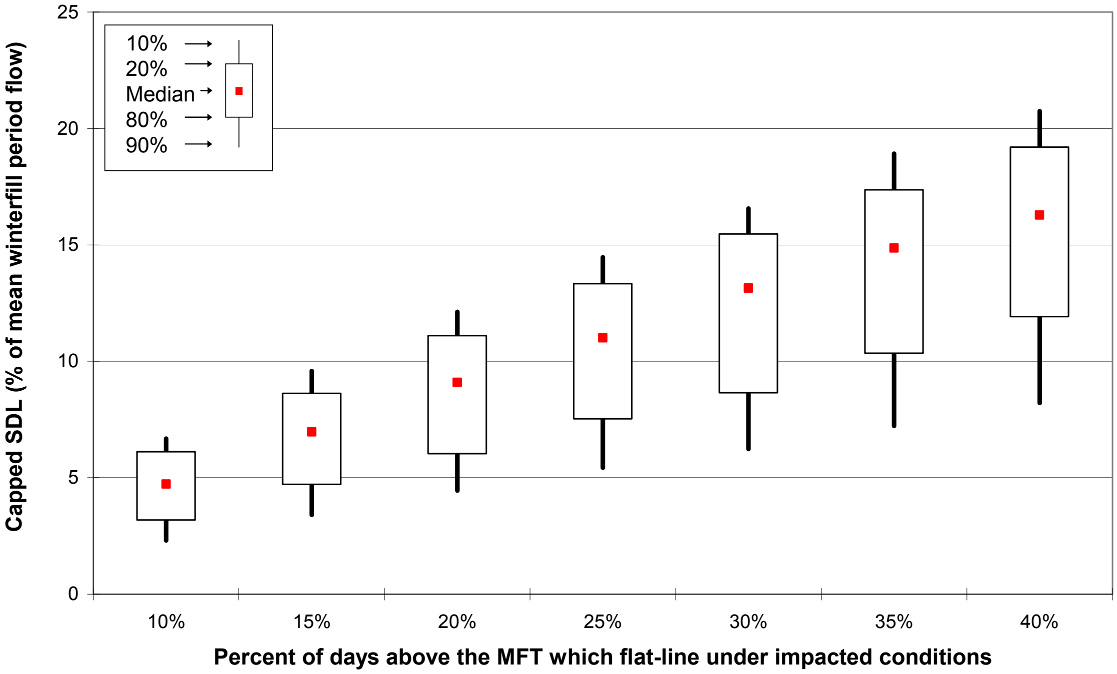


- **Figure 6.6: The impact of different MERs on the percent of days above the MFT that flat-line under impacted conditions in the three driest winterfill periods on record, for the 75 sites with at least 25 years of record.**

It should be noted that the appropriateness of the chosen percentage of time the impacted time-series flat-lines is dependent upon the MFT adopted. For example, if the MFT for the Denmark River at Mt Lindesay (603136) is reduced by one third, the MER also decreases (from 40.4 ML/d to 38.3 ML/d), because if too many low flows are above the MFT, the MER required to flat-line 25% of the days above the MFT reduces. This pattern is not constant from site to site, but illustrates the interdependence of the winterfill period, MFT and MER rules.

Based on an agreed winterfill period of 15 June – 15 October, and a MFT described by Equation 1, the study team considered a MER based on 25% of days above the MFT flat-lining under impacted conditions to be acceptable. 20% and 30% were also considered by the study team to be reasonable, indicating the recommended MER stands in the middle of what could be considered an appropriate range. This is important; given the MER described here is the recommended rule for defining MERs for the entire study area, without consideration of site specific issues.

If a MER based on 25% of days above the MFT flat-lining under impacted conditions were adopted, the median SDL (capped at 80% reliability, Section 7) would be 11% of mean winterfill period flow, for the 75 sites with at least 25 years of record (Figure 6.7).



- **Figure 6.7: SDLs (capped at 80% reliability) versus different MERs (determined by the percentage of days that flat-line under impacted conditions), for the 75 sites with at least 25 years of record.**

6.4 Selection of the Maximum Extraction Rate

Based on the results presented in Section 6.3, and time-series (similar to Figure 6.2) for the 16 sites in Table 1.1, the study team made the following conclusions regarding the maximum extraction rate (MER) for diversions from unregulated rivers in south-west Western Australia:

Adopting a MER which results in 25% of days above the MFT flat-lining under impacted conditions is a direct method for restricting the proportion of time streamflows flat-line, thereby ensuring the impacted flow duration curve remains within the envelope of natural variability at the high flow end of the streamflow regime, the impact on spells above the MFT is limited, and inter-annual variability of streamflows is maintained. The relative benefits to diverters or the environment, are not sufficient to warrant increasing or decreasing the recommended MER.

7. Reliability of Supply

7.1 Introduction

The preceding sections have described the development of the three main rules for governing diversions from the unregulated rivers of south-west Western Australia; namely, the period over which diversions are allowed, the minimum flow threshold (MFT) below which diversions cease, and the maximum extraction rate (MER). If these three rules are applied to diversions, then the overall impacted streamflow regime remains within the envelope of natural variability at any given site.

The last issue resolved by the study team was the SDL itself, and its associated reliability of supply. Generally, extractions from unregulated rivers are from either direct pumping, or storage of streamflow in on-stream structures such as farm dams. The SDL represents the maximum sum of water that diverters within a given catchment can be licensed to extract each year, without posing an unacceptable risk to the environment.

The SDL and the adopted reliability of supply are directly related. Issuing a license to extract a volume of water from an unregulated river, with a given reliability of supply, necessitates the introduction of an annual 'volumetric cap' (i.e. SDL) on extractions for each unregulated catchment. Once a diverter has reached their individual annual volumetric cap, they are not allowed to extract more water that year. In return, the licenses issued to diverters state that in 80% of years (or whatever reliability of supply is adopted), the winterfill rules will enable them to extract enough water to reach their individual annual volumetric cap. Therefore, while reliability of supply is not in itself an ecological concern, it does determine the maximum annual volume of water diverted, and therefore the volume of water left to pass undiverted.

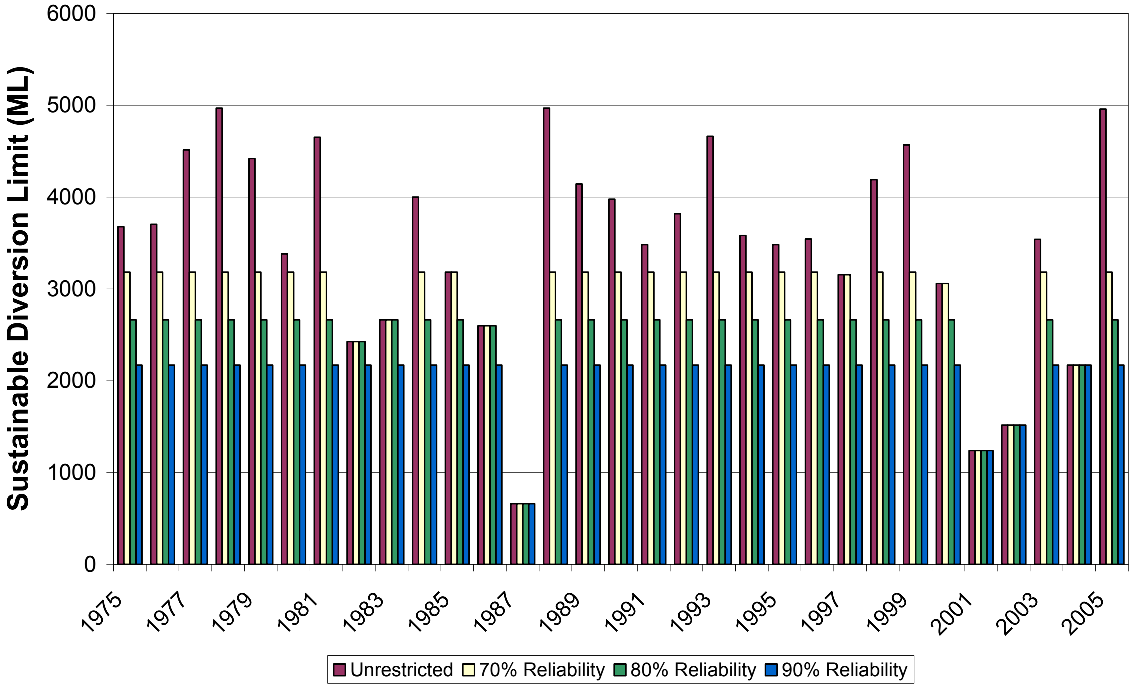
In practice, the adoption of a reliability of supply will be a decision for the Department of Water, should they decide to issue licenses for diverters to extract water from the unregulated rivers of south-west Western Australia. However, it needs to be recognised that the adopted reliability of supply directly influences a catchment's SDL.

7.2 Approach

The study team considered reliabilities of supply ranging from 70% to 95%. Figure 7.1 shows how the reliability of supply influences the adopted annual volumetric cap, i.e. SDL, for the Denmark River at Mt Lindesay (603136).

The unrestricted time series shows the volume of water available for extraction through application of the winterfill period, MFT and MER. More water is available for extraction in wet years, and less in dry years. As the adopted reliability of supply increases, the volume of water that can be provided annually with that reliability decreases.

For example, the unrestricted time series shows that ~5,000 ML of water was available for extraction in 3 years (1978, 1988 and 2005) of the 31 years of record. Therefore, a SDL of ~5,000 ML for the Denmark River at Mt Lindesay catchment would have a reliability of supply of ~10% (i.e. it could be safely extracted only 1 in every 10 years). Obviously, diverters cannot develop sustainable industrial or agricultural enterprises if the volume of water they are licensed to divert is only available to them in 10% of years. As the reliability increases, the SDL decreases so that the number of years in which it cannot be extracted reduces. For example, a reliability of 80% for the Denmark River at Mt Lindesay catchment, translates to a SDL of ~2,660 ML, which can safely be extracted in 20 of 25 years. In the years where more than ~2,660 ML of water can be diverted (based on the winterfill period, MFT and MER rules), extractions are still capped at ~2,660 ML.



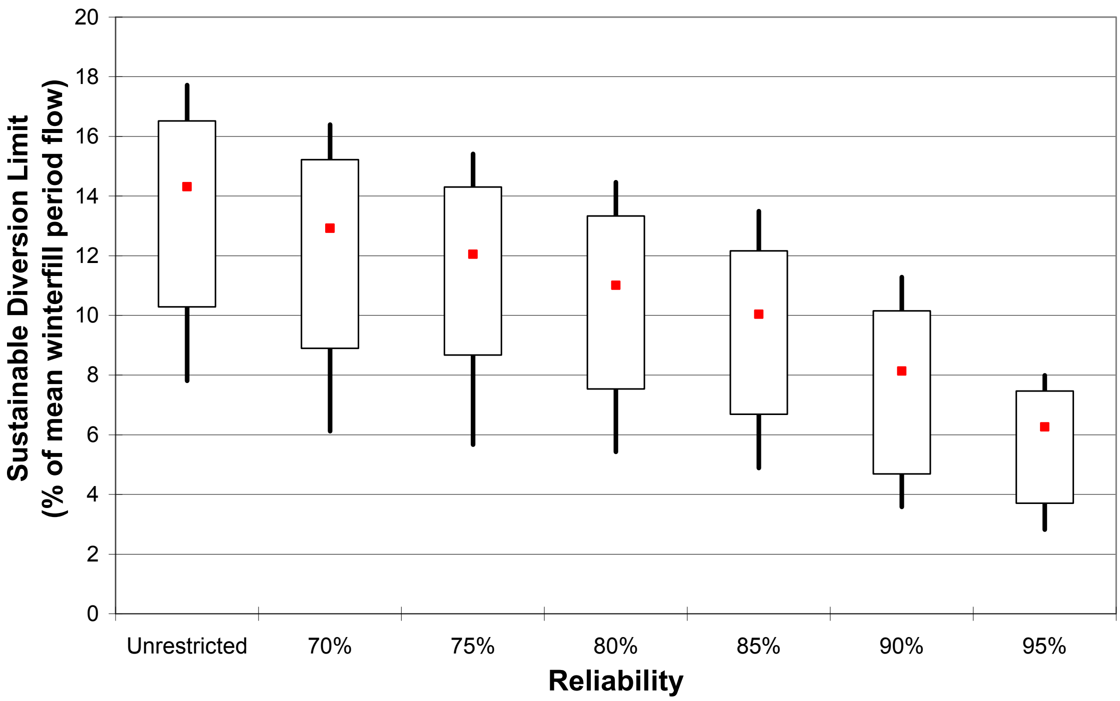
- **Figure 7.1: Time series of annual volumetric caps on SDL, with different reliabilities of supply, for the Denmark River at Mt Lindesay (603136).**

7.3 Evaluation of Candidate Criteria

If the analysis in Section 7.2 is repeated for the 75 sites with at least 25 years of record, it is possible to see for a 'typical' unregulated catchment, how the SDL varies as reliability of supply varies.

Figure 7.2 shows that (for the 75 sites with at least 25 years of record) if an 80% level of reliability is adopted across south-west Western Australia, the median SDL is 11.0% of the mean winterfill period flow. If the level of reliability is decreased to 70%, the median SDL increases to 12.9%, while if the level of reliability is increased to 90%, the median SDL decreases to 6.3%. As the level of reliability approaches 100%, the reduction in SDL becomes pronounced.

As mentioned in Section 7.1, the trade-off between SDL and reliability is best considered by the Department of Water in consultation with landholders. However, for the purposes of characterising the SDLs of south-west Western Australia and investigating the impacts of diversions, it was necessary for the study team to adopt a reliability of supply.



- **Figure 7.2: The impact of different levels of reliability on the calculated SDL (represented as a percentage of the mean winterfill period flow), for the 75 gauging sites with at least 25 years of record.**

7.4 Selection of Reliability of Supply

For the purposes of characterising SDLs and investigating the impacts of diversions on spells, and the inter-annual sequencing of ‘wet’ and ‘dry’ years, an 80% reliability of supply was adopted. 80% was also adopted during the Victorian SDL project for investigating the impacts of diversions during the Victorian winterfill period (NRE, 2002). If the Department of Water adopts a lower level of reliability, SDL volumes will be higher than those presented in Section 8, and the impacts of diversions more severe that those presented in Section 9. Alternatively, if the Department of Water adopts a higher level of reliability, the SDL volumes will be lower and the impact of diversions less.

8. Characteristics of Sustainable Diversion Limits

Figure 8.1 and Figure 8.2 show the spatial distribution of Sustainable Diversion Limits (for the 142 unregulated rivers for which streamflow data was available), capped at 80% reliability,

- as a proportion of the mean winterfill period flow, and
- per unit area of catchment

SDLs range from 0% – 20.9% of mean winterfill period flow, and from 0 – 39.4 ML per square kilometre. The background colour of Figure 8.1 and Figure 8.2 represents rainfall contours, with blue being high rainfall, and red low rainfall.

Not surprisingly, catchments in the wet south-west corner of Western Australia tend to have larger SDLs than catchments in the drier interior. However, the distribution of rainfall alone does not explain the distribution in SDL. For example, the Canning River at Glen Eagle (616065) and 31 Mile Brook at 31 Mile Road (616026) sites are side-by-side, but their SDLs as a per unit area of catchment are 2.9 ML/km^2 and 19.2 ML/km^2 respectively.

Two catchment characteristics which explain some of the variability in observed SDL are the base flow index (BFI) (Figure 8.3) and monthly coefficient of variation (CV) (Figure 8.4). Generally, as the BFI increases or the CV decreases, the SDL in ML/km^2 increases. For example, the BFI and CV for the Canning River at Glen Eagle are 0.43 and 1.20 respectively, whereas for 31 Mile Brook at 31 Mile Road, the BFI and CV are 0.56 and 0.64 respectively.

The BFI and CV are good indicators of the ability of a catchment to store and gradually release water. A high BFI and low CV indicate a catchment with persistent flows, a large component of which comes from groundwater stores (e.g. the 31 Mile Brook at 31 Mile Road; Figure 8.5). In contrast, a low BFI and high CV indicate a catchment which flows only in direct response to rainfall (e.g. the Canning River at Glen Eagle; Figure 8.5). Given the ability of an unregulated river to persistently flow is a large driver in determining its potential for sustainable extractions, it follows that catchments with high BFI and low CV will also have a high SDL.

A summary of the variability of SDL for the 142 gauged sites is provided in Figure 8.6. The median SDL is 11.0% of mean winterfill period flow, or 7.4 ML per square kilometre. 10% of sites have an SDL greater than 14.6% of mean winterfill period flow (or 21.7 ML/km^2), or less than 5.7% of mean winterfill period flow (or 1.1 ML/km^2). Interestingly, the variability in south-west Western Australia SDLs is much less than the variability in Victorian SDLs (Figure 8.7). The large variability in Victorian results is attributable to the extremely high SDLs assigned to catchments along the Great Dividing Range (Figure 8.8).

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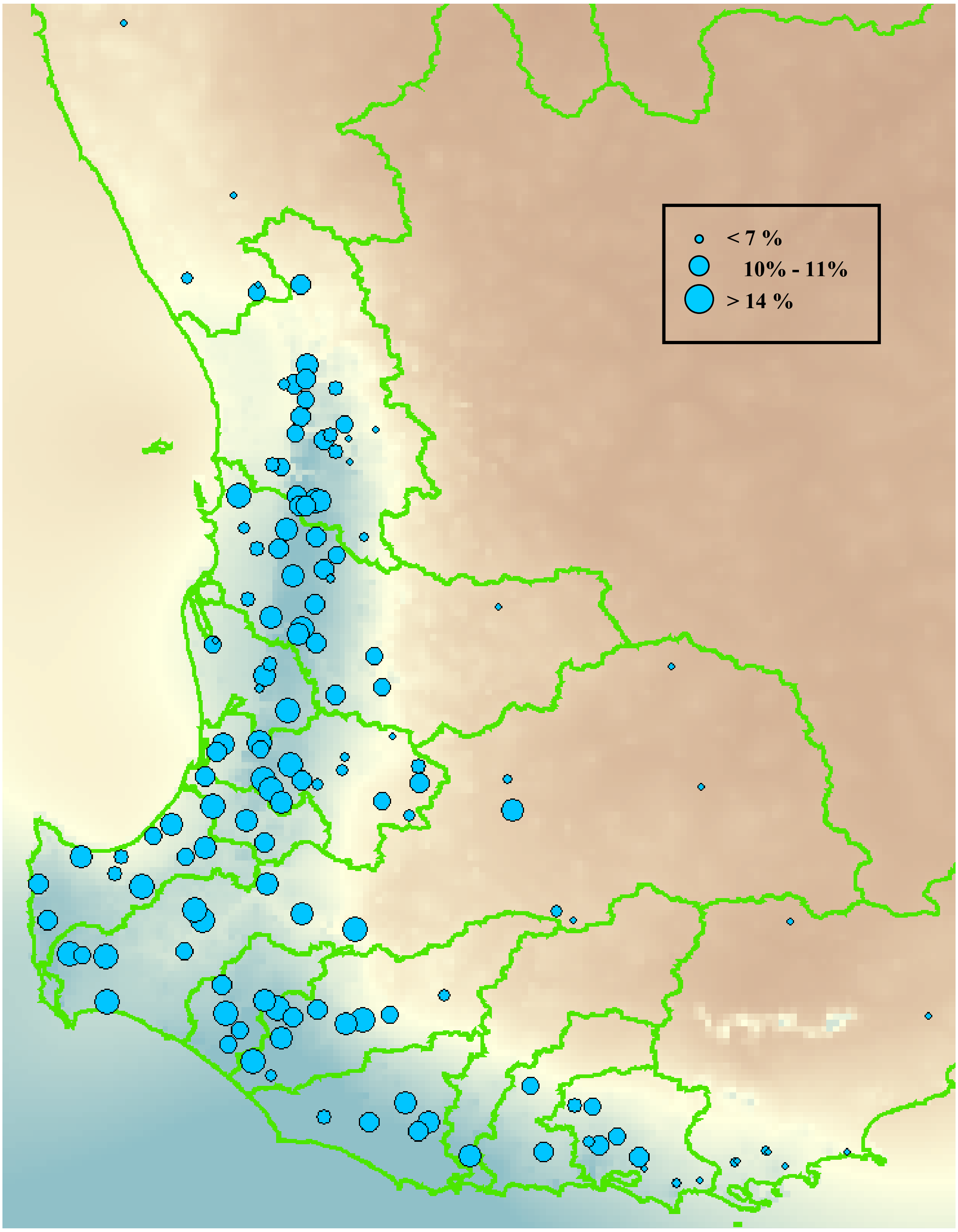
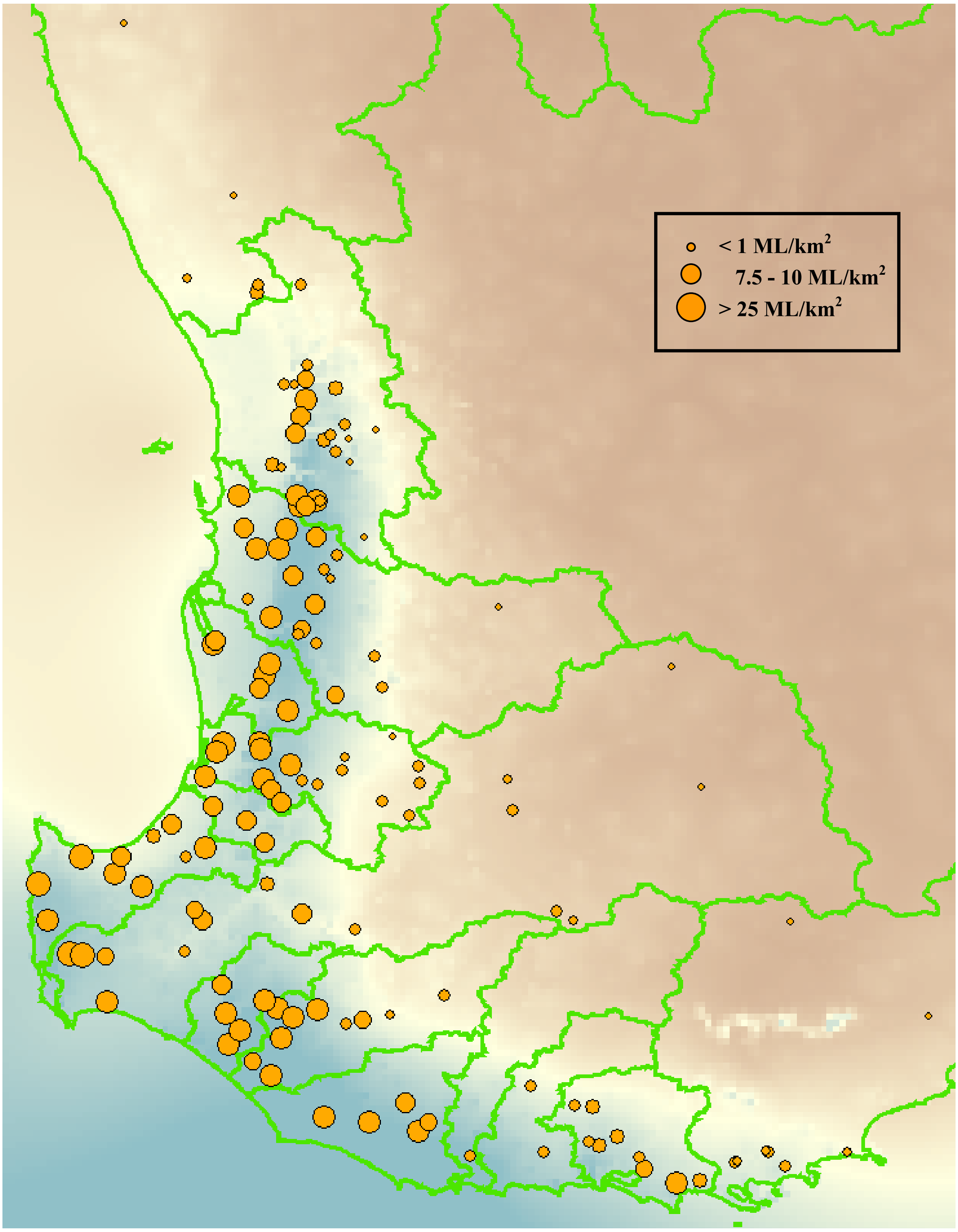
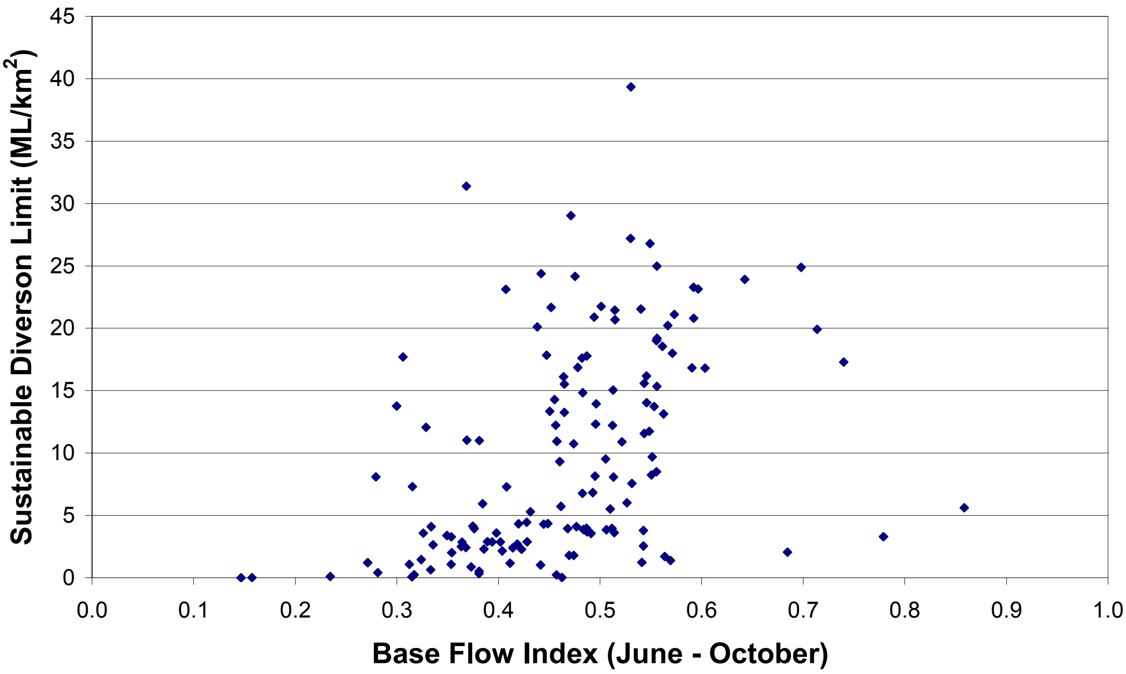


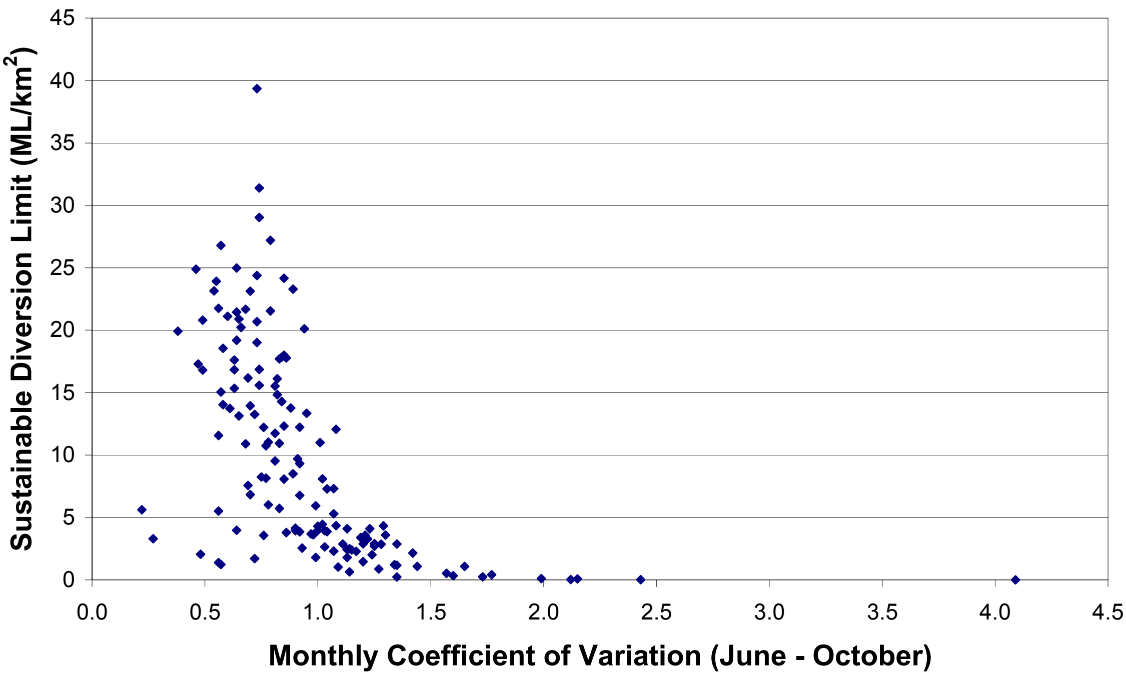
- **Figure 8.1: The geographical distribution of SDL (capped at 80% reliability) as a proportion of mean winterfill period flows (%). The background colour represents rainfall contours (blue: high rainfall, red: low rainfall).**



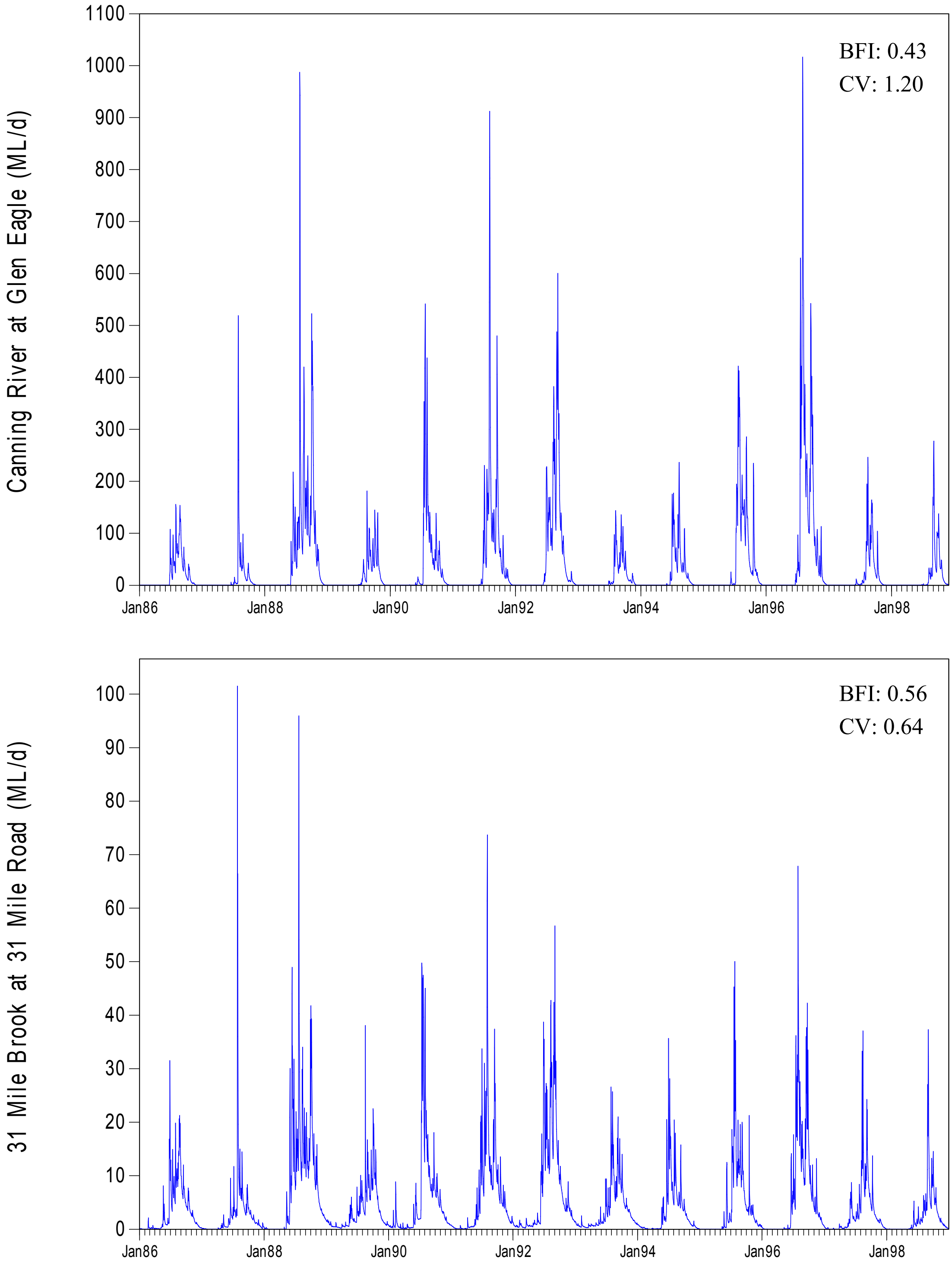
- **Figure 8.2: The geographical distribution of SDL (capped at 80% reliability) per unit catchment area (ML/km^2). The background colour represents rainfall contours (blue: high rainfall, red: low rainfall).**



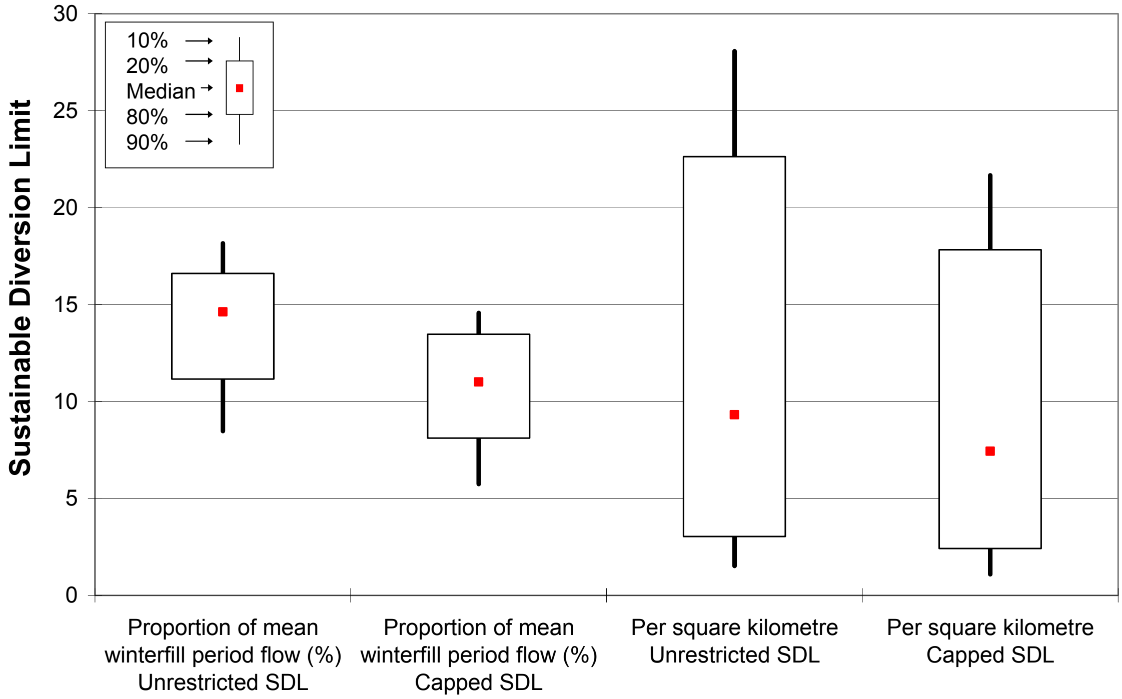
- **Figure 8.3: Standardised SDL (capped at 80% reliability) versus base flow index (for the months June to October inclusive). The base flow index was calculated using a digital filter (Nathan and McMahon, 1990).**



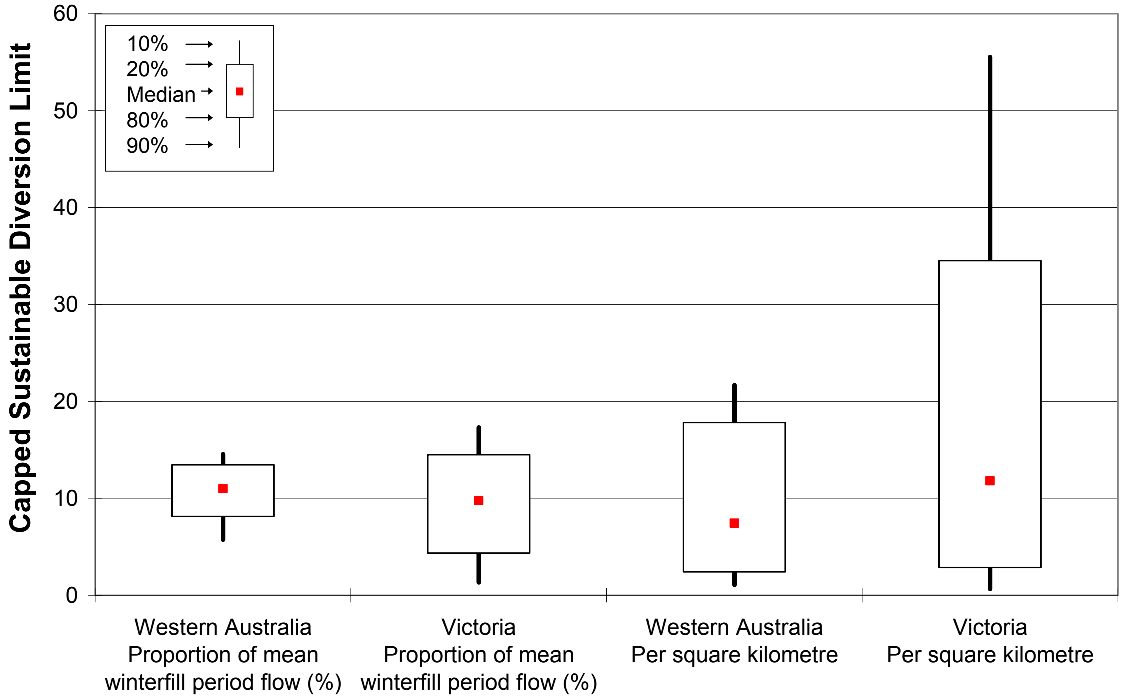
- **Figure 8.4: Standardised SDL (capped at 80% reliability) versus monthly coefficient of variation (for the months June to October inclusive).**



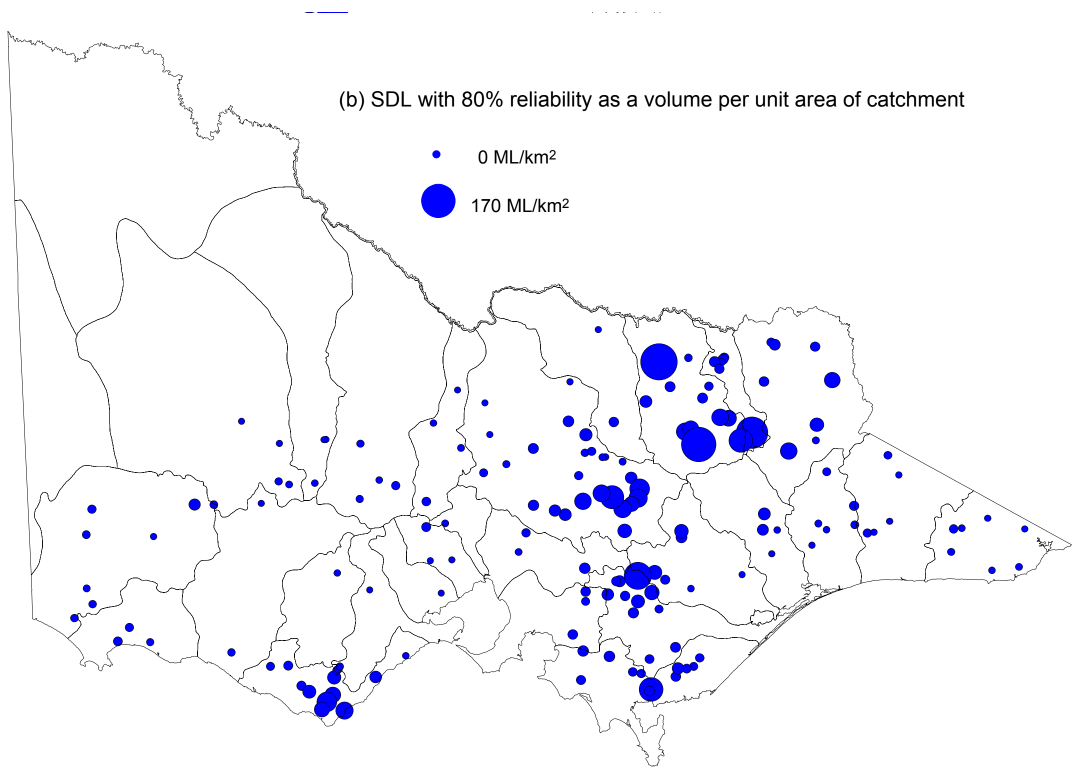
- **Figure 8.5: The hydrograph response of two catchments with distinctly different catchment storage attributes within the same climatic region. The SDL for the Canning River at Glen Eagle is 2.9 ML/km^2, while the SDL for 31 Mile Brook at 31 Mile Road is 19.2 ML/km^2.**



- **Figure 8.6: The distribution of standardised south-west Western Australia SDL volumes, unrestricted and capped at 80% reliability.**



- **Figure 8.7: The distribution of standardised south-west Western Australia and Victorian SDL volumes, capped at 80% reliability.**



- **Figure 8.8: The geographical distribution of Victorian SDLs (capped at 80% reliability) per unit catchment area (ML/km^2) (NRE, 2002).**

9. Assessment of Impacts

9.1 Introduction

The information presented in Sections 5 and 6 focused on the relative impacts of varying the minimum flow threshold (MFT) and maximum extraction rate (MER) rules. While it was difficult for the study team to objectively assess the threat to the environment of one specific rule over another, systematically raising and lowering the MFT and MER did enable comparison of the relative benefits of different rules. However, this approach did not specifically illustrate the impacts of diversions on hydrologic measures assumed to be of ecological significance.

This section explores the impacts of diversions (governed by SDL rules) on two characteristics believed to be of ecological importance; namely the frequency and duration of spells above various thresholds, and the inter-annual sequencing of wet and dry periods.

All results presented assume the SDL rules described in Sections 4 – 6 are applied, and an 80% reliability of supply is adopted.

9.2 Impact on Spells

Diversions from unregulated rivers (governed by SDL rules) impact both the frequency and duration of spells. The magnitude of these impacts depends on the spell threshold. Figure 9.1 and Figure 9.2 show the impact of diversions on the frequency and duration of spells during the winterfill period above a range of thresholds (using results from all 142 gauged sites). The thresholds are the 80th, 65th, 50th, 35th and 20th exceedance percentiles of daily flows in the months July – September, calculated using the available period of record. 'Low flows' are typically represented by the 80th percentile, and 'high flows' by the 20th percentile. Therefore the thresholds examined cover a range which is likely to contain the majority of ecologically significant flows which occur during the winterfill period.

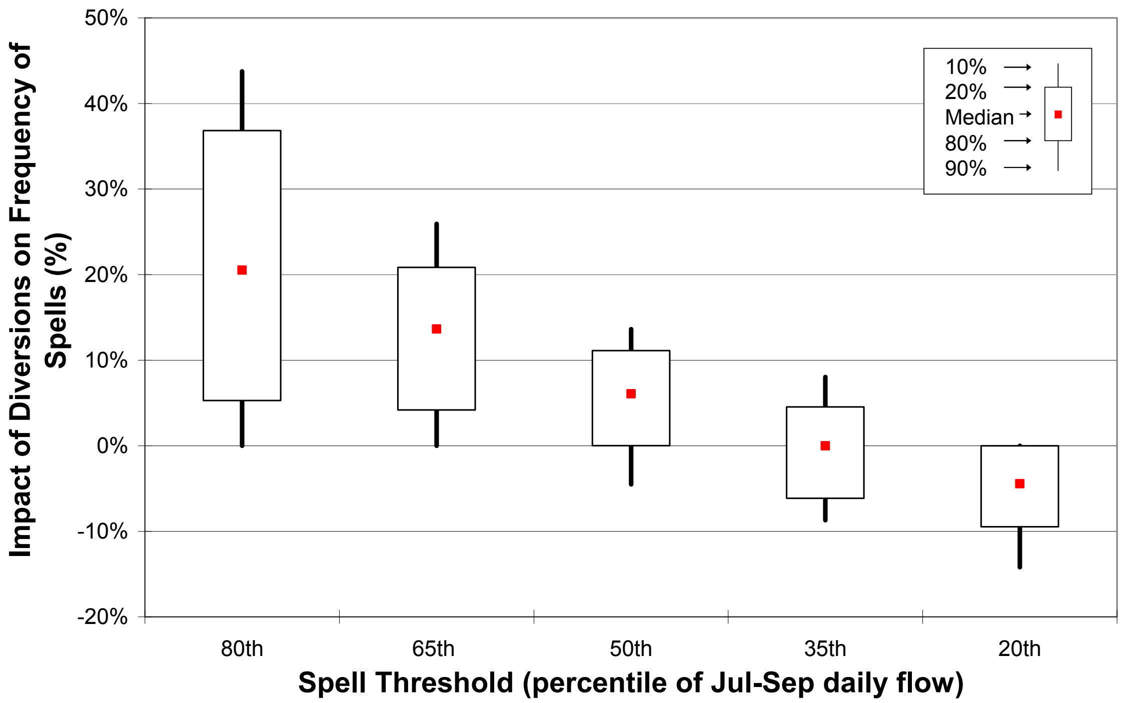
Figure 9.1 shows that spells above the lower thresholds actually occur more often under impacted conditions than natural conditions. For example, at 50% of sites, the frequency of spells above the 80th percentile of July-September daily flows increases by ~20%. This is because long interrupted spells under natural conditions may be divided into two or more 'spells' by diversions. As the spell threshold increases, this situation becomes rarer, and the frequency of spells under impacted conditions decreases. However, in absolute terms, the impact of diversions on average spell frequencies is minimal (Table 9.1).

With regard to spell durations, Figure 9.2 shows that, not unexpectedly, the impact of diversions decreases the duration as the threshold increases. For example, at 50% of sites, the duration of spells above the 50th percentile of July-September daily flows decreases by ~20%. On average, this represents a decrease from spells of 20.9 days duration to 17.0 days duration (Table 9.1).

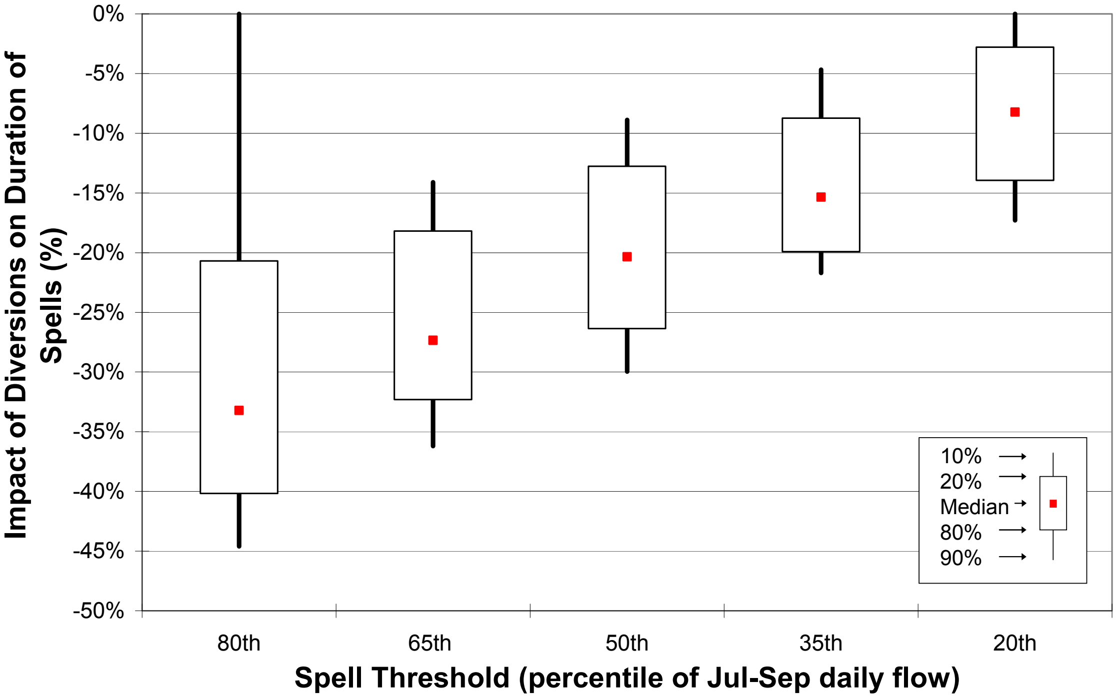
In summary, under impacted conditions, spells above the lower thresholds become more frequent, but with shorter durations. Spells above the higher thresholds become slightly less frequent, and have slightly shorter durations.

- **Table 9.1: Average spell frequency and durations during the winterfill period, under natural and impacted conditions (using the results from all 142 selected sites)**

	Average Duration (days)		Average Frequency (per winterfill period)	
Threshold	Natural	Impacted	Natural	Impacted
80th percentile	49.8	35.3	1.8	2.2
65th percentile	31.7	23.8	2.3	2.6
50th percentile	20.9	17.0	2.7	2.9
35th percentile	13.2	11.4	3.0	2.9
20th percentile	8.2	7.6	2.7	2.6



- **Figure 9.1: The impact of diversions (governed by the SDL rules) on the frequency of spells during the winterfill period above thresholds based on percentiles of daily flows for the months July-September.**

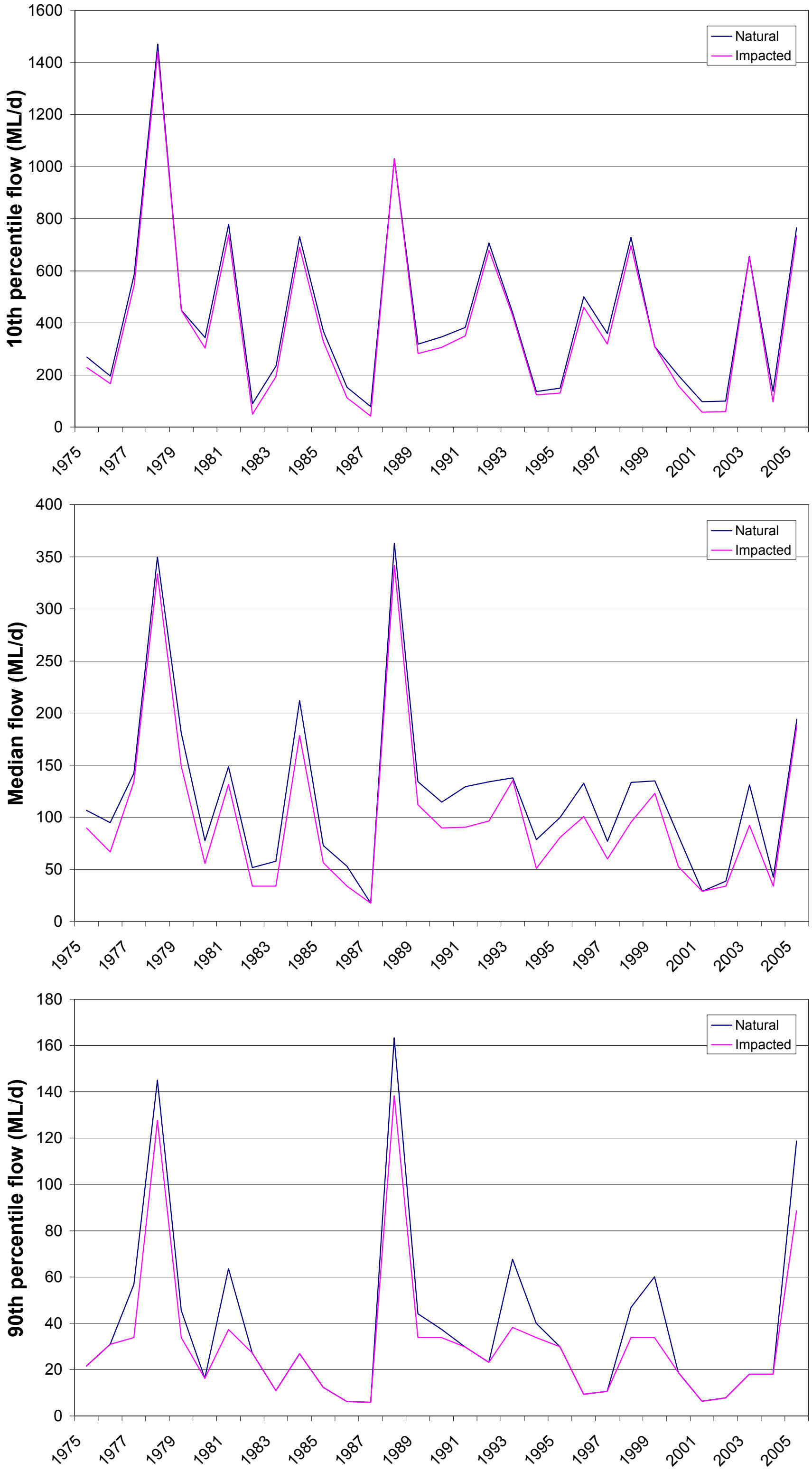


- **Figure 9.2: The impact of diversions (governed by SDL rules) on the duration of spells during the winterfill period above thresholds based on percentiles of daily flows for the months July-September.**

9.3 Impact on Inter-Annual Sequencing

To investigate the impacts of diversions governed by SDL rules on the inter-annual sequencing of flows, the 10th percentile, median and 90th percentile flow of individual winterfill periods was plotted as a time-series for the Denmark River at Mt Lindesay (Figure 9.3).

Figure 9.3 shows that impact of diversions is more apparent at low flows (i.e. the 90th percentile) than high flows (i.e. the 10th percentile), and that the biggest differences between natural and impacted flow percentiles occur in 'average' years. That is, in years when there is enough streamflow to enable extractions on most days of the winterfill period, but not so much water that extractions are only a small fraction of streamflows. However, most importantly, Figure 9.3 also shows that the natural sequence of wet and dry years is maintained after diversions.



- **Figure 9.3: 10th percentile, median and 90th percentile flows during the winterfill period under natural and impacted conditions for the Denmark River at Mt Lindesay (603136).**

9.4 Summary

In summary, following diversions during the winterfill period governed by SDL rules:

- The median frequency of spells during the winterfill period above 80^{th}, 65^{th} and 50^{th} percentile thresholds increases by 21%, 14% and 6% respectively,
- The median frequency of spells during the winterfill period above the 35^{th} percentile threshold is maintained, and the median frequency above the 20^{th} percentile threshold decreases by 4%,
- The median duration of spells during the winterfill period above 80^{th}, 65^{th}, 50^{th}, 35^{th} and 20^{th} percentile thresholds decreases by 33%, 27%, 20%, 15% and 8% respectively,
- Inter-annual variability is maintained, with the largest difference between flow percentiles under natural and impacted conditions occurring in years with near average flows.

10. Important Considerations

10.1 Introduction

It is important that results from this project be seen in the context of overall ecosystem health. While it may be possible to determine the SDL for any unregulated catchment in south-west Western Australia using the recommendations contained in this report, decisions about the allocation of water need to be made with other aspects of the ecosystem in mind. In particular, in-stream habitat condition, water quality and riparian condition need to be part of the decision making process.

Therefore, it is emphasised that estimates of SDL is only one of many tools which should be used by the Department of Water when making decisions about surface water sharing arrangements.

10.2 Accuracy of SDL Estimates

All results presented in this report are based on the analysis of flows over the period of available record. And not surprisingly, the accuracy of SDL estimates is dependent upon the record length (Table 10.1).

The standard error and confidence limits in Table 10.1 were estimated using a Bootstrap technique. (Efron and Tibshirani, 1993). The Bootstrap technique involved calculating the SDL for each of the 142 gauged sites 1000 times; each time omitting a different year from the streamflow record.

Table 10.1 shows that, given the average length of record for the 142 gauged sites used to develop the SDL rules was 24.4 years,

- the average standard error of SDL estimates in gauged catchments is ~6% of the mean, and
- the average 90% confidence interval is ~20% of the mean.

Table 10.1 also shows that SDL estimates based on 10 years of record are generally acceptable, and have confidence limits comparable to other simple hydrological indices transposed using regional information (e.g. McMahon, 1983; Nathan and McMahon, 1992).

- **Table 10.1: Accuracy of SDL estimates as a function of record length.**

Number of Winterfill Periods	Average Standard Error of SDL Estimate (% of mean)	Average Range of 90% Confidence Intervals (% of mean)
10 – 19	7.4	25.5
20 – 29	5.6	18.6
30+	4.1	14.6

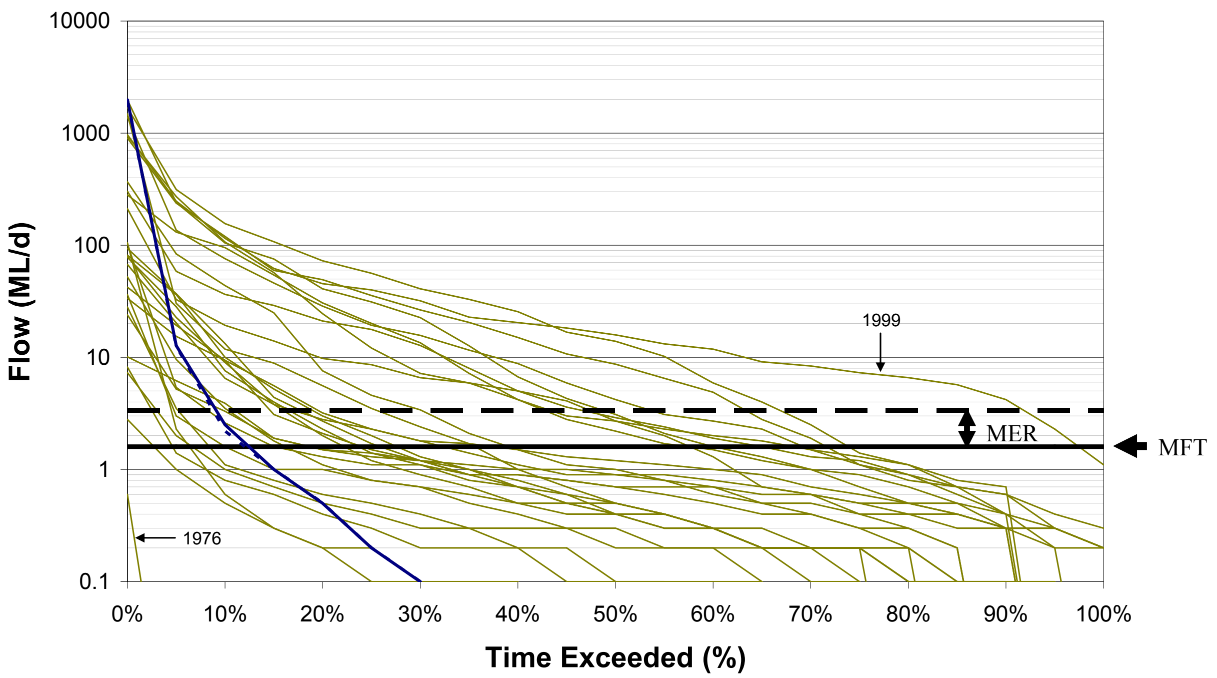
10.3 Low Yielding Catchments

In Section 8, it was suggested a catchment's SDL was dependent on its available storage: the smaller the catchment storage (as characterised by low BFI and high CV values), the smaller the SDL estimate. While this may be self-evident, it is perhaps worthwhile examining which aspects of the recommended diversion rules limit the SDL of low yielding catchments.

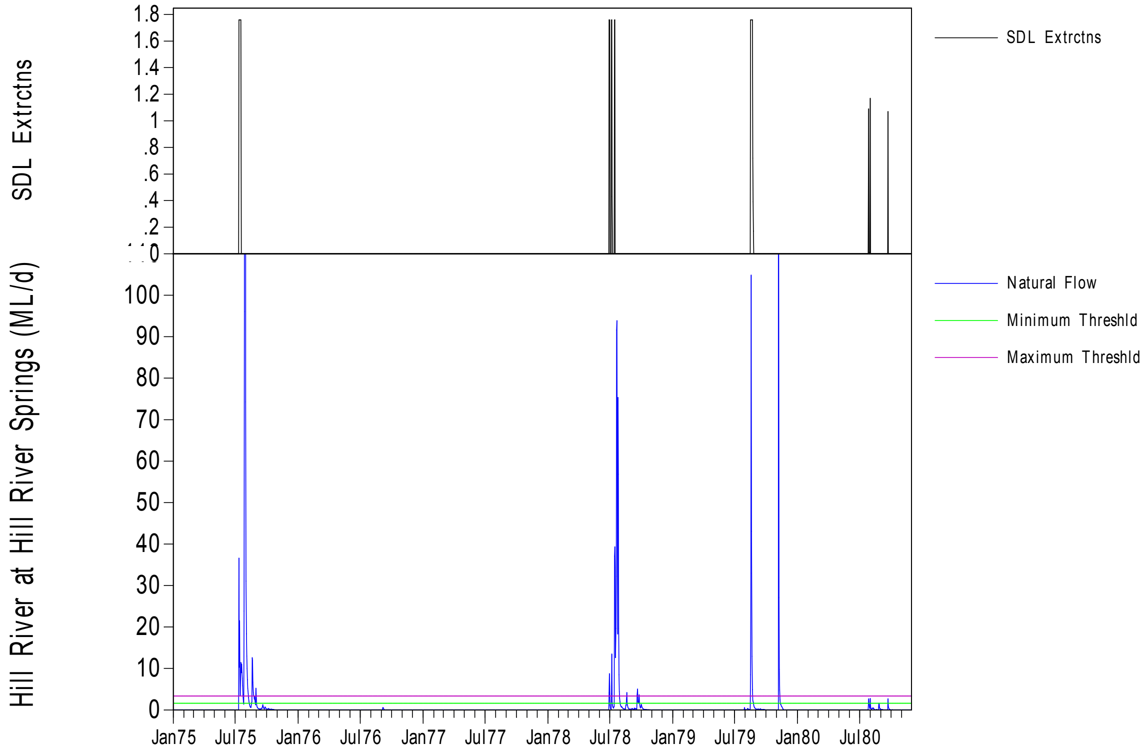
The influence of the diversion rules on SDL estimates for low yielding catchments is illustrated using the Hill River at Hill River Springs, which despite its catchment area of 925.9 km^2, has an SDL of only 14 ML. Figure 10.1 plots the flow duration curves for this site from 1975 – 2005.

As shown by Figure 10.1 and Figure 10.2, the Hill River at Hill River Springs is ephemeral in nature. This suggests the catchment receives sporadic rainfall, and has a limited ability to store and gradually release water.

The winterfill period median daily flow exceeded in 95% of years is 0.01 ML/d, and 30% of the mean daily flow is 1.6 ML/d. Therefore the minimum flow threshold (MFT) for the Hill River at Hill River Springs is 1.6 ML/d. The maximum extraction rate (MER) needed so that 25% of days above the MFT under natural conditions (during the winterfill period over the available period of record) flat-line at the MFT under impacted conditions is 1.8 ML/d.



- **Figure 10.1: The overall flow duration curve under natural (highlighted) and impacted (dashed) conditions during the winterfill period for the Hill River at Hill River Springs (617002). The minimum flow threshold (MFT) is 1.6 ML/d, and the maximum extraction rate (MER) 1.8 ML/d. The flow duration curves for every winterfill period from 1975 to 2004 are also shown.**



- **Figure 10.2: The time-series of natural flows for the Hill River at Hill River Springs (617002), for the period 1975 – 1980, illustrating the ephemeral nature of Hill River.**

However, it is not the MFT and MER rules that limit the SDL for this catchment. In fact, if these rules were applied with no reliability of supply, an average of 61 ML would be available for extraction in the winterfill period, with a high of 203 ML available in 1999. Rather, adopting a reliability of supply of 80% caps the SDL at 14 ML. Even if the MER is almost doubled to 3.4 ML/d, applying a reliability of supply of 80% would result in a relatively modest increase in SDL from 14 ML to 22 ML.

The reliability of supply has the largest effect on the SDL estimate for the Hill River at Hill River Springs because streamflows are highly variable from one year to the next. No diversions would have been possible in 1976 or 1977, while little water was available in 1979, 1980, 1985, 1989, 1993 and 1997. Given that in >20% of years, there is little or no water available for extraction, adopting an 80% reliability of supply automatically assigns the catchment a low SDL.

10.4 Farm Dams

The recommended rules for estimating a catchment's SDL have been based on the assumption that all extractions are via pumped diversions. However, in most catchments, a significant proportion of current and presumably future diversions are attributable to farm dams.

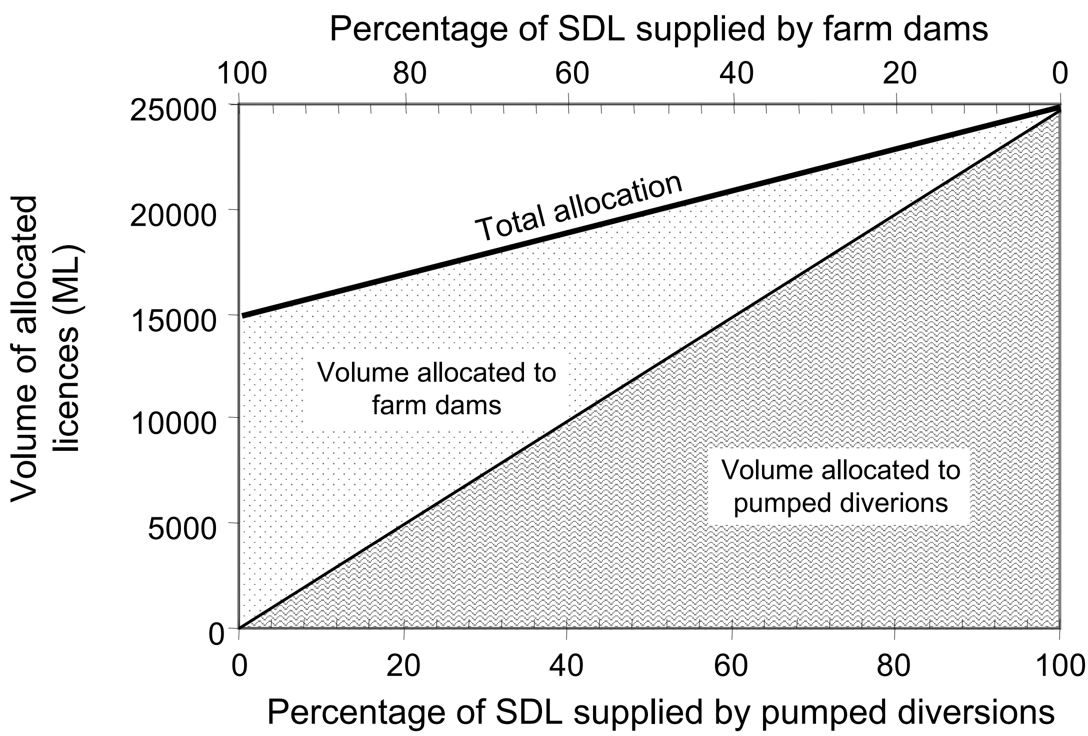
Using simulation modelling (e.g. Neal et al, 2000) it is possible to calculate the volume of farm dams that have an average annual impact equivalent to the SDL. A relationship between pumped diversions and farm dam volumes can therefore be developed (e.g. Figure 10.3). For example, if the SDL for an unregulated catchment is 25,000 ML, and if all extractions are via pumped diversions, 25,000 ML can be licensed for extraction. If however, all diversions are via farm dams, the volume of farm dams which can be licensed, and the SDL met, is 15,000 ML.

Using relationships such as that illustrated in Figure 10.3, it is possible to allocate licenses to varying combinations of pumped diversions and farm dam volumes, such that the combined impact on streamflows is within the SDL. For example, if 10,000 ML of farm dams currently existed, the remainder of the SDL could be allocated to an additional 5,000 ML of farm dams, 8,333 ML of pumped diversions, or a combination of the two.

In reality, the relationship between farm dam volumes and pumped diversions is not as simple as indicated by Figure 10.3. The impact of farm dams, and hence their equivalence with pumped diversions, depends upon the size and distribution of farm dams, and other site-specific factors such as topography. In practice therefore, the slope of the total allocation line in Figure 10.3 will vary from catchment to catchment. It may be necessary to develop a set of generalised relationships that take into account physiographic and dam distribution factors, or adopt a region wide relationship similar to Figure 10.3, with the knowledge that site-specific factors will limit the accuracy of a region wide approach.

While it is possible to calculate the volume of farm dams which have an impact equivalent to pumped diversions, restricting the period over which farm dams harvest streamflows is more problematic. Unless modified, farm dams will harvest streamflows whenever there is storage capacity to do so. Therefore, the selection of an equivalence measure between farm dams and pumped diversions should also take into account differences in their seasonal impacts.

In summary, the underlying principle which should be adopted when decisions about allowing additional diversion are made is that pumped diversions are preferable to farm dams. Pumped diversions can be closely controlled through SDL rules, whereas controls on farm dams are limited to volume restrictions. That is, without modifying farm dams, it is difficult to limit their impacts on streamflows outside the winterfill period, and below minimum flow thresholds, especially during the ecologically important transition from 'dry' to 'wet' conditions when most dams are empty.



- **Figure 10.3: A hypothetical relationship of the distribution of water allocated to pumped diversions and farm dams, for an unregulated catchment with a SDL of 25,000 ML.**

However, given pumped diversions are not possible in some unregulated catchments, and new farm dams are inevitable, it is the opinion of the study team that the following operational rules should be seriously considered by the Department of Water:

- In the first instance, preference should be given to off-stream storages filled via pumped diversions. Acknowledging that this is not always possible, new farms dams should have a bypass facility, which ensures runoff is not harvested until the winterfill period has begun and the catchment's minimum flow threshold has been exceeded, and
- Licenses for pumped diversions should carry a lesser charge per unit volume than farm dams, thus providing diverters an incentive to avoid building new farm dams, and to perhaps change their water harvesting infrastructure from farm dams to off-stream storages filled via pumped diversions.

10.5 Monitoring and Research

It was the opinion of the study team that no amount of regulation of diversions would protect the environment, unless complimentary compliance monitoring was also conducted by the Department of Water. Compliance monitoring requires the telemetry of streamflow at key gauges, the metering and monitoring of how water is diverted, and a process to ensure the SDL rules adopted are not breached.

It was also the opinion of the study team, that along with compliance monitoring, a distinct need exists for water agencies to monitor ecological responses to winterfill period diversions at key sites representative of the hydroclimatic conditions encountered across south-west Western Australia. In addition, additional field-based research is required into the environmental flow requirements of south-west Western Australia. As the pressures on water resources intensify, and volumes of licensed diversions approach SDL estimates, local environmental water requirement (EWR) studies will be required to refine water sharing arrangements. It would be preferable that the research and monitoring undertaken for each EWR study form part of an overall investigation into the environmental water requirements of south-west Western Australian rivers, rather than existing as stand alone pieces of information applicable only to individual catchments.

10.6 Summary

- Decisions about the allocation of water need to be made with other aspects of the ecosystem in mind (such as in-stream habitat condition), and therefore the SDL should be one of many tools used when water sharing arrangements are determined,
- The accuracy of SDL estimates for gauged catchments are dependent on the length of available record. For sites with an average record length of 24.4 years, the 90% confidence interval is about 20% of the mean,
- In low yielding catchments, which have streamflows that are highly variable from one year to the next, it is the adopted reliability of supply which limits the SDL estimate,
- The underlying principle which should be adopted when decisions about allowing additional diversion are made, is that pumped diversions are favourable to farm dams, and
- Compliance and ecological monitoring will be needed to ensure the adopted diversion rules are followed, and to gauge the ecological response to winterfill period diversions.

11. Conclusions and Recommendations

It is the recommendation of the study team, that diversions from the unregulated catchments of south-west Western Australia be controlled by four rules:

- The winterfill period
  - i.e. diversions should only occur between 15 June – 15 October inclusive.
- The minimum flow threshold (MFT)
  - i.e. diversions should cease once streamflows drop below the larger of 0.3 of the mean daily flow (calculated over all months), and the 95th percentile of the median winterfill period daily flow.
- The maximum extraction rate (MER)
  - i.e. the MER should be set so that a maximum of 25% of days above the MFT under natural conditions (during the winterfill period over the available period of record) flat-line at the MFT under impacted conditions.
- A fixed annual limit with associated reliability of supply.
  - i.e. allocations to individual diverters, should allow them to extract their licensed volume in at least 80% of years, while complying with the above three rules.

It is also the opinion of the study team that should these four rules be implemented, the threat to the riverine environment associated with diversions will remain within acceptable limits. However, decisions about the allocation of water need to be made with other aspects of the ecosystem (such as water quality) in mind, and therefore the SDL should be one of many tools used when water sharing arrangements are determined.

It is also recommended that:

- Department of Water develop procedures to ensure ongoing compliance with adopted diversion rules,
- The ecological response to winterfill period diversions be monitored at key sites representative of the hydroclimatic conditions encountered across south-west Western Australia, and
- A high priority is given to conducting further field-based research into the environmental flow requirements of unregulated rivers.

If the recommended SDL rules are implemented, the median SDL for the unregulated catchments of south-west Western Australia is 11.0% of mean winterfill period flow.

12. References

Arthington, A.H. & Zulucki, J.M. (Eds) (1998): Comparative evaluation of environmental flow assessment techniques: Review of methods. *LWRRDC Occasional Paper 27/98*. Land and Water Research and Development Corporation, Canberra.

Boulton, A.J. & Lake, P.S. (1990): The ecology of two intermittent streams in Victoria, Australia. Temporal changes in faunal composition. *Freshwater Biology*, **27**: 123-138.

Efron, B. & Tibshirani, R.J. (1993): *An introduction to the bootstrap*, Chapman and Hall.

Humphries, P. (1989): Variation in the life history of diadromous and landlocked populations of the spotted galaxias, *Galaxias truttaceus*, in Tasmania. *Australian Journal of Marine and Freshwater Research*, **40**: 510-518.

McMahon, T.A. (1983): Low flow and yield data requirements. In: Proceedings of Workshop on Surface Water Resources Data. *A.W.R.C. Conference Series No. 10*, A.G.P.S: 79-124.

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

Nathan, R.J. & McMahon, T.A. (1992): Estimating low flow characteristics in ungauged catchments. *Water Resources Management*, **6**: 85-100.

Nathan, R.J., Rahman, A., Bagg, S. & Green, J.H. (2000): An objective procedure for identifying regions of low flow homogeneity for the specification of environmental flows. *Proceedings of the 3rd International Hydrology and Water Resources Symposium*, Engineers Australia: 935-940.

Nathan, R.J., Doeg, T. & Voorwinde, L. (2002): Towards defining sustainable diversion limits to winter diversions in Victorian catchments. *Australian Journal of Water Resources*, **5**(1): 49-59.

Natural Resources and Environment (NRE, 2002): *Recommendations for defining the sustainable diversion limit over the winterfill period in Victorian catchments*.

Natural Resources and Environment (NRE, 2003): *Estimation of sustainable diversion limit parameters over winterfill periods in Victorian catchments*.

Neal, B.P., Shephard, P., Austin, K.A. & Nathan, R.J. (2000): The effect of catchment farm dams on streamflows – Victorian case studies. *Proceedings of the 3rd International Hydrology and Water Resources Symposium*, Engineers Australia: 836-841.

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Appendix A Selected Gauges

Gauge	River	Site	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

SKM

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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	D-S 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	SW 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
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

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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
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

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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