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# Development and Trial of a Methodology for Total Water Resource Assessment in Tropical Australia

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FINAL REPORT

- Final
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# Executive Summary

## Introduction

This report is the outcome of a pilot study to determine whether a proposed method of total water resource assessment is viable using the limited available data in catchments of tropical northern Australia. It seeks to formulate this proposed method and then test whether it can provide an integrated assessment of the surface water and groundwater resources available in two pilot river basins in the Northern Territory.

The Australian Government has established the Northern Australia Land and Water Taskforce to "examine the potential for further land and water development in northern Australia, in a manner that is ecologically, culturally and economically sustainable" (Minister for the Environment and Water Resources, 29/7/07). Assessment of water development proposals to date has been hampered by the lack of information that can be used to reasonably estimate the volume of water currently available to the environment and the proportion of that water potentially available for consumptive users. This project specifically seeks to address this knowledge gap and provide a method by which information can be obtained that is necessary for a technically defensible and environmentally responsible water allocation policy in individual river basins.

The basins selected for investigation in this study are the Adelaide and Finniss River basins. These basins were selected in consultation with project stakeholders (especially the Department of Natural Resources, Environment and The Arts, NRETA) based on their hydrogeological characteristics and the availability of gauged surface water data. The catchment area upstream of streamflow gauges was just under 20% of the total area of each of the Adelaide and Finniss River basins. These two river basins mainly interact with non-carbonate aquifers, which means that rivers in these basins typically display less point source discharge from groundwater into surface water, however some individual catchments within these river basins contained areas of carbonate aquifer that influence the low flow properties of local streams.

## Stakeholder requirements

Discussions with NRETA established a number of requirements for the method of water resource assessment being developed, namely:

- Methods should facilitate a water resource assessment which includes consideration of groundwater and surface water interaction and be applicable to ungauged areas of tropical northern Australia.
- Methods should take into consideration long-term climate variability, as the climate over the last few decades is considered to be wetter than previous decades.

- Methods should be clearly stated as being applicable to catchments with predominantly carbonate or non-carbonate aquifers or both, as hydrologic behaviour and hence water management decisions are likely to be different in catchments with predominantly carbonate aquifers, which have sustained dry season flows.
- Methods should practically inform the water resources allocation process.

## Research Outcomes

A method was established for reliably estimating hydrologic information in the largely ungauged trial basins of the Adelaide and Finniss Rivers. The development of this method and its application in the two trial basins produced the following outcomes:

*Period of assessment for water allocation* – There is high variability in climate and streamflow in the Adelaide and Finniss River basins. Average rainfall over the period of gauged streamflow data (1965-2005) was approximately 5-16% higher than the long-term average (1872-2005). Streamflow was estimated to be in the order of 7-20% higher than the long-term average in the Finniss River basin and lower reaches of the Adelaide River basin, and 46-64% higher in the upper reaches of the Adelaide River basin. Climate change projections from CSIRO indicate that conditions over the coming decades could either become wetter or drier relative to 1990 conditions, depending on the climate model used and the assumed level of greenhouse gas emissions. Given this uncertainty, it is considered prudent in the first instance to represent current streamflow conditions as based over the longer climate period (1872-2005) to allow for the possibility of a return to drier conditions as part of natural inter-decadal variability. Allowance for a range of climate change conditions as part of the allocation process should be undertaken with reference to this long-term baseline. The method of deriving longer-term hydrologic information for this trial project involved scaling of results based on rainfall-runoff models calibrated to the shorter period and applied over the longer period.

*Methods of determining groundwater and surface water interaction in gauged catchments* – A digital recursive filter has been used in the Adelaide and Finniss River basins to estimate baseflow. This technique is expected to be applicable to other catchments across tropical northern Australia which display relatively stable rating tables. Preliminary investigation of the use of rainfall-runoff models to estimate baseflow yielded mixed success, with no single model being able to replicate both baseflow and surface runoff in an objective manner. It is expected that more detailed investigations would allow the development of a conceptual model specifically tailored to groundwater processes, and that this would provide a more reliable means of estimating both quickflow and baseflow conjunctively in other parts of the tropical northern Australia where a mix of carbonate and non-carbonate aquifers exist.

This study does not consider in detail the time lag between groundwater extraction and a subsequent response on the river. This study does however highlight the stark differences in groundwater and surface water interaction from the wet season to the dry season. This creates the potential for seasonal groundwater extraction that is out of phase with baseflow discharge to streams during the dry season. That is, pumping groundwater in the dry season at some distance from surrounding rivers could result in a reduction in baseflow during the wet season rather than the dry season.

Evapotranspiration from groundwater was estimated using the results of field measurements from previously published studies to assist in quantifying the volume of groundwater that could be allocated in excess of baseflow at a given groundwater pumping location. The further that a groundwater bore is from a stream, the greater the opportunity for evaporative loss from groundwater between the bore and the stream. Lowering of groundwater tables due to groundwater pumping would result in lower losses due to evaporation and evapotranspiration between the bore and the stream, which would potentially mean that a higher volume could be allocated from groundwater at the bore than at the river, assuming no unacceptable impacts on groundwater dependent ecosystems.

Groundwater discharge that is not recorded at the streamflow gauge at each catchment outlet, such as discharge to offshore or adjacent catchments, was estimated using Darcy's Law and found to be negligible relative to baseflow volumes for the Adelaide and Finniss River basins.

*Applying the technique to ungauged areas* – A range of indicators relevant to both resource assessment and ecology estimated in catchments with gauged streamflow data was successfully transposed to ungauged areas using readily available catchment and climate characteristics. Catchment area was the main catchment characteristic which proved useful for predicting those streamflow indices which are expressed as a flow magnitude. Distance from the coast, which was a new variable introduced for this study, was useful in predicting high flow and wet season indices. Low flow dry season indices were generally found to be zero because of the general absence of carbonate aquifers in these two river basins. Independent variables used in the prediction equations were sometimes outside of the range of values used in developing the equations, particularly in the smaller coastal streams where there is limited long-term gauged flow data. The prediction equations used to estimate all flow indices were a good fit to the available data, but results will be further improved with larger sample sizes in subsequent applications of the method to broader areas across northern Australia. For this reason, the estimates of water availability in the Adelaide and Finniss River basins should be considered as reasonably reliable, but also preliminary in nature. Temporal variability of streamflow in the candidate catchments was found to be more important than spatial variability, which is an important finding when weighing up the relative differences in spatial and temporal availability of streamflow data in future applications of this method to the remainder of tropical northern Australia.

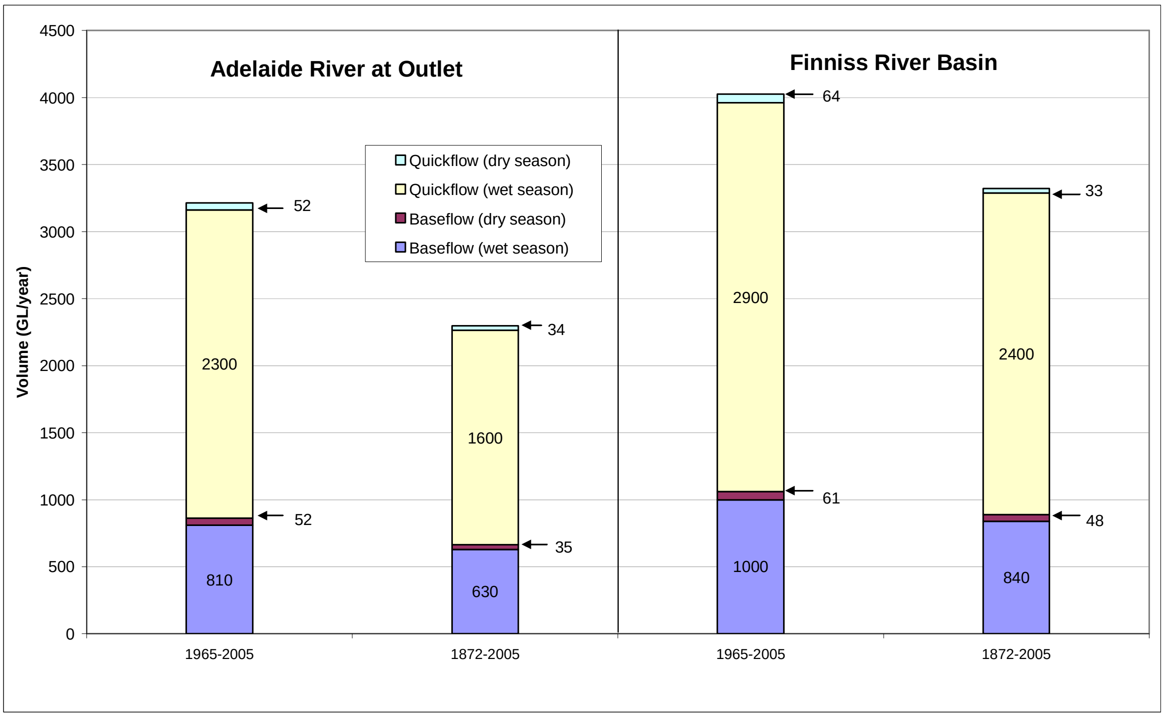
*Water availability for the Adelaide and Finniss River basins* – The potential benefits of the techniques adopted in this study are demonstrated in the estimate of water availability in rivers in the Adelaide and Finniss River basins shown in Figure 1. These results show the relative magnitude of dry season and wet season flows, as well as the relative magnitude of baseflow and quickflow. The sensitivity of results to the assessment period used in the analysis is also shown. The long-term (1872-2005) total resource available from rivers in the Adelaide River basin is estimated to be 2300 GL/yr with a dry season baseflow of 35 GL/yr. Similarly, the long-term resource available from rivers in the Finniss River basin is 3300 GL/yr with a dry season baseflow of 48 GL/yr.

It is proposed that the volume of the available annual groundwater resource from the Adelaide and Finniss River basins is equal to the volume of baseflow plus a spatially variable groundwater evapotranspiration loss. The long-term (1872-2005) average annual volume of baseflow is 660 GL/yr in the Adelaide River basin and 890 GL/yr in the Finniss River basin, with most of this being discharged to rivers during the wet season. There is the potential to possibly draw upon groundwater in the dry season without adversely affecting baseflow until the following wet season, when baseflow is more plentiful. Evapotranspiration from groundwater was estimated to be on average around 565 mm and 557 mm in the wet season in the Adelaide and Finniss River basins respectively and 109 mm in the dry season in both river basins. Whilst the change in groundwater level due to groundwater pumping will be localised and specific to individual bores or borefields, by way of example, if groundwater pumping were to cause a 10% reduction in groundwater evapotranspiration across these river basins then the volume associated with that change would be 500 GL in the Adelaide River basin and 610 GL in the Finniss River basin. Reduction in evapotranspiration from groundwater could however impact on groundwater dependent ecosystems due to reduced access to this water source. This example illustrates that reduction in groundwater evapotranspiration due to groundwater pumping could potentially be a very large volume, but would mostly likely only be made available to groundwater users if any impacts on groundwater dependent ecosystems could be appropriately managed. This would need to be assessed for specific bore locations and pumping rates.

Importantly, these estimates of water availability eliminate double counting of the resource in rivers due to groundwater and surface water interaction. The magnitude of double counting is in the order of the volume of baseflow.

These results differ from those of the Australian Water Resources Assessment of 2005 because they cover the whole of the Adelaide and Finniss River basins as well as smaller catchments within them, and because they have been climate corrected to be representative of long-term climate conditions rather than just a single year's value. The National Land and Water Resources Assessment of 2000 yielded similar results for mean annual flow from the Finniss River basin, but the current project has the advantage of accounting for longer term climate variability and more of the spatial variability in streamflows between catchments, as well as being able to report on baseflow and quickflow, seasonal behaviour and a range of hydrologic indices in addition to simply reporting on mean annual flows.

These estimates of water availability do not explicitly take into account current use. Estimated total average annual groundwater extraction across the Adelaide and Finniss River basins is in the order of 41 GL/yr. Further analysis and information would be required to adjust the existing estimates of baseflow availability for historical groundwater pumping, which could be expected to vary from the current 41 GL/yr over the 1965-2000 period over which baseflow estimates were initially derived for this study.




- **Figure 1 – Estimated surface water resource for the Adelaide and Finniss River basins (annual groundwater resource is the annual baseflow volume plus a spatially variable groundwater evapotranspiration loss)**

*Carbonate versus non-carbonate aquifers* – The techniques adopted in this trial project have been developed in catchments with predominantly non-carbonate aquifers and are considered applicable across tropical northern Australia wherever catchments are predominantly non-carbonate. Some of the catchments in the study area did however contain some carbonate aquifer and therefore produced sustained low flows during the dry season. Wet season flows were readily estimated in catchments with carbonate aquifers. As part of any future rollout of the techniques from this project, it will first be necessary to check rating table stability (as was done in this project) and ascertain the spatial extent of carbonate aquifers across tropical northern Australia. Preliminary investigations undertaken in this study suggest that there is a possibility of transposing dry season hydrologic indices by utilising measures of the extent of carbonate aquifer in each catchment. Alternatively, detailed numerical groundwater modelling would be required for carbonate aquifers, however this may not be practically feasible across all areas containing carbonate aquifers in tropical northern Australia in the short term due to the intensive data requirements and cost associated with this modelling.

### Recommendations

This study developed a methodology and applied it to two river basins, demonstrating proof of concept for the technique of estimating groundwater and surface water resources in river basins of tropical northern Australia with predominantly non-carbonate aquifers. As a result of undertaking this study, it is recommended that:

1. The method developed for this study should be applied to all river basins with predominantly non-carbonate aquifers across tropical northern Australia. This would provide a robust comprehensive assessment of groundwater and surface water resources and their interaction in the largely ungauged catchments in this region. The information that can be derived from this method is considered essential for the subsequent assessment of any large scale water resource development proposals across tropical northern Australia
2. Trial investigations should be undertaken to ascertain whether this technique could equally be applied to catchments with predominantly carbonate aquifers. Preliminary investigations undertaken in this study suggest that there is the possibility of transposing dry season hydrologic indices by utilising measures of the extent of carbonate aquifer in each catchment. Wet season hydrologic indices are generally a surface water resource and could readily be estimated independent of aquifer type.
3. Further work should be undertaken to develop a lumped conceptual rainfall-runoff model which better represents groundwater processes to more reliably extend streamflows. This is also expected to reduce the time required to calibrate rainfall-runoff models in other catchments in the future application of this technique across tropical northern Australia.
4. Additional long-term monitoring and groundwater modelling should be undertaken to allow better information to be fed into this analysis in the years and decades to come.

# Contents

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# 1. Introduction

The rivers of tropical northern Australia include those of the Timor Sea (XIII) and Gulf of Carpentaria (IX) drainage divisions (refer Figure 1-1). This report is the outcome of a pilot study to determine whether a proposed method of total water resource assessment is viable using the limited available data in catchments of tropical northern Australia. It seeks to provide an integrated assessment of the surface water and groundwater resources available in two pilot river basins in the Northern Territory.

The Australian Government has established the Northern Australia Land and Water Taskforce to “examine the potential for further land and water development in northern Australia, in a manner that is ecologically, culturally and economically sustainable” (Minister for the Environment and Water Resources, 29/7/07). Assessment of water development proposals to date has been hampered by the lack of information that can be used to reasonably estimate the volume of water currently available to the environment and the proportion of that water potentially available for consumptive users. This project specifically seeks to address this knowledge gap and provide information necessary for a technically defensible and environmentally responsible water allocation policy in individual river basins.

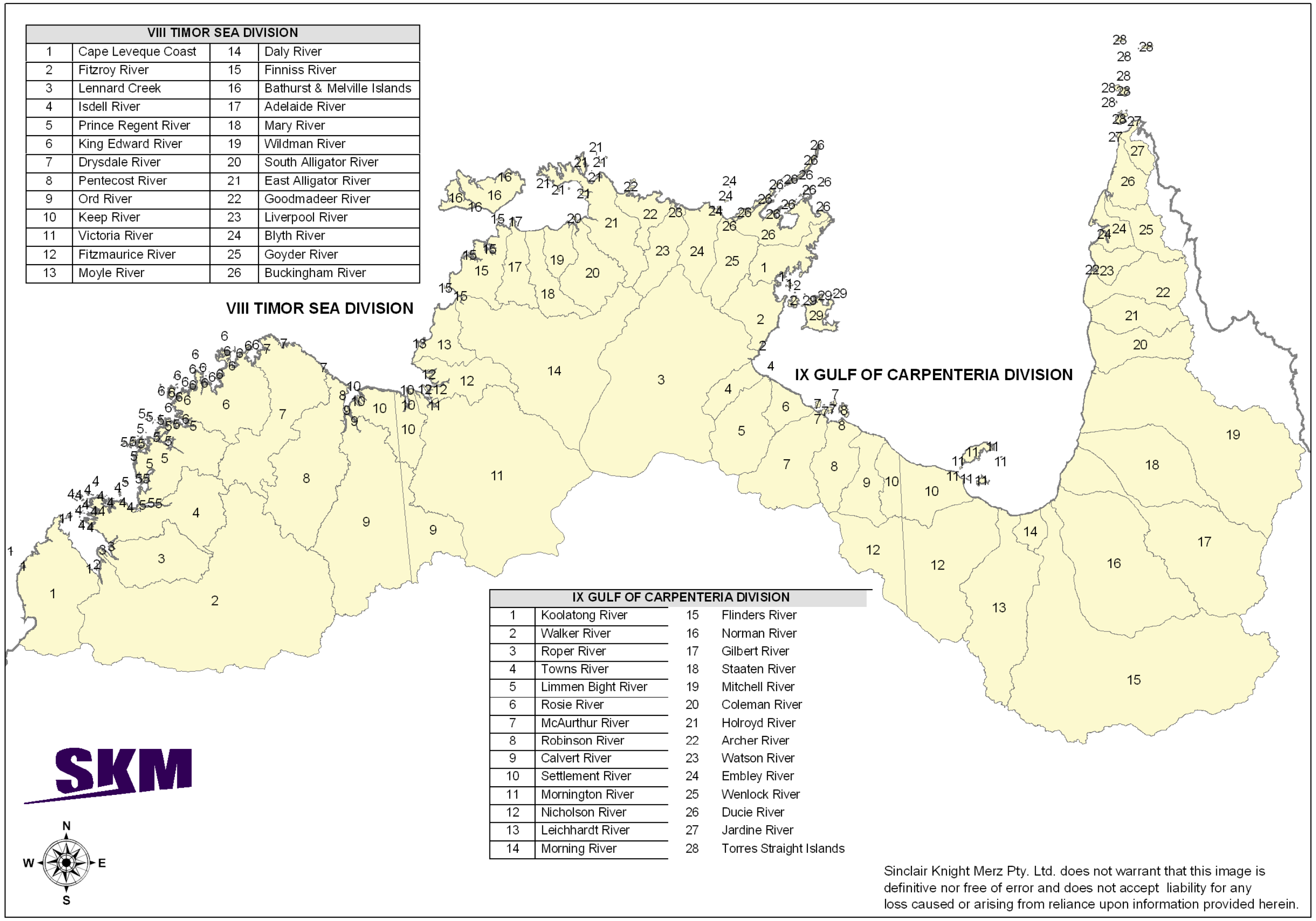
The basins selected for investigation in this study are the Adelaide and Finniss River basins, shown in Figure 1-2). These basins were selected in consultation with project stakeholders (including the Department of Natural Resources, Environment and The Arts, NRETA) based on their hydrogeological characteristics and the availability of gauged surface water data. The Adelaide and Finniss River basins mainly interact with non-carbonate aquifer systems, which means that rivers in these basins typically display less point source discharge from groundwater into surface water, however individual catchments within these river basins contained significant areas of carbonate aquifer that influence the low flow properties of local streams.

The basis of the methodology was for total water resource assessment – which means that surface water and groundwater resource assessments were conducted in parallel and in conjunction with one another. One of the main benefits in undertaking these assessments in an integrated manner is that overestimation of the total resource through double counting of groundwater can be avoided.

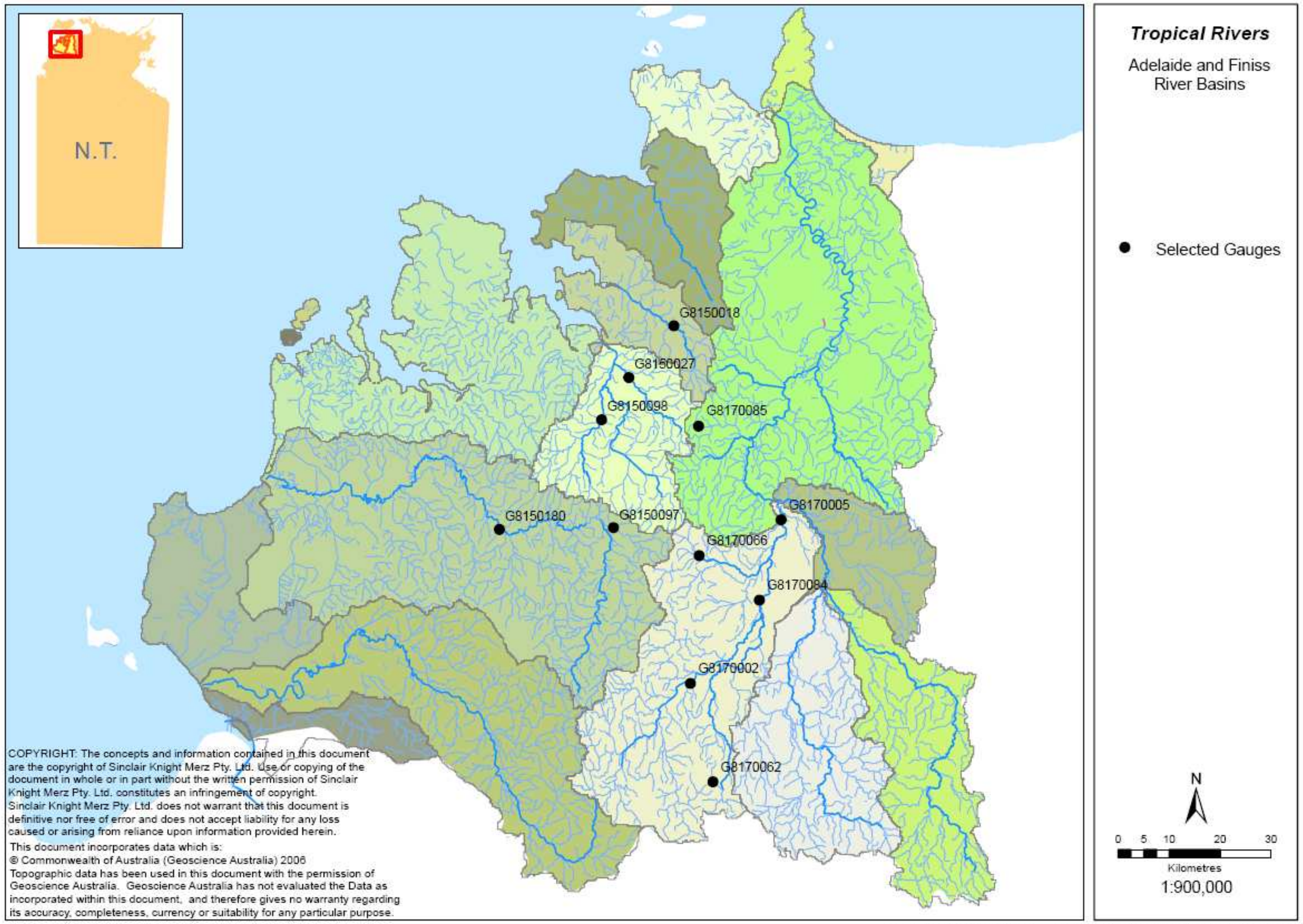
Aspects of the proposed approach have successfully been undertaken in regions of southern Australia in the past, but have never been comprehensively tested in tropical river basins. Tropical river basins exhibit a vastly different climate, hydrology and hydrogeology and typically have far less available data for use in water resource assessments due to the remoteness of the catchments. These circumstances require particular consideration specific to tropical northern Australia.

The contents of the report include:

- Consideration of the period of assessment for water allocation (Section 2) based on examination of long-term climate and streamflow data, as well as climate change projections.
- Groundwater and surface water interaction (Section 3), which includes a consideration of available techniques for baseflow estimation.
- Discussion of the technique used to estimate a range of ecologically relevant and useful hydrologic indices in ungauged areas (Section 4).
- A summary of water available in each river basin (Section 5) based on application of the technique to ungauged areas.
- A discussion of applications of the technique in catchments with carbonate versus non-carbonate aquifers (Section 6).
- Conclusions and recommendations (Section 7).




■ **Figure 1-1: Timor Sea and Gulf of Carpentaria Drainage Divisions**

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- **Figure 1-2: Location Map of Study Area Showing Selected Streamflow Gauges**

# 2. Period of Assessment for Water Allocation

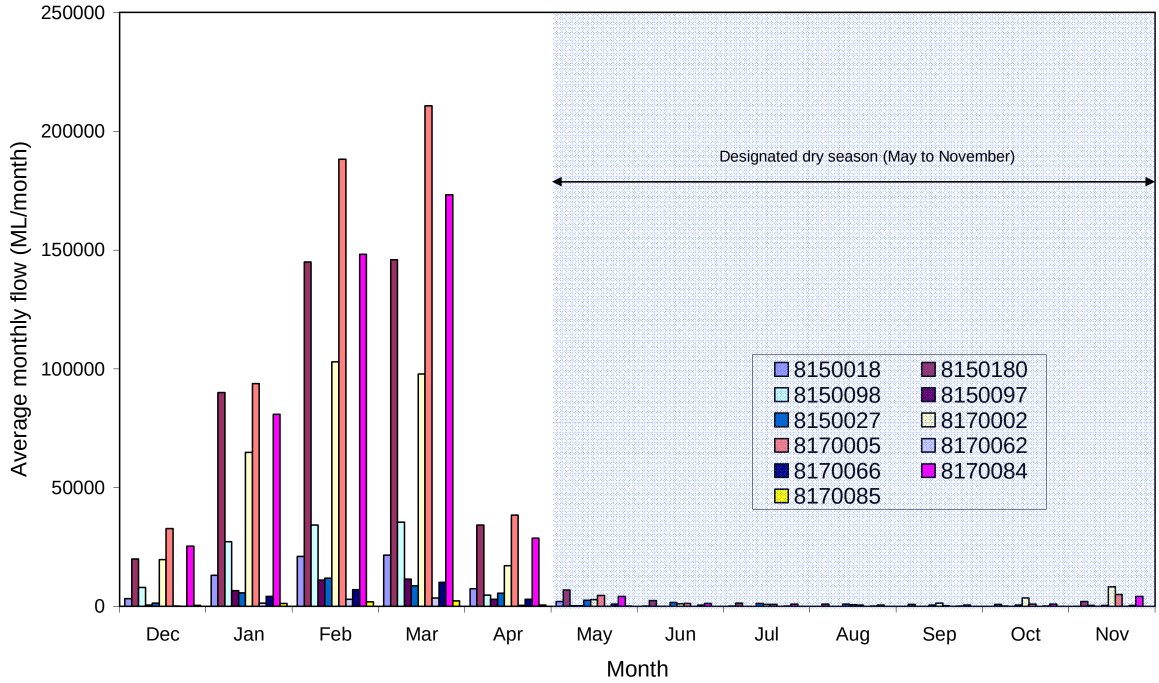
## 2.1 Introduction

One of the key lessons learnt from water allocation in highly developed regions of southern Australia, such as the Murray-Darling Basin, is that changes in climate can significantly change the amount of water available for consumptive users and the environment. This can lead to over-allocation of the water resource and result in the need to claw back water for the environment through sometimes costly water saving measures and/or a buy back of water licences. With the benefit of hindsight from southern Australia, this situation must be avoided in the relatively undeveloped areas of tropical northern Australia. Central to the allocation process is a decision about the climate conditions which will be assumed into the future as the basis for setting allocations.

This section of the report illustrates the differences in water availability which can result if different periods of assessment are used when determining allocations and recommends a preferred allocation period after considering data quality, climate variability and climate change.

## 2.2 Definition of wet and dry seasons

The analysis in this study produces information specific to the wet season, dry season and the whole year. Wet and dry seasons were determined from average monthly flow data at each streamflow gauge, as shown in Figure 2-1. It was apparent from this plot that the majority of streamflow gauges record their highest flows during the year between December and April, while the lowest flows occur between May and November. For the purposes of analysis, these two periods were thus selected as the wet and dry seasons. The boundary between the wet and dry seasons will vary slightly from year to year, but in the long-term it is considered a reasonably firm boundary. Streamflow response is expected to lag rainfall and hence the wet season would be considered to start slightly earlier from a purely climatic perspective.




- **Figure 2-1: Average Monthly Flow at All Gauges for Delineation of Wet and Dry Seasons**

## 2.3 Period of available rainfall data

Rainfall data was sourced from the Bureau of Meteorology. The period of available rainfall data is considerably longer than the available gauged streamflow data. The longest available record is at Darwin, where sites 014016 at the Darwin Post Office and 014015 at Darwin Airport collectively provide a record of daily rainfall from 1869 to date. The record is reasonably continuous from 1872 onwards. The period of record at specific locations within the Adelaide and Finniss River basins varies, however a continuous record of rainfall from 1872 could be readily derived by correlating the rainfall data at a particular location with that at Darwin. The quality of infilled rainfall data at each site of interest was generally considered to be very good, and is lower in earlier periods than more recent periods because the gauges used to infill data are further away from the site of interest. Monthly coefficients of determination for regression of rainfall data typically ranged from 0.6-0.9.

## 2.4 Period of available streamflow data

Streamflow data for all available gauges in the Finniss and Adelaide River basins was supplied by NRETA and is listed in Appendix B. Gauges that were downstream of major regulating structures such as the Darwin River Dam were excluded from the analysis. Tide gauges and gauges on water supply or small drainage channels were excluded, as well as gauges in urban areas. Finally, gauges with significant amounts (>10%) of missing data were excluded. Procedures for infilling data where less than 10% of the record was missing are presented in Appendix C.

The aim of the selection of the analysis period was to include as many gauges as possible, for as long a period of record as possible, while minimising the amount of missing data requiring infilling. It was found that this could most optimally be achieved for two different analysis periods in these two river basins:

- 1965-2005 for which 7 streamflow gauges were suitable to use in the analysis; and
- 1968-1978 for which 11 streamflow gauges were suitable to use in the analysis.

Further detail on the selection of these two periods is contained in Appendix B.

The available streamflow data was extended to cover the period of available rainfall data using lumped conceptual rainfall-runoff models. A variety of models were investigated and in general it was found that:

i. The four parameter MOSAZ rainfall-runoff model (Sukvanachiakul and Laurenson, 1983), which has successfully had its model parameters transposed to ungauged catchments in south-east Australia and offered particular advantages in this regard, was found to oversimplify rainfall-runoff processes in the study area and was not used after initial investigation.

ii. A four parameter NRETA baseflow model (Jolly, 2007), which was designed to estimate baseflow in catchments with some carbonate aquifers, performed well in this task on a daily time step, but was unable to model surface runoff processes in its current form and was difficult to accurately calibrate in some catchments, particularly in transition months between the wet and dry season.

iii. The ten parameter SIMHYD rainfall-runoff model (Chiew et al, 2002) was found to calibrate well in catchments with non-carbonate aquifers on both a daily and monthly timestep. It also performed well in catchments with carbonate aquifers on a monthly time step, but was unable to reproduce the two-phase recession curve on a daily time step that is seen in catchments with some carbonate and some non-carbonate aquifers. Good calibrations to the daily flow-duration curve could still be achieved.

iv. There is no observable difference in calibration accuracy whether the models were calibrated to spot readings or time series data in these largely non-carbonate catchments, other than having more data available to calibrate to when using the time series data.

On this basis, the approach for the trial study to estimate water availability over the longer climate sequence has been to undertake scaling of averages and flow percentiles using the SIMHYD model results. Average values have been transposed on the basis of scaling the gauged data using the more robust monthly SIMHYD models over the short and long climate periods, whilst daily flow percentiles have been transposed on the basis of daily SIMHYD model results over the short and long climate periods. Daily SIMHYD models were specifically calibrated to match the 20th, 50th and 80th percentile flows. Details of the SIMHYD calibrations are contained in Appendix D.

In catchments with a mix of carbonate and non-carbonate aquifers, a rainfall-runoff model would ideally contain the characteristics of SIMHYD for modelling overland flow and interflow processes, but the characteristics of the NRETA baseflow model or a two-bucket groundwater store for modelling baseflow. It is recommended that the desired model components from each model should be combined as part of the next phase of this project, which is expected to reduce the time required to calibrate rainfall-runoff models in other catchments in the future applications across tropical northern Australia.

### 2.5 Comparison of climate and hydrologic data over different historical periods

The rainfall at Darwin is shown in Table 2-1 over three different periods, namely the period of the rainfall record (1872 to date) and the two periods of concurrent streamflow data that were used in this study (1965-2005 and 1968-1978). It can be seen from this table that average annual rainfall is around 140 mm/yr or 9% higher over the last four decades when compared with the long-term average. The two alternative assessment periods of 1968-1978 and 1965-2005 contained reasonably similar average rainfalls. Rainfall prepared at other locations indicated that rainfall from 1965-2005 was up to 16% higher on average than the long-term assessment period of 1872-2005. This observation of above average rainfall since the mid-1960s is consistent with that observed at Katherine by Jolly and Jolly (2007).

- **Table 2-1: Rainfall at Darwin over different assessment periods**

| Period | Average annual rainfall (mm) | Average annual wet season rainfall (mm) | Average annual dry season rainfall (mm) |
|---|---|---|---|
| 1872-2005 | 1,577 | 1,359 | 219 |
| 1968-1978 | 1,713 | 1,470 | 265 |
| 1965-2005 | 1,715 | 1,482 | 233 |

Similarly, gauged streamflow data can be compared over these various analysis periods. A comparison in the catchments used in this study is presented in Table 2-2. It can be seen from these two tables that the effect of the wetter climate of the last four decades is amplified in the streamflow response. Streamflows in these catchments over the last four decades are on average around 7-20% higher than the long-term average in the Finniss River basin and lower reaches of the Adelaide River basin, and 46-64% higher in the upper reaches of the Adelaide River basin. Modelled and gauged streamflow data is shown at the same location in each case to provide an indication of model error when estimating streamflow data over the longer period. These model errors occur despite achieving a mass balance to within 1% over the full calibration period, which is often longer than 1965-2005.

**Table 2-2: Streamflow over different assessment periods**

| Streamflow Gauge | Mean Annual Flow (ML/yr) | | | 1965-2005 flow as % of long-term average |
|---|---|---|---|---|
| | Gauged 1965-2005 | SIMHYD monthly 1965-2005 | SIMHYD monthly 1872-2005 | |
| *Finniss River basin* | | | | |
| Elizabeth River at Stuart Highway (8150018) | 59,800 | 65,700 | 55,400 | 119% |
| East Finniss River at Rum Jungle (8150097) | 32,400 | 32,400 | 26,900 | 120% |
| Blackmore River at Tumbling Waters (8150098) | 115,000 | 113,000 | 105,000 | 107% |
| Finniss River at Gitchams (8150180) | 525,000 | 511,000 | 435,000 | 118% |
| *Upper Adelaide River basin* | | | | |
| Adelaide River at Railway Bridge (8170002) | 249,000 | 251,000 | 173,000 | 146% |
| Adelaide River at Tortilla Flats (8170084) | 473,000 | 462,000 | 282,000 | 164% |
| *Lower Adelaide River basin* | | | | |
| Acacia Creek at Stuart Highway (8170085) | 6,850 | 6,770 | 6,090 | 111% |

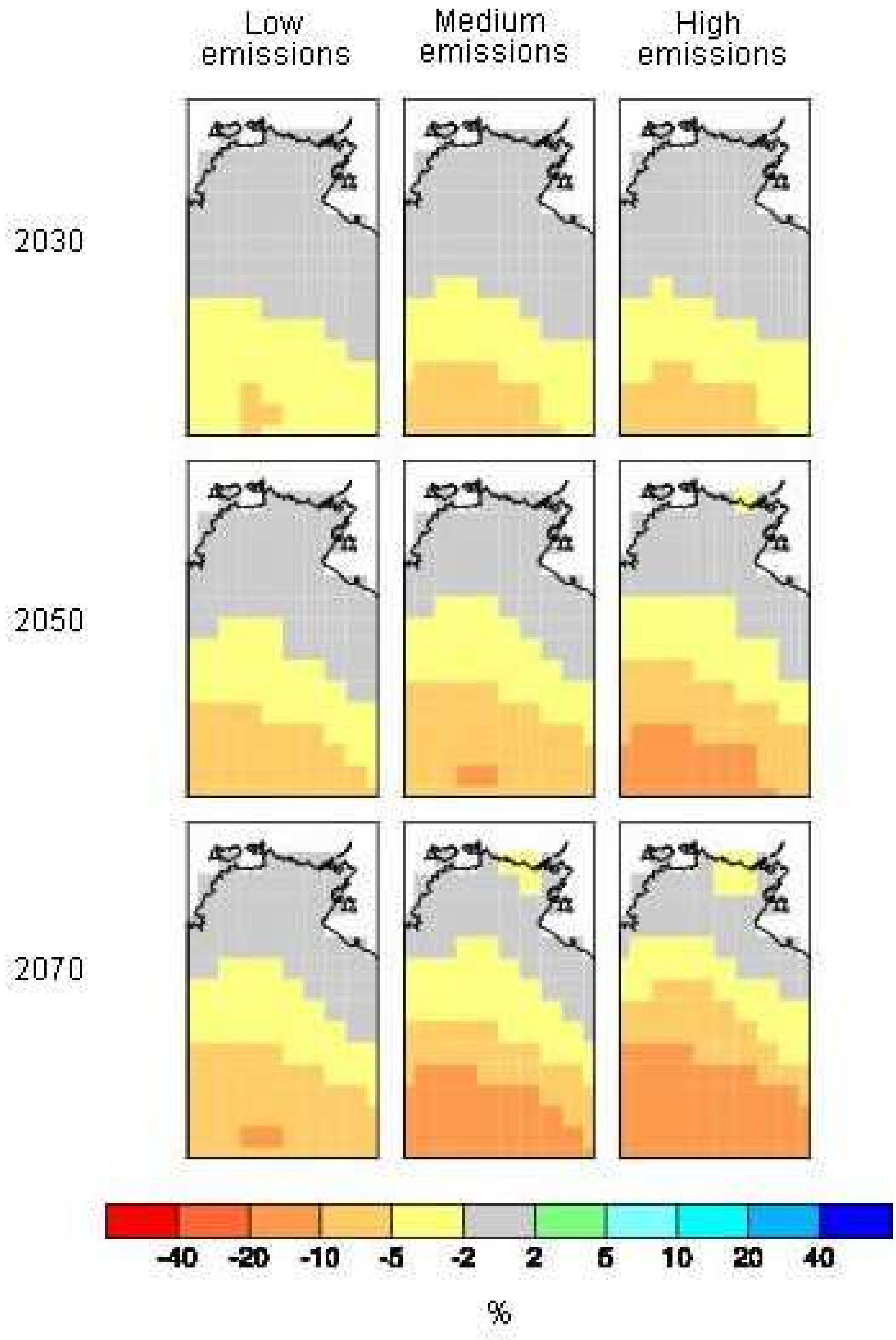
## 2.6 Climate change

It can be seen from the previous sections that average annual rainfall at Darwin and average annual streamflows in catchments south of Darwin are higher over the last four decades when compared to the long-term average. When determining a period of assessment for water allocation, one question which arises is whether either the last four decades of climate or the long-term climate are more likely to be representative to future conditions in light of anticipated climate change.

Predictions of the percentage change in annual rainfall from 1990 to 2030, 2050 and 2070 in the Northern Territory were obtained from the Climate Change in Australia website (CSIRO, 2007). These predictions indicate that for the 50$^{th}$ percentile estimate, rainfall is likely to change by less than ±2% to 2070. However, given the large uncertainty in global climate model predictions, the 10$^{th}$ percentile (driest) and 90$^{th}$ percentile (wettest) predictions were also considered. These predictions are also provided for low, medium and high emissions scenarios. This information is documented in Table 2-3 and is shown graphically for the 50$^{th}$ percentile estimate in Figure 2-2. The key result shown in this information is that climate change could result in average rainfall conditions becoming drier or wetter or remaining the same, with the magnitude of that change being amplified for higher emissions scenarios and over time. Seasonally, for the 50$^{th}$ percentile estimate, the wet season is expected to change in a similar manner to the changes in average annual rainfall displayed below, but the dry season is generally expected to become drier.

▪ **Table 2-3: Predicted Change in Rainfall (Finniss and Adelaide River Basins)**

| Year | Percentile | Percentage Change in Rainfall (Low Emissions) | Percentage Change in Rainfall (Medium Emissions) | Percentage Change in Rainfall (High Emissions) |
|---|---|---|---|---|
| 2030 | $10^{th}$ | -10% | -10% | -10% |
| | $50^{th}$ | ±2% | ±2% | ±2% |
| | $90^{th}$ | +10% | +10% | +10% |
| 2050 | $10^{th}$ | -10% | -20% | -20% |
| | $50^{th}$ | ±2% | ±2% | ±2% |
| | $90^{th}$ | +10% | +20% | +20% |
| 2070 | $10^{th}$ | -20% | -20% | -40% |
| | $50^{th}$ | ±2% | ±2% | ±2% |
| | $90^{th}$ | +20% | +20% | +40% |




- **Figure 2-2: 50th Percentile Predicted Change in Rainfall (Reproduced From Climate Change in Australia)**

## 2.7 Recommendation of assessment period for water allocation

It can be seen from the above information that there is high variability in climate and streamflow in the Adelaide and Finniss River basins and that there is high uncertainty about future climate conditions under climate change. Given the uncertainty of the climate change model outcomes, it would be prudent to allocate water under the assumption that future climate conditions could become drier and that the last four decades of above average rainfall are not necessarily representative of future climate conditions, because a return to the drier conditions prior to 1965 could occur. The anticipated 50$^{th}$ percentile estimate of change in rainfall by the year 2030 (and 2070) relative to 1990 under all emissions scenarios is $\pm$2%, which is small relative to the increase in rainfall that has occurred over the last four decades. Any reduction in rainfall of this magnitude may not be discernable from a more general return towards long-term average rainfall conditions as part of natural climate variability. Utilising the full period of available rainfall data from 1872 to date for the assessment period in allocation processes would therefore provide a prudent approach in light of anticipated climate change. If the anticipated 10$^{th}$ percentile estimate of change in rainfall were to eventuate, then this would need to be explicitly accounted for in addition to natural climate variability. If the anticipated 90$^{th}$ percentile estimate of change in rainfall were to eventuate, then further water resources could be allocated if required in a few decades time when scientific knowledge of future climate change is likely to have progressed.

The reasonably accurate calibration of rainfall-runoff models indicates that streamflows can be estimated beyond the period of available gauged streamflows without significant loss of accuracy. It was noted that in the analysis that average streamflows over the longer period are sensitive to changes in input rainfall.

# 3. Groundwater and surface water interaction

## 3.1 Introduction

The extent of groundwater discharge to rivers determines whether rivers flow during the dry season and hence will influence decisions about the allocation of groundwater and dry season river diversion licences. The focus of this study has been on catchments with non-carbonate aquifers, which typically exhibit low dry season flows and cease to flow during the dry season. However there were a small number of catchments within the study area which contained sustained dry season flow due to the presence of some carbonate aquifers.

This section of the report briefly discusses the alternative approaches to estimating the degree of groundwater and surface water interaction and recommends an approach for use in catchments with non-carbonate aquifers. Discussion is also made about the potential application of this technique to catchments with carbonate aquifers.

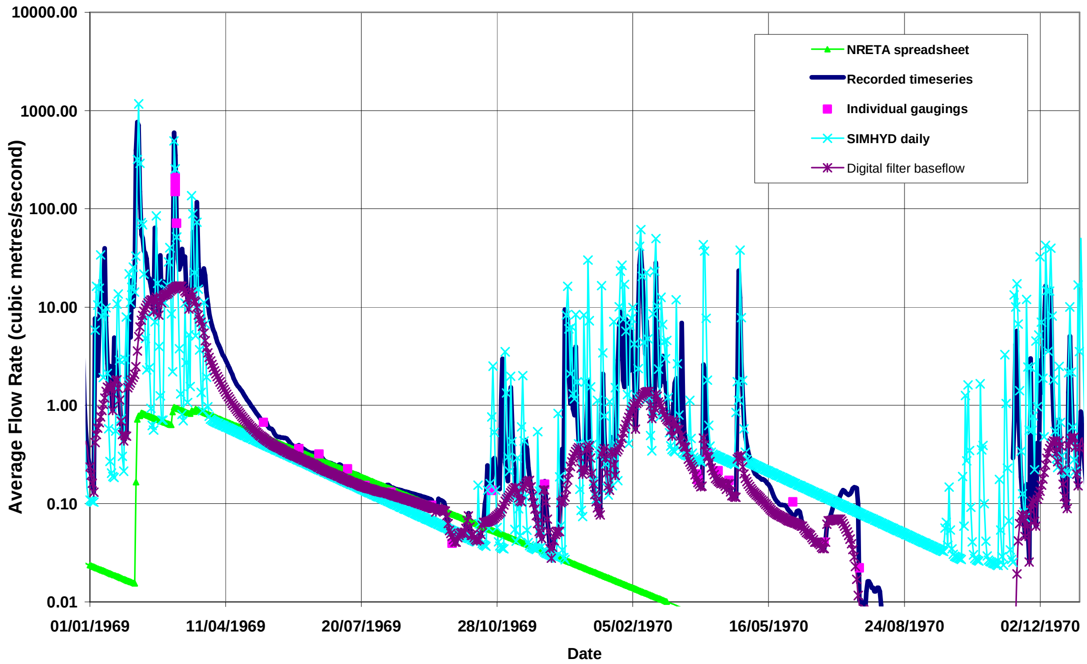
## 3.2 Baseflow estimation techniques

There are many methods available to estimate baseflow. Baseflow is the proportion of streamflow which is sourced from groundwater. As discussed in SKM (2007), all estimates of baseflow are largely subjective, however the absence of rainfall for significant periods of time in tropical northern Australia gives greater confidence in the absolute value of baseflow in the dry season. This study has focussed on two methods, namely the digital recursive filter and rainfall-runoff models. A comparison of those methods on a sample dataset is shown in Figure 3-1.

The digital recursive filter (Nathan & McMahon, 1990) has previously been applied in Neal et.al. (2000) and SKM (2007). The digital recursive filter algorithm utilises signal analysis procedures to filter the noise in the data caused by runoff events to retain an underlying baseflow signal. This approach has the advantage of being reproducible on a consistent basis across large areas and of being informed by recorded streamflow data, but has the disadvantage that the result is produced independent of any knowledge of hydrologic processes. Baseflow using a digital recursive filter is often considered to include some interflow through the unsaturated zone of the soil profile and some release of water from bank storage. For this study a filter parameter of 0.95 with 3 passes on the data was used.

Rainfall-runoff models can model rainfall-runoff, infiltration and groundwater discharge processes to obtain an estimate of total streamflow by calibrating the models to gauged streamflow data. Rainfall-runoff models have the advantage of being able to be applied over periods longer than the available gauged streamflow data, but have the disadvantage that an infinite number of parameter combinations are possible during the calibration process. These different parameter combinations can yield different estimates of baseflow and in some cases a better model fit to dry season flows can be achieved by using model interflow rather than baseflow, as can be seen in some model calibration results. In this study the SIMHYD rainfall-runoff model was used after undertaking some initial comparisons with an in-house spreadsheet model prepared by NRETA, as discussed previously in Section 2.4.

Groundwater models can also be used to estimate baseflow, however the degree of effort required to calibrate and apply groundwater models over large areas (ie the whole of tropical northern Australia) with minimal data is substantial and their use is currently limited to particular areas of interest after initial identification of groundwater and surface water interaction by other means, such as those listed above.




- **Figure 3-1 Example daily rainfall-runoff model calibration (Adelaide River at Railway Bridge)**

## 3.3 Recommended technique for estimating baseflow for water allocation purposes

The use of the digital recursive filter provides a robust estimate of baseflow that is readily reproducible and comparable across tropical northern Australia, however its application is limited to the period of historical gauged data and where hydrographic cross-sections are reasonably stable, which is known to not be the case in some other parts of tropical northern Australia with high proportions of carbonate aquifers.

The preferred approach for estimating baseflow in non-carbonate aquifers is to calibrate a rainfall-runoff model to the available gauged streamflow data, paying particular attention to achieving a good model fit to dry season streamflows. The outflow components of the rainfall-runoff model can be plotted during periods of negligible runoff to ensure that all outflow is baseflow during this period. The rainfall-runoff model can then be applied over the longer climate period using input rainfall data.

This technique is applicable to catchments with carbonate aquifers, however some of these catchments have groundwater models built by NRETA and hence the above technique will not necessarily be the best available if a well calibrated groundwater model exists for a particular area. Unstable rating tables for estimating streamflow from water level data are a common occurrence in catchments with a high proportion of carbonate aquifer. Where a rating table is unstable, only manual spot gaugings can be used rather than the time series data derived by applying the rating table to continuously recorded water level data. Under these circumstances the digital recursive filter cannot be applied and the rainfall-runoff model must be calibrated to relatively infrequent spot readings. This is discussed further in Section 6.

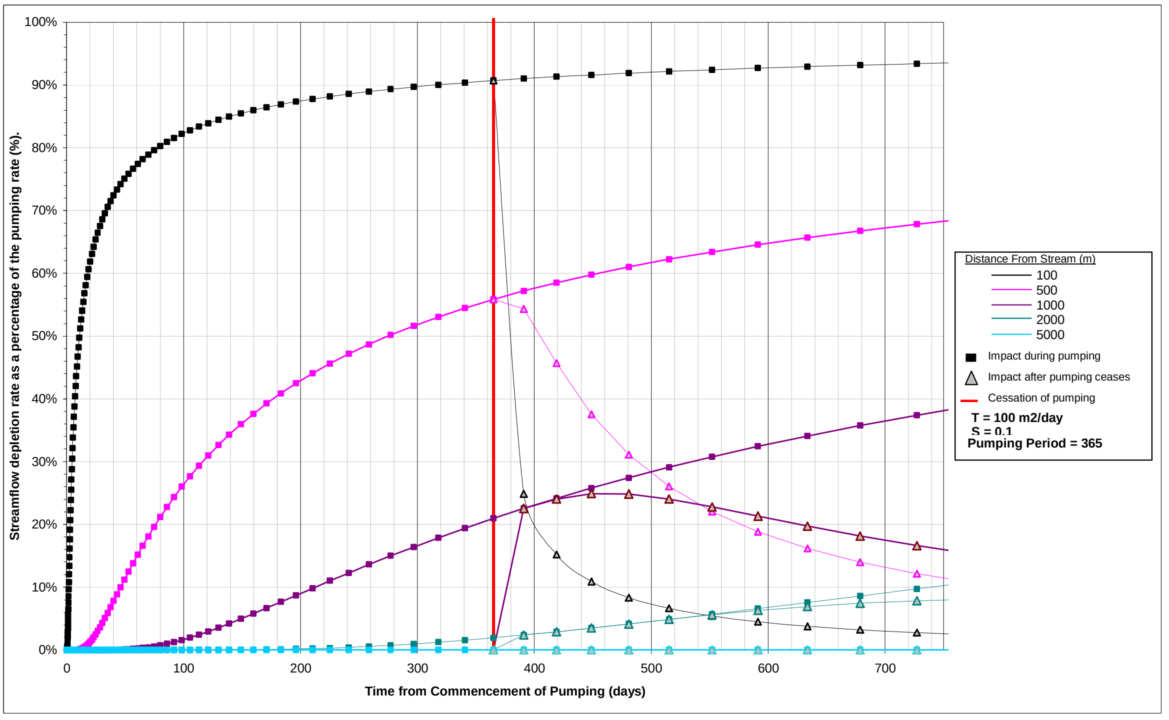
### 3.4 Time lag between groundwater pumping and streamflow response

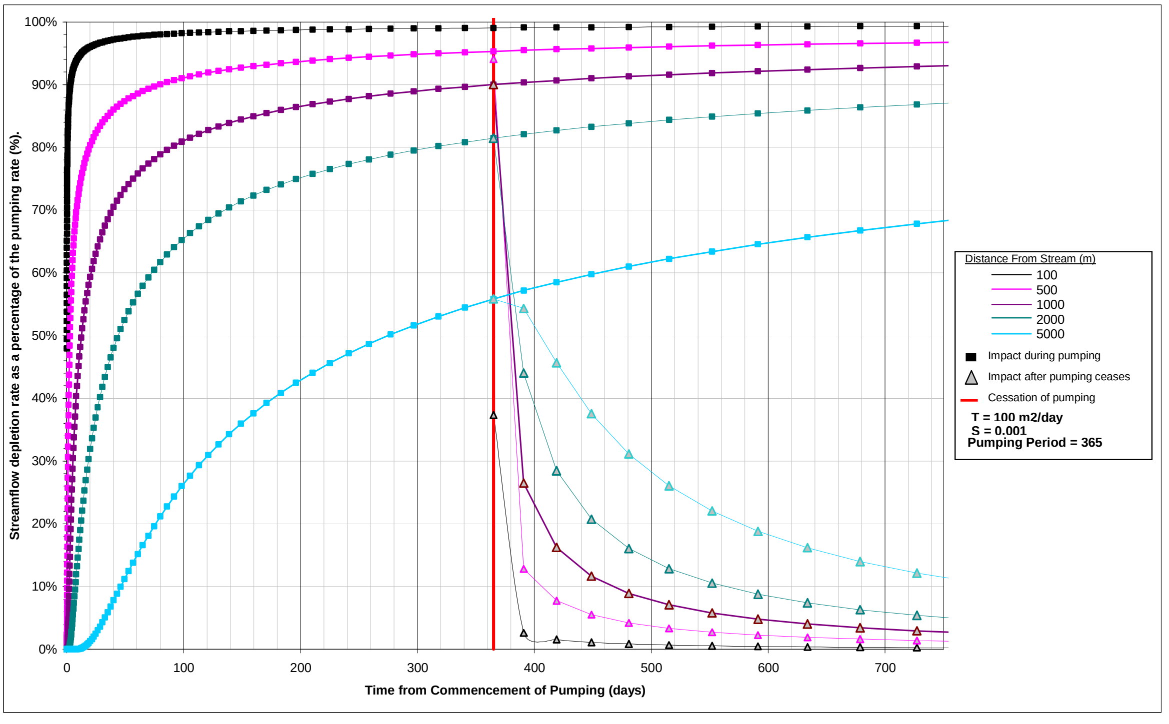
This study does not consider in detail the time lag between groundwater extraction and a subsequent response on the river. This study does however highlight the stark differences in groundwater and surface water interaction from the wet season to the dry season. This creates the potential for seasonal groundwater extraction that is out of phase with baseflow discharge to streams during the dry season. That is, pumping groundwater in the dry season at some distance from surrounding rivers could result in a reduction in baseflow during the wet season rather than the dry season.

Figure 3-2 provides two examples of estimated streamflow depletion as a function of time for a number of different distances from a river. The two graphs provided show the same distances and times, but different transmissivity and storage (specific yield) values. This figure has been prepared using the Jenkins (1968) equation which is applicable to extraction from an unconfined aquifer where the stream fully penetrates the aquifer. Although the Jenkins solution is for the ideal case and it is not directly applicable to the hydrogeology of the study area, it is considered adequate for the purposes of this discussion. Several other analytical solutions exist for the prediction of stream flow depletion for different hydrogeological conditions and levels of complexity (e.g. Hunt, 2003; Zlotnik and Huang, 1999; Baaker and Anderson, 2003; and Cook and Lamontange, 2002). Numerical modelling approaches can also be used, and may be more applicable to “real world” cases (Evans, 2007).

As is evident from Figure 3-2, the time lag before any significant impact to stream flow starts is a function of both the distance of the pumping bore from the river and the aquifer hydraulic parameters; the closer the bore, the higher the transmissivity and the lower the storage coefficient, the sooner the impact to stream flow will start. The pumping rate does not influence the time at which streamflow depletion commences. Dependent on the specific conditions in the groundwater basin, the time lag between groundwater extraction and significantly reduced stream flow can range from hours to hundreds of years (Evans, 2007). Figure 3-2 also shows, importantly, that stream flow depletion will continue after pumping ceases, and in some cases significant impact can continue for a lengthy period of time following the cessation of pumping.

In terms of groundwater resource management, a robust understanding of time lags may allow a management plan based on Zonal Management (Evans et al., 2005) whereby different management arrangements are applied for bores at varying distances from the river. This would allow the timing of groundwater extraction to be regulated such that significant reductions in stream flow occur during the wet season when there is “excess” surface water as defined by the gauged or transposed streamflow data.




- **Figure 3-2 Examples of Estimated Stream Flow Depletion at Differing Distances from the River for Different Aquifer Hydraulic Parameters**

### 3.5 Evapotranspiration

All estimates of baseflow in this study are provided at the outlet of catchments. The volume of groundwater flow at upstream locations will be higher than this volume due to a combination of upstream river evaporation and evapotranspiration. The volume of river evaporation and evapotranspiration is generally considered to be small relative to streamflow volumes. Evaporation from river surfaces has not been explicitly accounted for in this trial study. In the future rollout of this study to other areas, direct evaporation from rivers can be calculated by multiplying the length of rivers, as defined in GIS layers of the stream network, by point potential evaporation and an assumed average river width. Point potential evaporation is a measure of evaporation from a small open water body. River evaporation would need to be conditioned by the seasonal behaviour of gauged streamflow data, so that evaporation does not occur when no flow is estimated at the streamflow gauge. This requires an estimate of cease to flow behaviour when applying this to ungauged catchments.

Evaporation and evapotranspiration from groundwater can occur between a given individual groundwater bore and the point of groundwater discharge to the nearest stream. This means that the volume of water that could be allocated from groundwater bores could be greater than the volume of baseflow if those bores are located at some distance from the nearest stream where groundwater discharges, provided that this does not cause any adverse impacts on groundwater dependent ecosystems. This is due to a lowering of the water table between the bore and the river as a result of groundwater pumping, which thereby reduces evapotranspiration from groundwater.

Details of groundwater evapotranspiration estimates are provided in Appendix F for the study area based on a review of field studies by Hutley et al. (2001) and Cook et al. (1998b). The approach involved separately estimating evaporation rates from woody vegetation and the understorey and then estimating the degree of access to groundwater from these different types of vegetation. The relationship derived by Hutley et al. (2001) for Howard Springs is considered to be applicable throughout the Adelaide and Finniss River basins, which was that evapotranspiration from woody vegetation is 26% of total evapotranspiration during the wet season and 47% of total evapotranspiration during the dry season.

The next part of the analysis involves estimating the degree of access of each vegetation type to groundwater. Hutley *et al*. (2001) found that tree stand water use was constant throughout the year despite the monsoonal water availability, suggesting that the trees are able to extract water from the water table throughout the year. Cook et al. (1998a) suggests that woody vegetation did not depend on groundwater during the dry season, but Cook et al. (1998b) notes that groundwater may be accessed by woody vegetation during times of drought. Root depths of up to 10 m have been found, but root density decreases significantly with depth. On the basis of these previous assessments, it is assumed for this study that 100% of wet season evapotranspiration from woody vegetation is sourced from groundwater and that 50% of dry season evapotranspiration from woody vegetation is sourced from groundwater, with the remainder coming from the unsaturated zone.

Cook *et al*. (1998b) found that at the beginning of the dry season, soil moisture and transpiration from the understorey resulted in an increased evaporation rate, following which the tree canopy transpired at a relatively constant rate throughout the remainder of the dry season. It was inferred that by the end of May, evaporation was almost completely evapotranspiration from woody vegetation, and suggested that the woody vegetation may be sustained by water in the unsaturated zone during the dry season. On this basis, it was assumed that understorey evapotranspiration occurred from groundwater in the wet season only, with all evapotranspiration in the dry season being sourced from the unsaturated zone. It is assumed during the wet season that the water table is close to the natural surface (ie within a metre or so) and hence both transpiration by woody vegetation and evaporation from very shallow groundwater will be high. However during the wet season the distinction between the unsaturated zone and the fully saturated zone (ie groundwater) becomes less clearly defined.

The proportion of woody vegetation was calculated using a vegetation coverage grid supplied by the Australian Greenhouse Office. It is not possible to determine the nature of the woody vegetation from this data to determine the areal extent of groundwater dependent ecosystems. Consistent with the definition of a savannah, the area of understorey used was equal to the total catchment area. On this basis, the estimate of wet season groundwater evapotranspiration was 565 mm for the Adelaide River basin and 557 mm for the Finniss River basin, whilst dry season groundwater evapotranspiration was estimated to be 109 mm for both river basins.

Whilst the change in groundwater level due to groundwater pumping will be localised and specific to individual bores or borefields, by way of example, if groundwater pumping were to cause a 10% reduction in groundwater evapotranspiration across these river basins then the volume associated with that change would be 502 GL in the Adelaide River basin and 611 GL in the Finniss River basin. Reduction in evapotranspiration from groundwater could however impact on groundwater dependent ecosystems due to reduced access to this water source. This example illustrates that reduction in groundwater evapotranspiration due to groundwater pumping could potentially be a very large volume, but would mostly likely only be made available to groundwater users if any impacts on groundwater dependent ecosystems could be appropriately managed. This would need to be assessed for specific bore locations and pumping rates.

### 3.6 Recharge

Groundwater recharge is the volume of rainfall that filters through the soil profile and contributes to aquifer storage. Understanding recharge volumes at any given location provides additional information that can be used to estimate groundwater evapotranspiration, which in the longer term is the difference between groundwater recharge and baseflow, assuming no significant inter-annual trends in aquifer storage volume and no significant groundwater discharge to adjacent catchments or offshore that does not appear as baseflow in the catchment of interest. Estimates of recharge were initially calculated based on published literature (Jolly, 1999) and by conducting a seasonal water balance on the stream-aquifer system. This process led to a wide range of recharge values due to uncertainties in input data. For this reason, estimates of recharge have not been provided in this report, with preference given to directly estimating groundwater evapotranspiration, as described in Section 3.5.

### 3.7 Groundwater discharge to other areas

This study estimates baseflow at catchment outlets. Groundwater may also discharge to other areas, such as to adjacent catchments and offshore. An estimate of groundwater discharge to other areas based on a conceptual hydrogeological model, discussed in Appendix F, indicated no significant discharge to other areas. The use of a conceptual hydrogeological model to estimate groundwater discharge that is not expressed as nearby baseflow is a useful procedure for considering whether the groundwater resource is likely to be in excess of baseflow volumes. Groundwater discharge to other areas would not necessarily be negligible in other parts of tropical northern Australia, hence there is value in estimating this volume using a conceptual hydrogeological model in similar future work on this project in other parts of tropical northern Australia.

### 3.8 Recommended technique for estimating groundwater allocations in excess of baseflow volumes

Estimates of baseflow derived in this study provide a basis for determining the allocation of groundwater from bores within close proximity to rivers. Allocating water to individual bores in excess of this volume will depend upon the location of individual bores. Given that a significant spatial and groundwater analysis would be required to determine connectivity of aquifers to particular streams and to precisely estimate groundwater evapotranspiration as a contour surface across the study area, it is considered that this analysis could be subsequently undertaken if the demand for groundwater and baseflow by consumptive users exceeds any allocation volume set by NRETA on the basis of allocation of baseflow alone. This is a conservative, but pragmatic approach that is considered appropriate given the low volumes of groundwater use relative to the current baseflow across most of tropical northern Australia.

# 4. Application to ungauged areas

## 4.1 Introduction

This section of the report discusses the process of transposing the hydrologic information on groundwater and surface water discharge to streams in gauged catchments and applies it to areas which do not contain any streamflow gauging information. It includes identification of useful and ecologically relevant hydrologic indicators, a brief overview of the transposition process and a discussion of potential application of these hydrologic indicators within the water allocation process.

## 4.2 Indicators relevant to resource assessment and ecology

A daily time series of hydrologic information is available at each streamflow gauging station used in the study from the process outlined in Section 2.4 of this report. A daily time series provides the greatest flexibility to water managers and planners because any amount of information can be gleaned from such a time series, including statistical properties (mean, median, percentiles) and spells above and below certain ecologically relevant thresholds.

Methods for transposing time series data were briefly investigated and they consist of two types. The first involves identifying regions of hydrologic similarity so that a time series can reliably be transposed to another site with a high degree of confidence that the transposed time series will be representative of actual streamflow behaviour. This technique requires a substantial stream gauging network to identify subtle changes in hydrologic similarity, which streamflow gauging in the study area and across tropical northern Australia does not currently support. The second technique is to transpose rainfall-runoff model parameters by relating them to catchment characteristics. The rainfall-runoff model (MOSAZ) for which this technique had been used in the southern Australia (Nathan et al, 1996) was found to poorly represent the hydrologic processes in the Berry River catchment where it was trialled. This is because the model was too simple. A more complex model (SIMHYD) was able to represent the hydrologic processes much better, but has the disadvantage that the higher number of parameters makes it difficult to transpose them on the basis of correlations with catchment characteristics (Chiew, et al. 2005). Therefore, in both cases, methods for transposing time series data were not considered to be appropriate.

Hydrologic indicators are however more readily transposed to ungauged catchments, which has been demonstrated on several occasions in southern Australia including SKM(2003), Lowe et al (2006) and Nathan et al. (2000). Two types of hydrologic indicators were used in this study:

- Useful indicators of mean flow conditions for use in water resource assessment; and
- Ecologically relevant indicators of various flow percentiles.

The set of indicators adopted in the study included those listed below, however it should be noted that any number of hydrologic indicators could be derived and transposed if ecologists working in tropical northern Australia require other indicators for any particular reason:

- Mean annual quickflow: wet season ($MAQF_w$);
- Mean annual quickflow: dry season ($MAQF_d$);
- Mean annual baseflow: wet season ($MABF_w$);
- Mean annual baseflow: dry season ($MABF_d$);
- Median daily flow: wet season ($Q50_w$);
- Median daily flow: dry season ($Q50_d$);
- 20$^{th}$ percentile flow: wet season ($Q20_w$);
- 20$^{th}$ percentile flow: dry season ($Q20_d$);
- 80$^{th}$ percentile flow: wet season ($Q80_w$); and
- 80$^{th}$ percentile flow: dry season ($Q80_d$).

Baseflow was calculated at each gauge by firstly undertaking a baseflow separation using a digital recursive filter. It was found that a filter parameter value of 0.95 with three passes provided the best results. Quickflow was the difference between total flow and the estimated baseflow.

The calculated hydrological prediction indices at each gauge are summarised in Table 4-1 (1965–2005 analysis period) and Table 4-2 (1968-1978 analysis period). The percentage of time that each gauge ceases to flow and the baseflow index are also presented for reference purposes.

## Table 4-1: Gauged Hydrological Indices (1965-2005)

| Gauge | $MAQF_w$ (GL/yr) | $MAQF_d$ (GL/yr) | $MABF_w$ (GL/yr) | $MABF_d$ (GL/yr) | $Q50_w$ (ML/d) | $Q50_d$ (ML/d) | $Q20_w$ (ML/d) | $Q20_d$ (ML/d) | $Q80_w$ (ML/d) | $Q80_d$ (ML/d) | CTF (%) | BFI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 8150018 | 41.0 | 0.7 | 17.6 | 0.4 | 139.7 | 0.0 | 578.3 | 3.3 | 10.7 | 0.0 | 45.7 | 0.302 |
| 8150097 | 23.0 | 0.3 | 8.9 | 0.2 | 68.9 | 0.0 | 270.2 | 0.3 | 3.0 | 0.0 | 47.6 | 0.278 |
| 8150098 | 87.7 | 1.0 | 25.9 | 0.2 | 146.1 | 0.0 | 970.4 | 0.5 | 9.4 | 0.0 | 46.4 | 0.228 |
| 8150180 | 363.5 | 6.5 | 144.7 | 10.1 | 1050.7 | 33.7 | 4766.0 | 86.3 | 160.2 | 16.9 | 0.0 | 0.295 |
| 8170002 | 182.4 | 5.2 | 56.7 | 5.0 | 347.6 | 17.0 | 1929.7 | 47.3 | 71.4 | 5.5 | 2.3 | 0.248 |
| 8170084 | 346.4 | 8.0 | 112.7 | 5.5 | 648.4 | 19.2 | 4251.2 | 57.8 | 110.1 | 0.7 | 10.0 | 0.250 |
| 8170085 | 4.8 | 0.1 | 1.8 | 0.1 | 14.2 | 0.0 | 57.3 | 0.1 | 0.6 | 0.0 | 51.8 | 0.281 |

## Table 4-2: Gauged Hydrological Indices (1968-1978)

| Gauge | $MAQF_w$ (GL/yr) | $MAQF_d$ (GL/yr) | $MABF_w$ (GL/yr) | $MABF_d$ (GL/yr) | $Q50_w$ (ML/d) | $Q50_d$ (ML/d) | $Q20_w$ (ML/d) | $Q20_d$ (ML/d) | $Q80_w$ (ML/d) | $Q80_d$ (ML/d) | CTF (%) | BFI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 8150018 | 45.3 | 0.9 | 19.7 | 0.5 | 128.2 | 0.0 | 734.6 | 3.2 | 2.7 | 0.0 | 45.9 | 0.305 |
| 8150027 | 42.0 | 1.3 | 21.6 | 7.3 | 160.1 | 32.1 | 701.9 | 63.2 | 20.3 | 17.5 | 0.6 | 0.398 |
| 8150097 | 28.0 | 0.6 | 10.9 | 0.4 | 71.0 | 0.0 | 318.0 | 3.4 | 7.9 | 0.0 | 35.5 | 0.282 |
| 8150098 | 108.4 | 1.9 | 30.6 | 0.5 | 179.7 | 0.0 | 1305.9 | 3.03 | 21.4 | 0.0 | 41.0 | 0.220 |
| 8150180 | 436.2 | 9.2 | 150.9 | 15.7 | 1272.3 | 43.6 | 5343.9 | 111.9 | 187.4 | 17.5 | 0.0 | 0.269 |
| 8170002 | 220.7 | 3.8 | 62.6 | 5.0 | 399.1 | 17.0 | 2354.3 | 43.1 | 54.1 | 4.8 | 3.7 | 0.231 |
| 8170005 | 485.2 | 5.6 | 172.8 | 5.9 | 980.9 | 20.4 | 7397.2 | 87.6 | 157.9 | 2.3 | 5.5 | 0.266 |
| 8170062 | 9.5 | 0.1 | 1.4 | 0.0 | 2.6 | 0.0 | 47.9 | 0.2 | 0.2 | 0.0 | 51.7 | 0.125 |
| 8170066 | 19.6 | 0.6 | 8.2 | 1.7 | 58.4 | 6.2 | 245.1 | 15.5 | 9.5 | 2.7 | 0.2 | 0.330 |
| 8170084 | 388.8 | 7.4 | 127.8 | 6.7 | 768.1 | 19.2 | 5230.9 | 53.0 | 89.9 | 0.2 | 11.5 | 0.252 |
| 8170085 | 5.9 | 0.2 | 2.2 | 0.1 | 17.5 | 0.0 | 67.8 | 0.5 | 0.6 | 0.0 | 49.4 | 0.278 |

### 4.3 Transposition to ungauged areas

In order to develop prediction equations for the hydrological indices, a number of catchment characteristics were extracted from GIS information. The catchment characteristics selected were mainly developed from those which have proved successful in previous studies, including Sinclair Knight Merz (2003), Lowe *et al.* (2006) and Nathan *et al.* (2000). This list was then supplemented with a number of other characteristics which were considered to be particularly relevant for northern Australia. The additional catchment characteristics calculated for this investigation are listed below:

- Latitude of the catchment centroid;
- Distance from the catchment centroid to the coast;
- Average wet and dry season rainfalls at the catchment centroid;
- Length of carbonate aquifer intersecting rivers within the catchment; and
- Area of carbonate aquifer within the catchment.

This project used the above measured streamflow indices and catchment characteristics to develop prediction equations that can be used to estimate the hydrological indices in ungauged catchments. These equations were developed using multiple linear regression. Multiple linear regression is a statistical technique that allows one dependent variable (in this case the hydrological prediction indices) to be predicted from a number of independent variables (the catchment characteristics). Details of the methods used to develop the prediction equations are presented in further detail in Appendix E. The prediction equations developed are as shown in Table 4-3 for the Adelaide and Finniss River basins.

- **Table 4-3: Recommended Regression Equations for the Adelaide and Finniss River basins**

| Index | Multiple Linear Regression Equation | $R^2$ | SEE (%) |
|---|---|---|---|
| $MAQF_w$ | $39.200 + (0.353 \times Area) - (1.140 \times DistToCoast)$ | 0.997 | 7 |
| $MABF_w$ | $23.221 + (0.142 \times Area) - (0.779 \times DistToCoast)$ | 0.987 | 15 |
| Q50w | $216.529 + (1.009 \times Area) - (7.322 \times DistToCoast)$ | 0.952 | 25 |
| Q20w | $661.118 + (4.782 \times Area) - (22.528 \times DistToCoast)$ | 0.997 | 6 |
| Q80w | $14.720 + (0.153 \times Area) - (0.716 \times DistToCoast)$ | 0.949 | 29 |
| $MAQF_d$ | $-6.184 + (0.006 \times Area) + (0.025 \times DrySeasonRain)$ | 0.997 | 7 |
| $MABF_d$ | $-2.788 + (0.007 \times Area) + (9.501 \times PercentWoody)$ | 0.993 | 55 |
| Q50d | 0* | NA | NA |
| Q20d | $-23.557 + (0.069 \times Area) + (74.902 \times PercentWoody)$ | 0.935 | 34 |
| Q80d | 0* | NA | NA |

*value may be greater than zero for catchments containing some carbonate aquifer

This analysis provided a number of important outcomes, which are summarised below:

1. **Catchment area was the main catchment characteristic which proved useful for predicting those streamflow indices which are expressed as a flow magnitude**. The results from the regression relationships developed for this study showed that the remaining variability in the streamflow indices after catchment area had been accounted for was generally very low. This indicates that catchment area alone would be a reasonable first order predictor for most of the hydrological indices in hydrogeologically similar catchments across northern Australia.
2. **Distance from the catchment centroid to the coast was useful for predicting high flow and wet season indices.** The distance of the catchment to the coast has hydrological significance in northern Australia because of the impact of cyclonic rainfall, which tends to occur in relatively intense periods for significant durations. Generally speaking, both the intensity and duration of these rainfall events decay as the low pressure system moves inland. Thus the further a given catchment is from the coast, the lower its mean annual flow and wet season flows are likely to be.
3. **Prediction of dry season/low flow indices in northern rivers generally requires a larger sample set of candidate catchments than was available for this pilot study.** Many of the dry season flow indices in these largely non-carbonate catchments were zero (ie streams ceased to flow), which has the effect of reducing an already small sample size. Similarly, when considering cease to flow, a number of streams were perennial, which also reduces the available sample size with variability in cease to flow. Broad correlations were evident between the area of carbonate aquifer and dry season flows, which indicates some potential to

better estimate dry season flows with a wider range of catchments with varying degrees of carbonate and non-carbonate aquifers.

4. **Temporal variability of candidate catchment streamflow data is more important than spatial variability**. Generally speaking, better streamflow prediction equations were developed for the longer analysis period (1965-2005) than the shorter analysis period (1968-1978), despite there being an additional three candidate catchments in the shorter period. This reflects the fact that 10 years of data is probably insufficient to capture a representative portion of streamflow variability at any given gauge. For this reason, all the streamflow prediction equations were developed for the longer analysis period. This is an important consideration when moving to apply this technique from the pilot catchments to larger areas.

### 4.4 Potential applications in the water allocation process

Water allocation lies within the domain of NRETA and it is beyond the scope of this project to make recommendations about how and at what level allocations should be set. The purpose of this project is to provide a technique which will result in the provision of background information that is both useful and relevant to the water allocation process.

Sustainable yield for diversion from rivers in the Northern Territory is currently estimated based on the 80/20 rule, which states that the environmental water requirements of a river basin are approximately 80% of natural streamflow (ANRAT, 2006a). Application of this rule means that consumptive water use is nominally limited to 20% of the available water resource. By providing the means to calculate a range of daily flow indices such as the 20$^{th}$ and 80$^{th}$ percentile flows, the current project contributes directly to the setting of allocations in currently ungauged areas. By linking this work with the broad scale environmental water requirement studies currently being undertaken by the Tropical Rivers And Coastal Knowledge (TRACK) consortium, the techniques used in this project could be used to determine any number of hydrological indices of environmental significance in each basin that would allow a vastly improved process for review of water licence applications.

By way of example, in the Blackmore River catchment (8150098) it was calculated that the average annual streamflow from 1965-2005 is 115 GL and that baseflow is estimated to represent 26 GL of this volume. This means that at the outset, if more than 26 GL of groundwater licences or dry season surface water licences are allocated, then the available resource would be exhausted, notwithstanding changes in groundwater evapotranspiration between any given bore and point of baseflow discharge. If 80% of flow were to be reserved for the environment, then on average, the maximum flow that could be allocated would be 23 GL in total, of which not more than 5 GL could be sourced from baseflow. Dry season baseflow is close to zero and median dry season flow is zero, indicating that dry season streamflows would probably not be a viable resource in this particular catchment for most consumptive uses. When setting specific diversion rules, it could be formulated, for example, that no diversions would occur when say the 80$^{th}$ percentile low flow is reached, which would be 9.4 ML/d in the wet season and 0 ML/d in the dry season. This would enable the retention of a minimum sustenance flow in the river. Cease to pump rules for groundwater could be developed along similar lines after considering the lag between groundwater pumping and streamflow response.

This approach would be applicable both at an individual catchment scale and at a basin scale.

### 4.5 Environmental Water Requirements

Determination of environmental water requirements is a significant task and is outside the scope of this project. As a result, the available water resources estimated in this report refer simply to the total available volume of water which could be harvested from surface water and groundwater resources in the trial catchments.

Understanding the water requirements of groundwater dependent ecosystems (GDEs) is in its infancy in Australia. Over the past decade there has been increased recognition of the role of groundwater in ecosystem function and increased effort to include this in water allocation planning and ensuring that water extraction is ecologically sustainable has become one the key objects of current water resource planning. Difficulties in water allocation to GDEs arises due to the complexities in defining GDE water requirements, particularly as it varies both spatially and temporally.

Ecosystems may source water from rainfall, surface water, soil water and groundwater. Assessing the environmental requirements of the ecosystem needs to recognise the relative contributions of each of these sources (SKM, 2001a).

As a broad example of how qualitative environmental water requirements could be determined, it is again necessary to consider both wet and dry seasons. During the dry season surface water flows are minimal, and it could be expected that the existing ecosystems may depend entirely on the historically available dry season flow regime. Hence the major limitation on groundwater extraction during the dry season relates to the previously discussed issue of time lag to streamflow impacts. Groundwater extractions could be limited to occur some distance from a stream such that the time lag of streamflow depletion from groundwater extraction corresponds to the wet season when recharge occurs and the watertable depth is at its shallowest. Such an approach would maximise sustainable volumes of groundwater that could be utilised and would cause minimal impacts to existing ecosystems.

During the wet season, it is likely that investigation of the existing hydrological regime will provide examples of the necessary environmental water requirements that may be necessary to meet ecological objectives. For example, the 80$^{th}$ percentile flow (Q80) has been used in other studies to provide an example of the minimum environmental water requirement during periods of surface water extraction. There may be other ecologically relevant indicators such as provision of a Q20 flow, for example, once per wet season. Whilst the setting of such guidelines must be undertaken in conjunction with specialist stakeholders in the field, this project has successfully demonstrated that ecologically relevant indices can be readily transposed from gauged catchments to ungauged catchments.

# 5. Water availability for the Adelaide and Finniss River basins

## 5.1 Introduction

The methods outlined in previous sections of this report were applied to the ungauged areas of the Adelaide and Finniss River basins to provide an estimate of water availability in these two basins.

## 5.2 Application of the method in the Adelaide and Finniss River basins

In the previous section, a number of prediction equations were developed for various hydrologic indices based on information from catchment characteristics and hydrogeological data. This was regarded as a successful application of the project methodology to the study area, as it could be demonstrated that prediction equations with a reasonable goodness of fit could be developed for northern Australia.

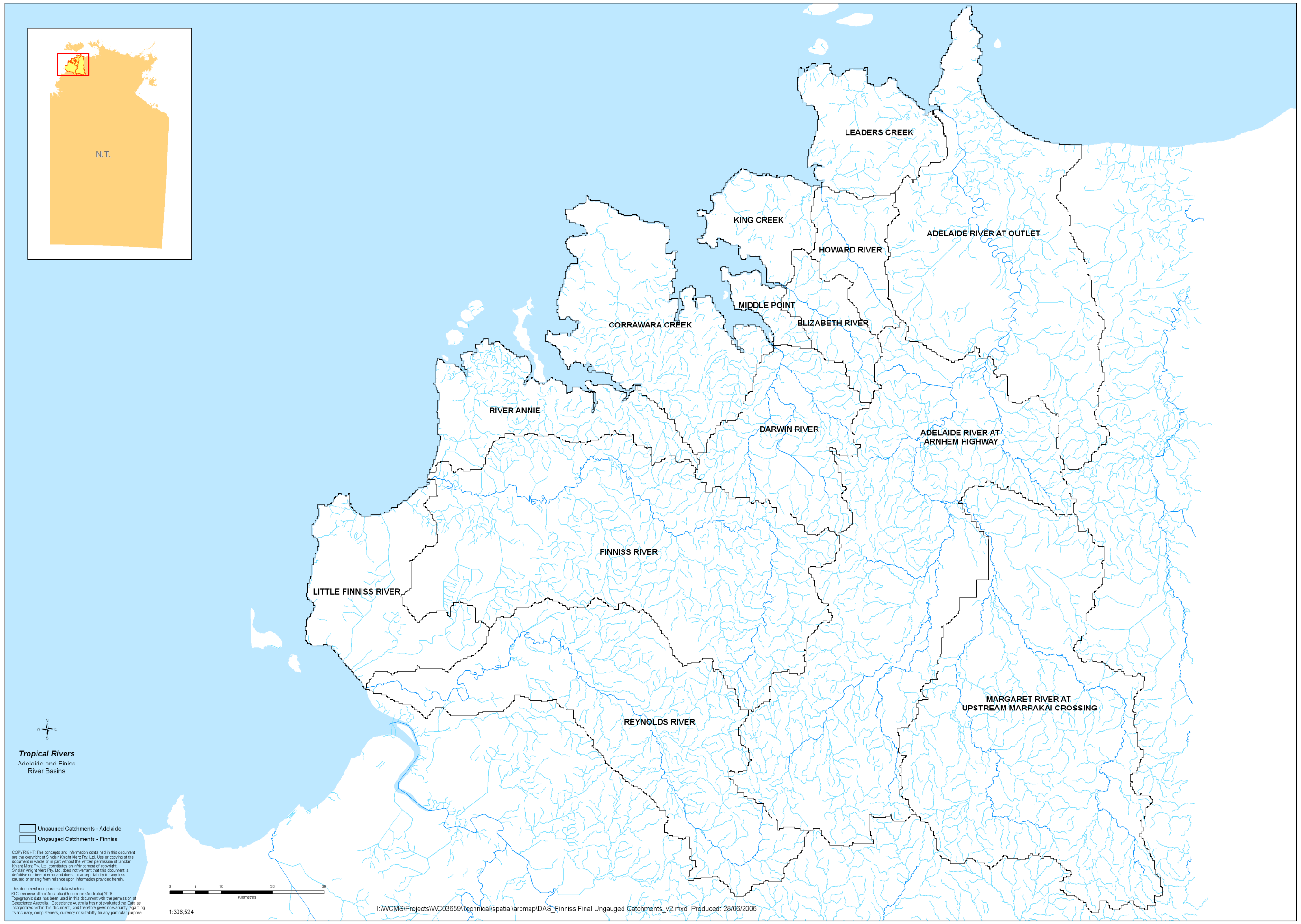
To complete the process, the equations were used to transpose the hydrological indices to the outlet of the Adelaide River basin and the outlet of each major river or coastal tributary catchment of the Finniss River basin. A total of 14 ungauged catchments at major tributary points in both basins were identified, and the required catchment characteristics extracted using GIS. These catchments are shown on the map in Figure 5-1.

The main difficulty in application of the methodology to the ungauged catchments is that some of the independent variables, particularly catchment area, are outside the range of the values used to develop the regression equations. Ideally, these equations would not be extrapolated as it is difficult to determine the accuracy of any predictions made outside the range of the values used to develop the equations. This is not so much an issue with catchment area, for which there is a great deal of evidence to show that increasing area proportionally increases flow. The relatively low elevations and low topographic gradients across the study area mean that the relationship between flow and catchment area is not highly non-linear and can be reasonably extrapolated. Some of the other variables such as distance to coast and the percentage of woody vegetation are more problematic. In particular, distance to coast for some of the ungauged coastal catchments in the Finniss River is lower than the values used to develop the regressions. As such, it is difficult to state with any certainty that these values remain reliable predictors below this range. For the percentage of woody vegetation, there is no clear causative relationship between this characteristics and the dry season baseflow, so it is a leap of faith to assume that values outside the range of the input values will generate reliable estimates of dry season baseflow. Plots showing the distribution of each catchment characteristic for the gauged and ungauged catchments are shown in Figure 5-2, Figure 5-3, Figure 5-4 and Figure 5-5.

In general this difficulty can be overcome principally by expanding the sample size of gauged catchments used to develop the predication equations, as would take place in any future stages of this project. This will provide a greater range of catchment characteristic values and allow in greater certainty when applying the equations to ungauged catchments.

For the trial study, there were two possibilities for approaching this issue. The first is that ungauged catchments are selected as required and catchment characteristics such as area are allowed to range well outside the values used to develop the equations. The second possibility is that catchment area is kept within the range of the input variables by simply breaking larger ungauged catchments down into smaller tributary streams and summing the water resource in each tributary stream from upstream to downstream.

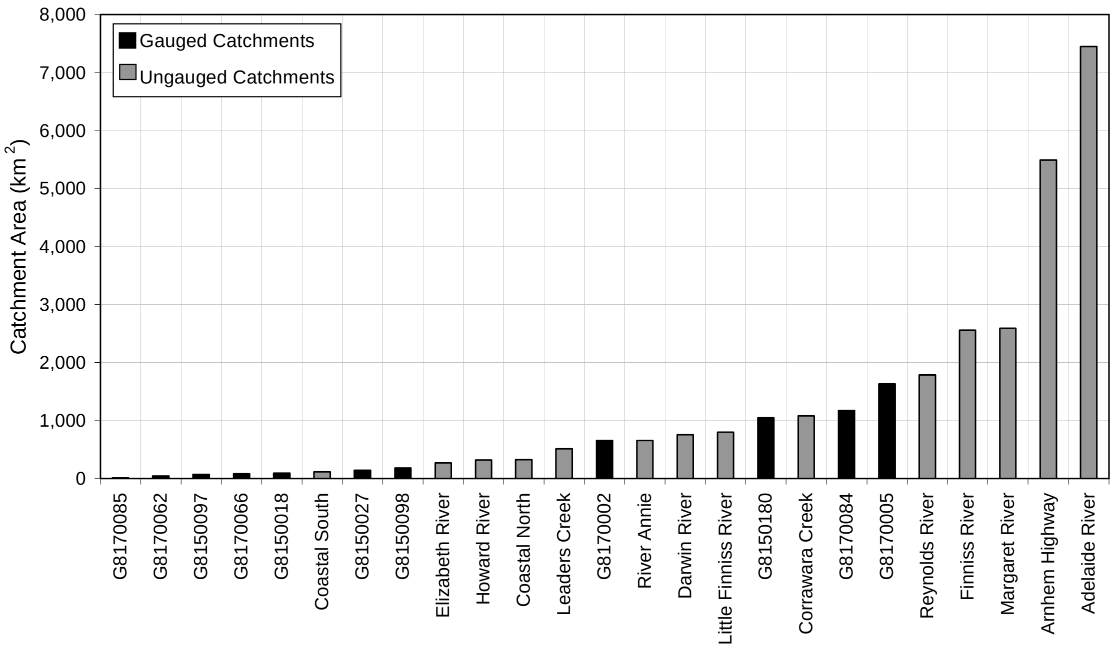
The first approach was used to delineate ungauged catchments and estimate the surface water resource for both basins. The ungauged catchments and their catchment characteristics are listed in Table 5-1. The results of the regression equations used to predict the hydrological indices for each ungauged catchment are shown in Table 5-2. The decision to adopt the first approach was a pragmatic one to simply demonstrate proof of concept and was cross-checked using the second approach and found to produce similar results. In any future extension of this project it is envisaged that the second approach would be adopted to allow information in ungauged areas to be estimated with greater confidence at a finer catchment scale.



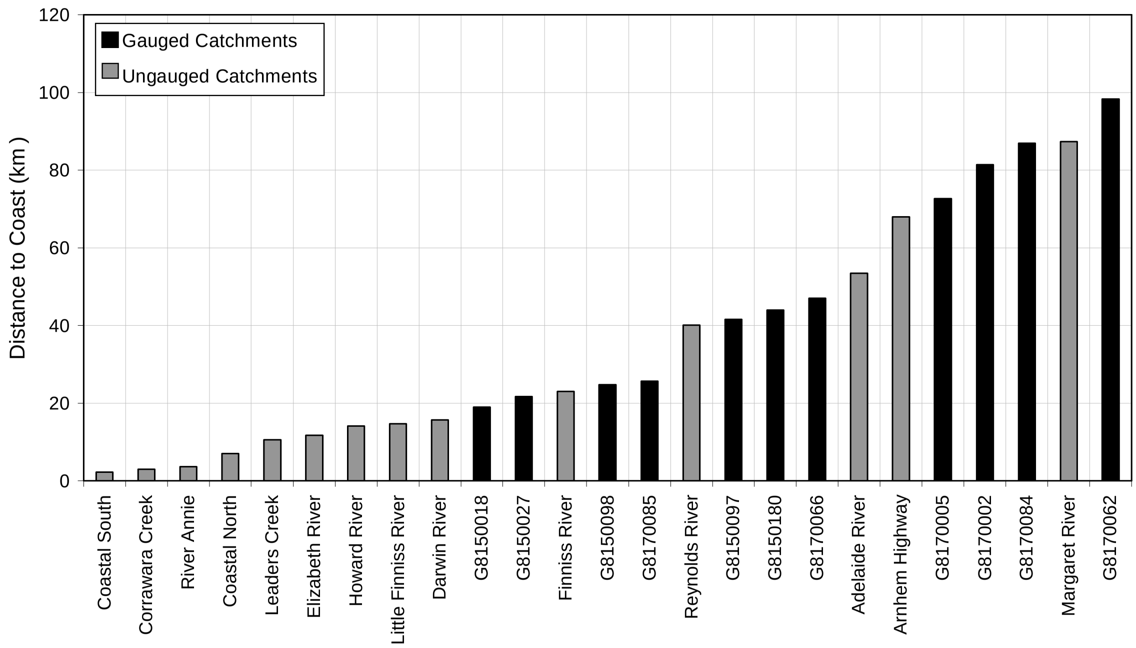

■ **Figure 5-1: Ungauged Catchments Used for Adelaide and Finniss River Surface Water Resource Assessment**

■ **Table 5-1: Ungauged Catchment Characteristics**

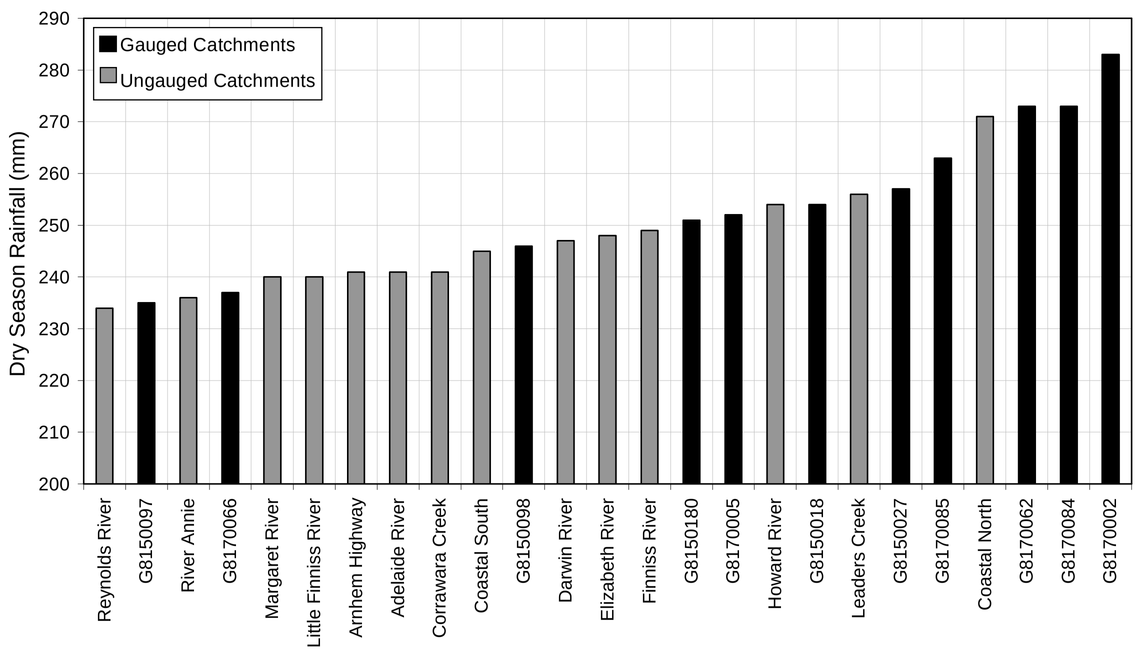
| Ungauged Catchment | Catchment Area ($km^2$) | Distance to Coast (km) | Dry Season Rainfall (mm) | Percentage of Woody Vegetation (%) |
|---|---|---|---|---|
| Margaret River at Upstream Marrakai Crossing | 2,590 | 87.3 | 240 | 2 |
| Adelaide River at Arnhem Highway | 5,489 | 68.0 | 241 | 9 |
| Adelaide River at Outlet | 7,448 | 53.5 | 241 | 18 |
| Little Finniss River | 799 | 14.7 | 240 | 51 |
| River Annie | 656 | 3.7 | 236 | 65 |
| Corrawara Creek | 1,083 | 3.0 | 241 | 73 |
| Middle Point | 115 | 2.2 | 245 | 42 |
| King Creek | 325 | 7.1 | 271 | 33 |
| Leaders Creek | 514 | 10.6 | 256 | 82 |
| Howard River | 319 | 14.1 | 254 | 64 |
| Elizabeth River | 269 | 11.8 | 248 | 10 |
| Darwin River | 756 | 15.6 | 247 | 2 |
| Finniss River | 2,559 | 23.0 | 249 | 10 |
| Reynolds River | 1,784 | 40.1 | 234 | 17 |



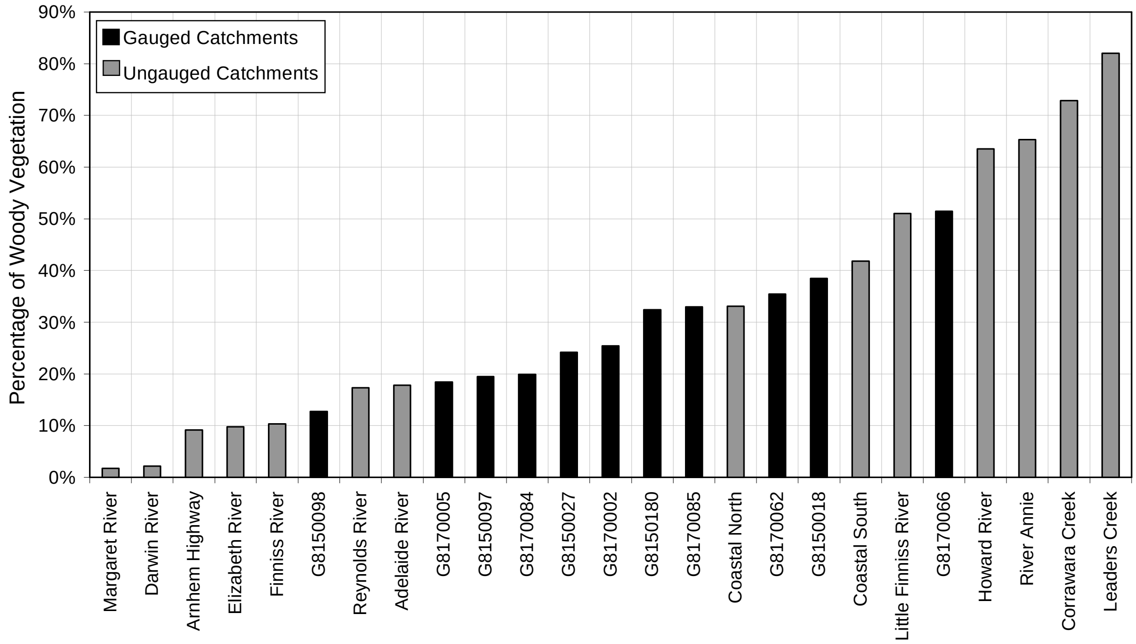
■ Figure 5-2: Comparison of Catchment Areas in Gauged and Ungauged Catchments




■ Figure 5-3: Comparison of Distance to Coast in Gauged and Ungauged Catchments




■ Figure 5-4: Comparison of Dry Season Rainfall in Gauged and Ungauged Catchments




▪ **Figure 5-5: Comparison of Percentage Woody in Gauged and Ungauged Catchments**

## 5.3 Surface water availability results

Estimates of various hydrologic indices are presented for the period of available gauged record (1965-2005) in Table 5-2 and the extended period of available climate data (1872-2005) in Table 5-3. These were estimated for the ungauged catchments shown in Figure 5-1. In translating data between the shorter and longer period, factors were applied utilising the ratio of the various hydrologic indices over the shorter term relative to the longer term. For all flow percentiles, the ratio of SIMHYD daily flows from 1965-2005 relative to 1872-2005 values were used. For seasonal baseflow and quickflow, representative flow percentiles were used to translate the data. The ratio of short to long-term 20$^{th}$ percentile flows was used to translate quickflow estimates, whilst the ratio of short to long-term 80$^{th}$ percentile flows was used to translate baseflow estimates. Where 80$^{th}$ percentile flows were zero in the dry season then either the non-zero median or 20$^{th}$ percentile dry season flow ratios were used. Factors were also grouped regionally, with separate factors being applied in the upper Adelaide (upstream of Arnhem Highway), lower Adelaide and across the Finniss River basin according to spatial differences in rainfall and runoff over the shorter and longer assessment periods used in this project.

## Table 5-2: Ungauged Catchment Hydrological Indices 1965-2005

| Catchment | $MAQF_w$ (GL/yr) | $MAQF_d$ (GL/yr) | $MABF_w$ (GL/yr) | $MABF_d$ (GL/yr) | $Q50_w$ (ML/d) | $Q50_d$ (ML/d) | $Q20_w$ (ML/d) | $Q20_d$ (ML/d) | $Q80_w$ (ML/d) | $Q80_d$ (ML/d) |
|---|---|---|---|---|---|---|---|---|---|---|
| Margaret R at US Marrakai Crossing | 800 | 18 | 280 | 18 | 2,200 | 0# | 11,000 | 160 | 350 | 0# |
| Adelaide R at Arnhem Hwy | 1,700 | 38 | 600 | 38 | 5,300 | 0 | 25,000 | 360 | 810 | 0 |
| **Adelaide River Basin at Outlet** | **2,300** | **52** | **810** | **52** | **7,300** | **0*** | **35,000** | **500** | **1,100** | **0*** |
| Little Finniss River | 250 | 5.6 | 90 | 5.3 | 910 | 0 | 4,100 | 70 | 130 | 0 |
| River Annie | 210 | 4.6 | 74 | 4.3 | 850 | 0 | 3,700 | 71 | 110 | 0 |
| Corrawara Creek | 340 | 7.6 | 120 | 7.3 | 1,300 | 0 | 5,800 | 110 | 180 | 0 |
| Middle Point | 44 | 0.8 | 15 | 0.5 | 320 | 0 | 1,200 | 16 | 31 | 0 |
| King Creek | 110 | 2.3 | 38 | 2.0 | 490 | 0 | 2,100 | 24 | 59 | 0 |
| Leaders Creek | 170 | 3.6 | 58 | 3.3 | 660 | 0* | 2,900 | 73 | 86 | 0* |
| Howard River | 110 | 2.2 | 37 | 2.0 | 440 | 0* | 1,900 | 46 | 53 | 0* |
| Elizabeth River | 91 | 1.9 | 32 | 1.6 | 400 | 0 | 1,700 | 2.0 | 47 | 0 |
| Darwin River | 240 | 5.3 | 85 | 5.0 | 870 | 0* | 3,900 | 30 | 120 | 0* |
| Finniss River | 790 | 17.9 | 280 | 18 | 2,600 | 0* | 12,000 | 160 | 390 | 0* |
| Reynolds River | 550 | 12.5 | 200 | 12 | 1,700 | 0 | 8,300 | 110 | 260 | 0 |
| **Total Finniss River Basin** | **2,900** | **64** | **1,000** | **61** | **11,000** | **0** | **48,000** | **710** | **1500** | **0** |

*catchment contains some carbonate aquifer – value may be greater than zero

#catchment contains some carbonate aquifer but streamflows are gauged and were found to be zero

## Table 5-3: Ungauged Catchment Hydrological Indices 1872-2005

| Catchment | $MAQF_w$ (GL/yr) | $MAQF_d$ (GL/yr) | $MABF_w$ (GL/yr) | $MABF_d$ (GL/yr) | $Q50_w$ (ML/d) | $Q50_d$ (ML/d) | $Q20_w$ (ML/d) | $Q20_d$ (ML/d) | $Q80_w$ (ML/d) | $Q80_d$ (ML/d) |
|---|---|---|---|---|---|---|---|---|---|---|
| Margaret R at US Marrakai Crossing | 520 | 12 | 200 | 12 | 1,300 | 0 | 7,300 | 77 | 240 | 0 |
| Adelaide R at Arnhem Hwy | 1,100 | 25 | 430 | 26 | 3,200 | 0 | 17,000 | 180 | 550 | 0 |
| **Adelaide River at Outlet** | **1,600** | **34** | **630** | **35** | **4,400** | **0*** | **23,000** | **250** | **760** | **0*** |
| Little Finniss River | 210 | 2.9 | 74 | 4.1 | 550 | 0 | 2,700 | 34 | 86 | 0 |
| River Annie | 170 | 2.4 | 61 | 3.4 | 510 | 0 | 2,500 | 35 | 76 | 0 |
| Corrawara Creek | 280 | 3.9 | 100 | 5.7 | 800 | 0 | 3,800 | 52 | 120 | 0 |
| Middle Point | 36 | 0.4 | 12 | 0.4 | 190 | 0 | 770 | 8.0 | 21 | 0 |
| King Creek | 88 | 1.2 | 31 | 1.6 | 300 | 0 | 1,400 | 12 | 40 | 0 |
| Leaders Creek | 140 | 1.9 | 48 | 2.6 | 400 | 0* | 1,900 | 36 | 59 | 0* |
| Howard River | 87 | 1.2 | 31 | 1.5 | 260 | 0* | 1,200 | 23 | 36 | 0* |
| Elizabeth River | 74 | 1.0 | 26 | 1.3 | 240 | 0 | 1,100 | 1.0 | 32 | 0 |
| Darwin River | 200 | 2.7 | 70 | 3.9 | 520 | 0* | 2,600 | 15 | 81 | 0* |
| Finniss River | 650 | 9.3 | 230 | 14 | 1,600 | 0* | 8,200 | 79 | 270 | 0* |
| Reynolds River | 450 | 6.5 | 160 | 9.5 | 1,000 | 0 | 5,500 | 56 | 180 | 0 |
| **Total Finniss River Basin** | **2,400** | **33** | **840** | **48** | **6,400** | **0*** | **32,000** | **350** | **1,000** | **0*** |

*catchment contains some carbonate aquifer – value may be greater than zero

[#]catchment contains some carbonate aquifer but streamflows are gauged and were found to be zero

It can be seen from these tables, for example, that the dry season baseflow is estimated to be 35 GL and 48 GL respectively in the Adelaide and Finniss River basins over the longer climate period.

### 5.4 Groundwater availability results

It is proposed that the volume of the available annual groundwater resource from the Adelaide and Finniss River basins is equal to the volume of baseflow plus a spatially variable groundwater evapotranspiration loss. The long-term (1872-2005) average annual volume of baseflow is 670 GL/yr in the Adelaide River basin and 890 GL/yr in the Finniss River basin, with most of this being discharged to rivers during the wet season.

Evapotranspiration from groundwater was estimated to be on average around 565 mm and 557 mm in the wet season in the Adelaide and Finniss River basins respectively and 109 mm in the dry season in both river basins. Whilst the change in groundwater level due to groundwater pumping will be localised and specific to individual bores or borefields, by way of example, if groundwater pumping were to cause a 10% reduction in groundwater evapotranspiration across these river basins then the volume associated with that change would be 500 GL in the Adelaide River basin and 610 GL in the Finniss River basin. Reduction in evapotranspiration from groundwater could however impact on groundwater dependent ecosystems due to reduced access to this water source. This example illustrates that reduction in groundwater evapotranspiration due to groundwater pumping could potentially be a very large volume, but would mostly likely only be made available to groundwater users if any impacts on groundwater dependent ecosystems could be appropriately managed. This would need to be assessed for specific bore locations and pumping rates.

There is the potential for seasonal groundwater extraction that is out of phase with baseflow discharge to streams during the dry season. That is, pumping groundwater in the dry season at some distance from surrounding rivers could result in a reduction in baseflow during the wet season rather than the dry season. In catchments with no carbonate aquifers, streams cease to flow during the dry season and hence groundwater storage close to the river could be utilised after baseflow has ceased without affecting baseflow until the following wet season, when streamflows are high again.

Groundwater discharge that is not recorded at the streamflow gauge at each catchment outlet, such as discharge to offshore or adjacent catchments, was estimated using Darcy's Law and found to be negligible relative to baseflow volumes for the Adelaide and Finniss River basins.

These estimates of water availability do not explicitly take into account historical use. Estimated average annual groundwater extraction across the Adelaide and Finniss River basins is in the order of 41 GL/yr (ANRA, 2006) as presented in Appendix F. Further analysis and information would be required to adjust the existing estimates of baseflow availability for historical groundwater pumping, which could be expected to vary from the current 41 GL/yr over the 1965-2000 period over which baseflow estimates were initially derived for this study.

### 5.5 Comparison with AWR and NLWRA

To date, there have been no detailed, long term water resource assessments undertaken on the Adelaide or Finniss River basins. The most detailed recent investigation was performed as part of the Australian Water Resources 2005 baseline assessment project, which considered part of the Finniss River basin as the 'Darwin Water Supply Area', and undertook a one year (July 2004 to June 2005) water balance on this area. The water balance included components such as the change in storage over that period for the Darwin River Dam, rainfall, estimated evaporation and estimated water use. The results of this water balance indicated that the available surface water resource for the Darwin WSA was 262 GL for the 2004/05 year. The available groundwater resource was estimated to be 27 GL, giving a total resource of 288 GL (AWR, 2007).

The key difference between this assessment and the one undertaken as part of the current project is that the current project is taking a long-term average approach to water resources assessment. AWR 2005 considered only the 2004/05 year, and the inflows and changes in surface water and groundwater storage across that year. In comparison, the current project has used over 100 years of recorded and modelled rainfall and streamflow data to estimate available water resources given the historic climatic conditions. Thus, when compared to the figures calculated in this project (Finniss River basin wet season water resource of 3200 GL, dry season water resource of 81 GL) the AWR 2005 water resource estimates appear an order of magnitude lower. However, the 2004/05 year had significantly less rainfall (1234 mm) than the long-term climatic average (1584 mm). Additionally, the AWR 2005 water balance only accounts for part of the Finniss River basin, whereas the techniques presented in this report consider the whole basin.

A more valid comparison can be made with the National Land and Water Resources Audit (NLWRA) in 2000. This study estimated sustainable water resources for the Finniss River basin by transposing gauged mean annual flow data to the basin outlet as a function of catchment area (ANRAT, 2006a). This method is similar to the approach used in the current project, although the 2000 study only considered mean annual flow whereas this study has developed regression relationships for a variety of seasonal indices.  The NLWRA estimated that the total available surface water yield for the Finniss River basin was 3120 GL, which is approximately 200 GL less than that estimated by the current project.

The NLWRA also attempted to define the sustainable yield of each basin. This was done in the Northern Territory by use of the 80/20 rule, which states that the environmental water requirements of a river basin are approximately 80% of natural streamflow (ANRAT, 2006a). Application of this rule means that consumptive water use is nominally limited to 20% of the available water resource. By providing the means to calculate a range of daily flow indices such as the 20$^{th}$ and 80$^{th}$

percentile flows, the current project is contributing to a more detailed and rigorous understanding of the temporal variability of flow within a basin. By linking this work with the broad scale environmental water requirement studies currently being undertaken by the Tropical Rivers And Coastal Knowledge (TRACK) consortium, the regression relationships developed in this project could be used to determine hydrological indices of environmental significance in each basin that would allow a vastly improved process for review of water licence applications.

No comparison can readily be made between the sustainable groundwater yield estimates calculated as part of the NLWRA and the estimates calculated in this project. The NLWRA groundwater figures apply to groundwater management units which are significantly larger than the surface water basins considered as part of this study. Additionally, sustainable groundwater yields were calculated as 50% of available recharge, which in turn was calculated based on a recharge rate of between 0.2 and 5.0 ML/ha/year (ANRAT, 2006a). It is considered that the approach adopted in this project has produced much more accurate estimates of the groundwater resource within the Adelaide and Finniss Rivers for the purposes of conjunctive management, but further work would be required to spatially represent the effect of groundwater evapotranspiration on the magnitude of the groundwater resource at any given location.

# 6. Carbonate and non-carbonate aquifers

## 6.1 Introduction

The hydrologic properties of rivers in catchments with carbonate and non-carbonate aquifers can be vastly different during low flow periods, because of the sustained baseflows from carbonate aquifers which can occur during the dry season. Carbonate aquifers also introduce particular difficulties in establishing stable hydrographic rating tables for the conversion of recorded water levels to time series streamflow data.

The study area for this project was specifically selected so as to exclude carbonate aquifers. However, there were still some areas with a small proportion of carbonate aquifer. This section of the report discusses how these small areas of carbonate aquifer have been integrated into the project to date, and some of the advantages, disadvantages and modifications to methodology that would be applicable if applying the methods from this project to carbonate aquifers in the future.

## 6.2 Summary of the geology of gauged catchments in the Adelaide and Finniss River basins

The 1:250,000 geological map was interrogated using the GIS to determine the surface geology of each of the gauged catchments. In order to simplify the data, the geology was divided into groups based on the age of the units. This information is tabulated in Table 6-1 and shown spatially across the study area in Appendix F.

- **Table 6-1: Surface Geology of Each Gauged Catchment**

| Gauge/ Catchment No | Total Catchment Area (km$^2$) | Proportion of Catchment with each Age Geological Unit by area | | | | |
|---|---|---|---|---|---|---|
| | | Precambrian | Paleozoic | Mesozoic | Tertiary | Quaternary |
| G8150018 | 94 | 0.1419 | 0.0000 | 0.0000 | 0.5489 | 0.3092 |
| G8150027 | 141 | 0.1034 | 0.0000 | 0.0020 | 0.6435 | 0.2512 |
| G8150097 | 74 | 0.4804 | 0.0000 | 0.0014 | 0.4264 | 0.0875 |
| G8150098 | 182 | 0.2991 | 0.0000 | 0.0000 | 0.4495 | 0.2514 |
| G8150180 | 1,048 | 0.5379 | 0.0000 | 0.0006 | 0.0948 | 0.3668 |
| G8170002 | 655 | 0.6235 | 0.0019 | 0.0523 | 0.0000 | 0.3224 |
| G8170005 | 1,636 | 0.2155 | 0.0000 | 0.0000 | 0.0191 | 0.7654 |
| G8170062 | 42 | 0.6477 | 0.0000 | 0.2420 | 0.0000 | 0.1103 |
| G8170066 | 84 | 0.3460 | 0.0000 | 0.0000 | 0.1724 | 0.4817 |
| G8170084 | 1,173 | 0.3400 | 0.0000 | 0.0315 | 0.0000 | 0.6285 |
| G8170085 | 11 | 0.2267 | 0.0000 | 0.0000 | 0.6288 | 0.1445 |

NRETA (pers. comm. L. Rajaratnam and P. Jolly) has indicated that perennial flows in G8150027 (Berry River) and G8170066 (Coomalie Creek) are sustained discharge from carbonate geology. In order to quantify this, the proportion of carbonate aquifer in each catchment was investigated in more detail. This proved to be somewhat difficult given the scale of the available geological information. Carbonate units are not necessarily explicitly mapped at 1:250,000 scale, and carbonate geology may be obscured by the presence of thin overlying alluvial sediments which may reduce the relative amount of carbonate geology extracted without significant reinterpretation or mapping of the geology. This information was extracted from the geological information in two different formats, area and river length. Area is simply the total area of carbonate surface lithologies within each catchment, whereas river length is the total length of stream in each catchment that intersects with carbonate geology. Carbonate geology was defined as any lithological unit that contained carbonate rock-types in the lithological description (e.g. dolomitic marble; dolomitic mica schist; mica-quartz schist; sandy, interaclastic, dolomitic limestone; calcareous quartzite; basal conglomerate) and will by virtue of this definition result in an overestimate of the actual amount of carbonate in the catchment. This is shown in Table 6-2.

- **Table 6-2: Carbonate Geology in the Gauged Catchments**

| Catchment | Area of Carbonate ($km^2$) | Carbonate Area as a Percentage of Catchment Area | River Length Intersecting With Carbonate (km) | Carbonate River Length as a Percentage of Total River Length | Cease to flow 1968-1978 (% of time) |
|---|---|---|---|---|---|
| G8150018 | 0.0 | 0.0% | 0.3 | 0.5% | 45.9% |
| G8150027 | 5.4 | 3.8% | 2.3 | 2.1% | 0.6% |
| G8150097 | 4.2 | 5.7% | 0.0 | 0.0% | 35.5% |
| G8150098 | 0.6 | 0.3% | 0.0 | 0.0% | 41.0% |
| G8150180 | 19.7 | 2.0% | 3.0 | 0.4% | 0.0% |
| G8170002 | 279.0 | 42.6% | 1.5 | 0.3% | 3.7% |
| G8170005 | 71.4 | 18.9% | 16.7 | 7.1% | 5.5% |
| G8170062 | 23.3 | 55.9% | 0.0 | 0.0% | 51.7% |
| G8170066 | 23.7 | 28.2% | 4.1 | 7.6% | 0.2% |
| G8170084 | 105.0 | 22.0% | 4.7 | 1.5% | 11.5% |
| G8170085 | 0.8 | 6.8% | 1.3 | 20.1% | 49.4% |

It can be seen that there is a great deal of variability in these figures, and the proportion of carbonate aquifer by area is often quite different to the proportion by river length. This reflects the uncertainty associated with both the geological and stream information used to derive these numbers. The two catchments identified by NRETA display a high proportion of carbonate aquifer by river length, however there are other catchments with a higher proportion that do not exhibit the sustained dry season flows observed at 8150027 and 8170066. The likely explanations of this are that the amount of carbonate geology in the catchment has been overestimated, or that karstic geomorphology has not necessarily developed in the carbonate rock types that may result in preferential pathways of groundwater flow and point-source discharge from the aquifer to the streams.

## 6.3 Transposing hydrologic information to ungauged catchments with carbonate aquifers

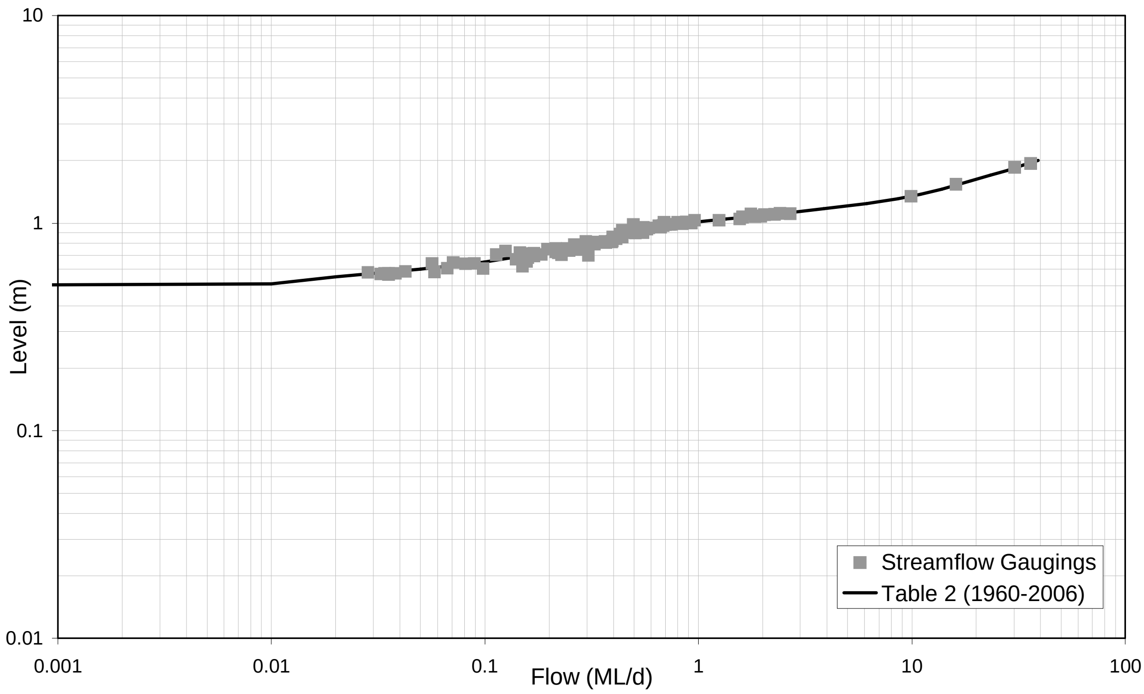
In the predominantly non-carbonate aquifers of this study, dry season low flows were found to be zero or close to zero. The presence of carbonate aquifers increases the potential for baseflow to occur during the dry season. It is therefore advisable to check the extent of carbonate aquifers in any catchment to which data is being transposed.

With a larger sample size of a mix of catchments with carbonate and non-carbonate aquifers, it is speculated that either the length or area of carbonate aquifer (or a combination of both) could be used as a predictive variable in the development of regression equations to estimate baseflow, particularly in the dry season. The distance of the carbonate aquifer to the catchment outlet would presumably also be a factor where losses from the river to groundwater are high in reaches downstream of the point of discharge from the carbonate aquifer.

## 6.4 Rating table stability in the Adelaide and Finniss River basins

Rating tables convert recorded water level data in a stream to a flow rate based on relationships established through hydrographic measurement at periodic intervals, typically from months to years. If a cross-section regularly changes then the rating table will only be valid for a short period of time after a hydrographic measurement is taken, whereas if a cross-section is stable then additional hydrographic gaugings will simply confirm the relationship between water level and streamflow volume that was previously established.

A review of rating table stability was undertaken at the commencement of this trial project to ensure that time series data was suitable to use in this study and is presented in Appendix A. The outcomes of this review were that all of the rating tables were considered to be stable and that the time series data was suitable for use. This is illustrated through the examination of the rating table for Berry River, which contains some carbonate aquifers, shown in Figure 6-1. It can be seen from this graph that the individual gaugings over a 46 year period plot consistently along the same rating curve with only minor scatter that could readily be attributable to instrument error at the time of gauging.




- **Figure 6-1 Rating table for all gaugings at Berry River at March Fly Weir**

### 6.5 Rating table stability in catchments with carbonate aquifers

The stability of rating tables at streamflow gauges in tropical northern Australia should always be examined before utilising the data, as was done in this study. Some streamflow gauges in other parts of tropical northern Australia are known to have relatively unstable cross-sections (eg in the Daly River basin in DIPE, 2004b). These typically occur in catchments with a high proportion of carbonate aquifers, which result in limestone deposits forming across the control section at the site, thereby changing the shape of the cross-section. In high-flow events, some of these deposits can be washed away again, causing the cross-section to change once more. Where rating tables are unstable, rainfall-runoff models can be calibrated to individual gaugings, with baseflow estimated from rainfall-runoff model components rather than by the use of a digital recursive filter. As stated previously, baseflow from rainfall-runoff models can be checked against dry season flows, which will consist solely of baseflow during the middle of the dry season.

# 7. Conclusions and Recommendations

## 7.1 Conclusions

A method was established for reliably estimating hydrologic information in the largely ungauged trial basins of the Adelaide and Finniss Rivers. The development of this method and its application in the two trial basins produced the following outcomes:

*Period of assessment for water allocation* – There is high variability in climate and streamflow in the Adelaide and Finniss River basins. Average rainfall over the period of gauged streamflow data (1965-2005) was approximately 5-16% higher than the long-term average (1872-2005) and streamflow was estimated to be in the order of 7-20% higher than the long-term average in the Finniss River basin and lower reaches of the Adelaide River basin, and 46-64% higher in the upper reaches of the Adelaide River basin. Climate change projections from CSIRO indicate that conditions over the coming decades could either become wetter or drier relative to 1990 conditions, depending on the climate model used and the assumed level of greenhouse gas emissions. Given this uncertainty, it is considered prudent in the first instance to represent current streamflow conditions as based over the longer climate period (1872-2005) to allow for the possibility of a return to drier conditions as part of natural inter-decadal variability. Allowance for a range of climate change conditions as part of the allocation process should be undertaken with reference to this long-term baseline. The method of deriving longer-term hydrologic information for this trial project involved scaling of results based on rainfall-runoff models calibrated to the shorter period and applied over the longer period.

*Methods of determining groundwater and surface water interaction in gauged catchments* – A digital recursive filter has been used in the Adelaide and Finniss River basins to estimate baseflow. This technique is expected to be applicable to other catchments across tropical northern Australia which display relatively stable rating tables. Preliminary investigation of the use of rainfall-runoff models to estimate baseflow yielded mixed success, with no single model being able to replicate both baseflow and surface runoff in an objective manner. It is expected that more detailed investigations would allow the development of a conceptual model specifically tailored to groundwater processes, and that this would provide a more reliable means of estimating both quickflow and baseflow conjunctively in other parts of the tropical northern Australia where a mix of carbonate and non-carbonate aquifers exist.

This study does not consider in detail the time lag between groundwater extraction and a subsequent response on the river. This study does however highlight the stark differences in groundwater and surface water interaction from the wet season to the dry season. This creates the potential for seasonal groundwater extraction that is out of phase with baseflow discharge to streams during the dry season. That is, pumping groundwater in the dry season at some distance from surrounding rivers could result in a reduction in baseflow during the wet season rather than the dry season.

Evapotranspiration from groundwater was estimated using the results of field measurements from previously published studies to assist in quantifying the volume of groundwater that could be allocated in excess of baseflow at a given groundwater pumping location. The further that a groundwater bore is from a stream, the greater the opportunity for evaporative loss from groundwater between the bore and the stream. Lowering of groundwater tables due to groundwater pumping would result in lower losses due to evaporation and evapotranspiration between the bore and the stream, which would potentially mean that a higher volume could be allocated from groundwater at the bore than at the river, assuming no unacceptable impacts on groundwater dependent ecosystems.

Groundwater discharge that is not recorded at the streamflow gauge at each catchment outlet, such as discharge to offshore or adjacent catchments, was estimated using Darcy's Law and found to be negligible relative to baseflow volumes for the Adelaide and Finniss River basins.

*Applying the technique to ungauged areas* – A range of indicators relevant to both resource assessment and ecology estimated in catchments with gauged streamflow data was successfully transposed to ungauged areas using readily available catchment and climate characteristics. Catchment area was the main catchment characteristic which proved useful for predicting those streamflow indices which are expressed as a flow magnitude. Distance from the coast, which was a new variable introduced for this study, was useful in predicting high flow and wet season indices. Low flow dry season indices were generally found to be zero because of the general absence of carbonate aquifers in these two river basins. Independent variables used in the prediction equations were sometimes outside of the range of values used in developing the equations, particularly in the smaller coastal streams where there is limited long-term gauged flow data. The prediction equations used to estimate all flow indices were a good fit to the available data, but results will be further improved with larger sample sizes in subsequent applications of the method to broader areas across northern Australia. For this reason, the estimates of water availability in the Adelaide and Finniss River basins should be considered as reasonably reliable, but also preliminary in nature. Temporal variability of streamflow in the candidate catchments was found to be more important than spatial variability, which is an important finding when weighing up the relative differences in spatial and temporal availability of streamflow data in future applications of this method to the remainder of tropical northern Australia.

*Water availability for the Adelaide and Finniss River basins* – The potential benefits of the techniques adopted in this study are demonstrated in the estimate of water availability in rivers in the Adelaide and Finniss River basins. These results show the relative magnitude of dry season and wet season flows, as well as the relative magnitude of baseflow and quickflow. The sensitivity of results to the assessment period used in the analysis is also shown. The long-term (1872-2005) total resource available from rivers in the Adelaide River basin is estimated to be 2307 GL/yr with a dry season baseflow of 35 GL/yr. Similarly, the long-term resource available from rivers in the Finniss River basin is 3293 GL/yr with a dry season baseflow of 48 GL/yr.

It is proposed that the volume of the available annual groundwater resource from the Adelaide and Finniss River basins is equal to the volume of baseflow plus a spatially variable groundwater evapotranspiration loss. The long-term (1872-2005) average annual volume of baseflow is 665 GL/yr in the Adelaide River basin and 891 GL/yr in the Finniss River basin, with most of this being discharged to rivers during the wet season. There is the potential to possibly draw upon groundwater in the dry season without adversely affecting baseflow until the following wet season, when baseflow is more plentiful. Evapotranspiration from groundwater was estimated to be on average around 565 mm and 557 mm in the wet season in the Adelaide and Finniss River basins respectively and 109 mm in the dry season in both river basins. Whilst the change in groundwater level due to groundwater pumping will be localised and specific to individual bores or borefields, by way of example, if groundwater pumping were to cause a 10% reduction in groundwater evapotranspiration across these river basins then the volume associated with that change would be 502 GL in the Adelaide River basin and 611 GL in the Finniss River basin. Reduction in evapotranspiration from groundwater could however impact on groundwater dependent ecosystems due to reduced access to this water source. This example illustrates that reduction in groundwater evapotranspiration due to groundwater pumping could potentially be a very large volume, but would mostly likely only be made available to groundwater users if any impacts on groundwater dependent ecosystems could be appropriately managed. This would need to be assessed for specific bore locations and pumping rates.

Importantly, these estimates of water availability eliminate double counting of the resource in rivers due to groundwater and surface water interaction. The magnitude of double counting is in the order of the volume of baseflow.

These results differ from those of the Australian Water Resources Assessment of 2005 because they cover the whole of the Adelaide and Finniss River basins as well as smaller catchments within them, and because they have been climate corrected to be representative of long-term climate conditions rather than just a single year's value. The National Land and Water Resources Assessment of 2000 yielded similar results for mean annual flow from the Finniss River basin, but the current project has the advantage of accounting for longer term climate variability and more of the spatial variability in streamflows between catchments, as well as being able to report on baseflow and quickflow, seasonal behaviour and a range of hydrologic indices in addition to simply reporting on mean annual flows.

These estimates of water availability do not explicitly take into account current use. Estimated total average annual groundwater extraction across the Adelaide and Finniss River basins is in the order of 41 GL/yr. Further analysis and information would be required to adjust the existing estimates of baseflow availability for historical groundwater pumping, which could be expected to vary from the current 41 GL/yr over the 1965-2000 period over which baseflow estimates were initially derived for this study.

*Carbonate versus non-carbonate aquifers* – The techniques adopted in this trial project have been developed in catchments with predominantly non-carbonate aquifers and are considered applicable across tropical northern Australia wherever catchments are predominantly non-carbonate. Some of the catchments in the study area did however contain some carbonate aquifer and therefore produced sustained low flows during the dry season. Wet season flows were readily estimated in catchments with carbonate aquifers. As part of any future rollout of the techniques from this project, it will first be necessary to check rating table stability (as was done in this project) and ascertain the spatial extent of carbonate aquifers across tropical northern Australia. Preliminary investigations undertaken in this study suggest that there is a possibility of transposing dry season hydrologic indices by utilising measures of the extent of carbonate aquifer in each catchment. Alternatively, detailed numerical groundwater modelling would be required for carbonate aquifers, however this may not be practically feasible across all areas containing carbonate aquifers in tropical northern Australia in the short term due to the intensive data requirements and cost associated with this modelling.

## 7.2 Recommendations

As a result of undertaking this study, it is recommended that:

1. The method developed for this study should be applied to all river basins with predominantly non-carbonate aquifers across tropical northern Australia. This would provide a robust comprehensive assessment of groundwater and surface water resources and their interaction in the largely ungauged catchments in this region. The information that can be derived from this method is considered essential for the subsequent assessment of any large scale water resource development proposals across tropical northern Australia
2. Trial investigations should be undertaken to ascertain whether this technique could equally be applied to catchments with predominantly carbonate aquifers. Preliminary investigations undertaken in this study suggest that there is the possibility of transposing dry season hydrologic indices by utilising measures of the extent of carbonate aquifer in each catchment. Wet season hydrologic indices are generally a surface water resource and could readily be estimated independent of aquifer type.

3. Further work should be undertaken to develop a lumped conceptual rainfall-runoff model which better represents groundwater processes to more reliably extend streamflows. This is also expected to reduce the time required to calibrate rainfall-runoff models in other catchments in the future application of this technique across tropical northern Australia.
4. Additional long-term monitoring and groundwater modelling should be undertaken to allow better information to be fed into this analysis in the years and decades to come.

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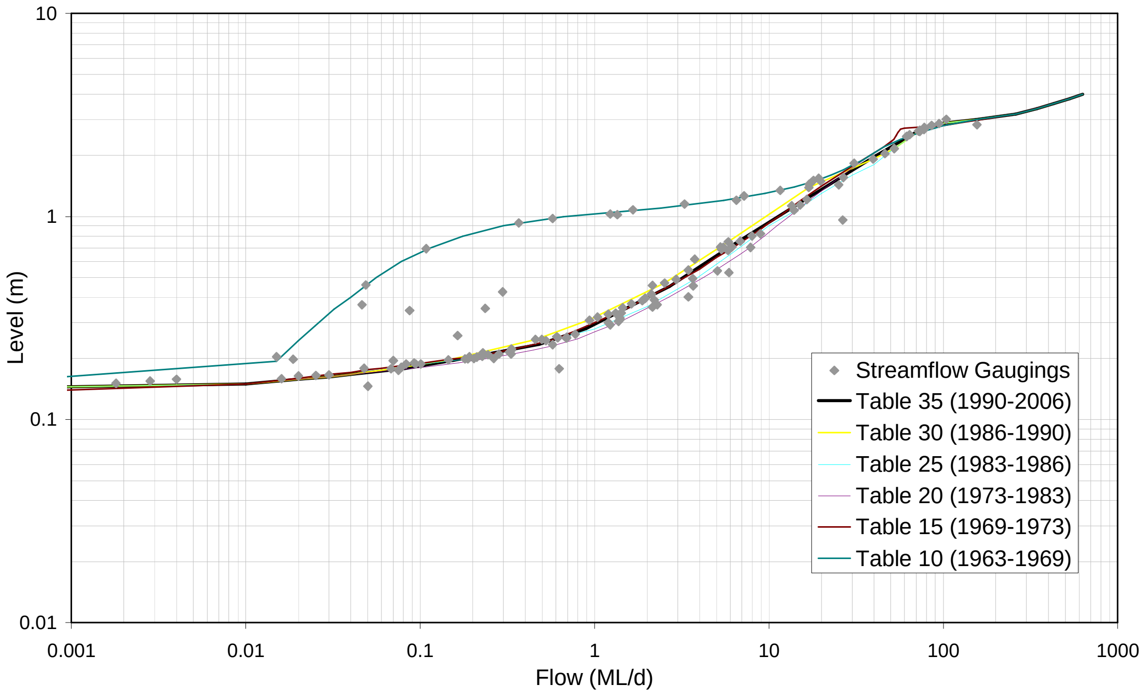
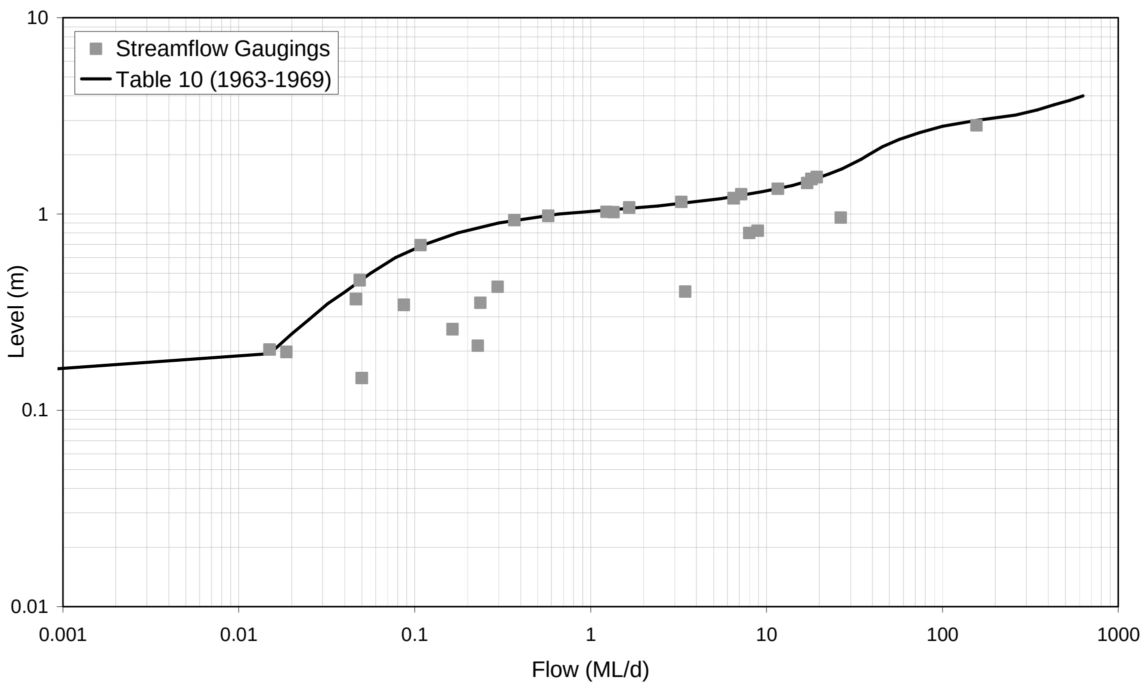
# Appendix A Rating Table Review

## A.1 Elizabeth River at Stuart Highway (8150018)

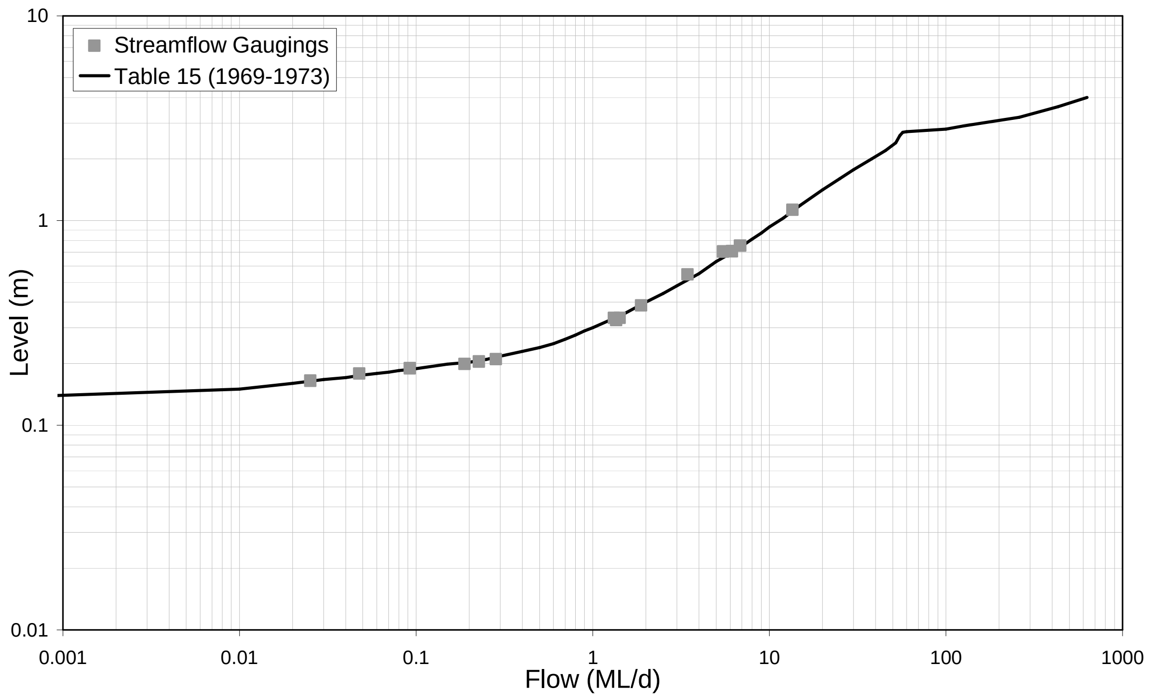
The gauge at 8150018 has had six rating table changes over the period of interest, as shown in Figure A-1. In general, all of these rating tables are fairly similar, except for Table 10, used in 1963-1969, which is considerably different between approximately 0.01 and 11 ML/d. However, all of the rating tables (including Table 10) are based on consistent streamflow gaugings with relatively little scatter. The individual rating tables with their associated streamflow gauging points are shown below.



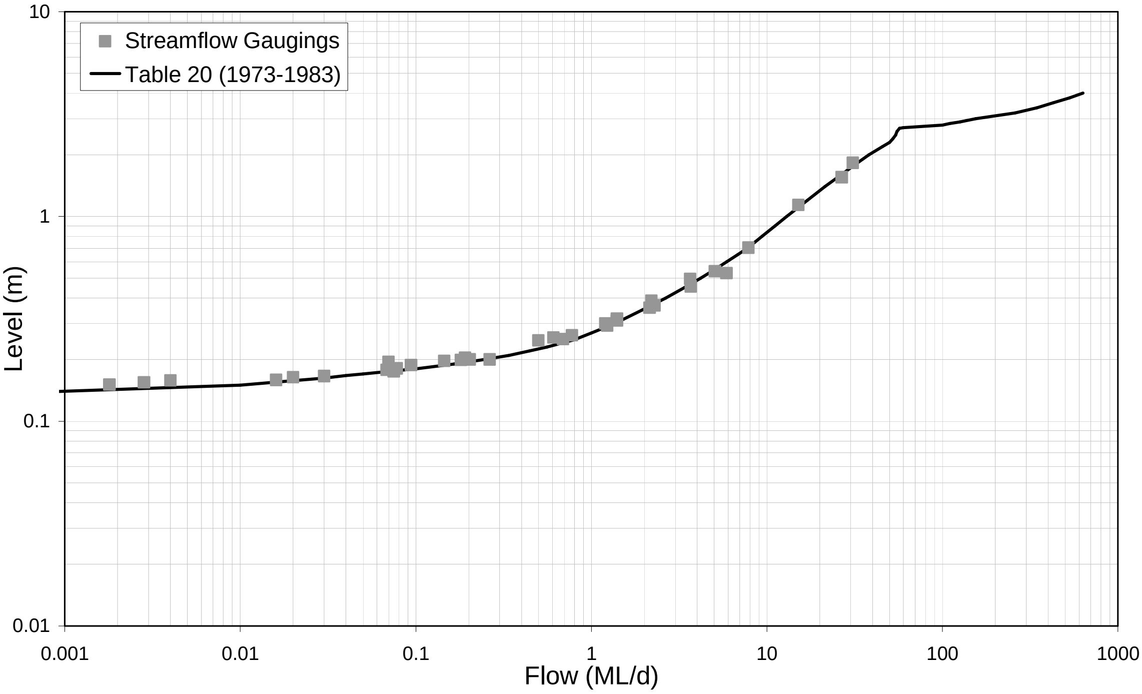

▪ **Figure A-1: All Rating Tables and Streamflow Gaugings for 8180018**



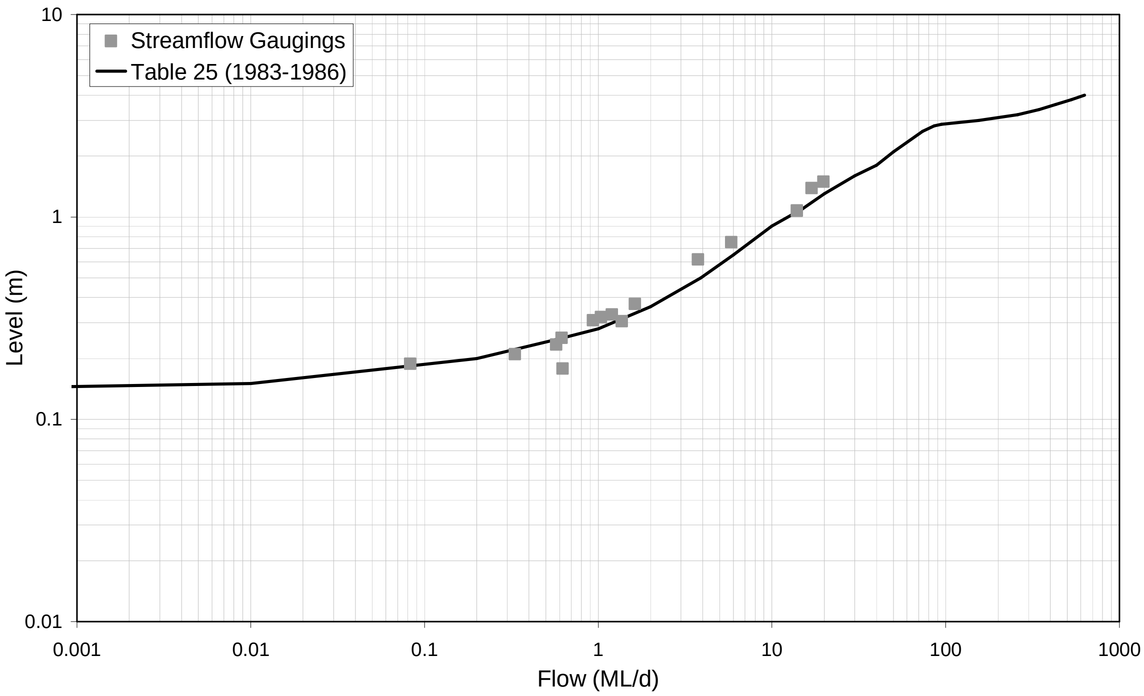

■ **Figure A-2: Rating Table 10 and Streamflow Gaugings for 8150018 (1963-1969)**



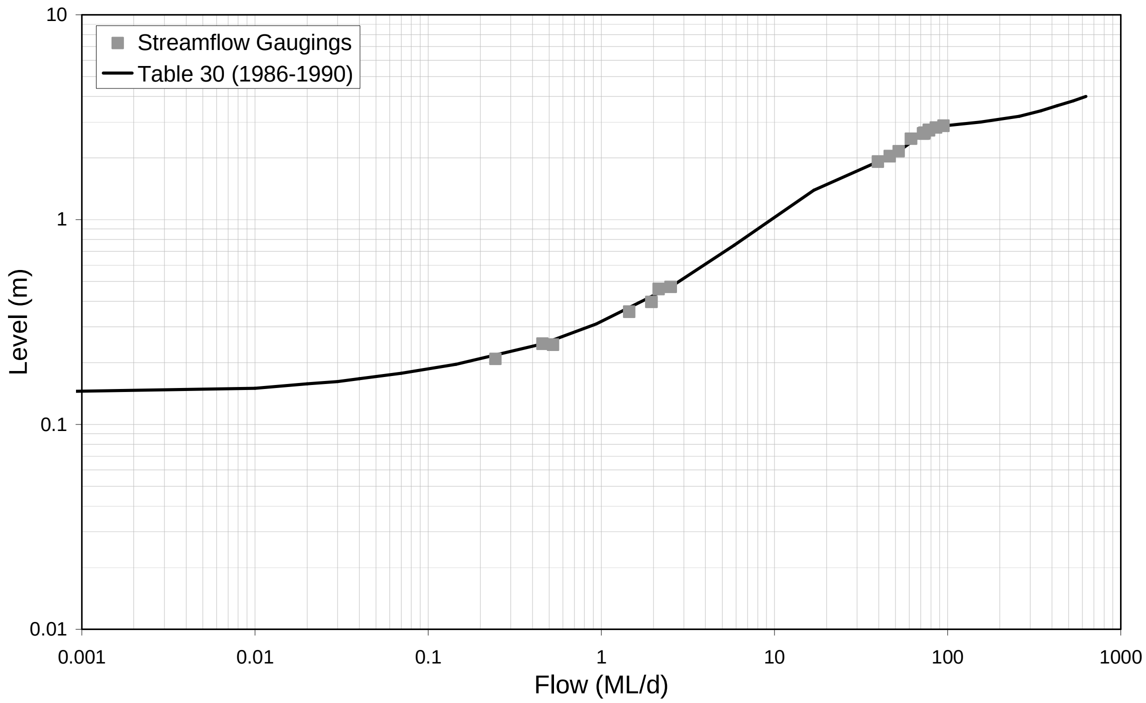

■ **Figure A-3: Rating Table 15 and Streamflow Gaugings for 8150018 (1969-1973)**



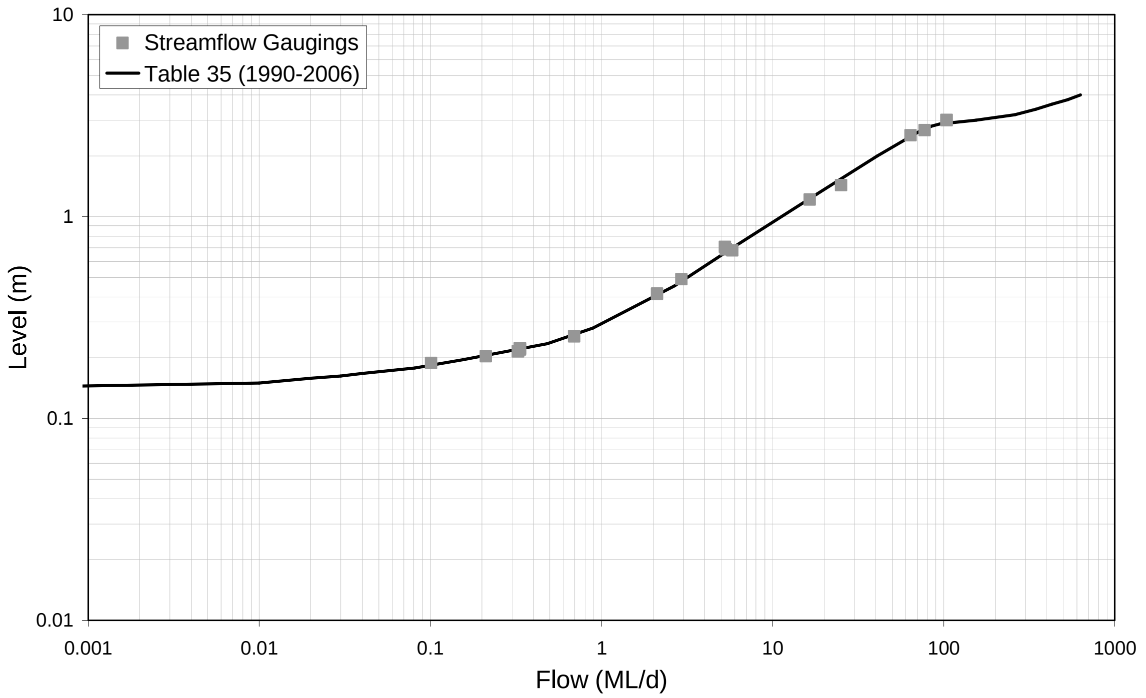

- **Figure A-4: Rating Table 20 and Streamflow Gaugings for 8150018 (1973-1983)**




- **Figure A-5: Rating Table 25 and Streamflow Gaugings for 8150018 (1983-1986)**



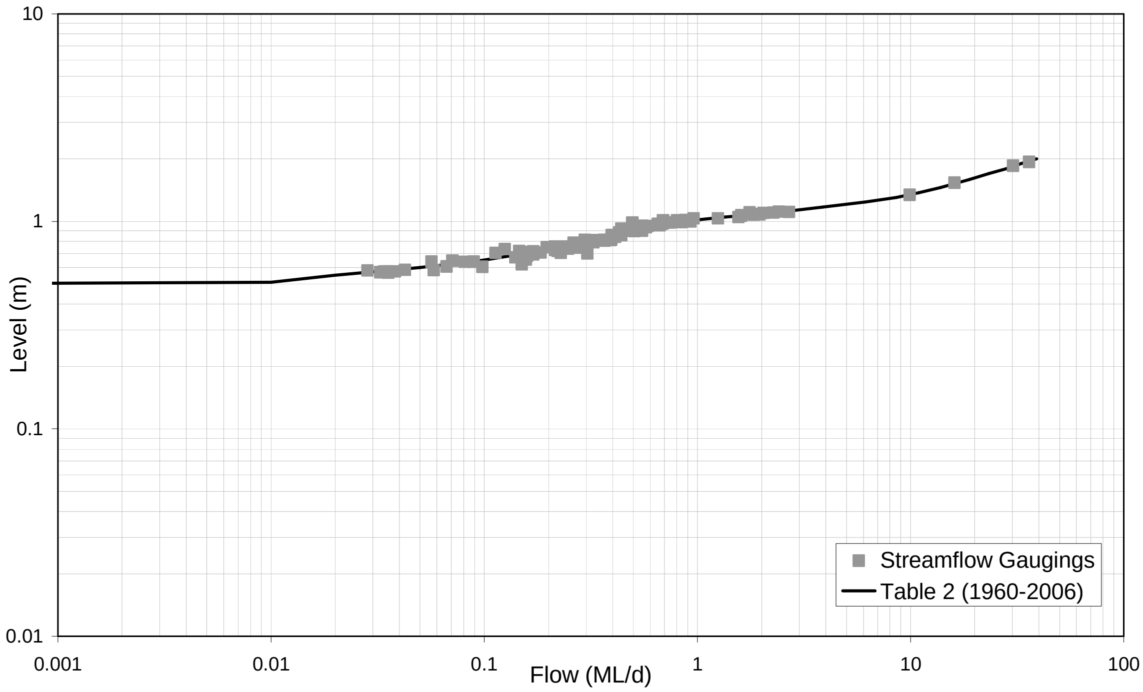

■ **Figure A-6: Rating Table 30 and Streamflow Gaugings for 8150018 (1986-1990)**




■ **Figure A-7: Rating Table 35 and Streamflow Gaugings for 8150018 (1990-2006)**

## A.2 Berry River at March Fly Weir (8150027)

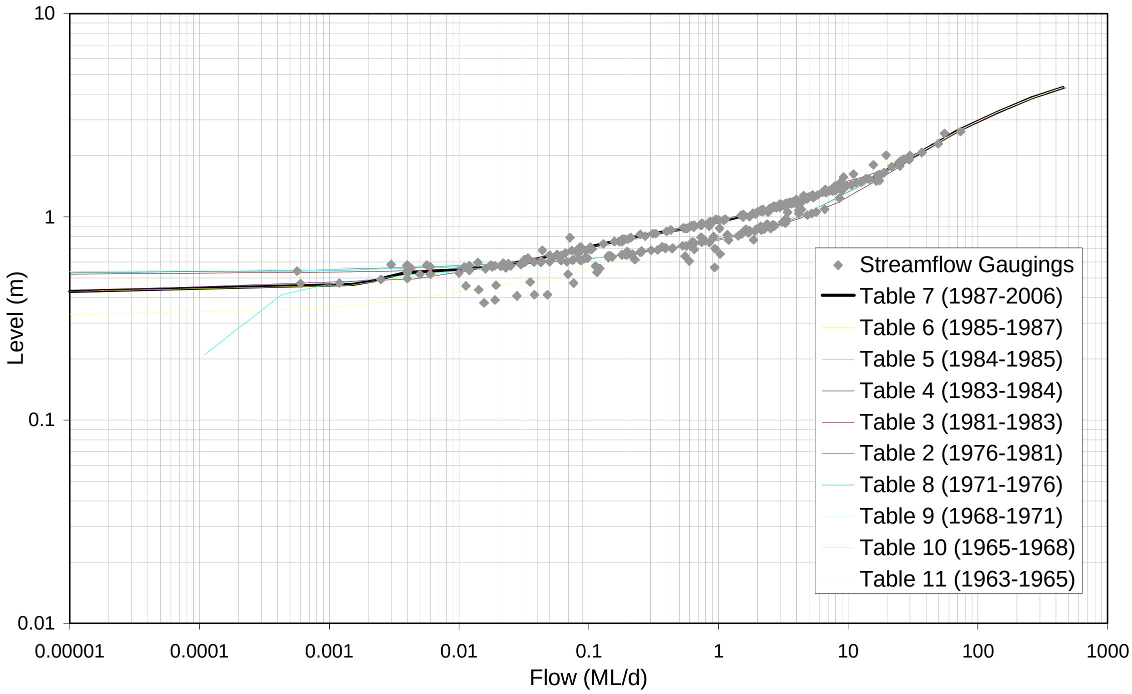
One rating table has been used for the gauge at 8150027 over its period of record, as shown in Figure A-8. This rating table has had two releases, but the releases are very similar and it is unclear whether the original release has in fact ever been used. It can be seen that the rating table is supported by a large number of streamflow gaugings, and is stable with little scatter. No adjustments were made to this rating.



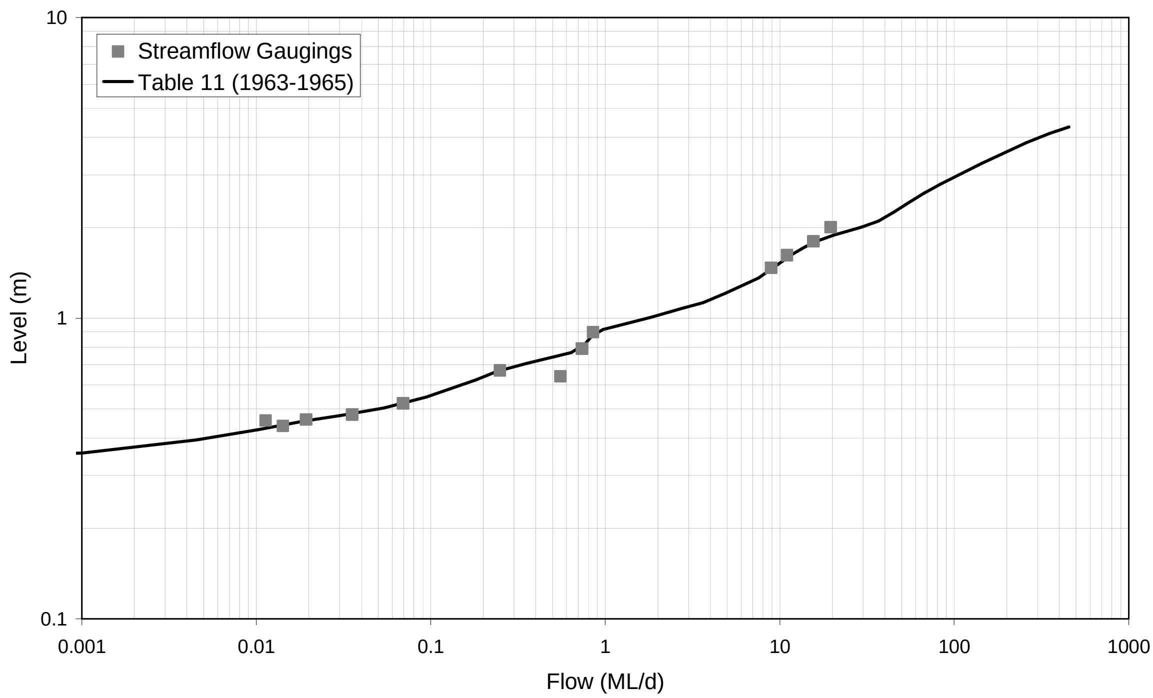

- **Figure A-8: All Rating Tables and Streamflow Gaugings for 8150027**

## A.3 East Finniss River at Rum Jungle (8150097)

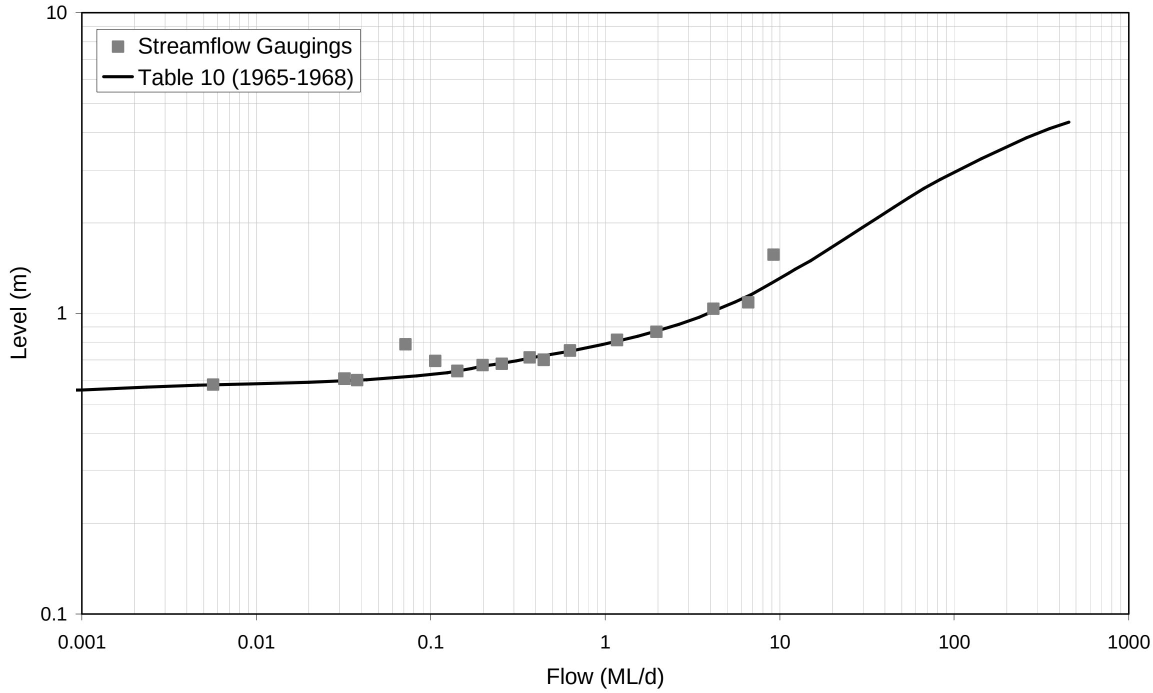
The gauge at 8150097 has had 10 rating table changes over the period of interest, as shown in Figure A-9. In general, all of these rating tables are fairly similar, except for Table 5, used in 1984-1985, which is considerably different between approximately 0 and 0.005 ML/d. All of the rating tables (except for Table 5 below 0.005 ML/d) are based on consistent streamflow gaugings with relatively little scatter. The individual rating tables with their associated streamflow gauging points are shown below.



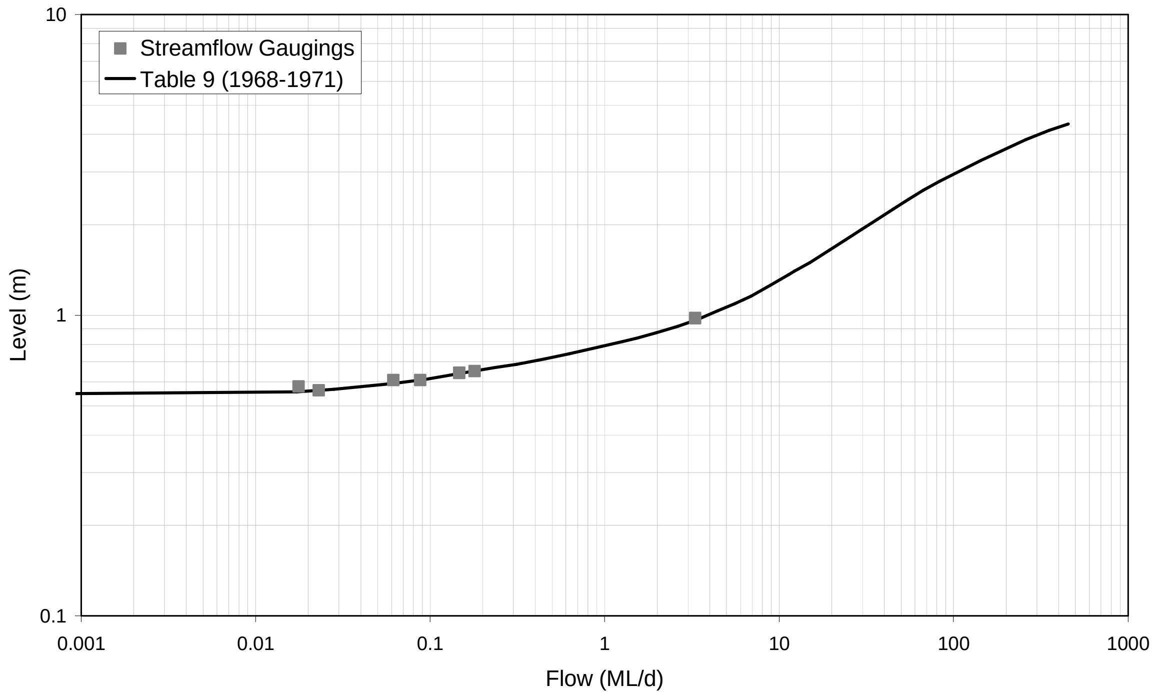

- **Figure A-9: All Rating Tables and Streamflow Gaugings for 8150097**



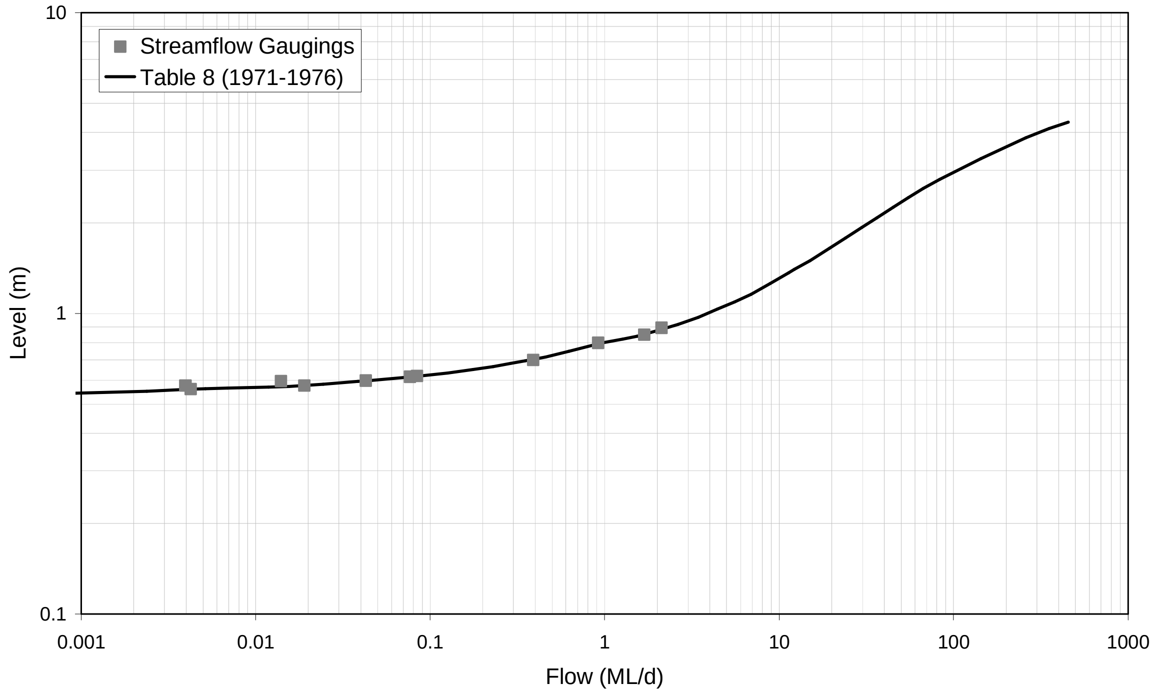

- **Figure A-10: Rating Table 11 and Streamflow Gaugings for 8150097 (1963-1965)**



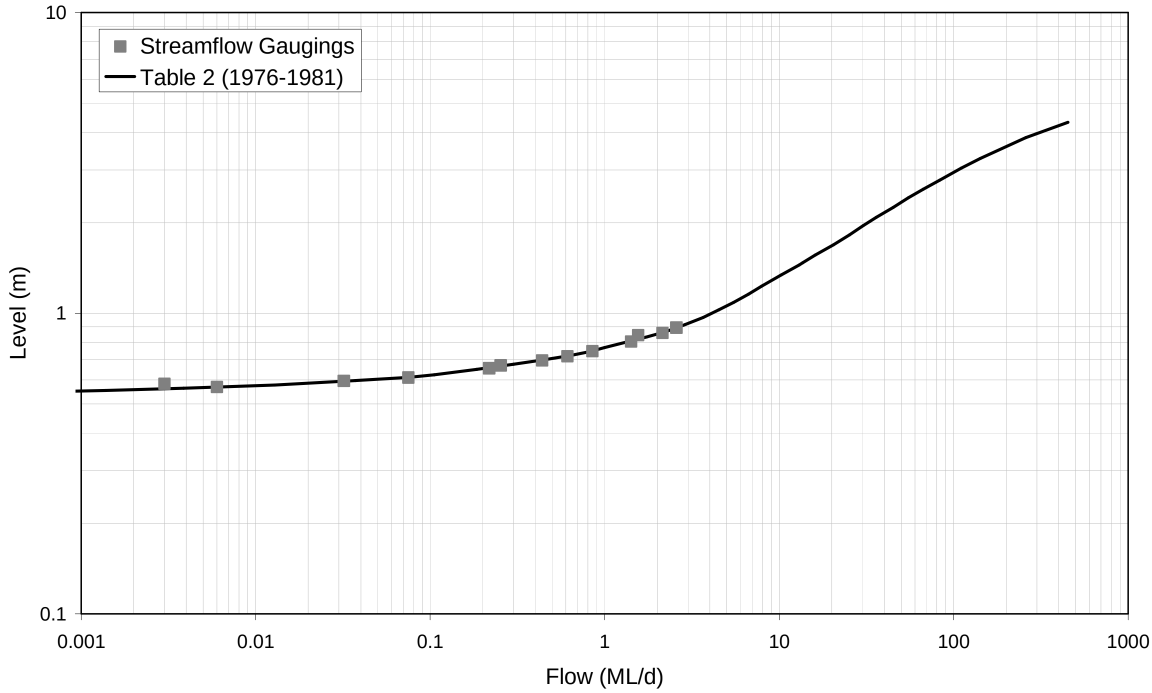

▪ **Figure A-11: Rating Table 10 and Streamflow Gaugings for 8150097 (1965-1968)**



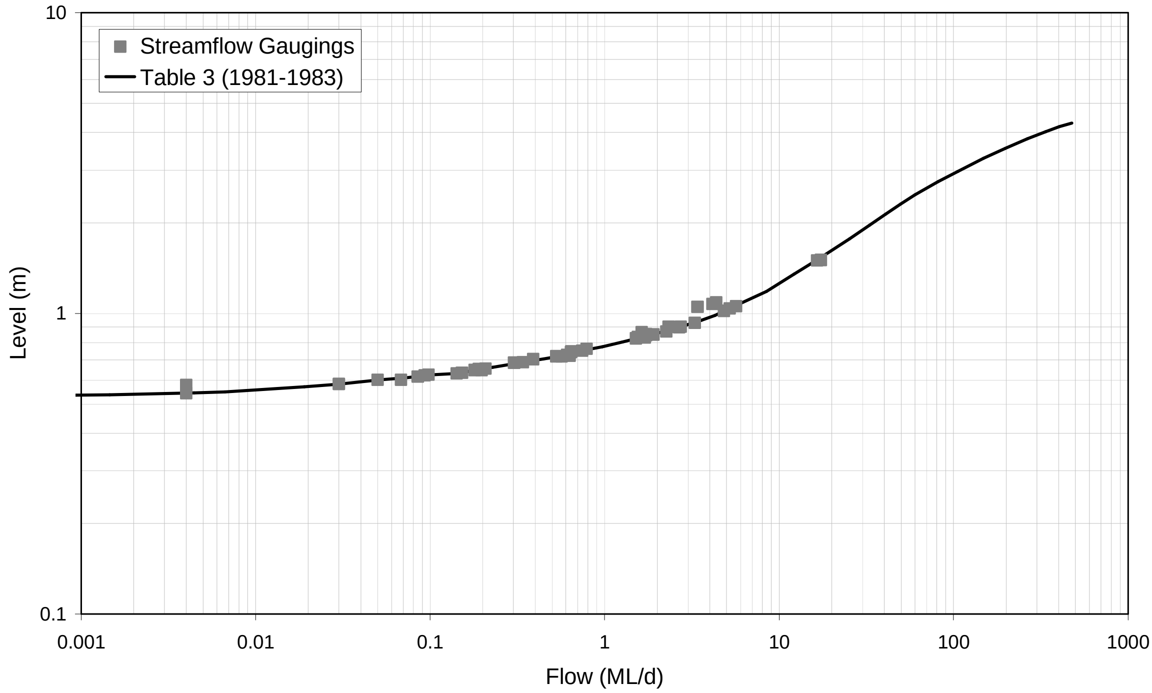

▪ **Figure A-12: Rating Table 9 and Streamflow Gaugings for 8150097 (1968-1971)**



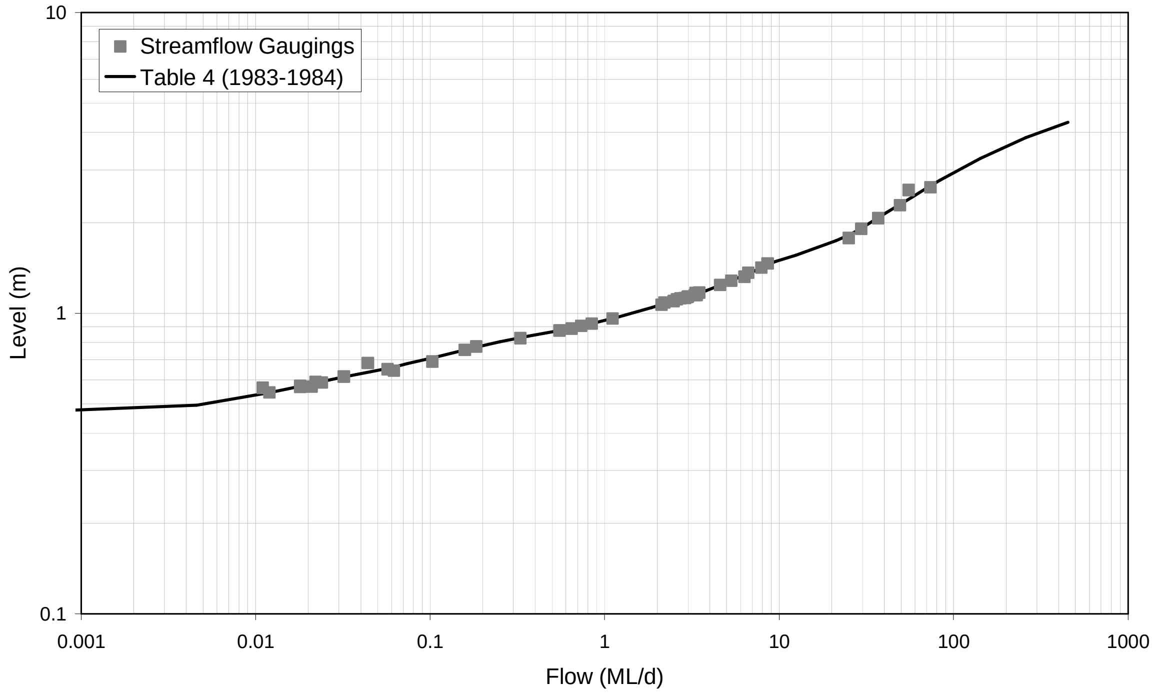

- **Figure A-13: Rating Table 8 and Streamflow Gaugings for 8150097 (1971-1976)**



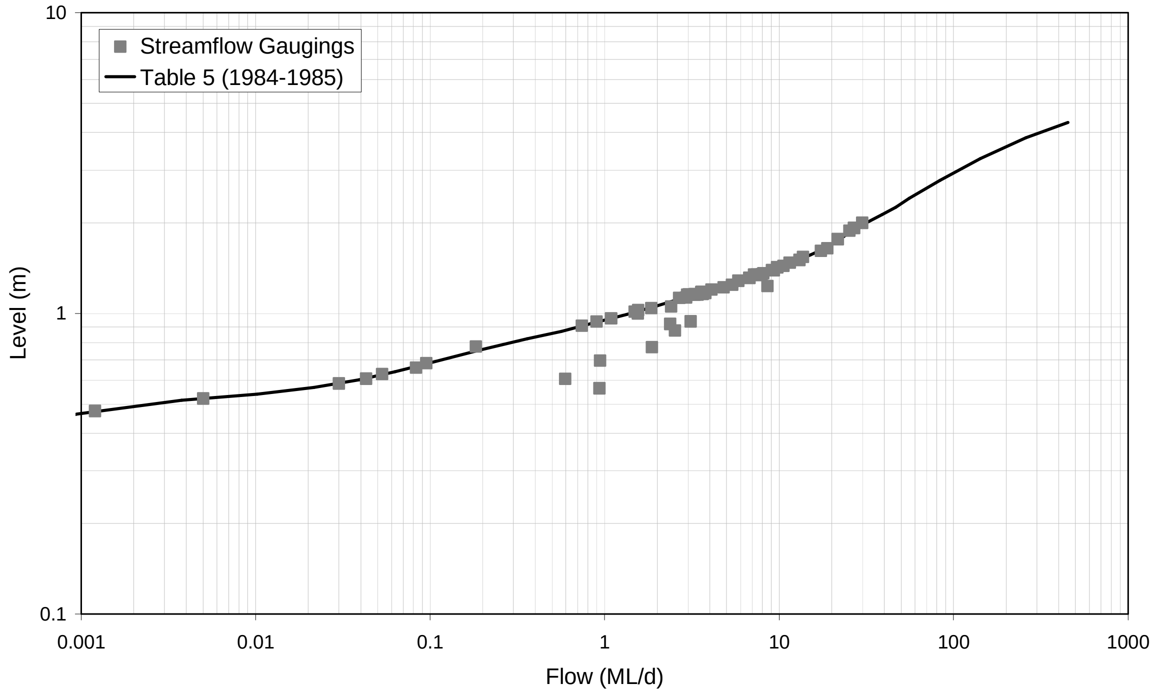

- **Figure A-14: Rating Table 2 and Streamflow Gaugings for 8150097 (1976-1981)**



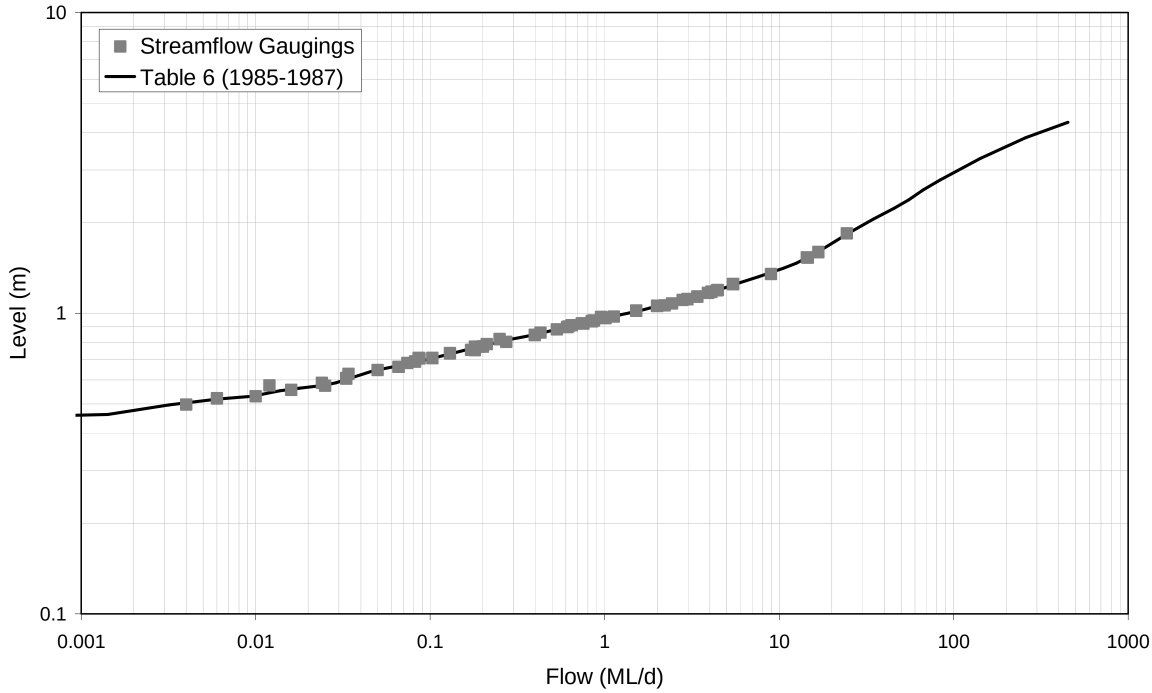

■ **Figure A-15: Rating Table 3 and Streamflow Gaugings for 8150097 (1981-1983)**



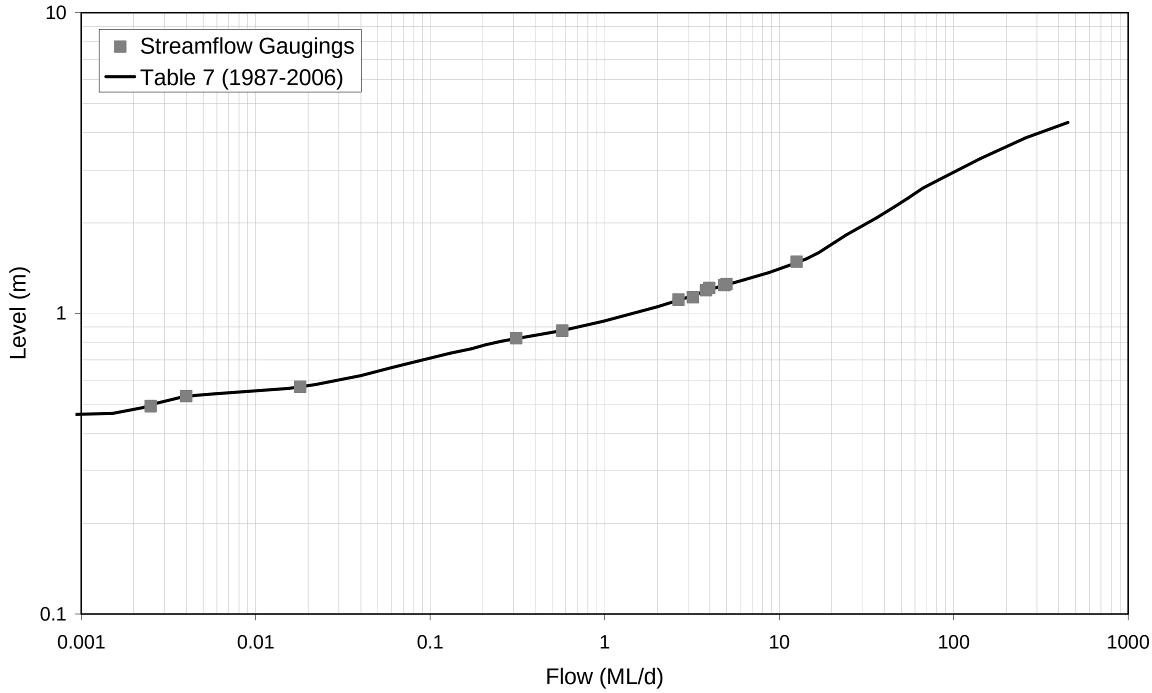

■ **Figure A-16: Rating Table 4 and Streamflow Gaugings for 8150097 (1983-1984)**




- **Figure A-17: Rating Table 5 and Streamflow Gaugings for 8150097 (1984-1985)**



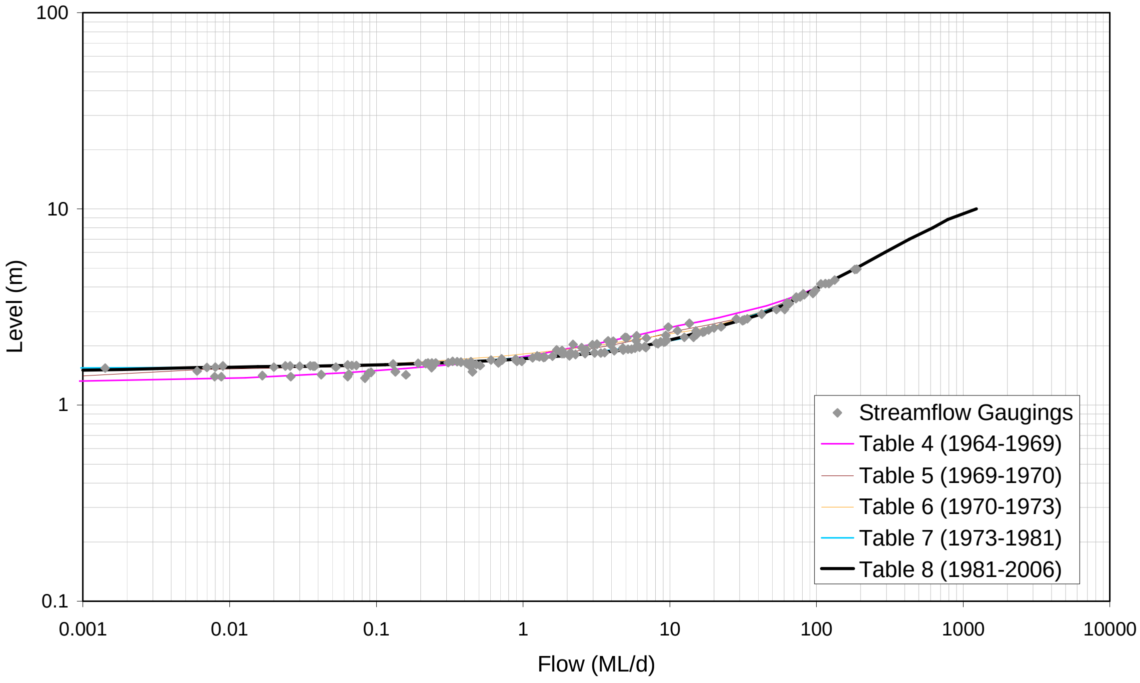

- **Figure A-18: Rating Table 6 and Streamflow Gaugings for 8150097 (1985-1987)**



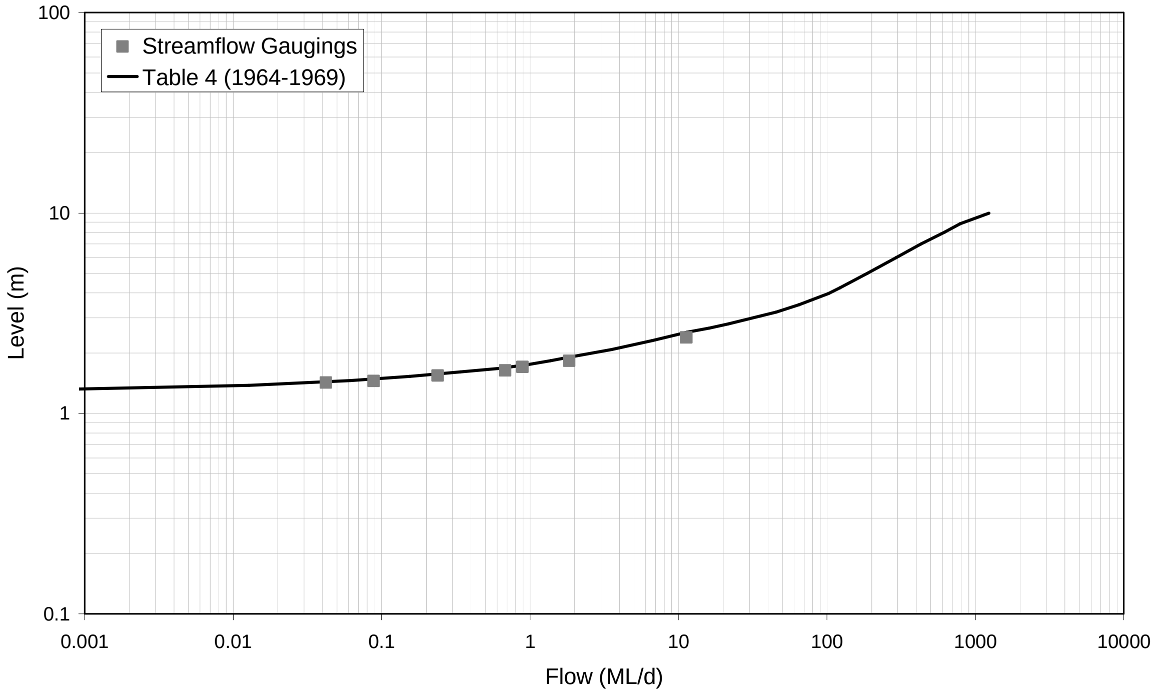

- **Figure A-19: Rating Table 7 and Streamflow Gaugings for 8150097 (1987-2006)**

## A.4 Blackmore River at Tumbling Waters (8150098)

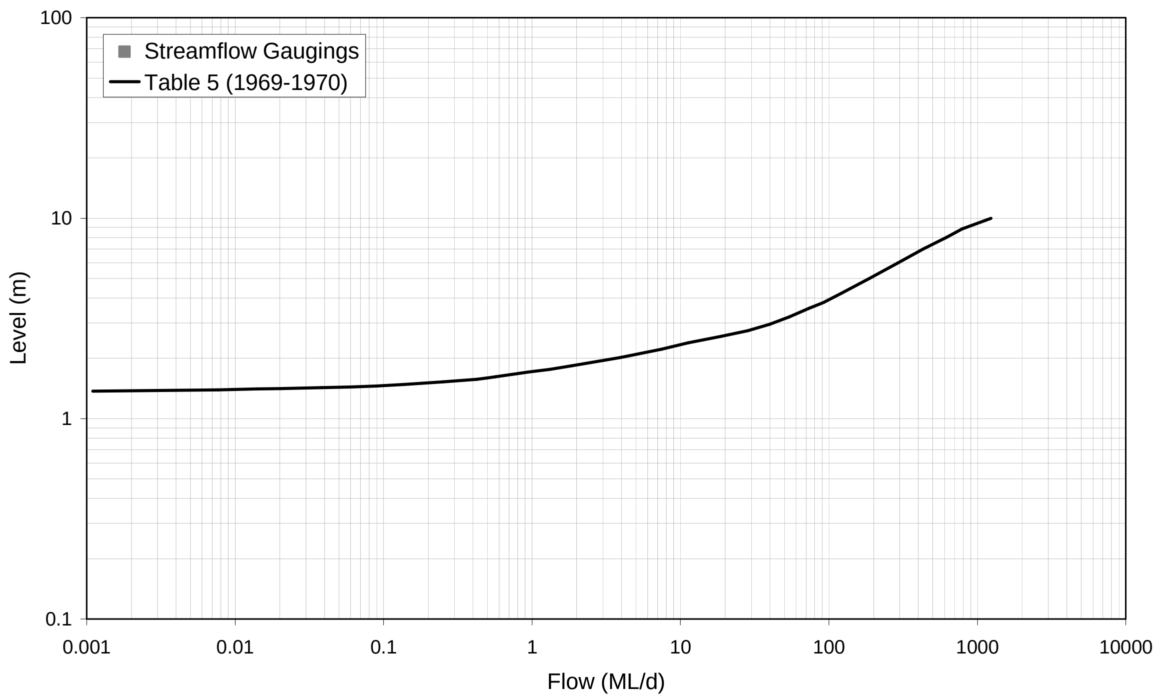
The gauge at 8150098 has had five changes in rating tables over the period of interest, as shown in Figure A-20. It can be seen that there has been little variation in the rating tables, and that they are all based on consistent streamflow gaugings. The individual rating tables with their associated streamflow gauging points are below



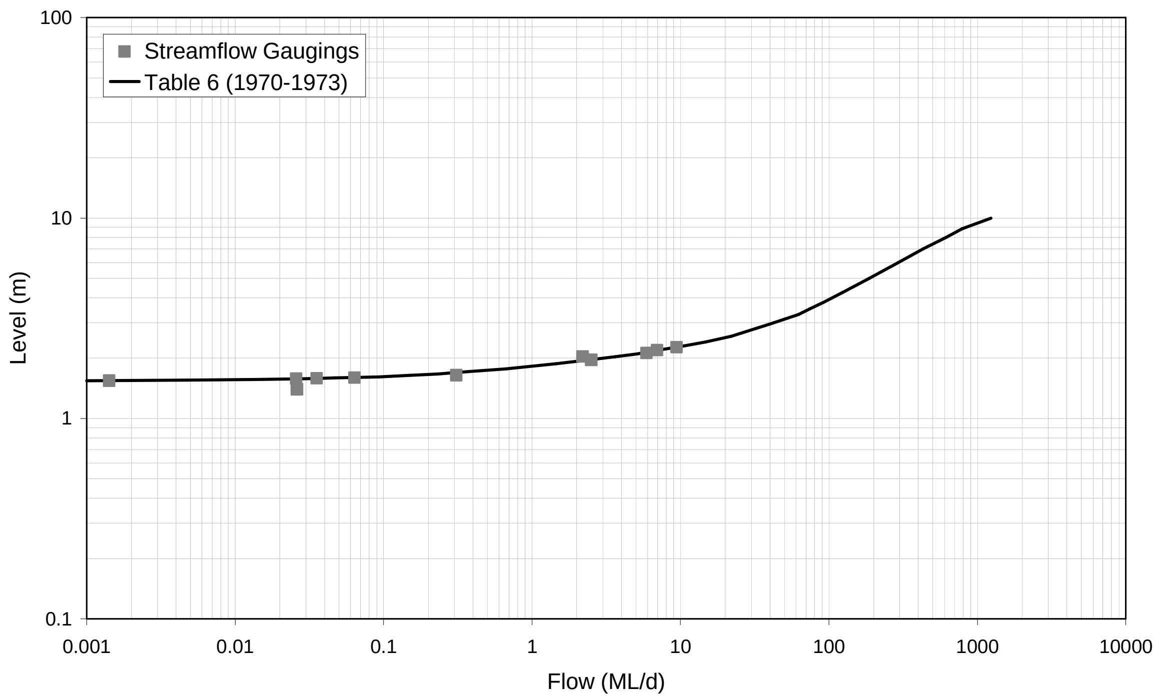

- **Figure A-20: All Rating Tables and Streamflow Gaugings for 8150098**



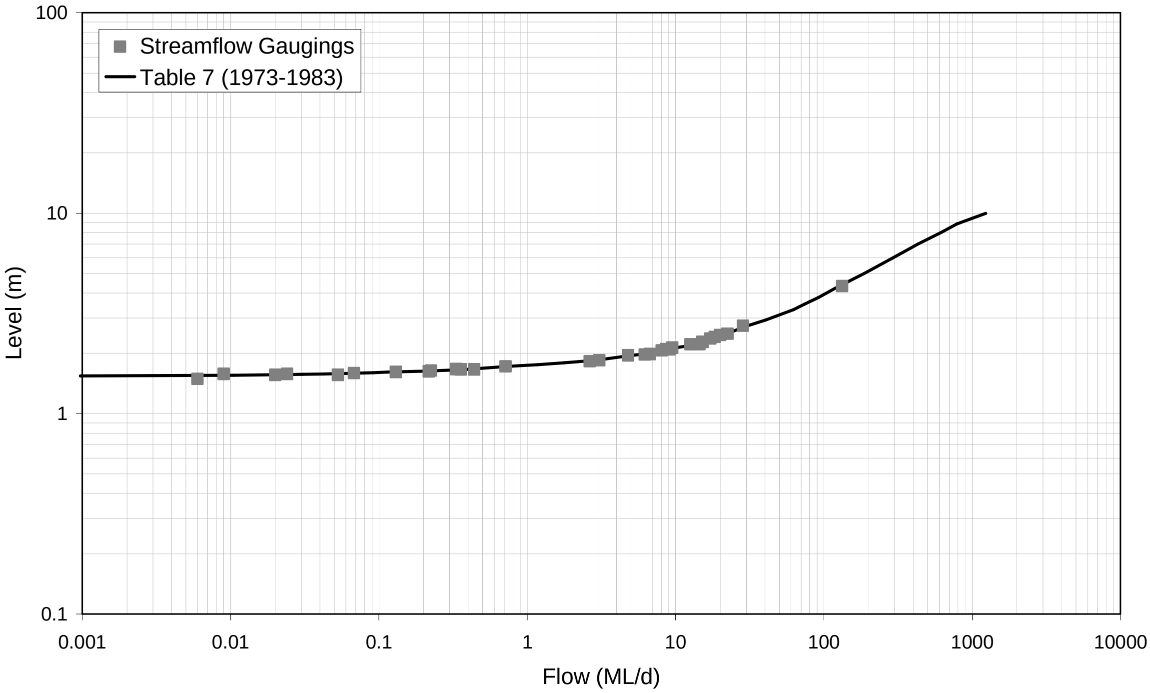

- **Figure A-21: Rating Table 4 and Streamflow Gaugings for 8150098 (1964-1969)**



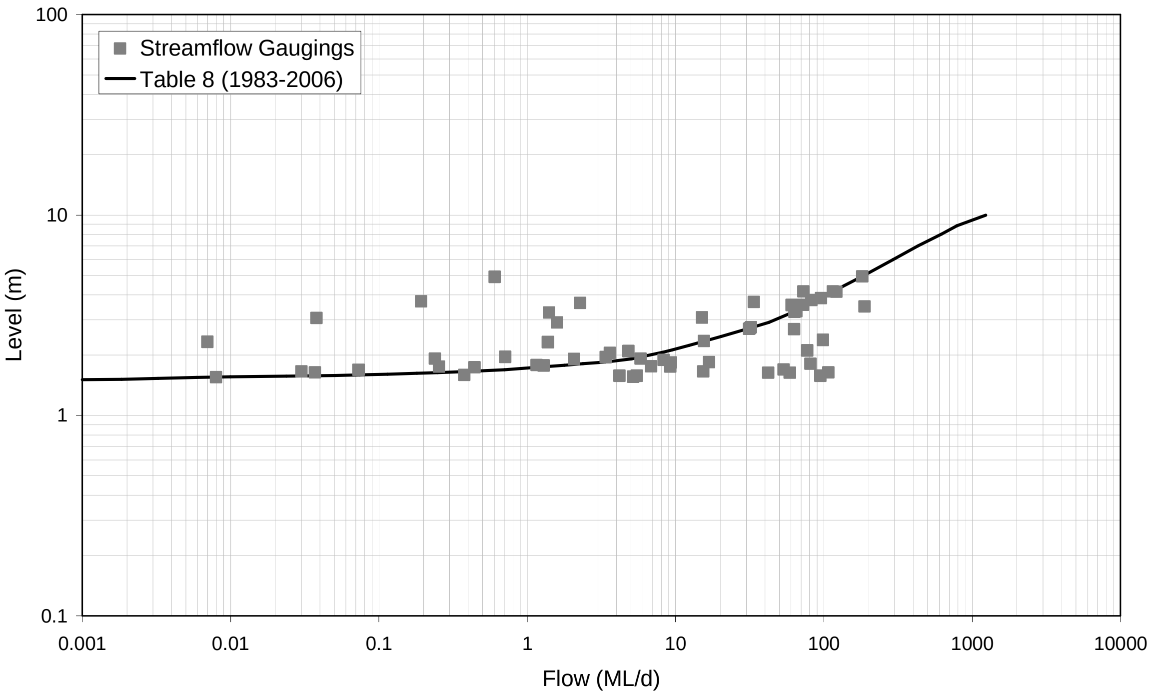

- **Figure A-22: Rating Table 5 and Streamflow Gaugings for 8150098 (1969-1970)**




- **Figure A-23: Rating Table 6 and Streamflow Gaugings for 8150098 (1970-1973)**



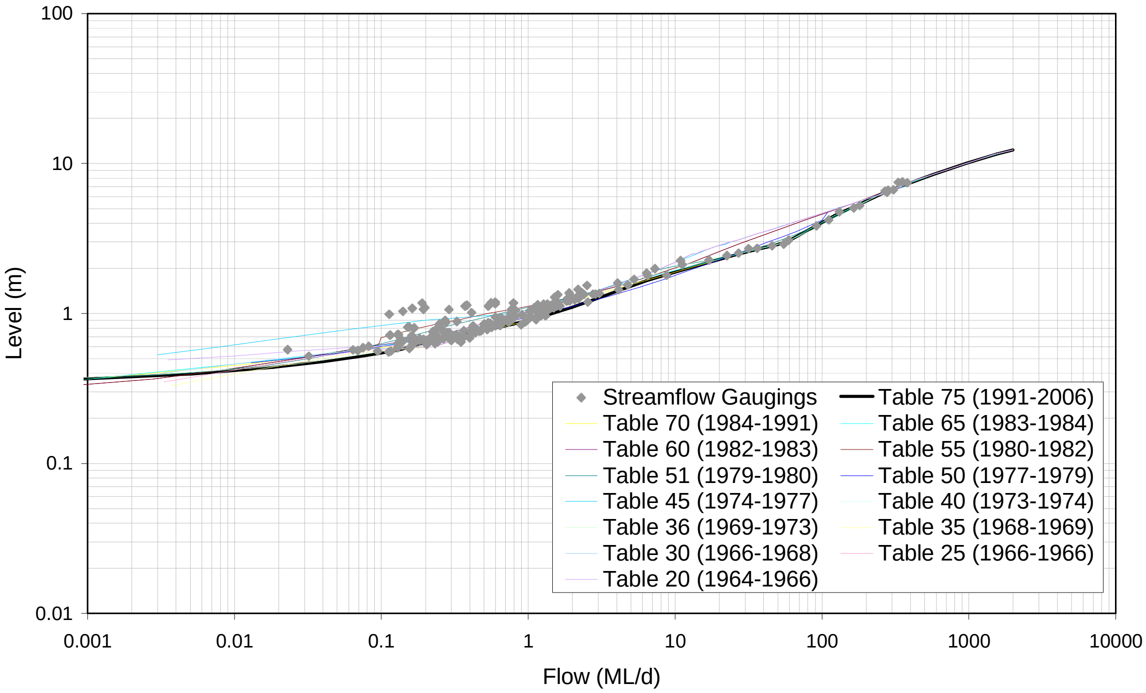

■ **Figure A-24: Rating Table 7 and Streamflow Gaugings for 8150098 (1973-1981)**



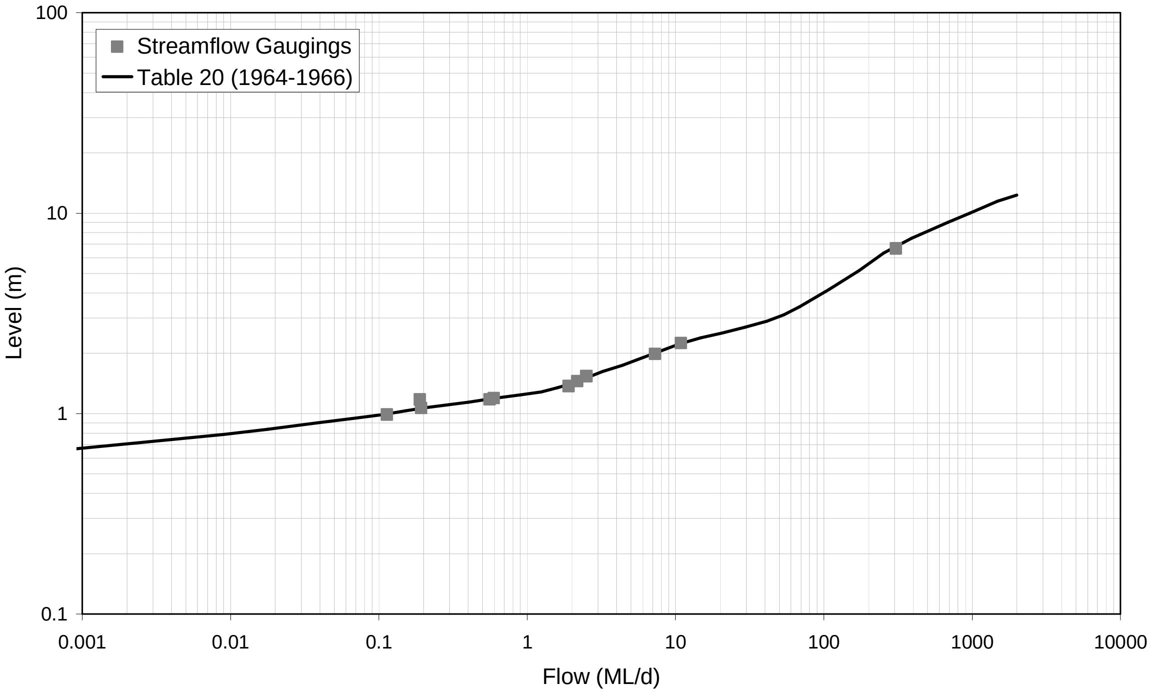

■ **Figure A-25: Rating Table 8 and Streamflow Gaugings for 8150098 (1981-2006)**

### A.5 Finniss River at Gitchams (8150180)

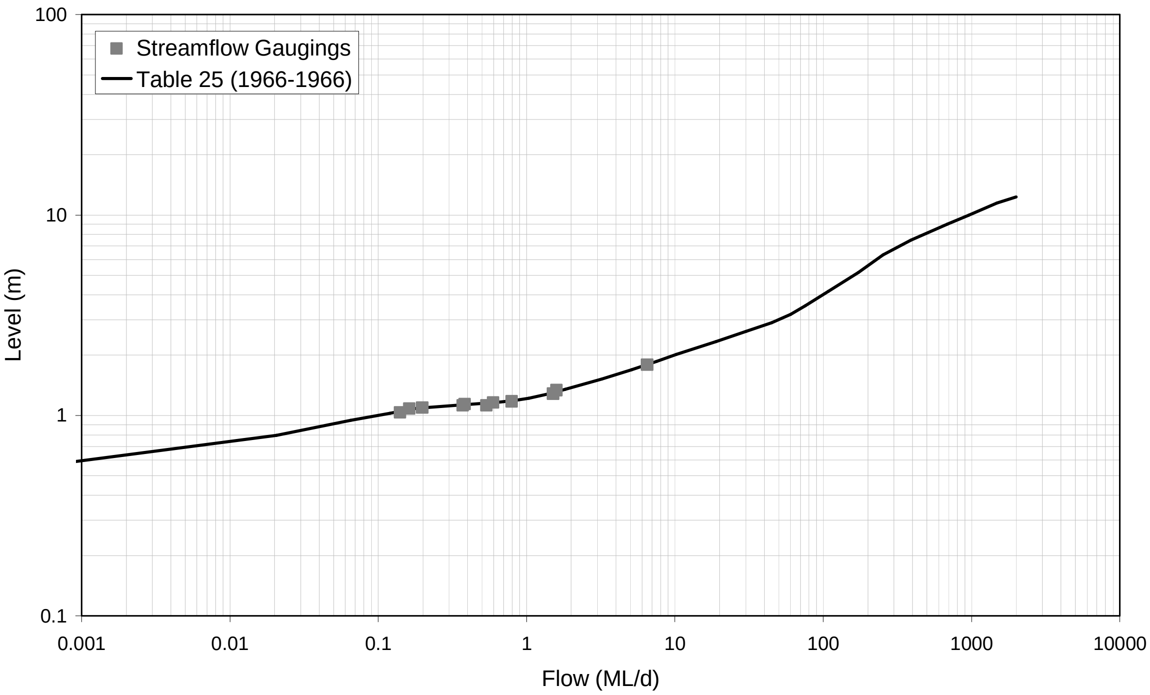
The gauge at 8150098 has had a number of changes in rating tables over the period of interest, as shown in Figure A-26. This indicates that the shape of the channel at this location is relatively unstable and thus the shape of the rating changes for low flows. However, all of the rating tables shown correspond well with the actual streamflow gaugings. The individual rating tables with their associated streamflow gauging points are shown below.



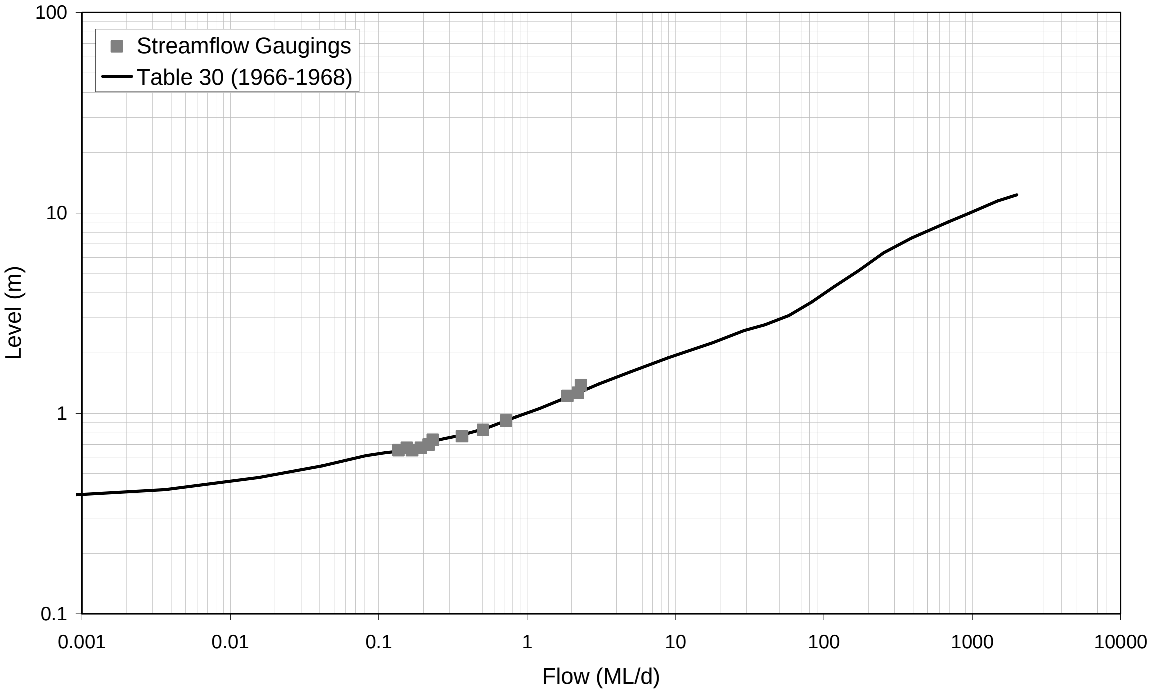

- **Figure A-26: All Rating Tables and Streamflow Gaugings for 8150180**



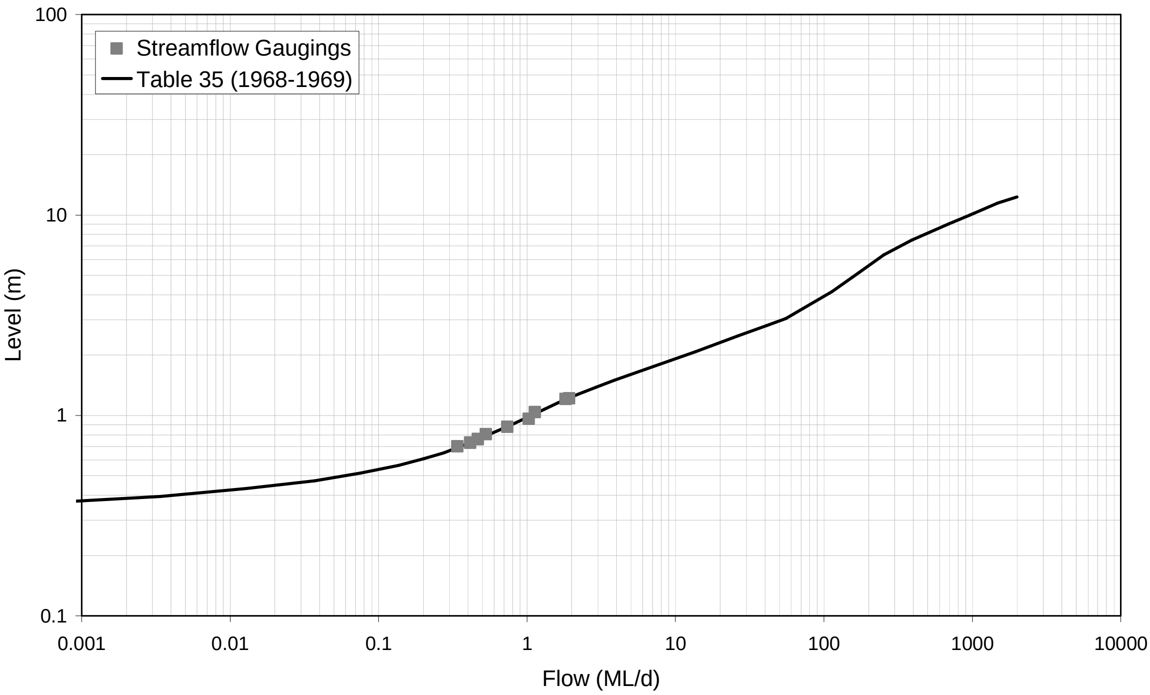

- **Figure A-27: Rating Table 20 and Streamflow Gaugings for 8150180 (1964-1966)**



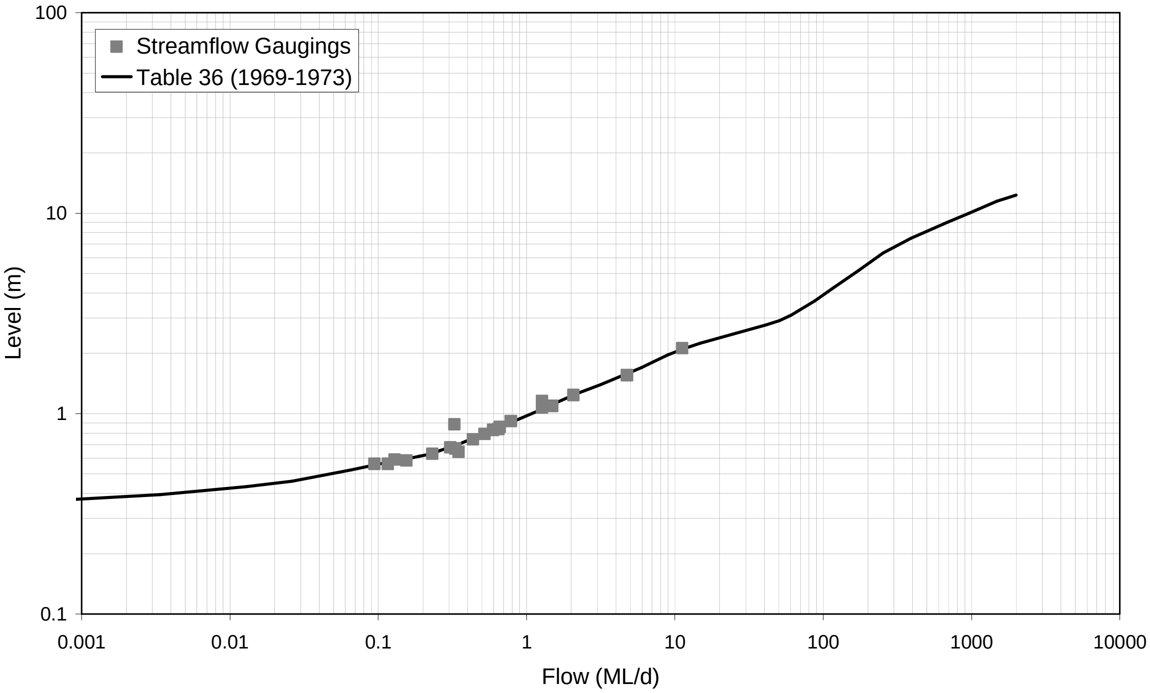

- **Figure A-28: Rating Table 25 and Streamflow Gaugings for 8150180 (1966)**



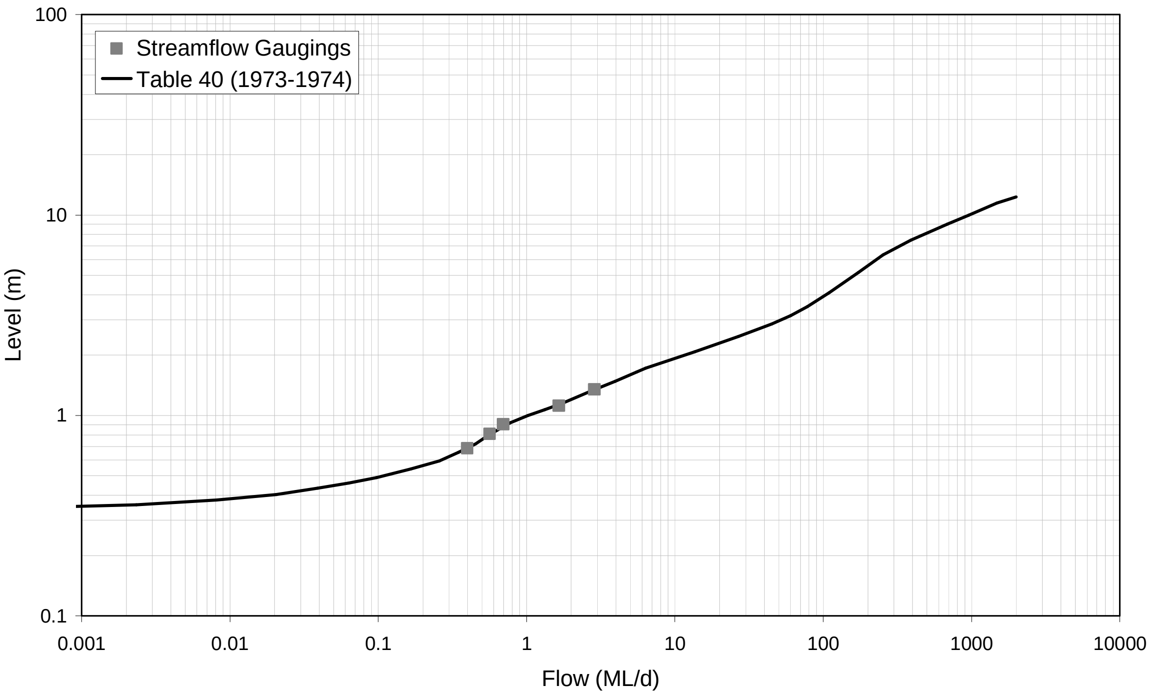

■ **Figure A-29: Rating Table 30 and Streamflow Gaugings for 8150180 (1966-1968)**



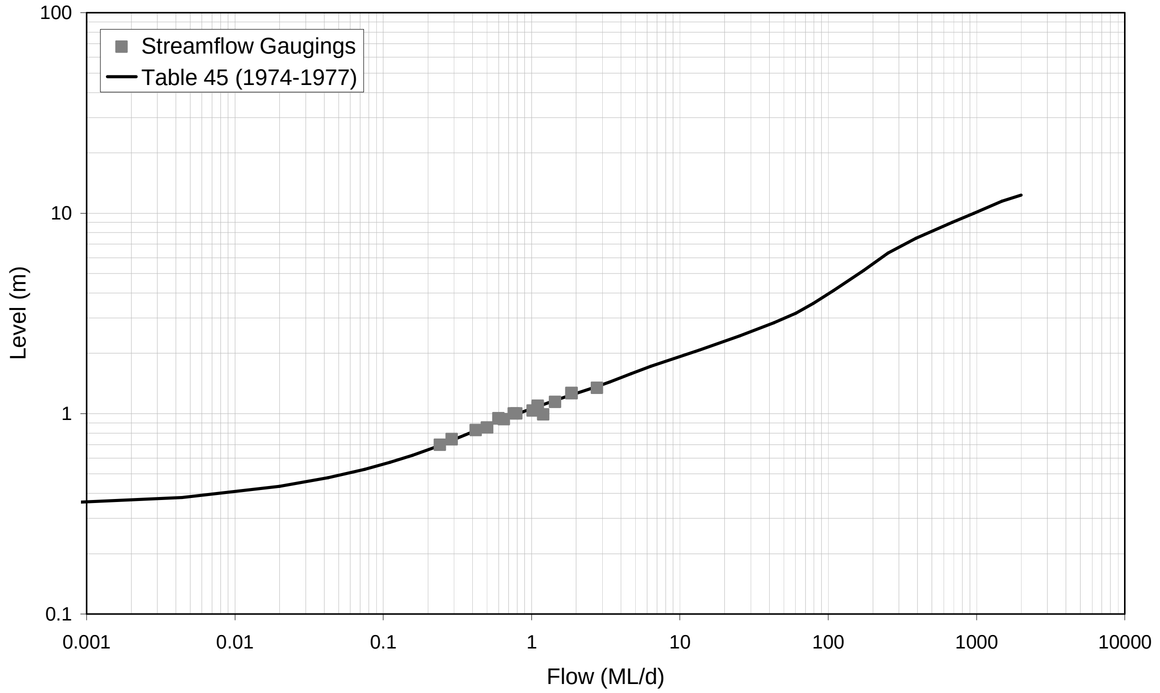

■ **Figure A-30: Rating Table 35 and Streamflow Gaugings for 8150180 (1968-1969)**



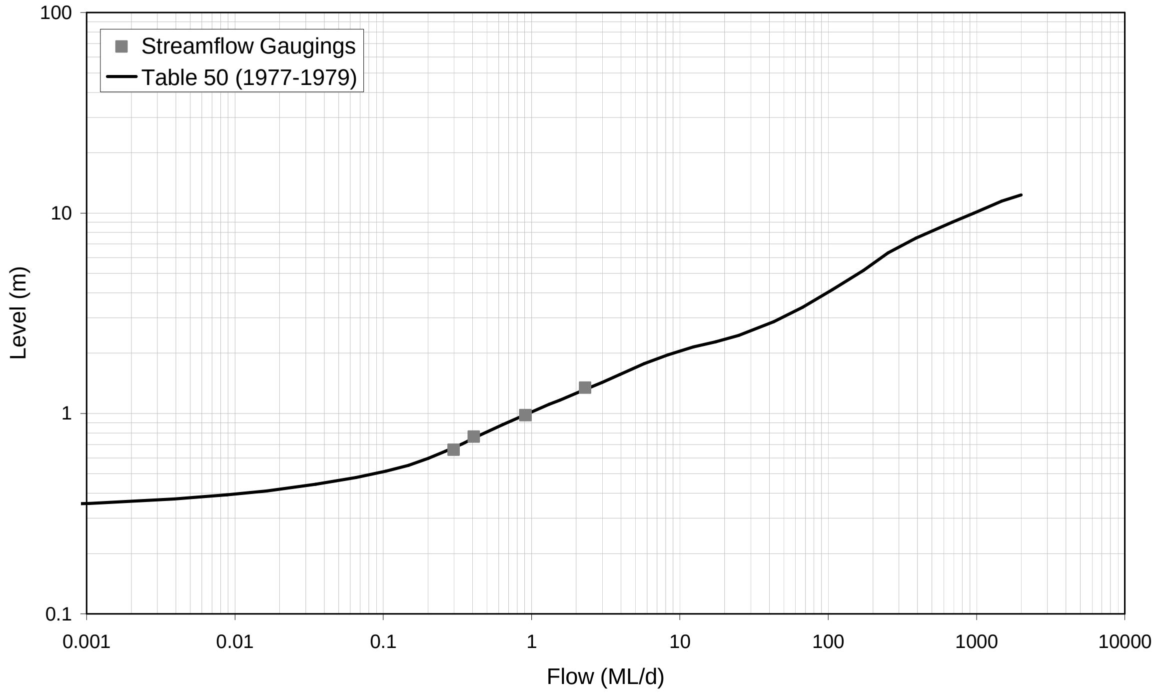

■ **Figure A-31: Rating Table 36 and Streamflow Gaugings for 8150180 (1969-1973)**



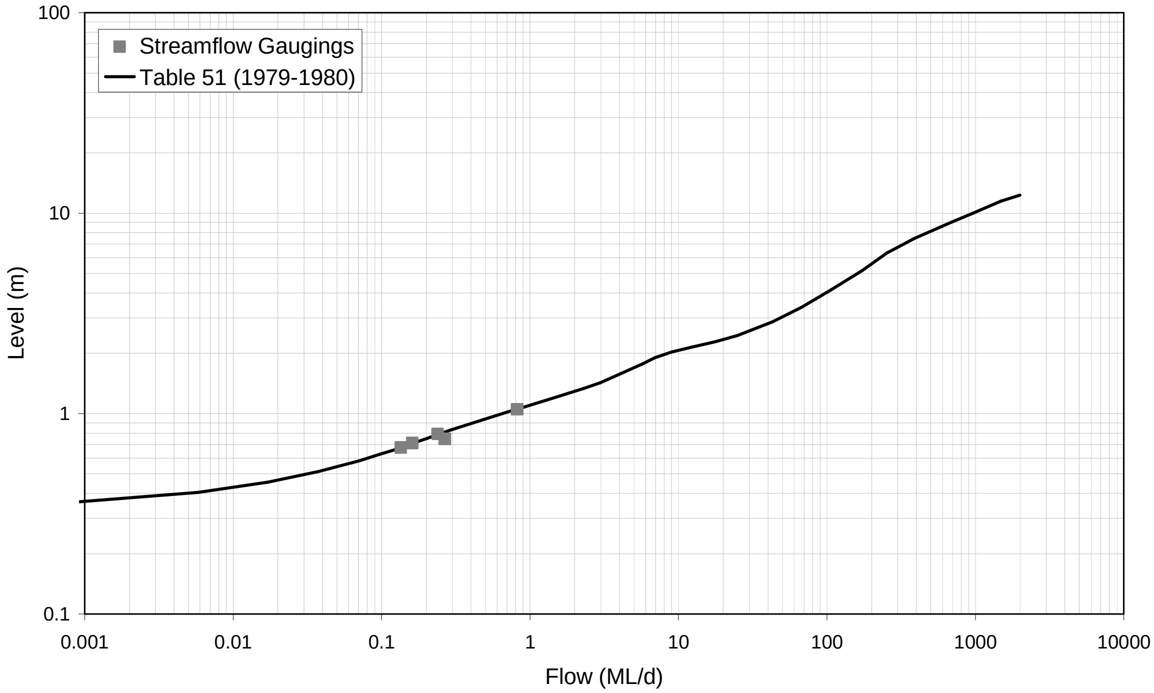

■ **Figure A-32: Rating Table 40 and Streamflow Gaugings for 8150180 (1973-1974)**



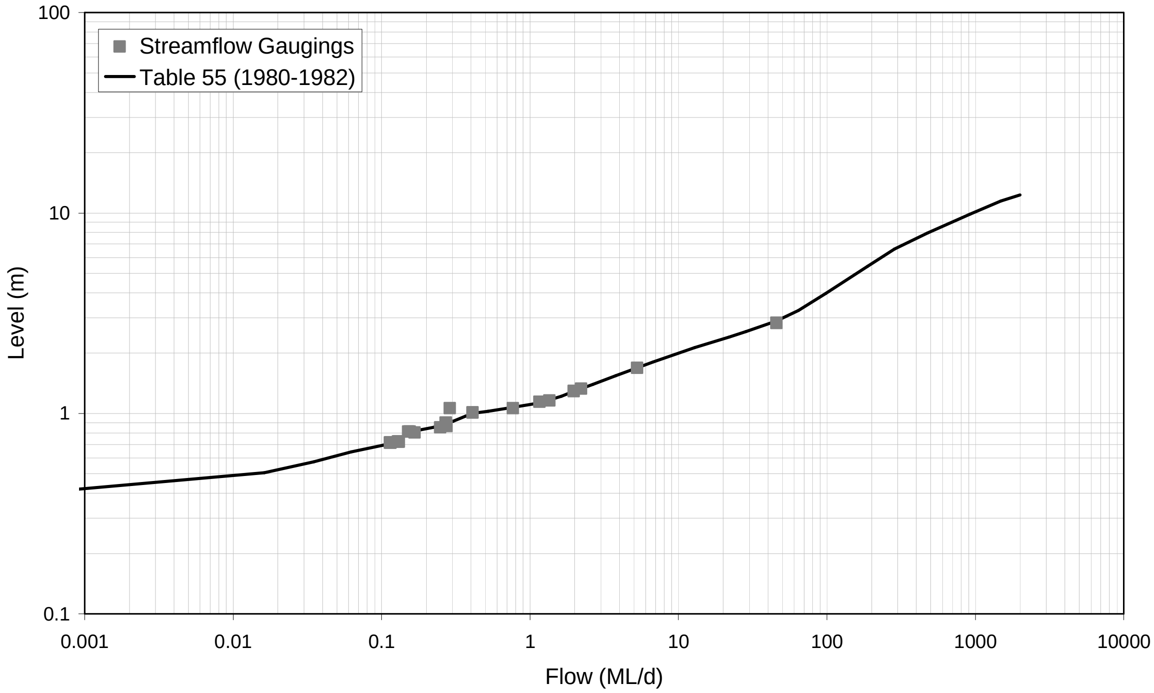

■ **Figure A-33: Rating Table 45 and Streamflow Gaugings for 8150180 (1974-1977)**




■ **Figure A-34: Rating Table 50 and Streamflow Gaugings for 8150180 (1977-1979)**

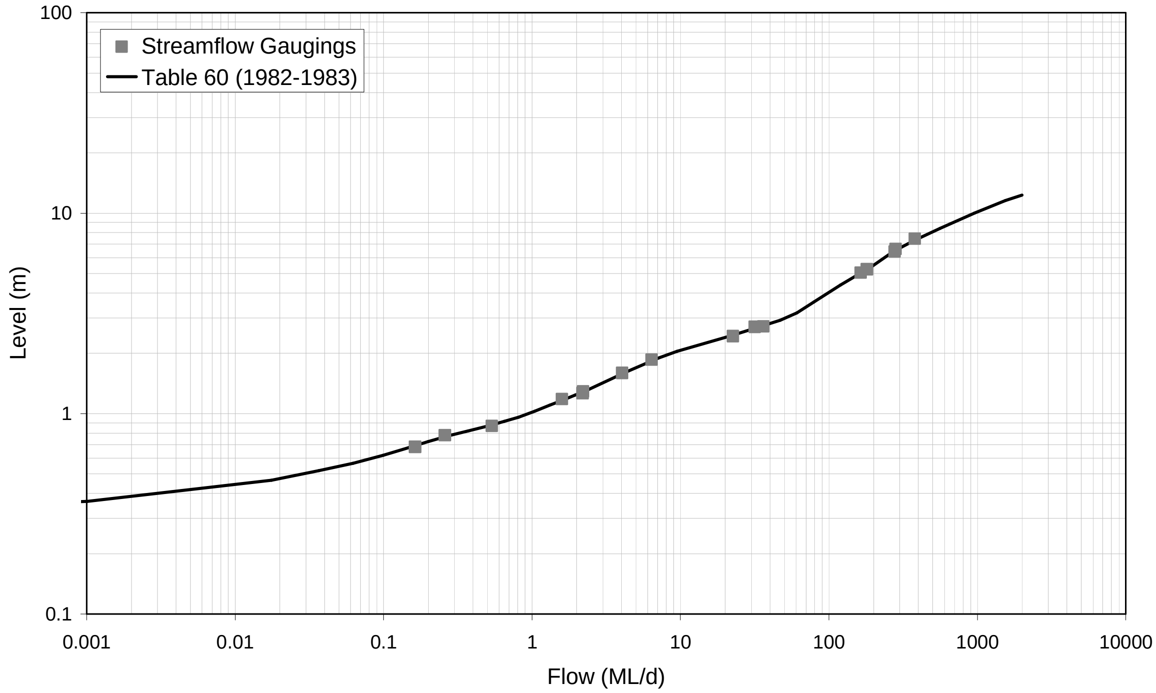



- **Figure A-35: Rating Table 51 and Streamflow Gaugings for 8150180 (1979-1980)**

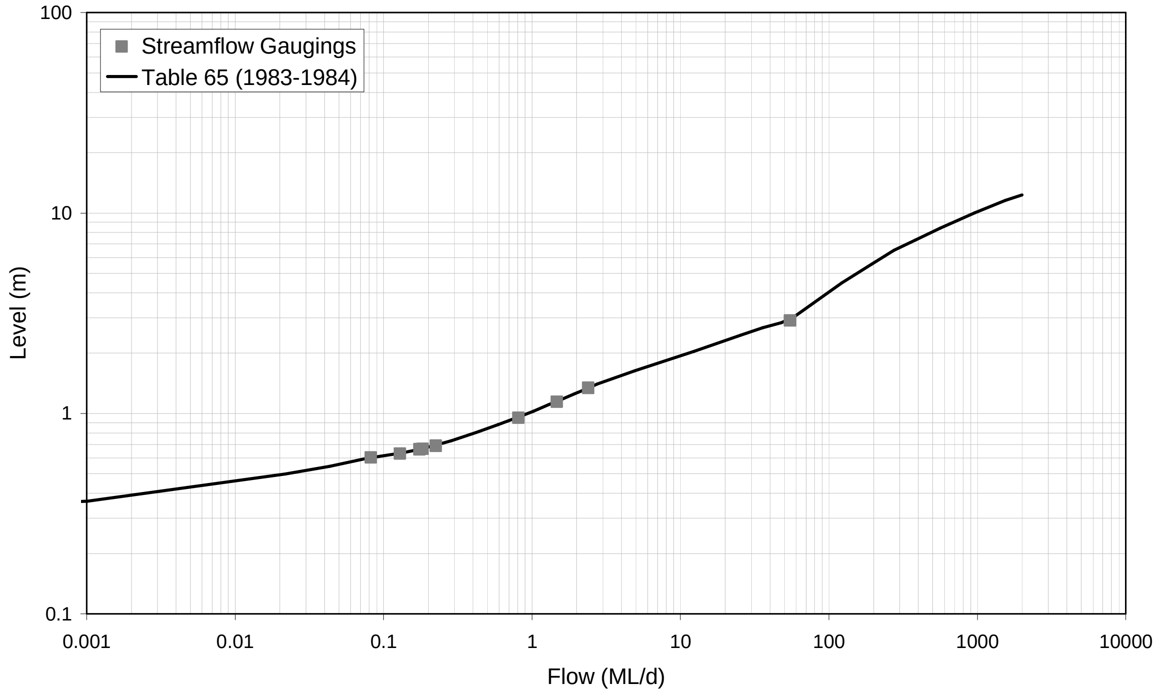



- **Figure A-36: Rating Table 55 and Streamflow Gaugings for 8150180 (1980-1982)**

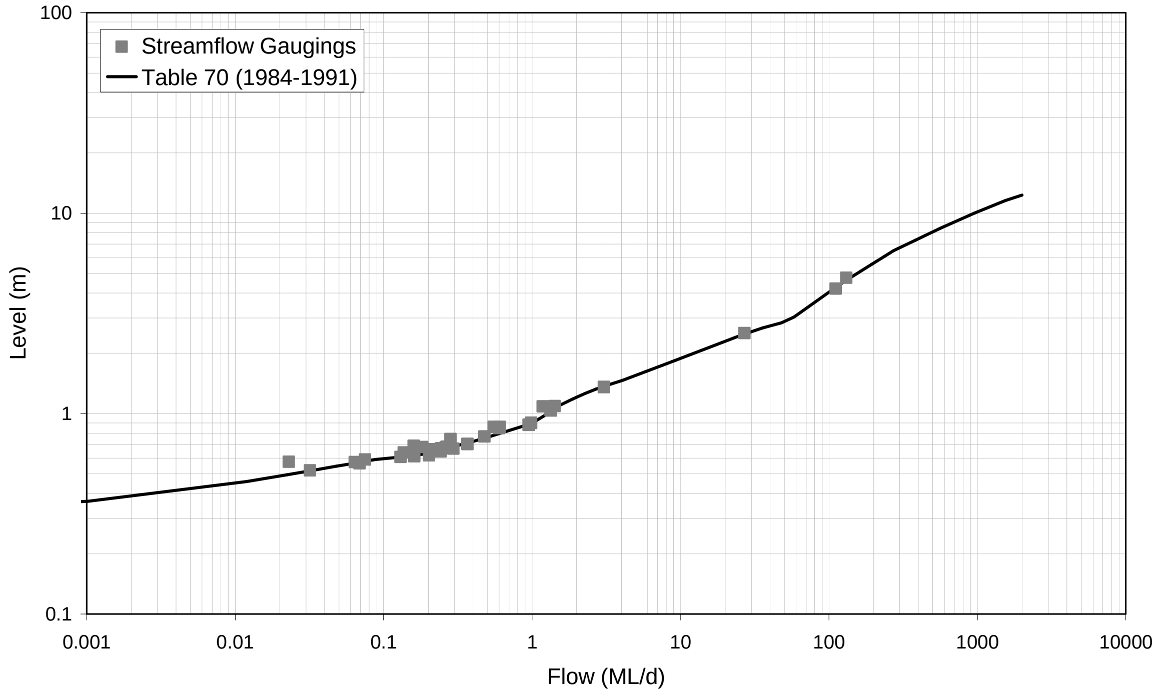
SKM



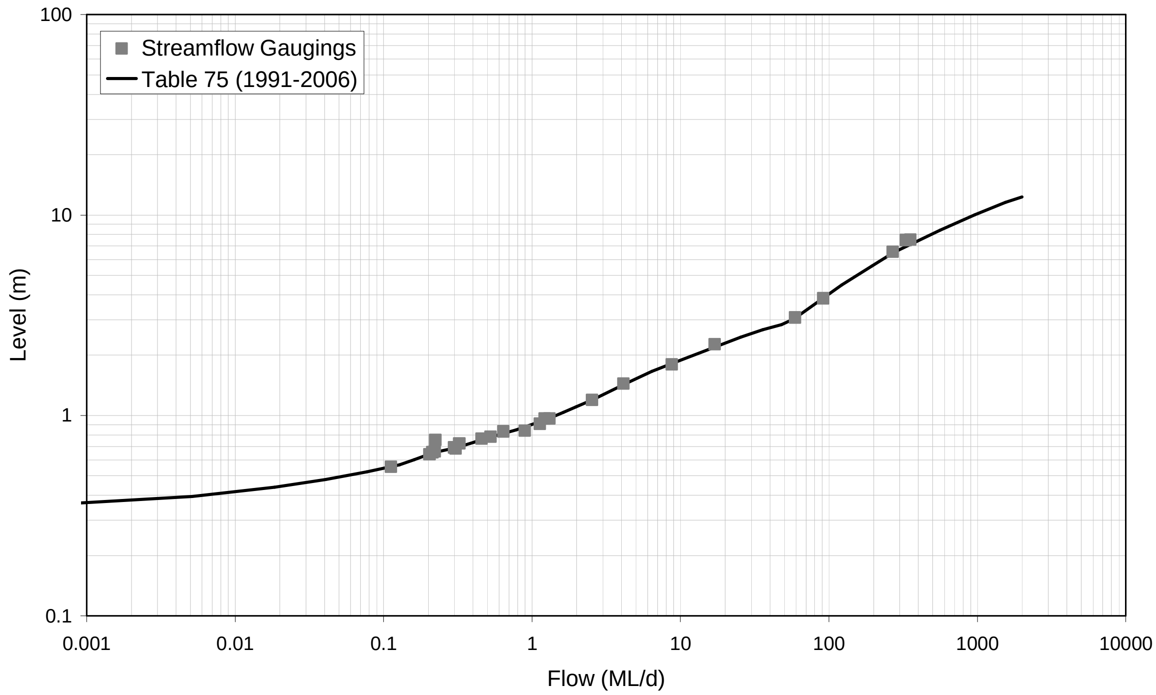

- **Figure A-37: Rating Table 60 and Streamflow Gaugings for 8150180 (1982-1983)**




- **Figure A-38: Rating Table 65 and Streamflow Gaugings for 8150180 (1983-1984)**



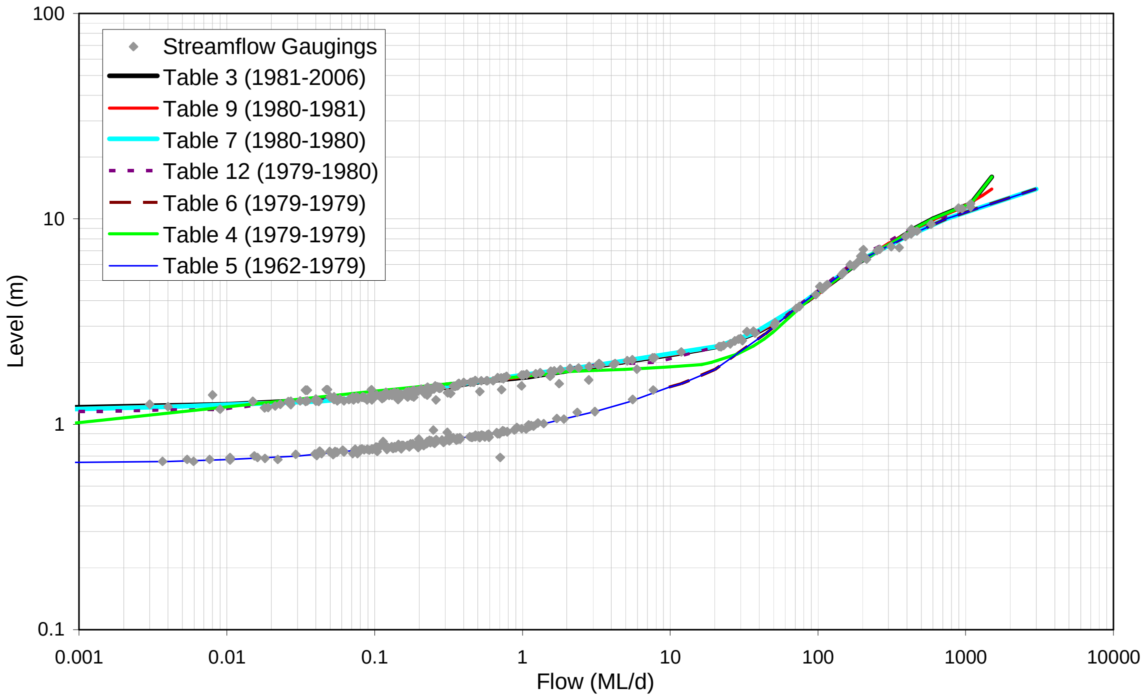

- **Figure A-39: Rating Table 70 and Streamflow Gaugings for 8150180 (1984-1991)**



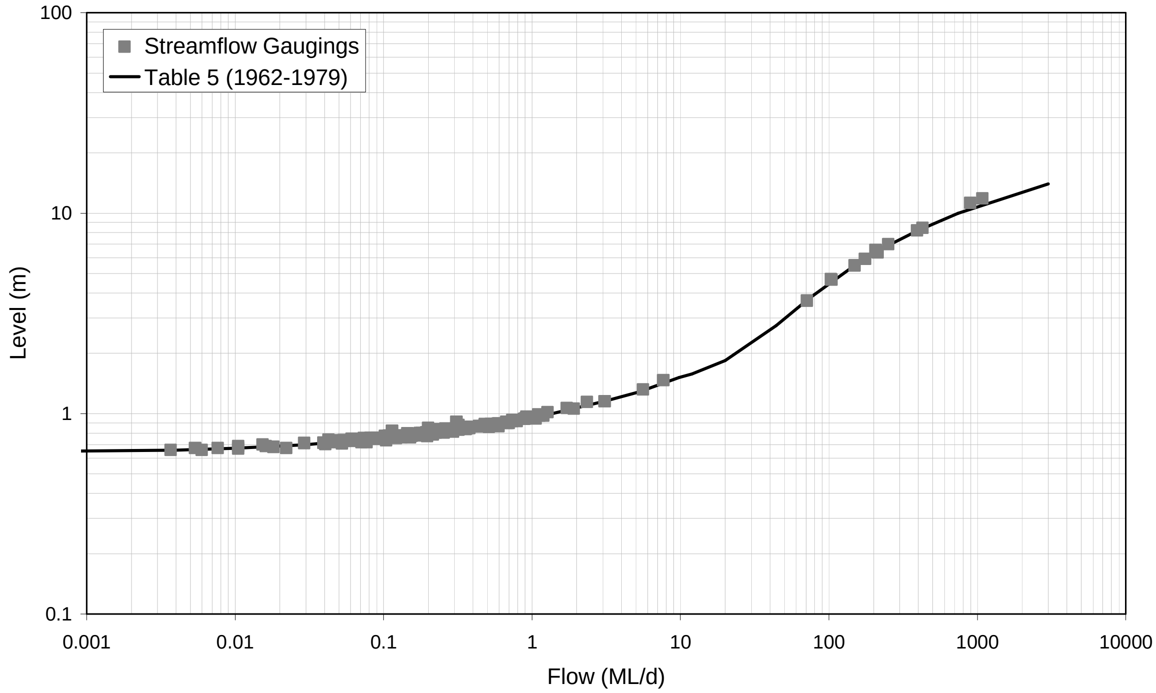

- **Figure A-40: Rating Table 75 and Streamflow Gaugings for 8150180 (1991-2006)**

## A.6 Adelaide River at Railway Bridge (8170002)

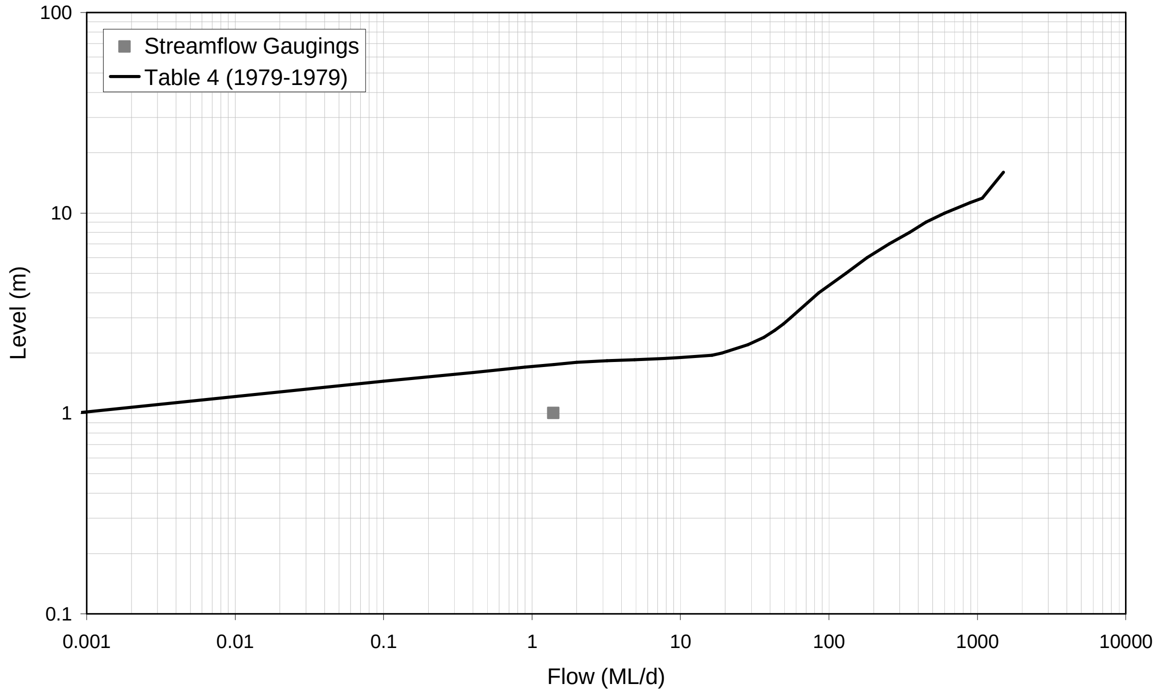
The gauge at 8170002 has had a number of changes in rating tables over the period of interest, as shown in Figure A-41. This indicates that the shape of the channel at this location is relatively unstable and thus there have been several significant changes in the shape of the rating at low flows. However, all of the rating tables shown correspond well with the actual streamflow gaugings. The individual rating tables with their associated streamflow gauging points are shown below.



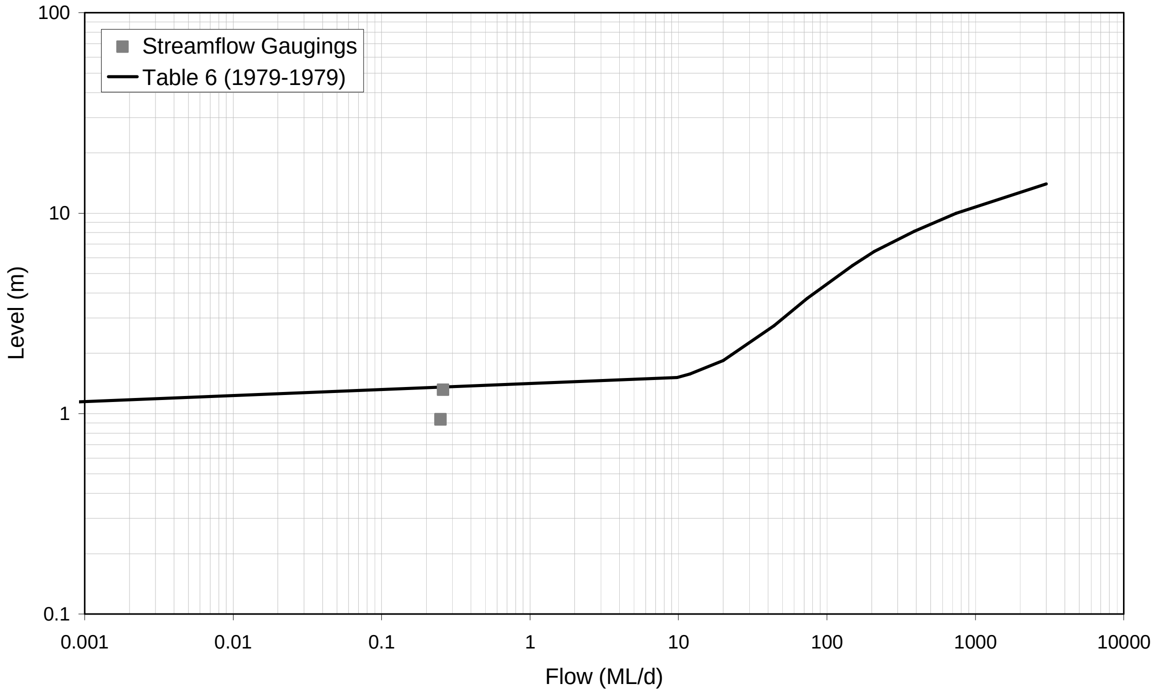

▪ **Figure A-41: All Rating Tables and Streamflow Gaugings for 8170002**



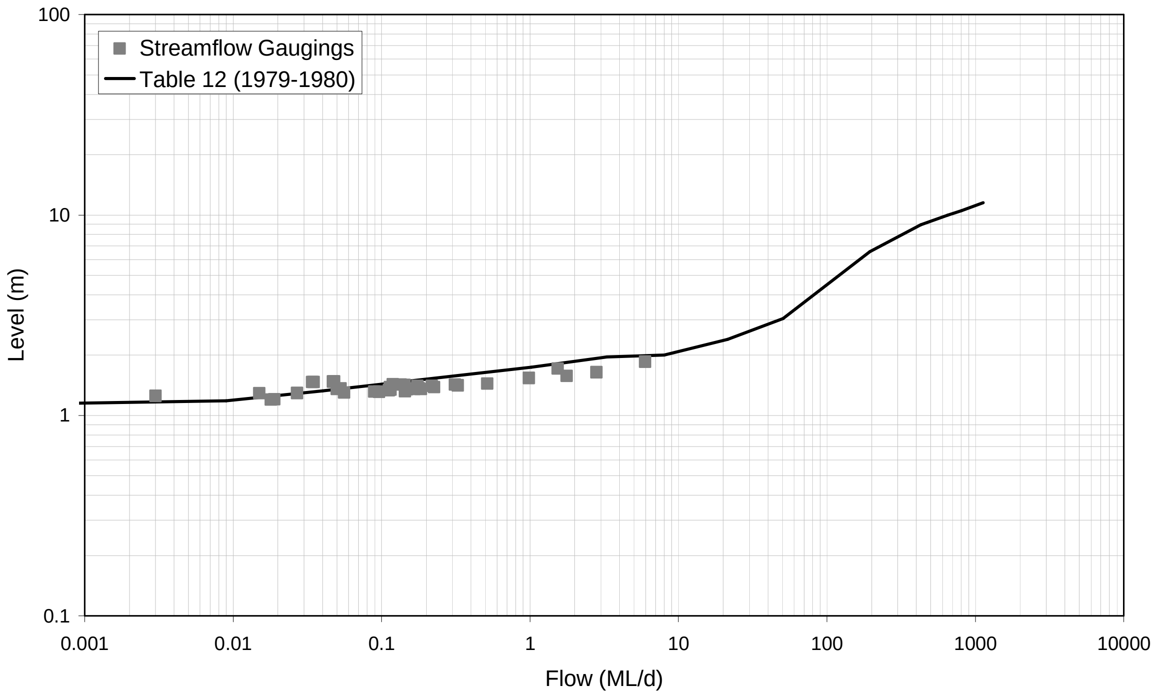

- **Figure A-42: Rating Table 5 and Streamflow Gaugings for 8170002 (1962-1979)**



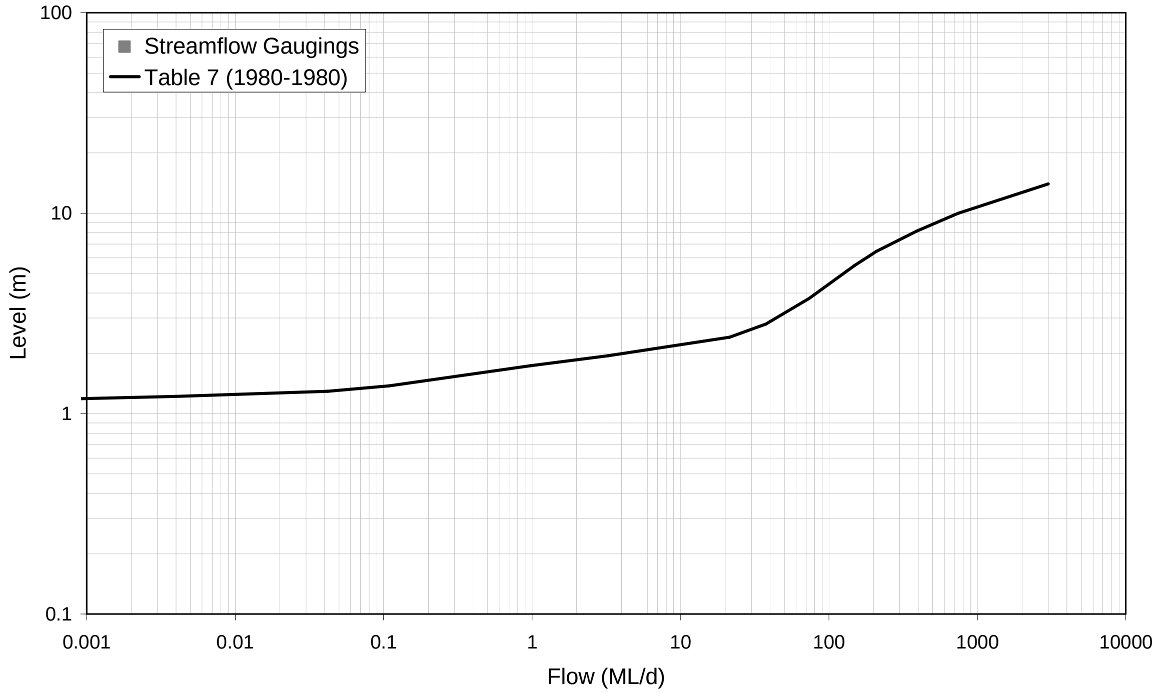

- **Figure A-43: Rating Table 4 and Streamflow Gaugings for 8170002 (1979)**



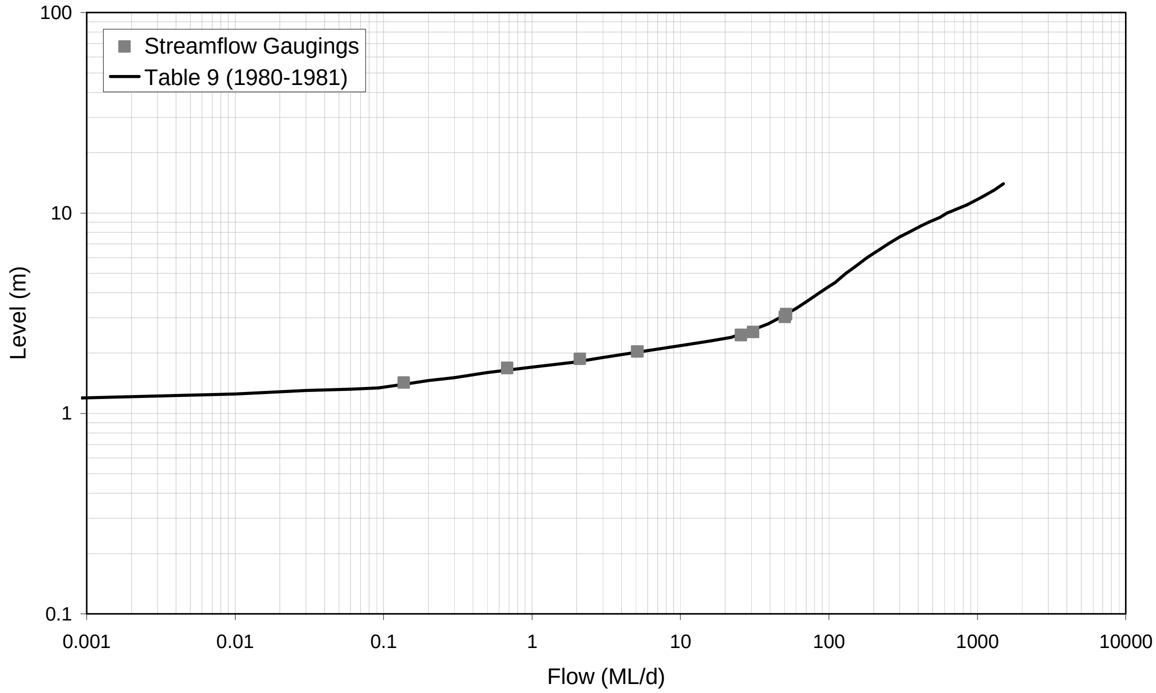

▪ **Figure A-44: Rating Table 6 and Streamflow Gaugings for 8170002 (1979)**



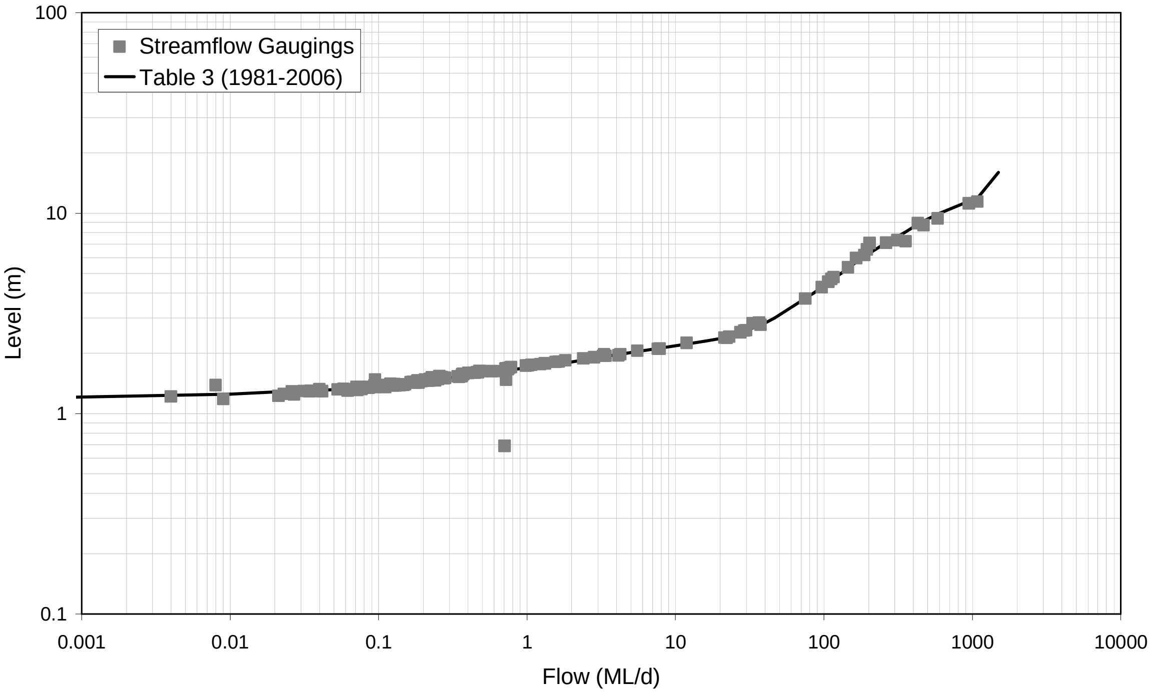

▪ **Figure A-45: Rating Table 12 and Streamflow Gaugings for 8170002 (1979-1980)**




- **Figure A-46: Rating Table 7 and Streamflow Gaugings for 8170002 (1980)**




- **Figure A-47: Rating Table 9 and Streamflow Gaugings for 8170002 (1980-1981)**




- **Figure A-48: Rating Table 3 and Streamflow Gaugings for 8170002 (1981-2006)**

## A.7 Adelaide River Upstream of Marrakai Crossing (8170005)

The gauge at 8170005 has had a number of changes in rating tables over the period of interest, as shown in Figure A-49. This indicates that the shape of the channel at this location is relatively unstable and thus there have been several significant changes in the shape of the rating at low flows. However, all of the rating tables shown correspond well with the actual streamflow gaugings. The individual rating tables with their associated streamflow gauging points are shown below.

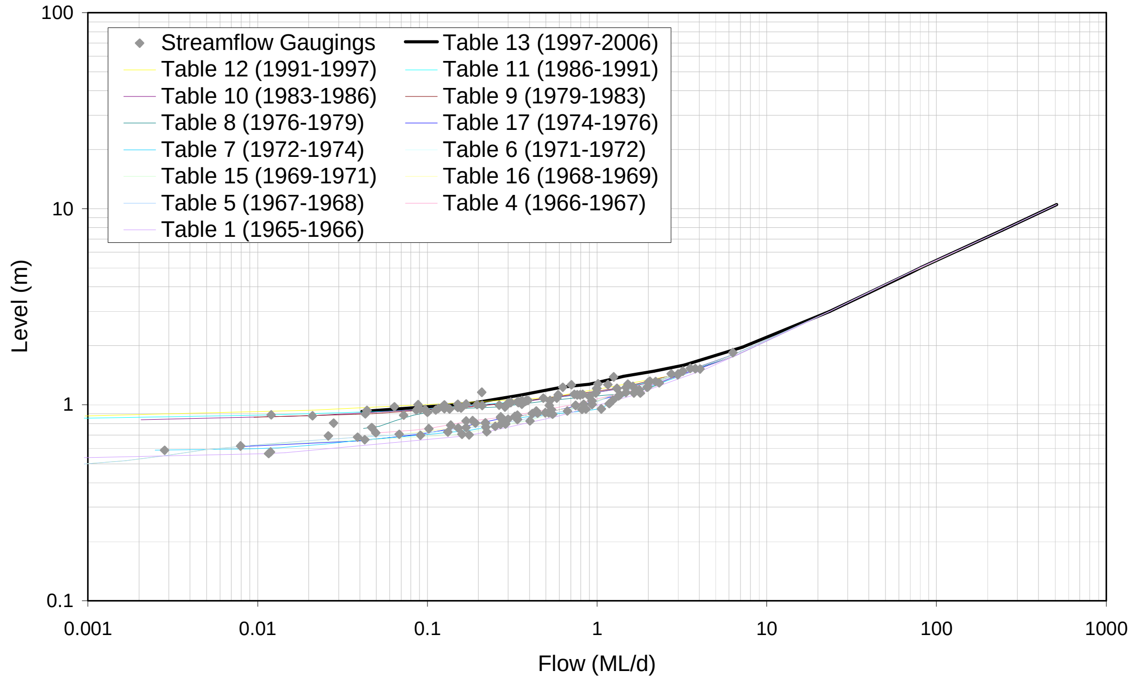



**Figure A-49: All Rating Tables and Streamflow Gaugings for 8170005**

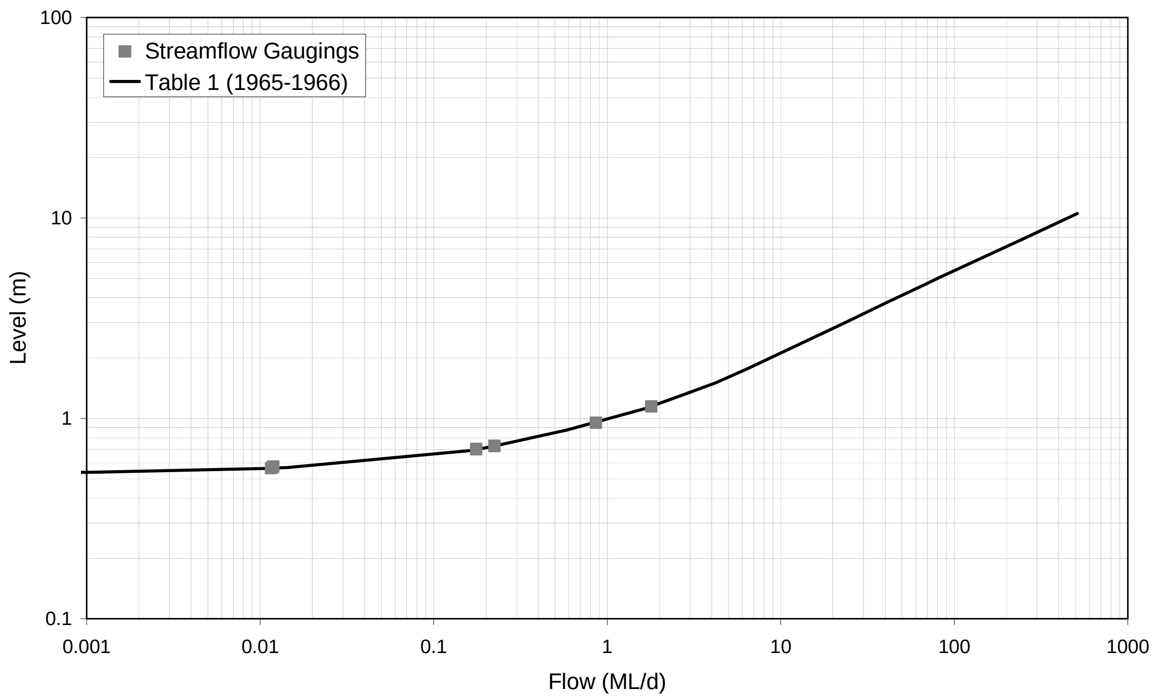
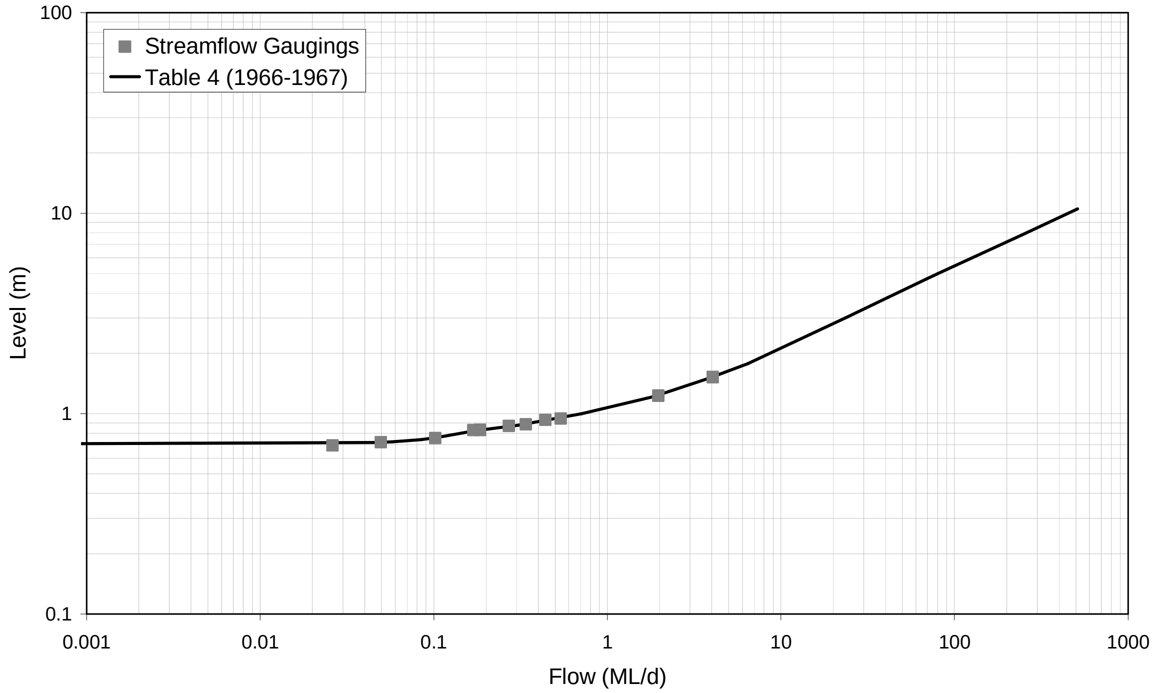
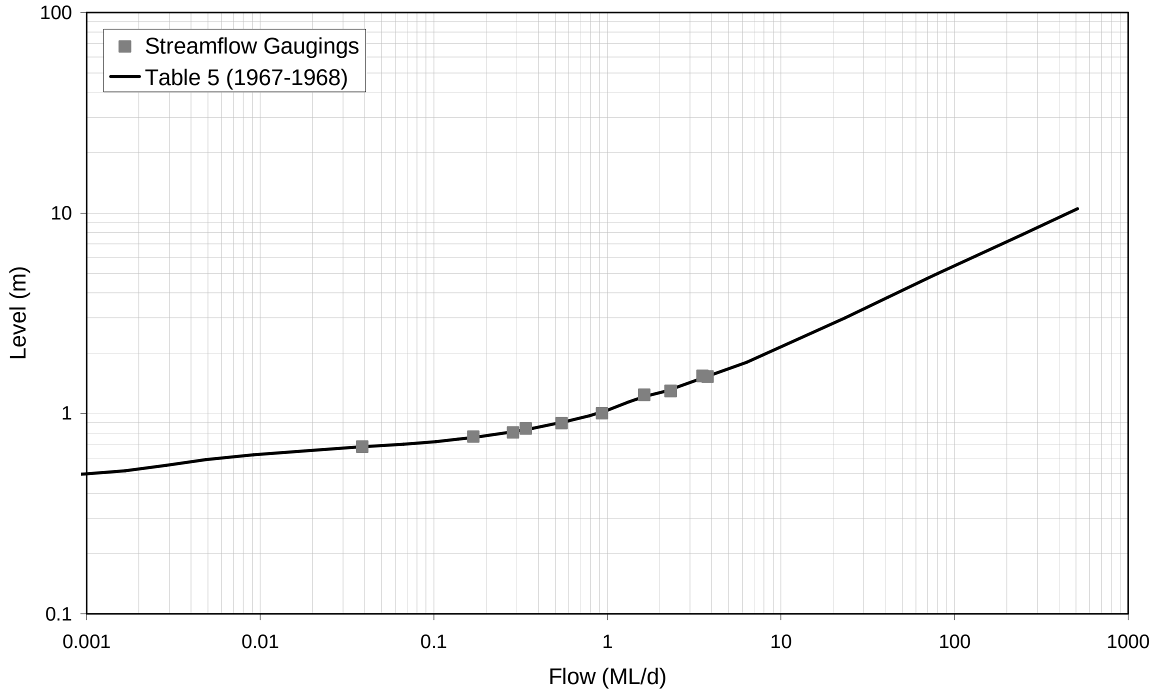


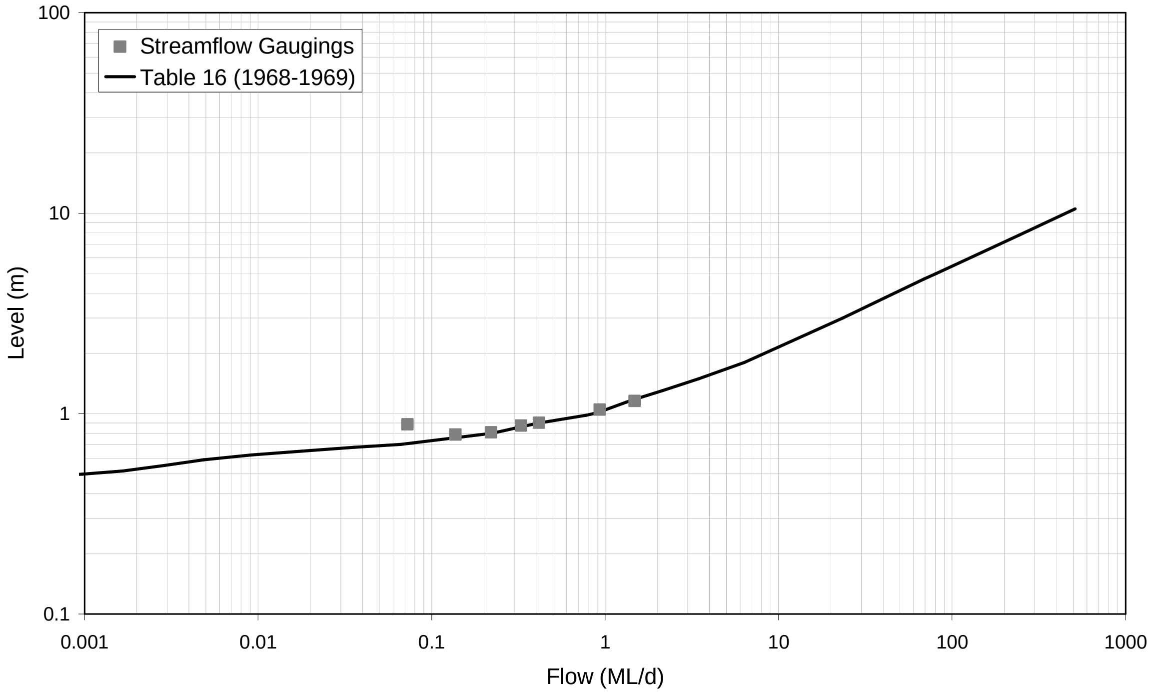

**Figure A-50: Rating Table 1 and Streamflow Gaugings for 8170005 (1965-1966)**



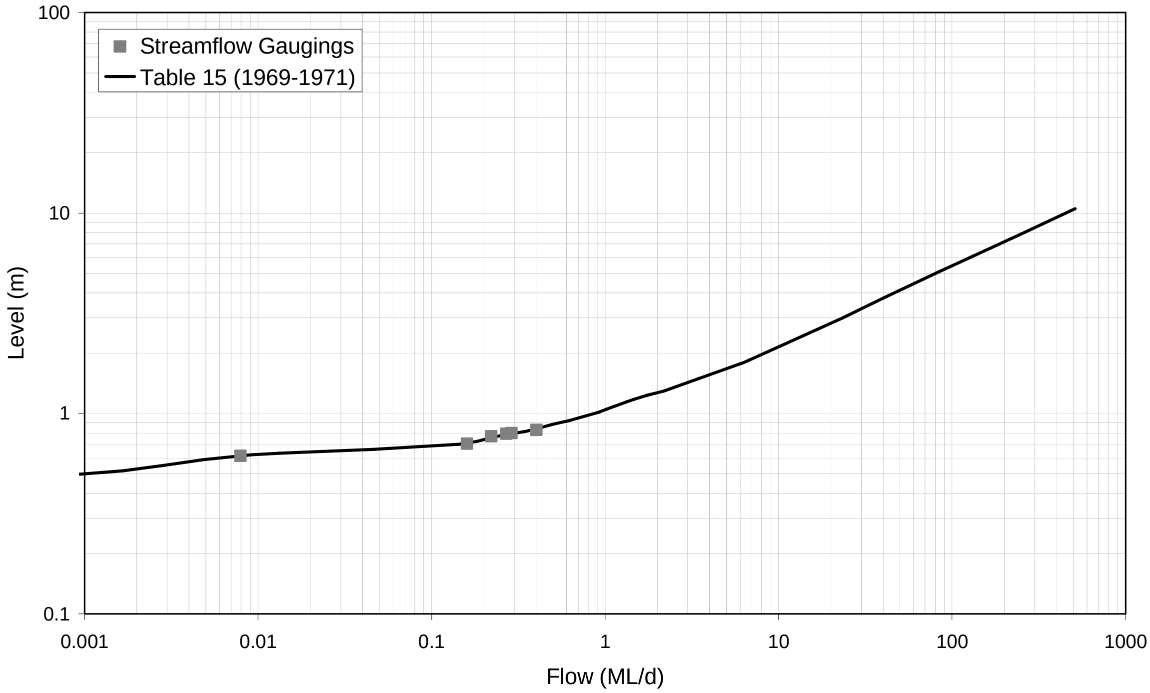

▪ **Figure A-51: Rating Table 4 and Streamflow Gaugings for 8170005 (1966-1967)**



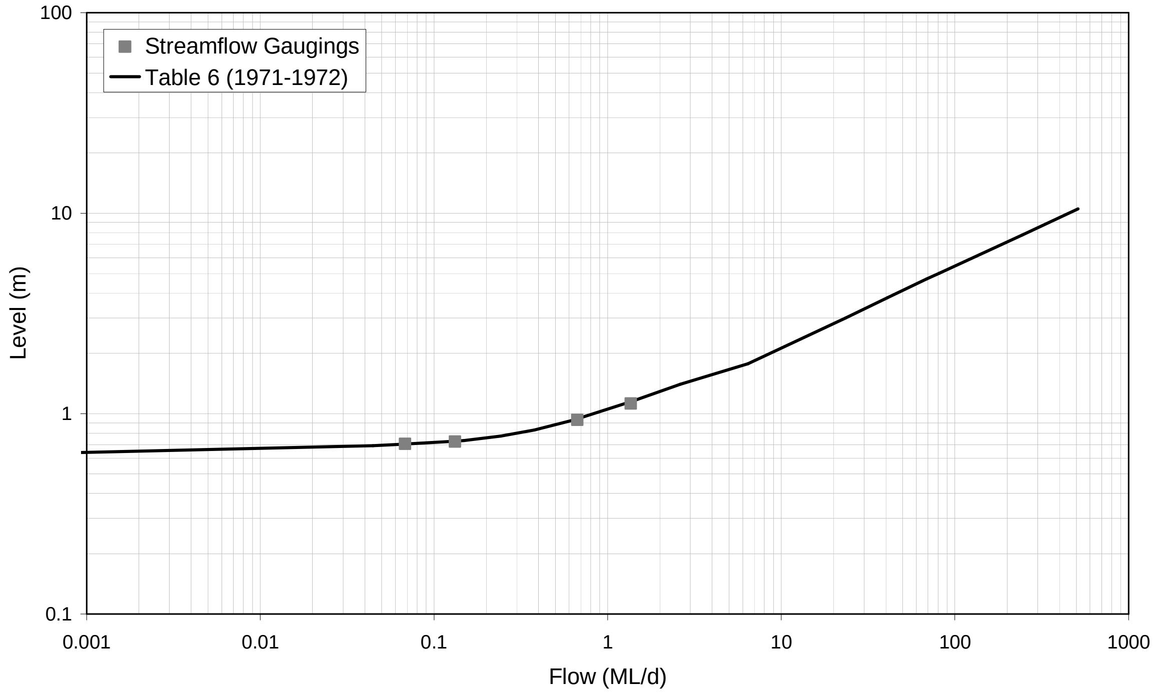

▪ **Figure A-52: Rating Table 5 and Streamflow Gaugings for 8170005 (1967-1968)**



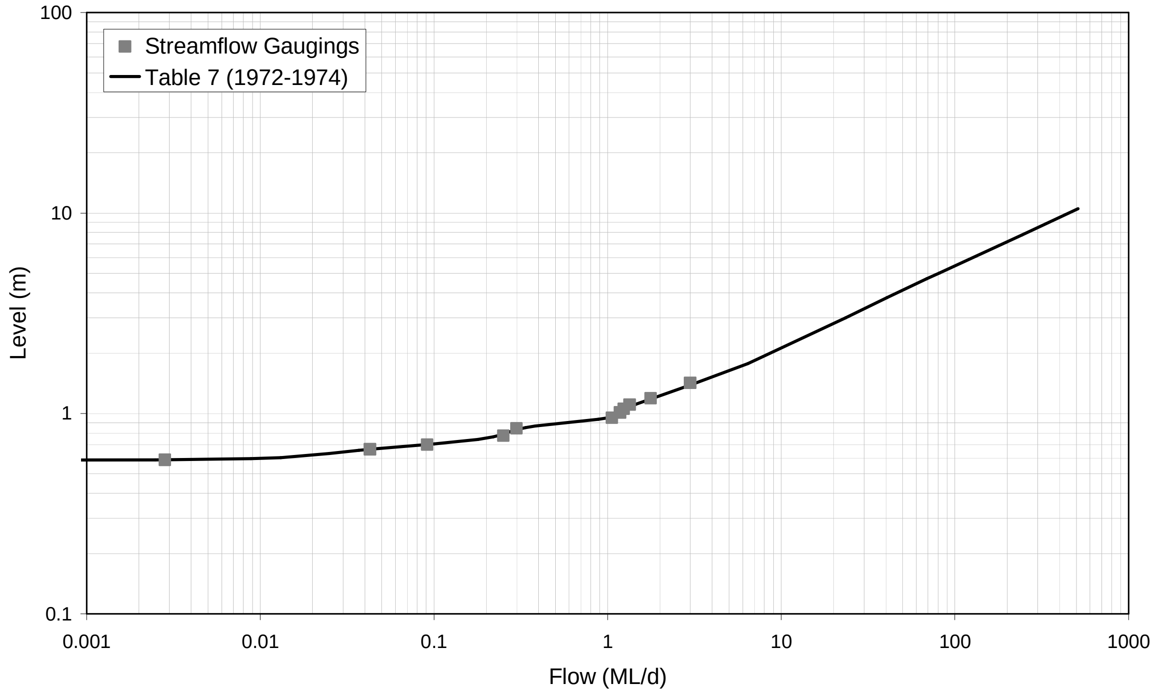

- **Figure A-53: Rating Table 16 and Streamflow Gaugings for 8170005 (1968-1969)**



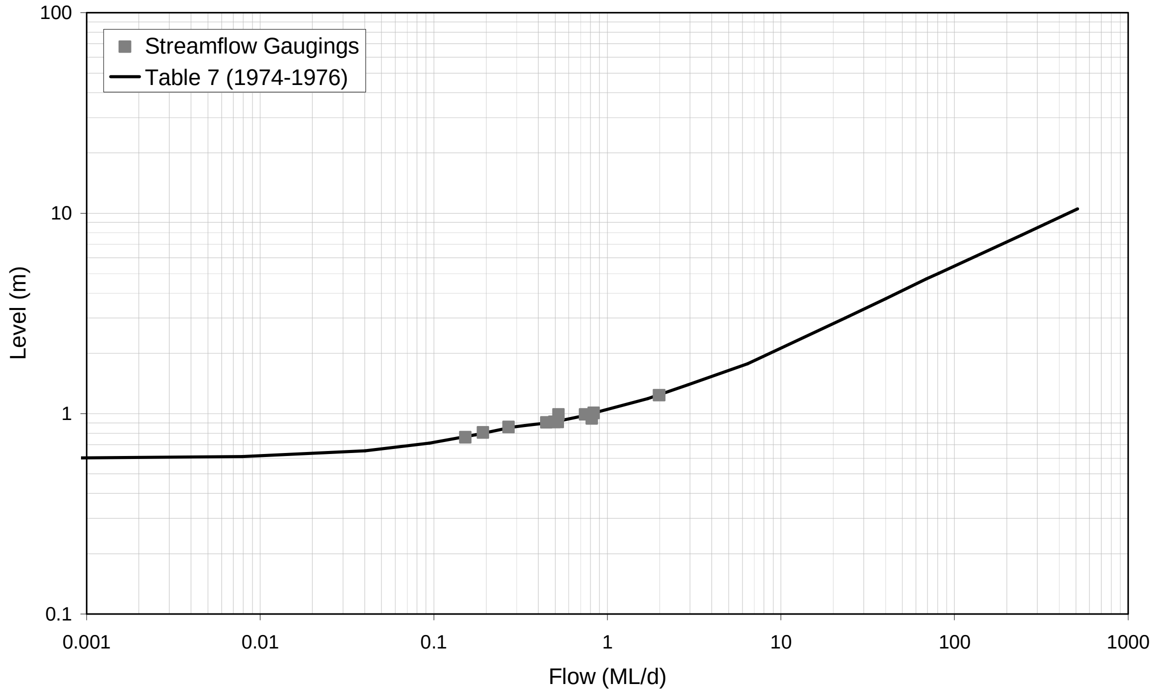

- **Figure A-54: Rating Table 15 and Streamflow Gaugings for 8170005 (1969-1971)**



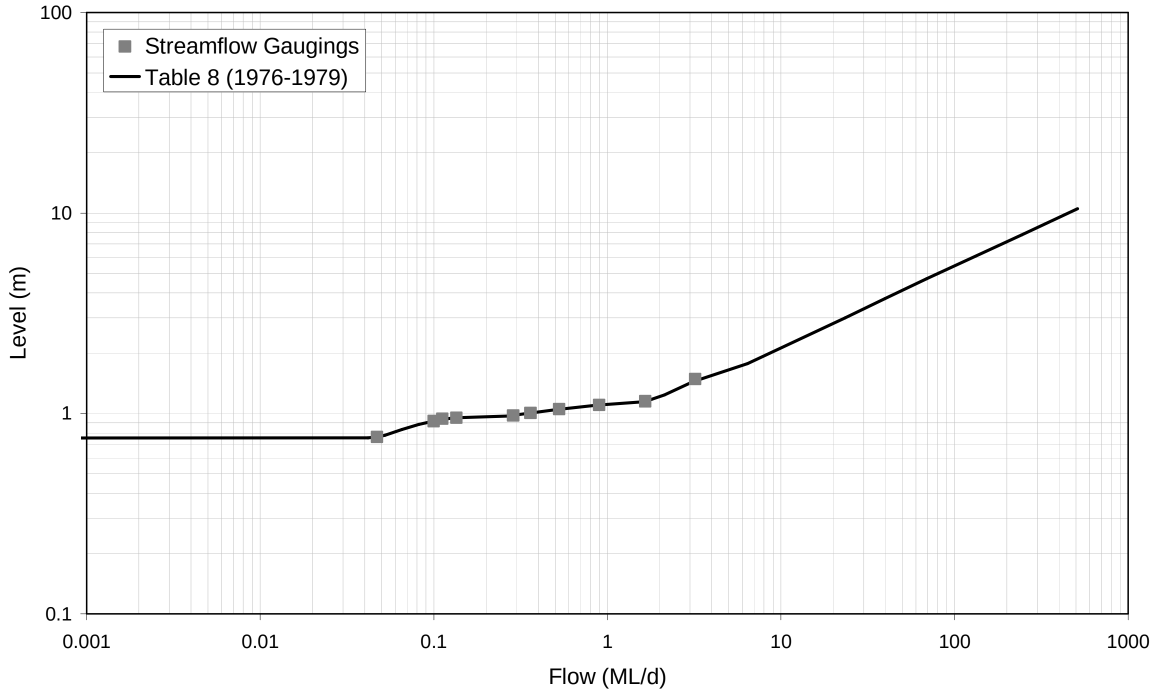

■ **Figure A-55: Rating Table 6 and Streamflow Gaugings for 8170005 (1971-1972)**



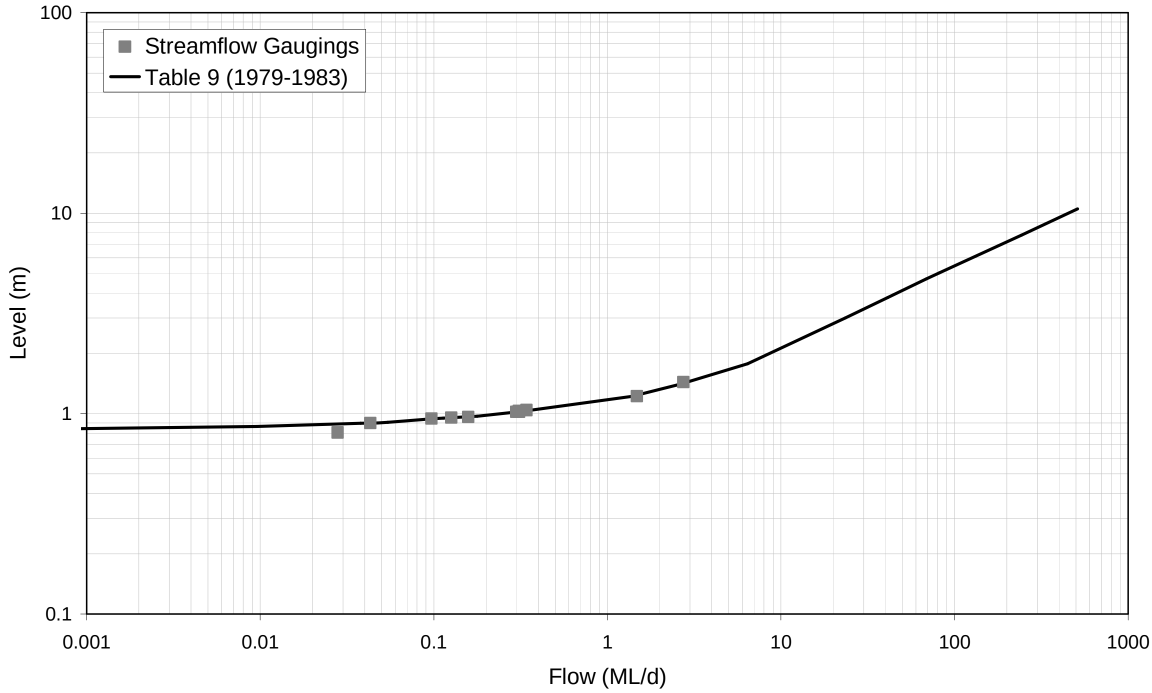

■ **Figure A-56: Rating Table 7 and Streamflow Gaugings for 8170005 (1972-1974)**



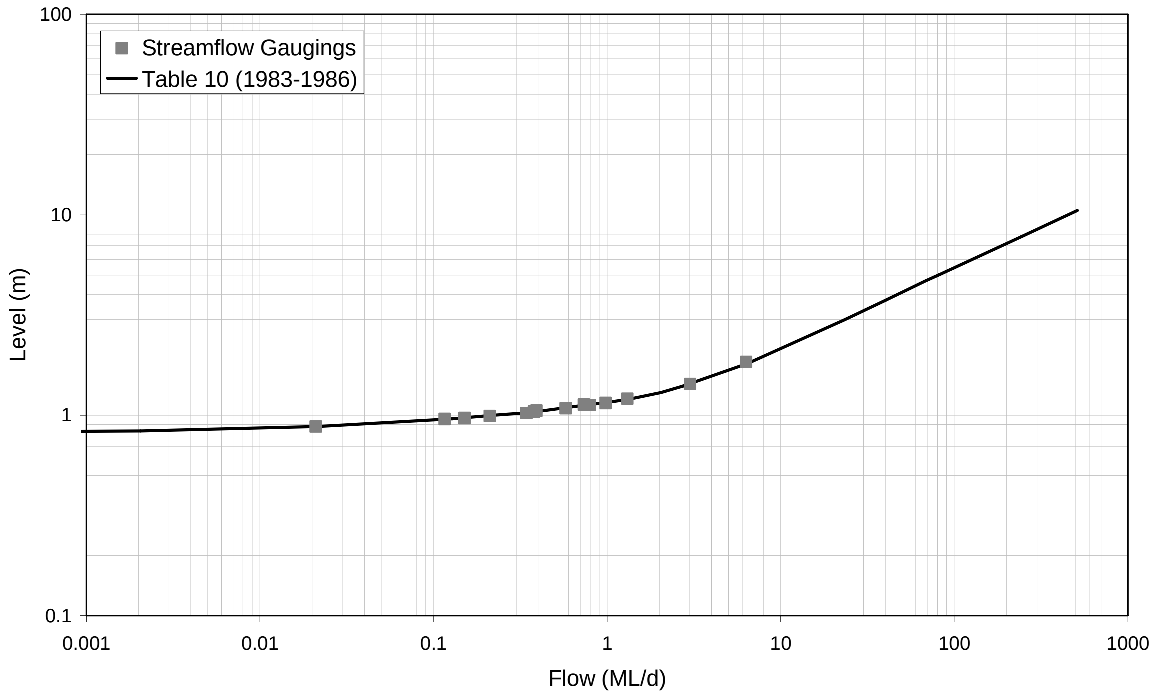

▪ **Figure A-57: Rating Table 7 and Streamflow Gaugings for 8170005 (1974-1976)**




▪ **Figure A-58: Rating Table 8 and Streamflow Gaugings for 8170005 (1976-1979)**




■ **Figure A-59: Rating Table 9 and Streamflow Gaugings for 8170005 (1979-1983)**




■ **Figure A-60: Rating Table 10 and Streamflow Gaugings for 8170005 (1983-1986)**

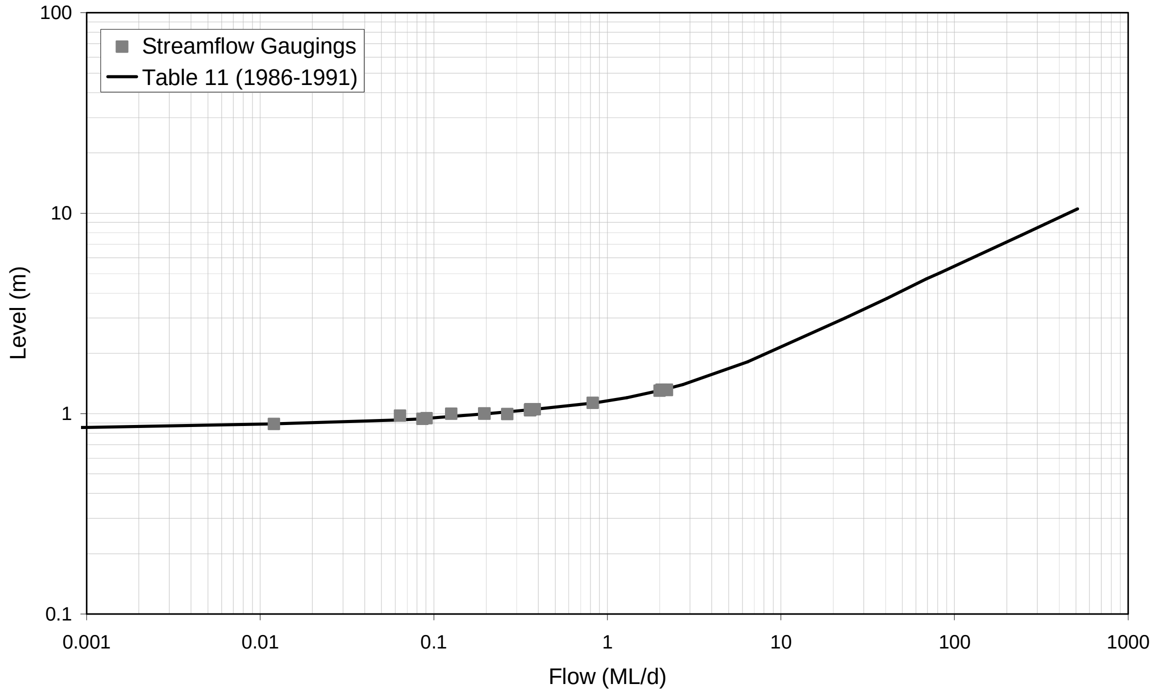



Figure A-61: Rating Table 11 and Streamflow Gaugings for 8170005 (1986-1991)

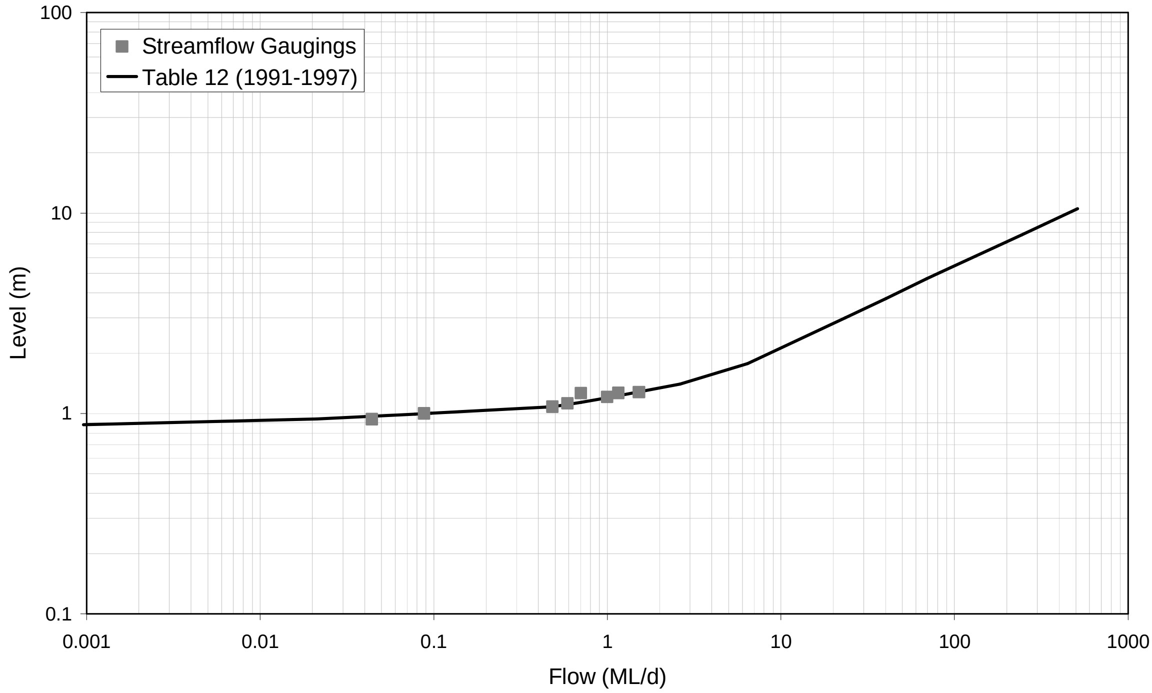
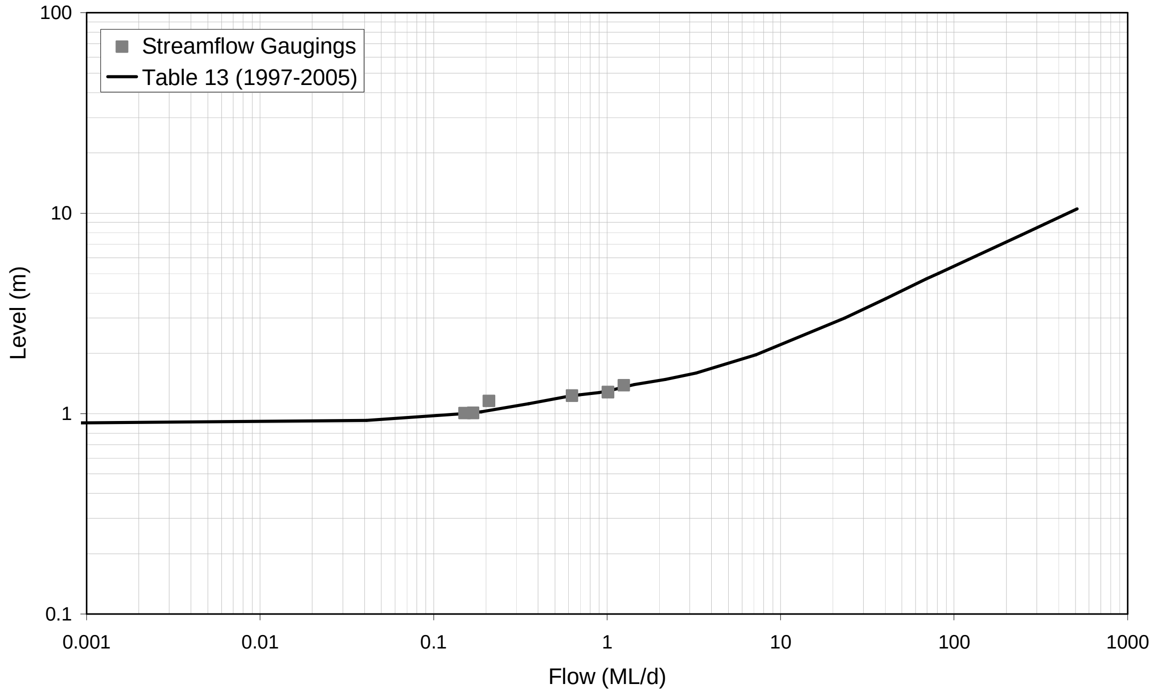


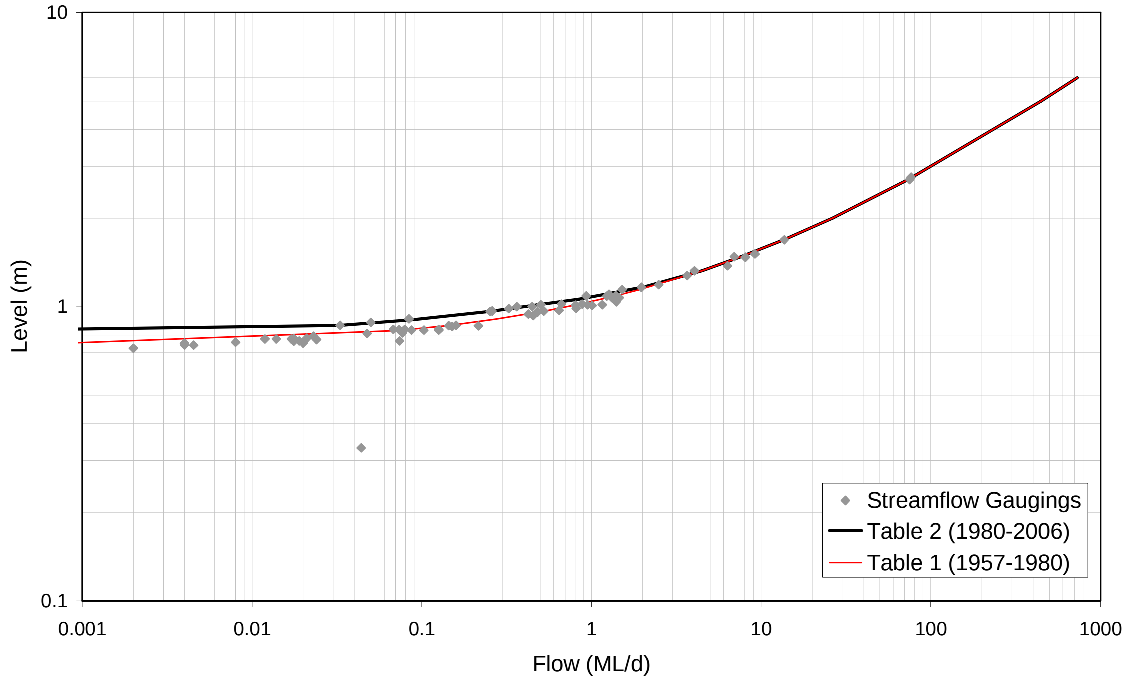

Figure A-62: Rating Table 12 and Streamflow Gaugings for 8170005 (1991-1997)



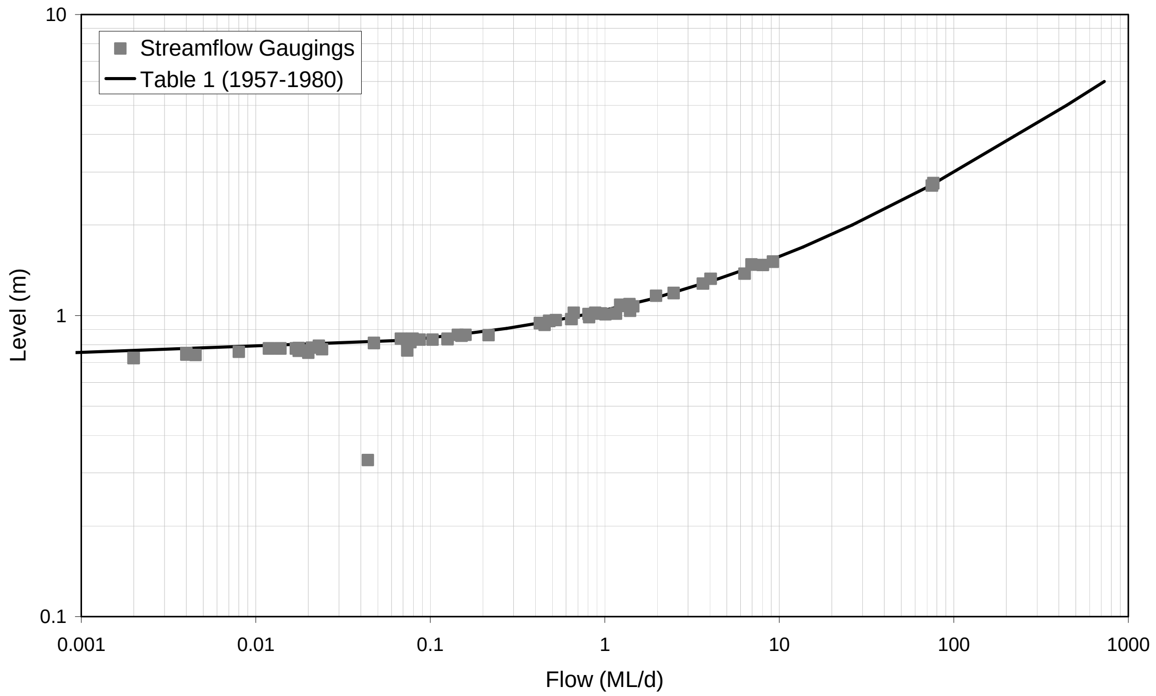

- **Figure A-63: Rating Table 13 and Streamflow Gaugings for 8170005 (1997-2006)**

## A.8 Burrell Creek at Eighty-Seven Mile Jump (8170062)

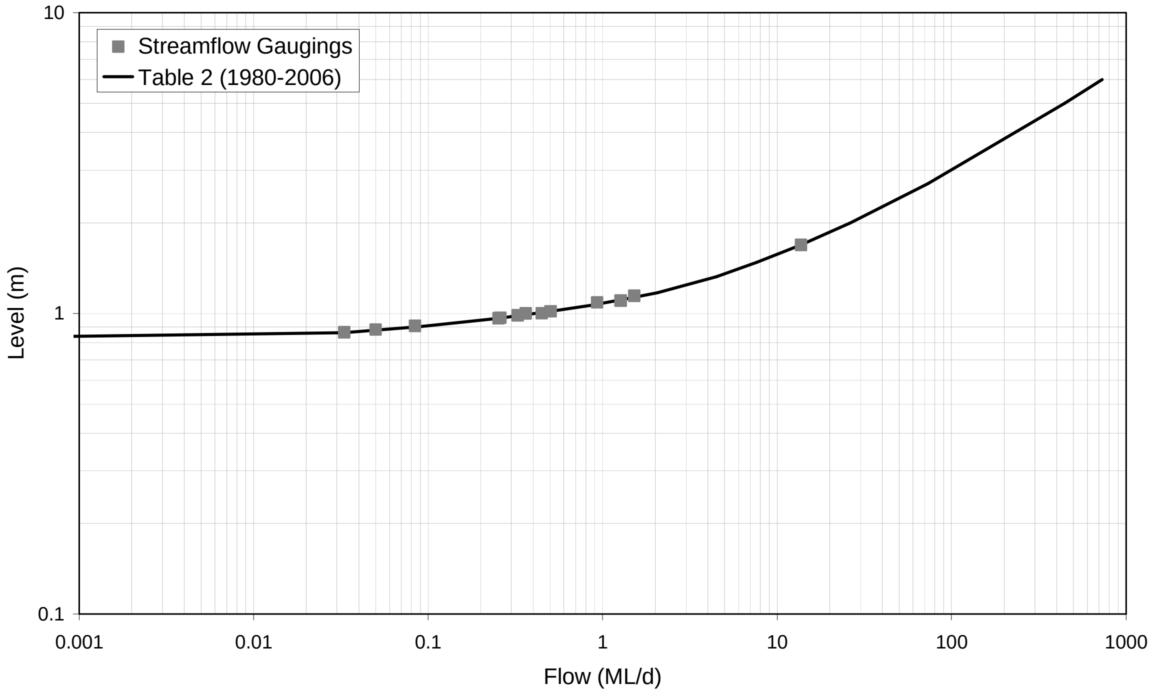
The gauge at 8170062 has had two changes in rating tables over the period of interest, as shown in Figure A-64. It can be seen that there has been little variation in the rating tables, and that they are both based on consistent streamflow gaugings. The individual rating tables with their associated streamflow gauging points are shown below.




- **Figure A-64: All Rating Tables and Streamflow Gaugings for 8170062**



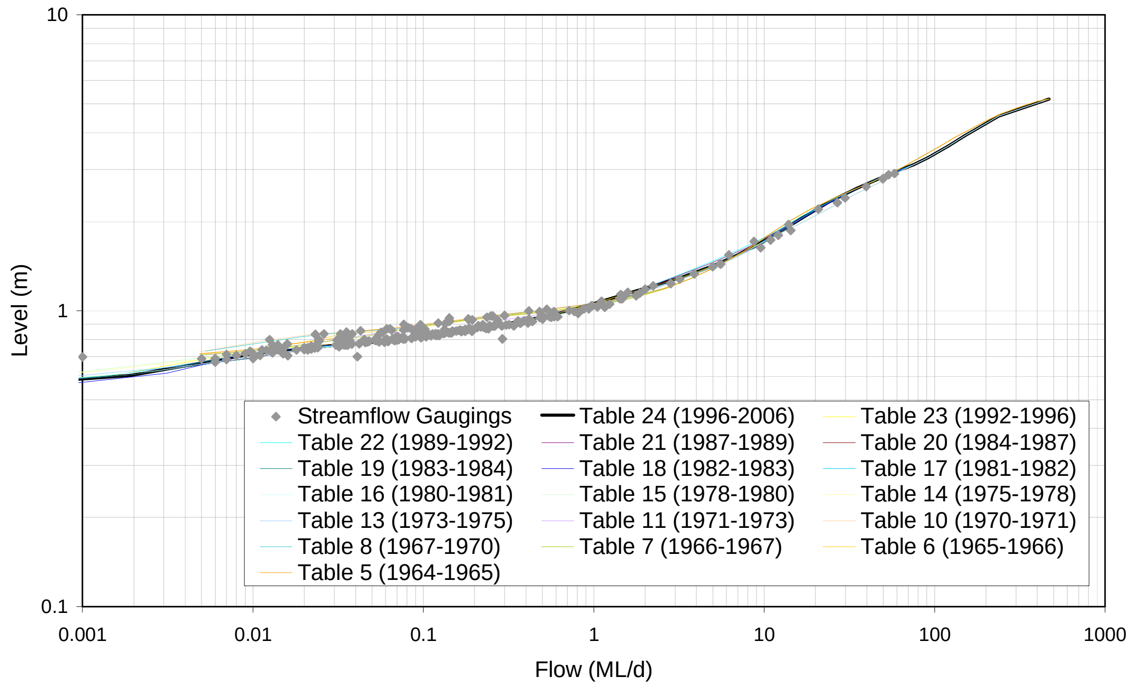

- **Figure A-65: Rating Table 1 and Streamflow Gaugings for 81700062 (1957-1980)**



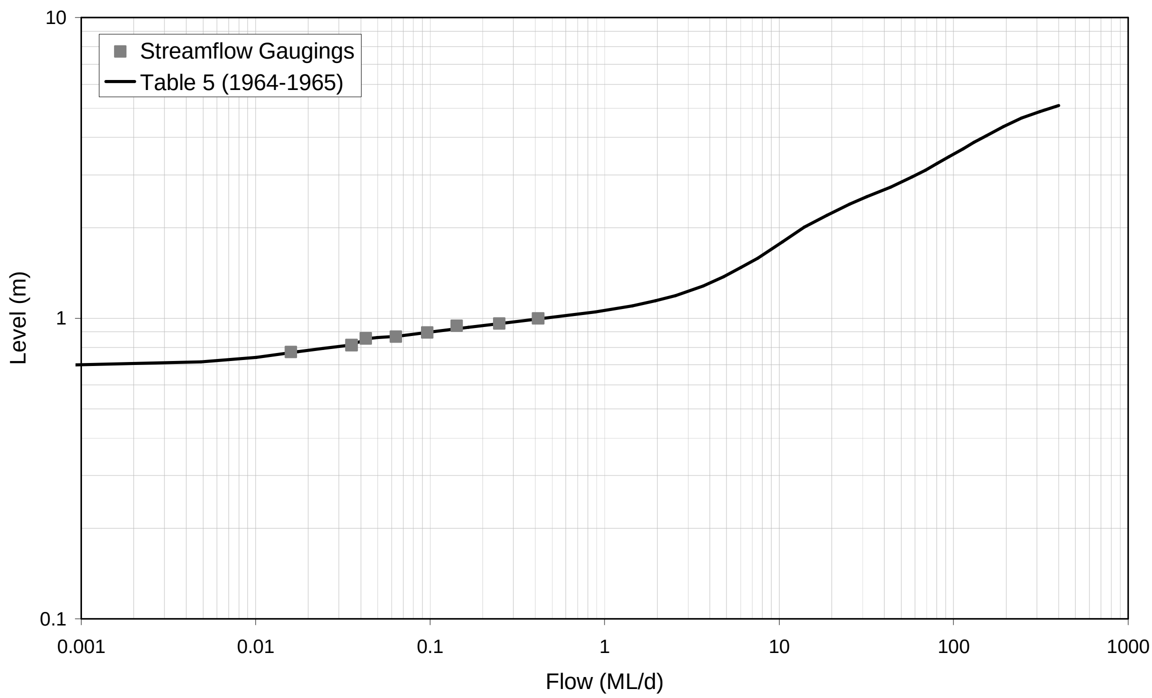

▪ **Figure A-66: Rating Table 1 and Streamflow Gaugings for 8170062 (1980-2006)**

## A.9 Coomalie Creek at Stuart Highway (8170066)

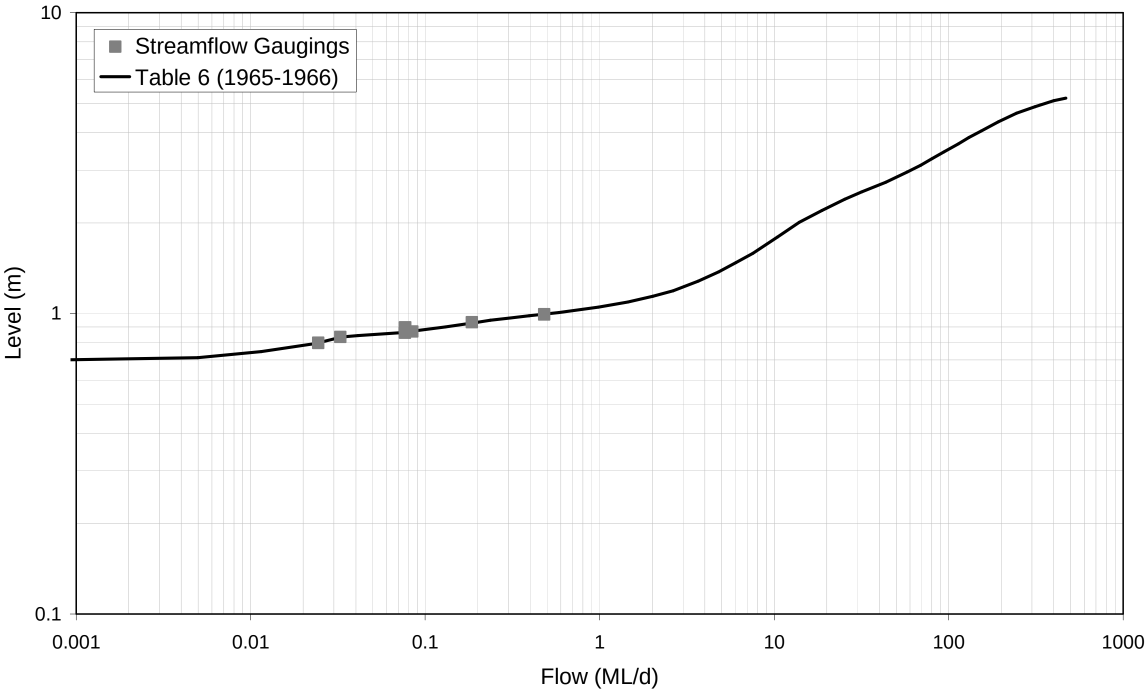
The gauge at 8170066 has had a number of changes in rating tables over the period of interest, as shown in Figure A-67. It can be seen that there has been little variation in the rating tables, and that they are all based on consistent streamflow gaugings. The individual rating tables with their associated streamflow gauging points are shown below.



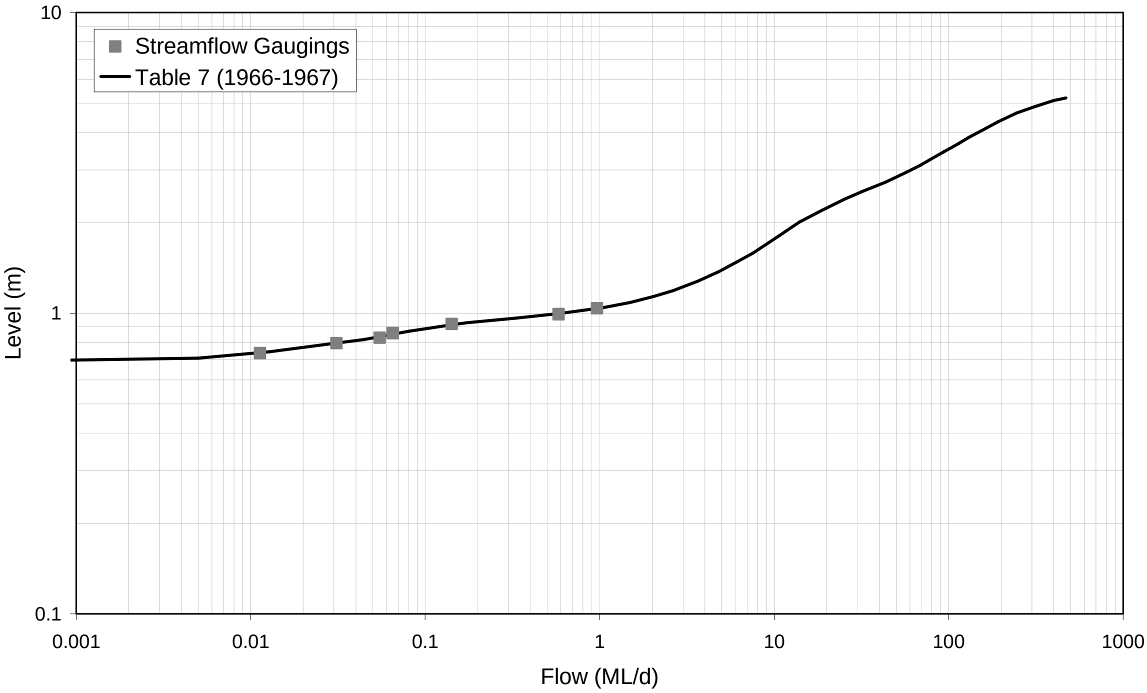

- **Figure A-67: All Rating Tables and Streamflow Gaugings for 8170066**



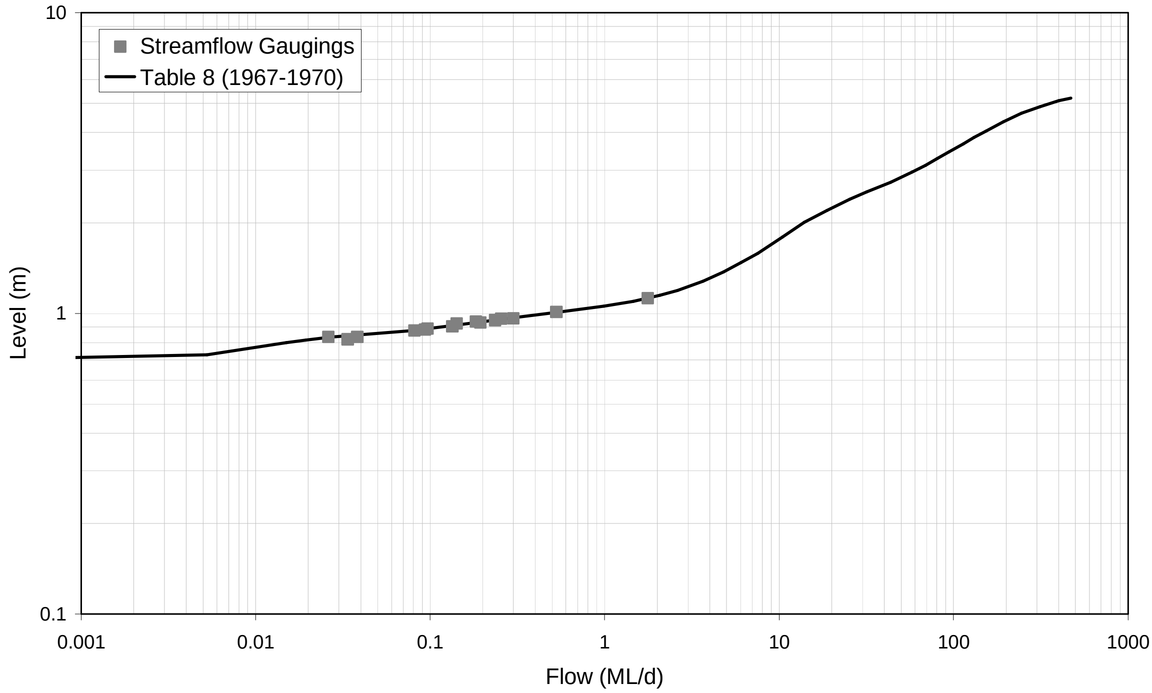

- **Figure A-68: Rating Table 1 and Streamflow Gaugings for 8170066 (1964-1965)**



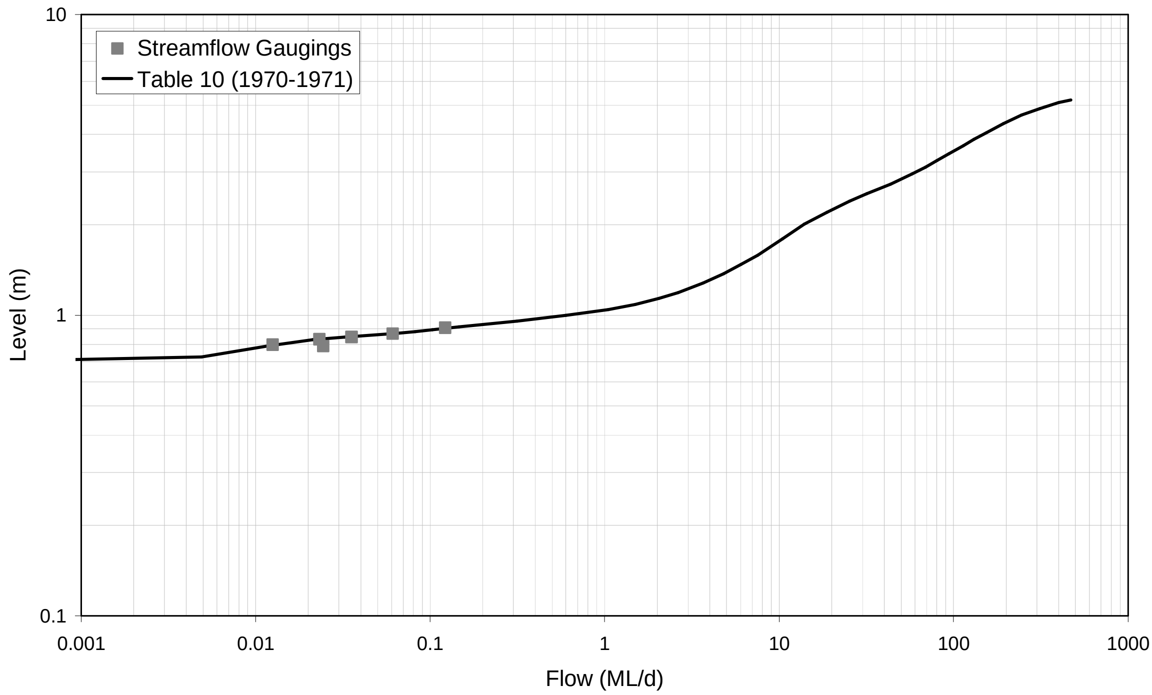

▪ **Figure A-69: Rating Table 6 and Streamflow Gaugings for 8170066 (1965-1966)**



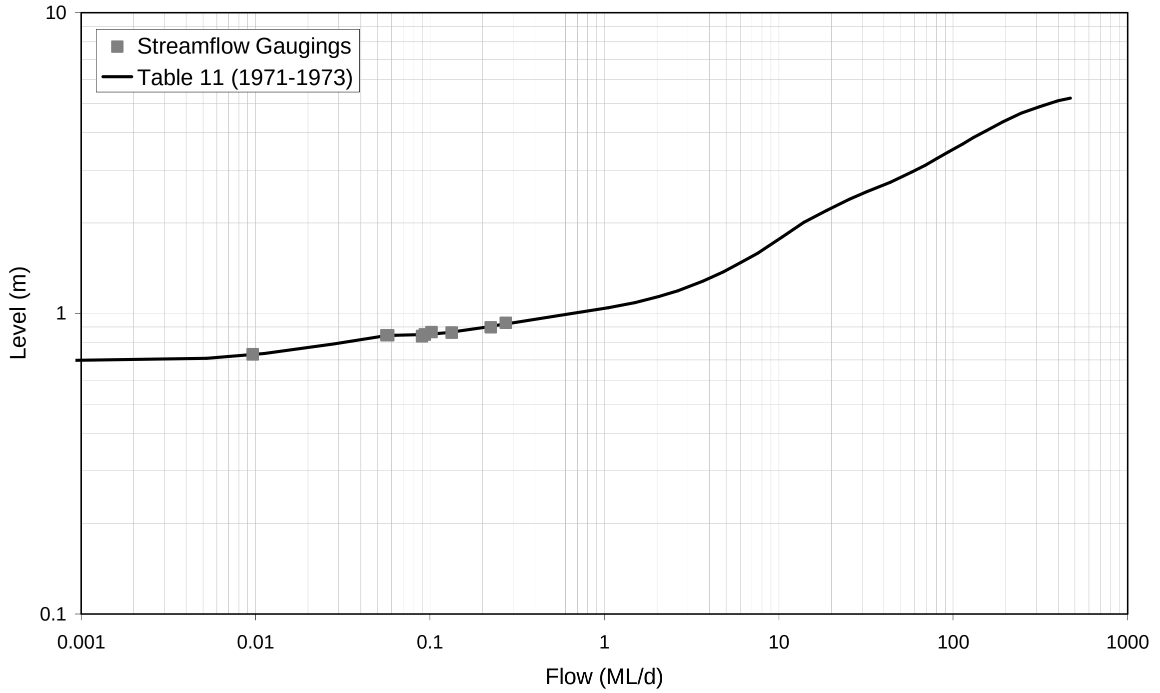

▪ **Figure A-70: Rating Table 7and Streamflow Gaugings for 8170066 (1966-1967)**



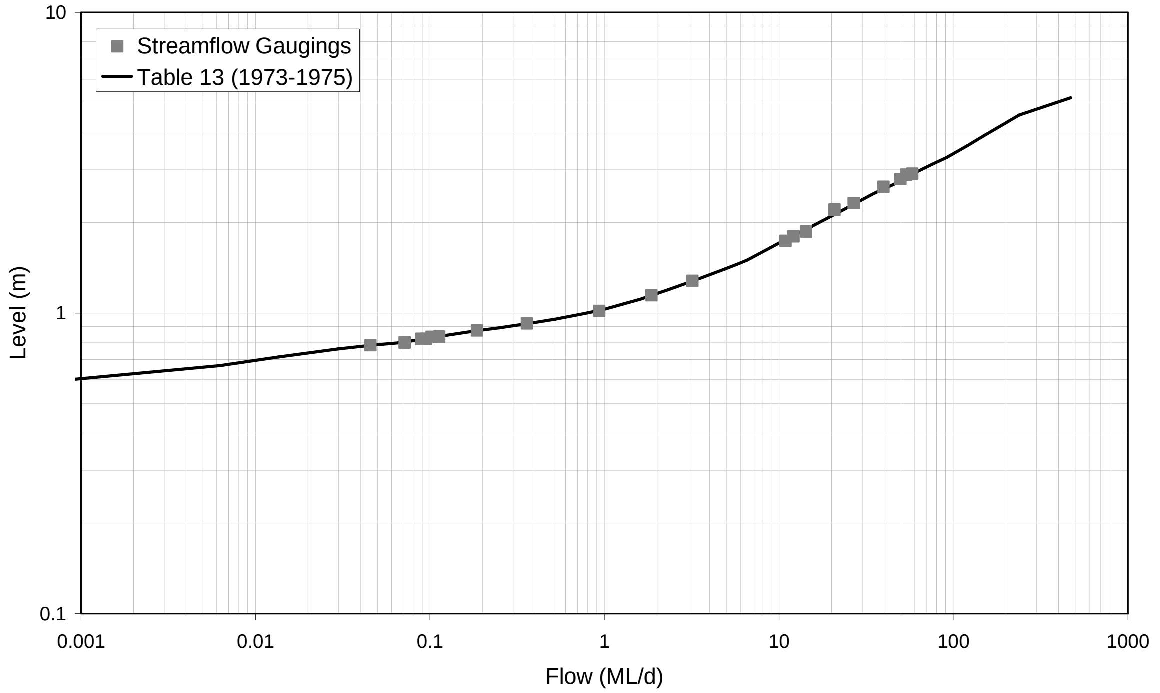

■ **Figure A-71: Rating Table 8 and Streamflow Gaugings for 8170066 (1967-1970)**



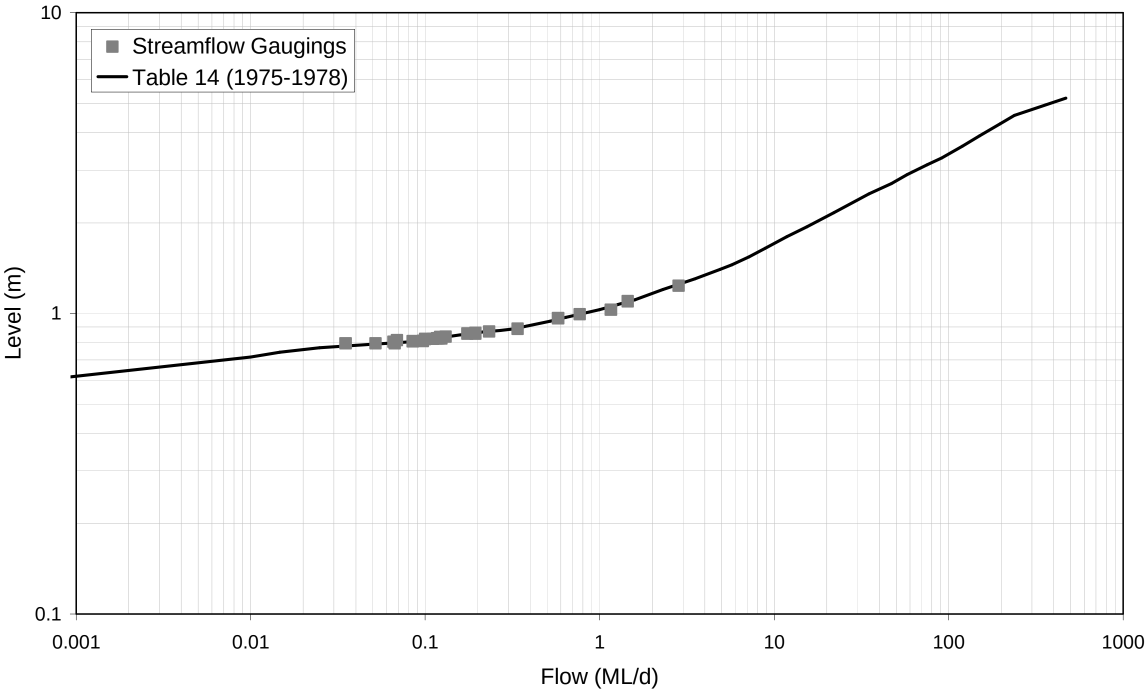

■ **Figure A-72: Rating Table 10 and Streamflow Gaugings for 8170066 (1970-1971)**



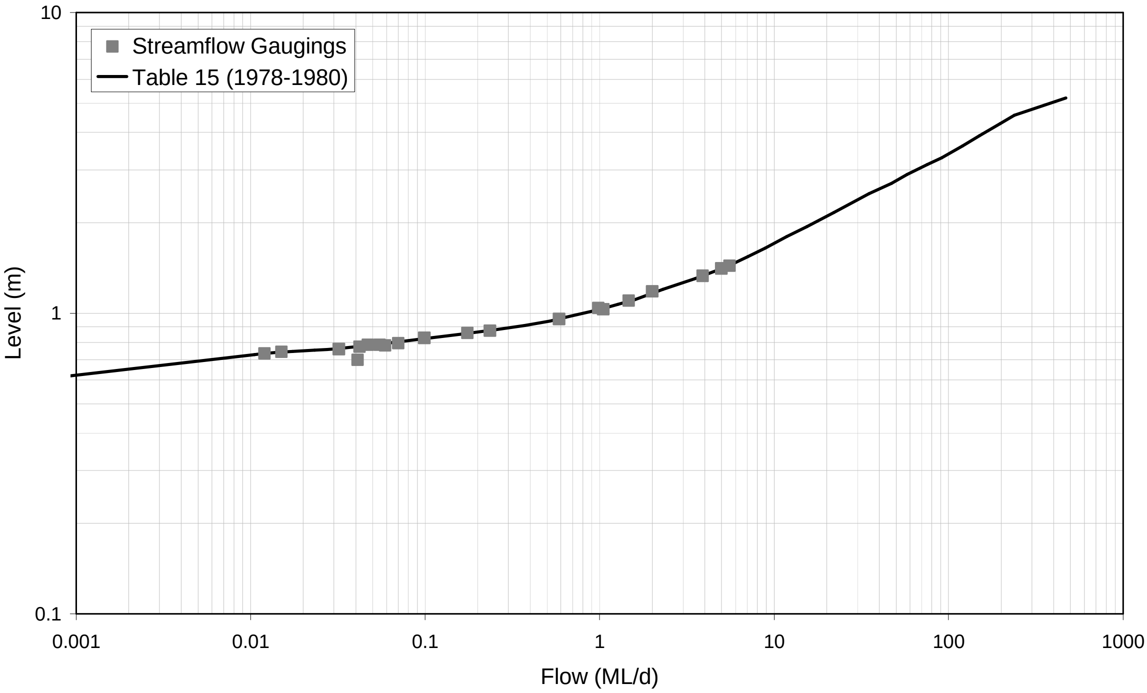

■ **Figure A-73: Rating Table 11 and Streamflow Gaugings for 8170066 (1971-1973)**




■ **Figure A-74: Rating Table 13 and Streamflow Gaugings for 8170066 (1973-1975)**




- **Figure A-75: Rating Table 14 and Streamflow Gaugings for 8170066 (1975-1978)**




- **Figure A-76: Rating Table 15 and Streamflow Gaugings for 8170066 (1978-1980)**

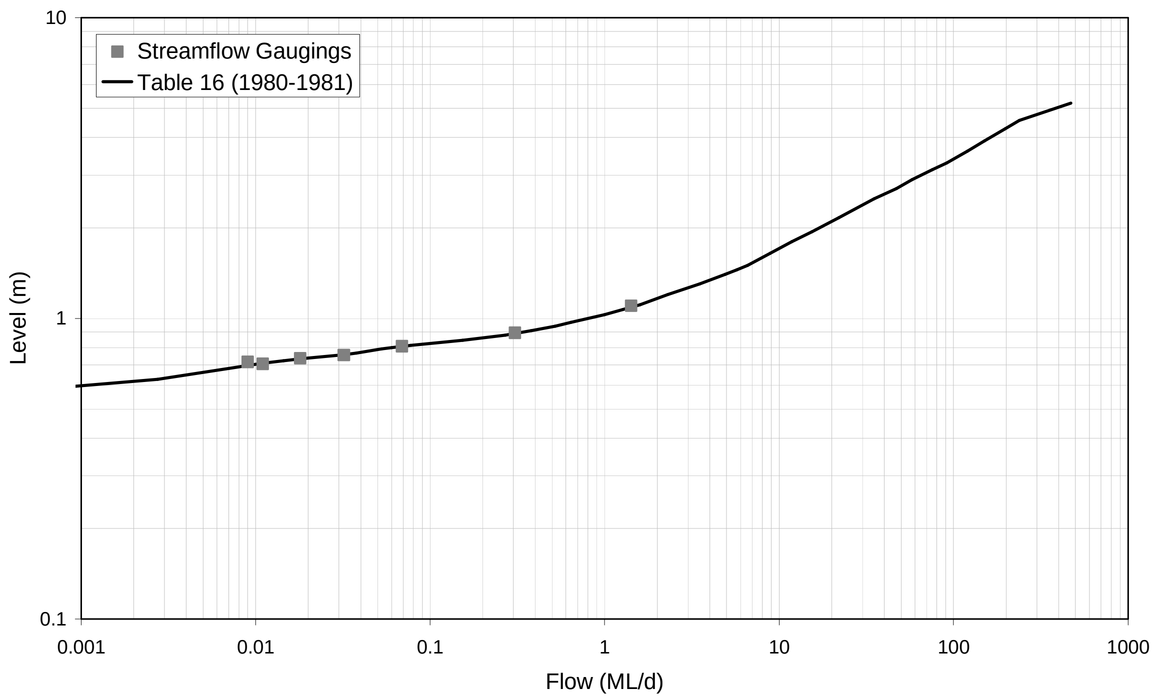



**Figure A-77: Rating Table 16 and Streamflow Gaugings for 8170066 (1980-1981)**

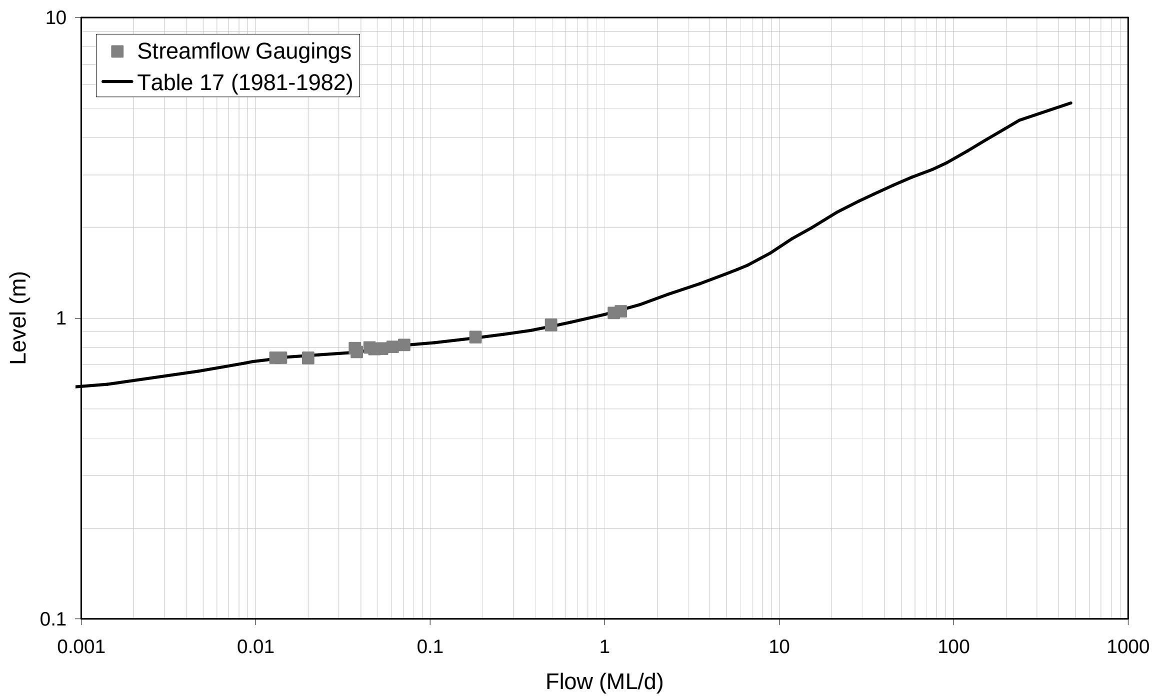
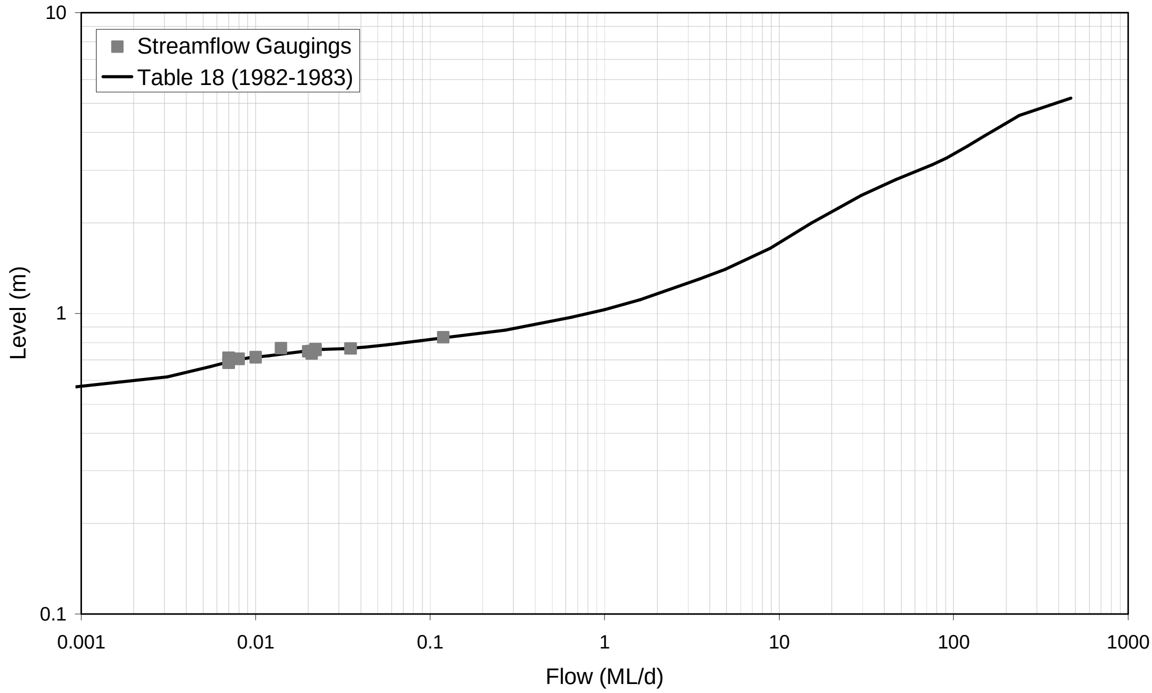
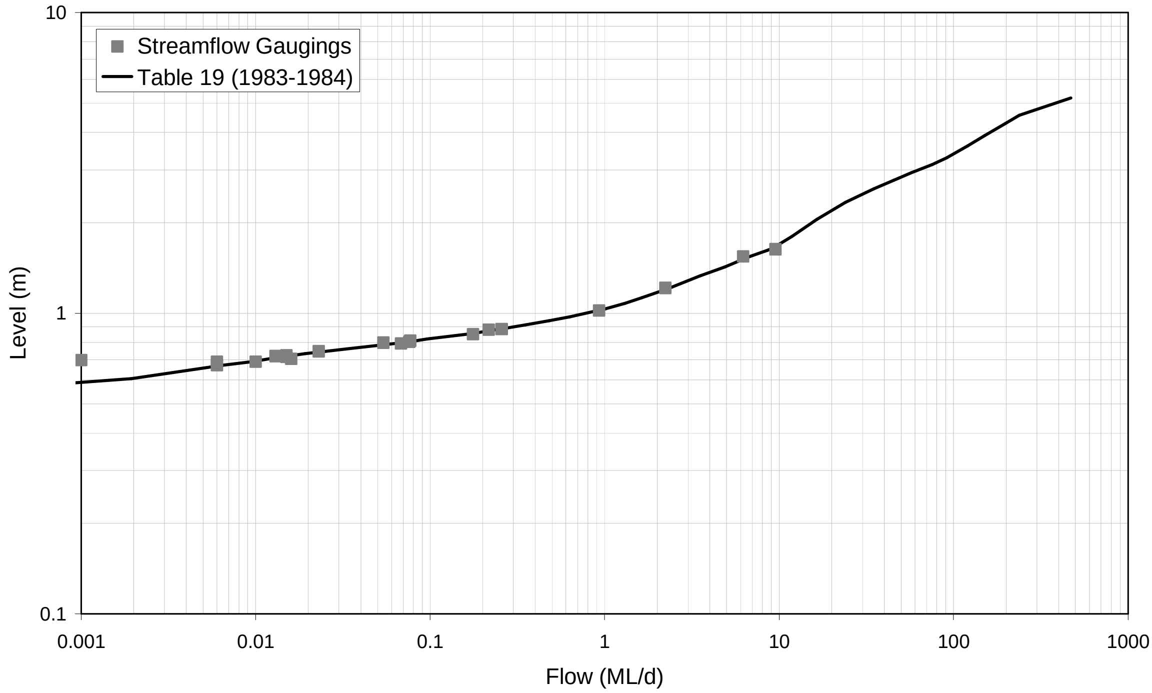


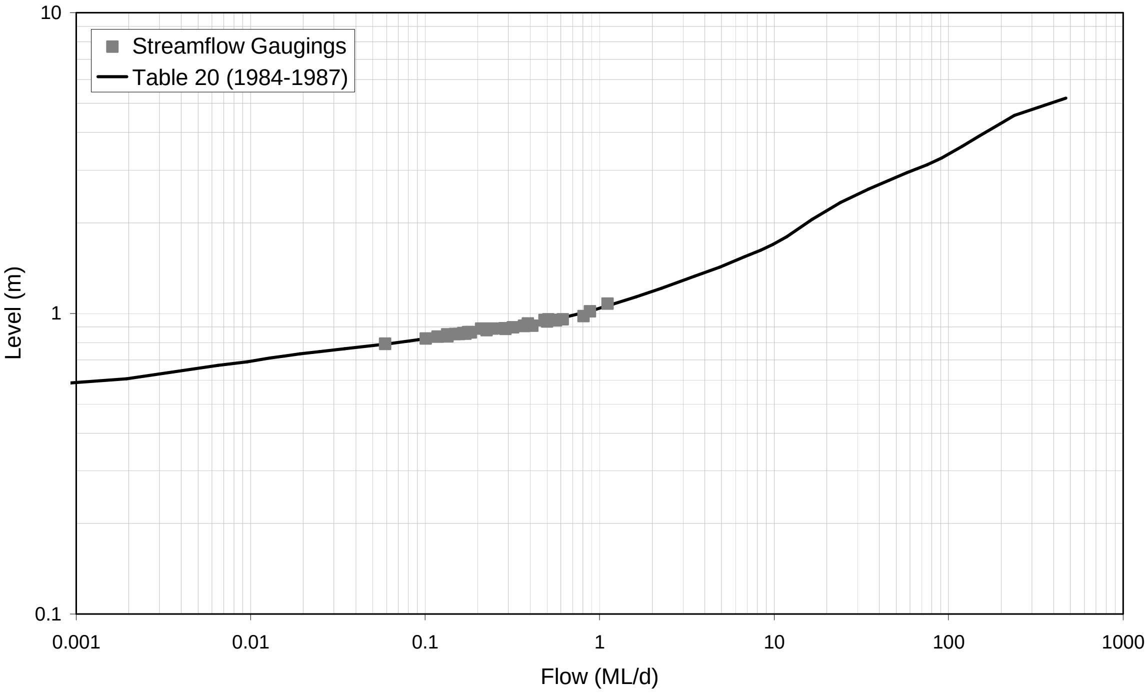

**Figure A-78: Rating Table 17 and Streamflow Gaugings for 8170066 (1981-1982)**



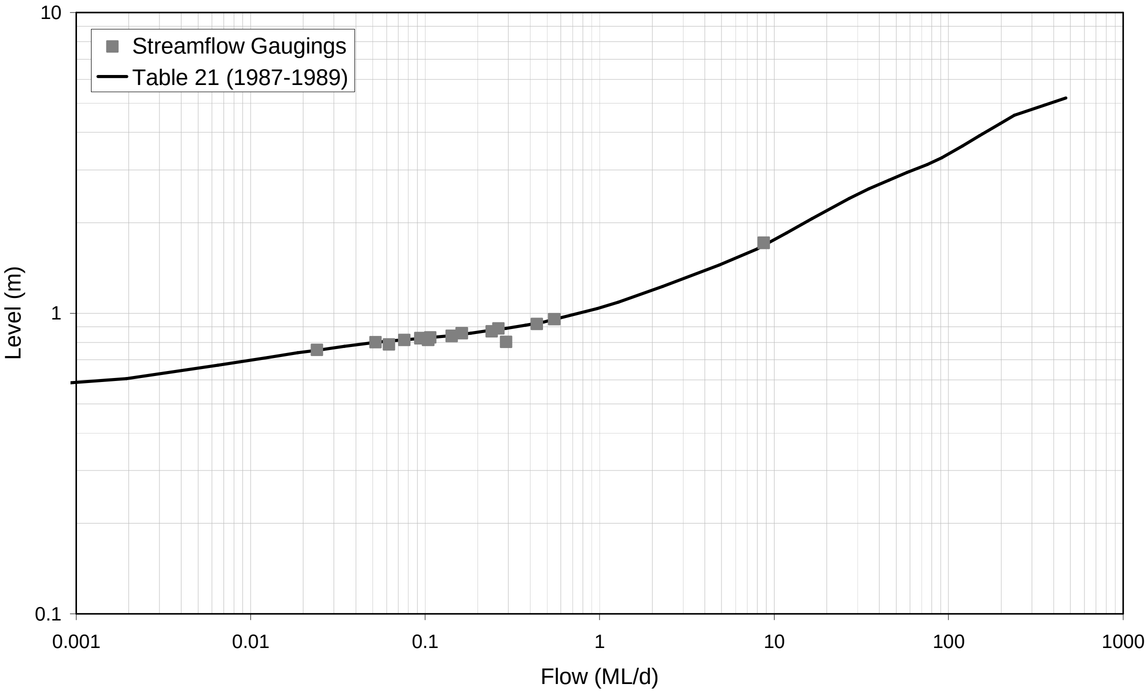

▪ **Figure A-79: Rating Table 18 and Streamflow Gaugings for 8170066 (1982-1983)**



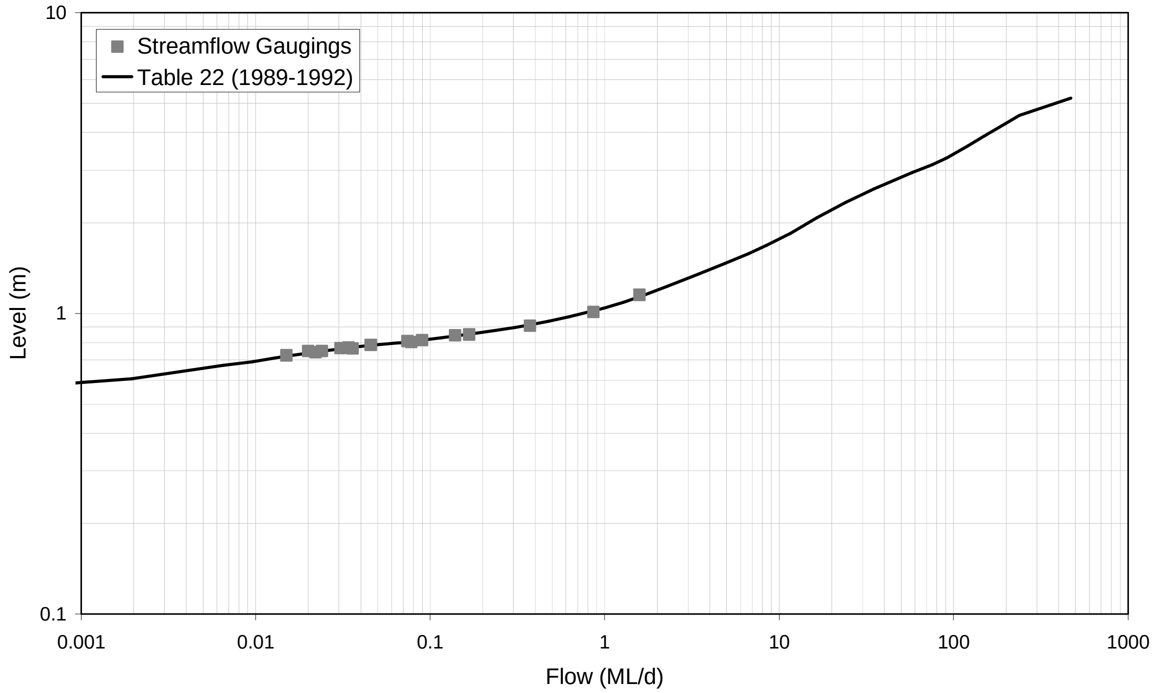

▪ **Figure A-80: Rating Table 19 and Streamflow Gaugings for 8170066 (1983-1984)**



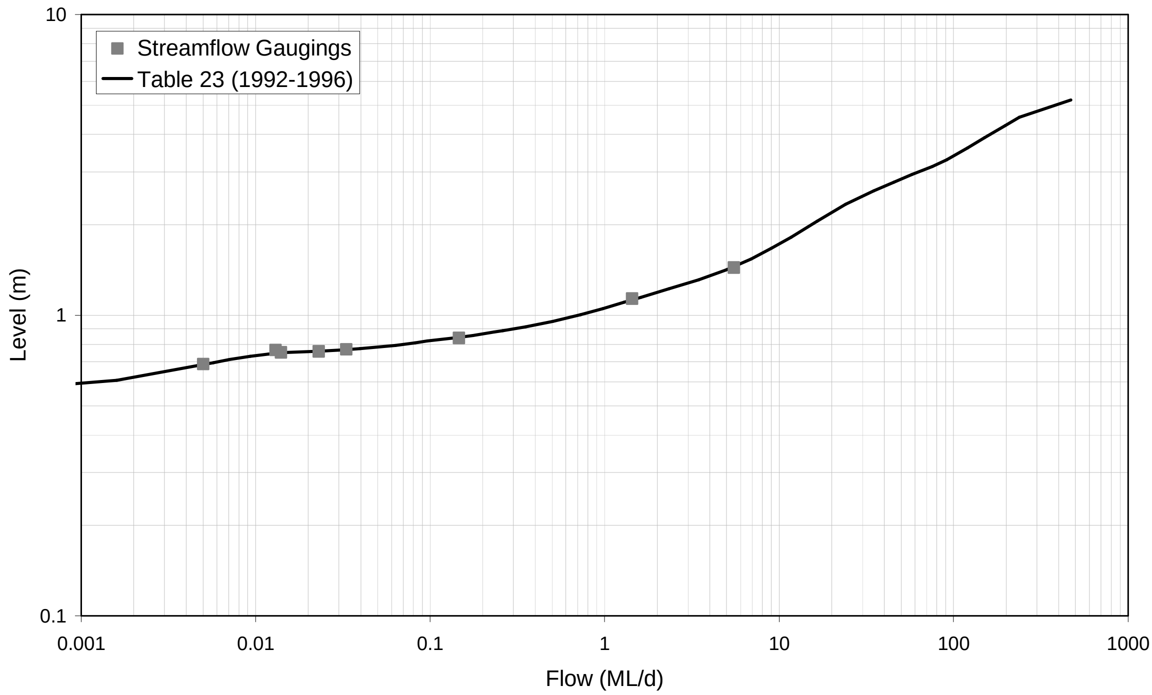

▪ **Figure A-81: Rating Table 20 and Streamflow Gaugings for 8170066 (1984-1987)**



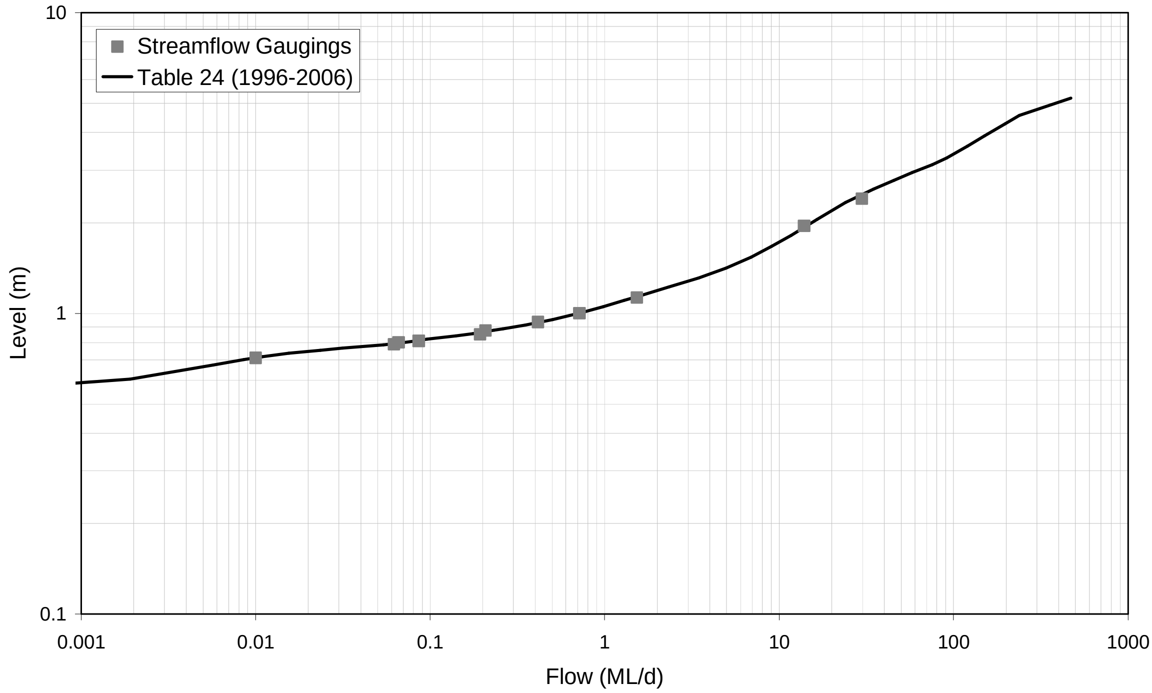

▪ **Figure A-82: Rating Table 21 and Streamflow Gaugings for 8170066 (1987-1989)**




■ **Figure A-83: Rating Table 22 and Streamflow Gaugings for 8170066 (1989-1992)**



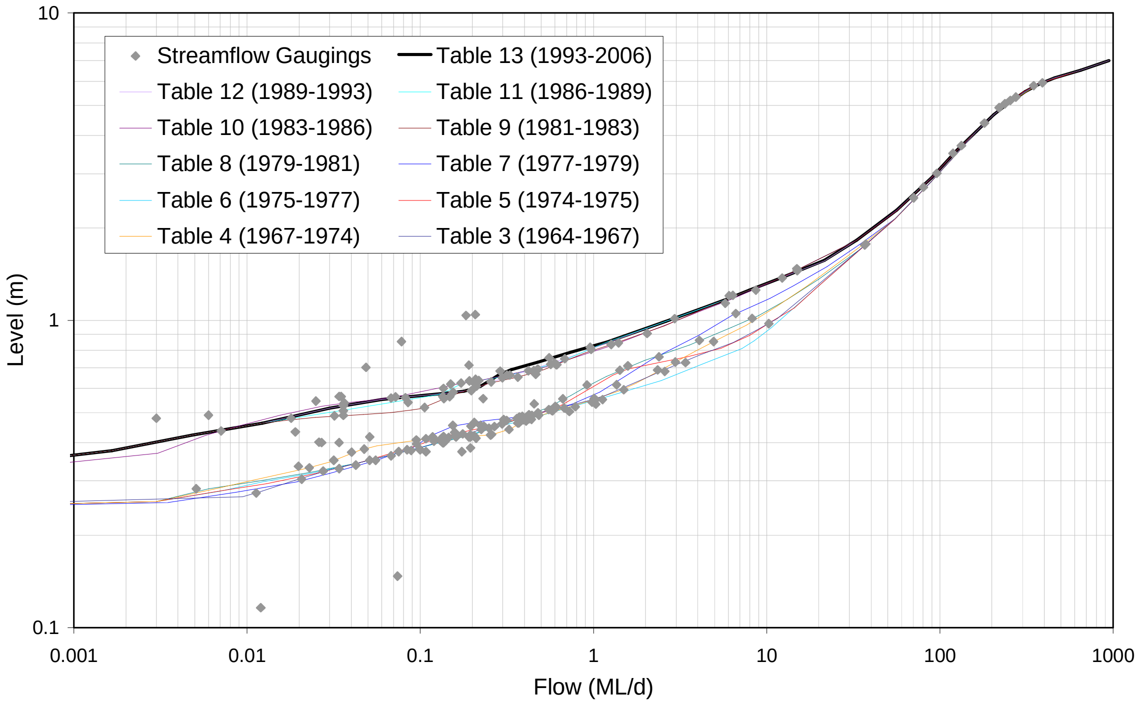

■ **Figure A-84: Rating Table 23 and Streamflow Gaugings for 8170066 (1992-1996)**



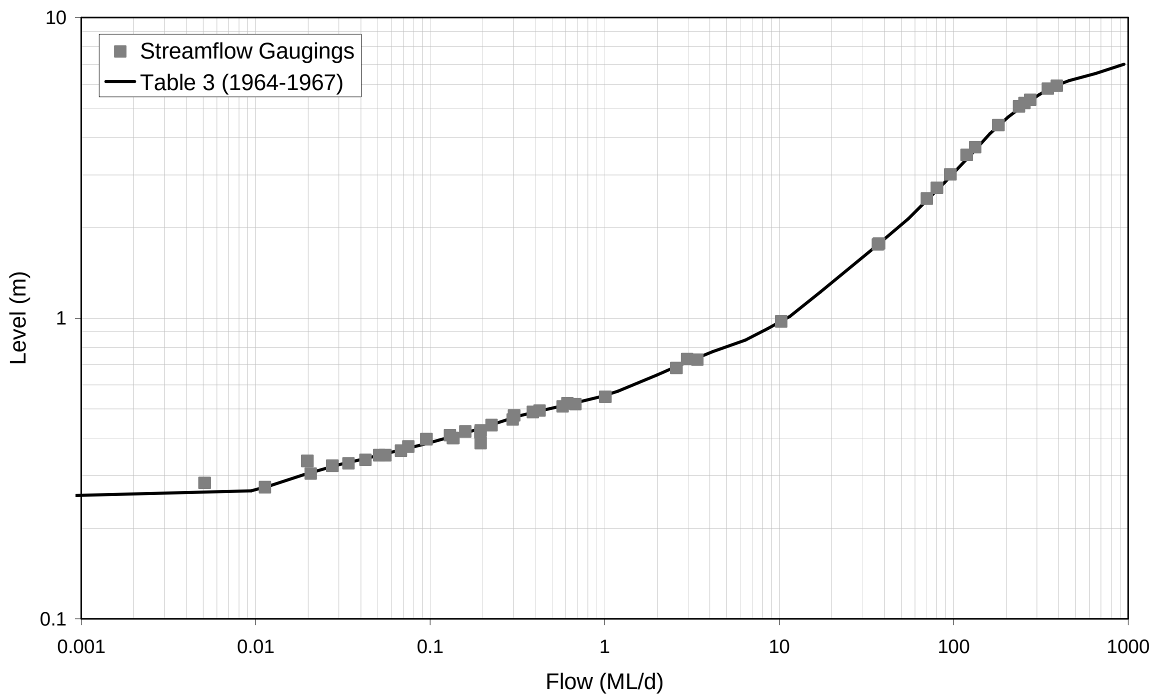

- **Figure A-85: Rating Table 24 and Streamflow Gaugings for 8170066 (1996-2006)**

## A.10 Adelaide River at Tortilla Flats (8170084)

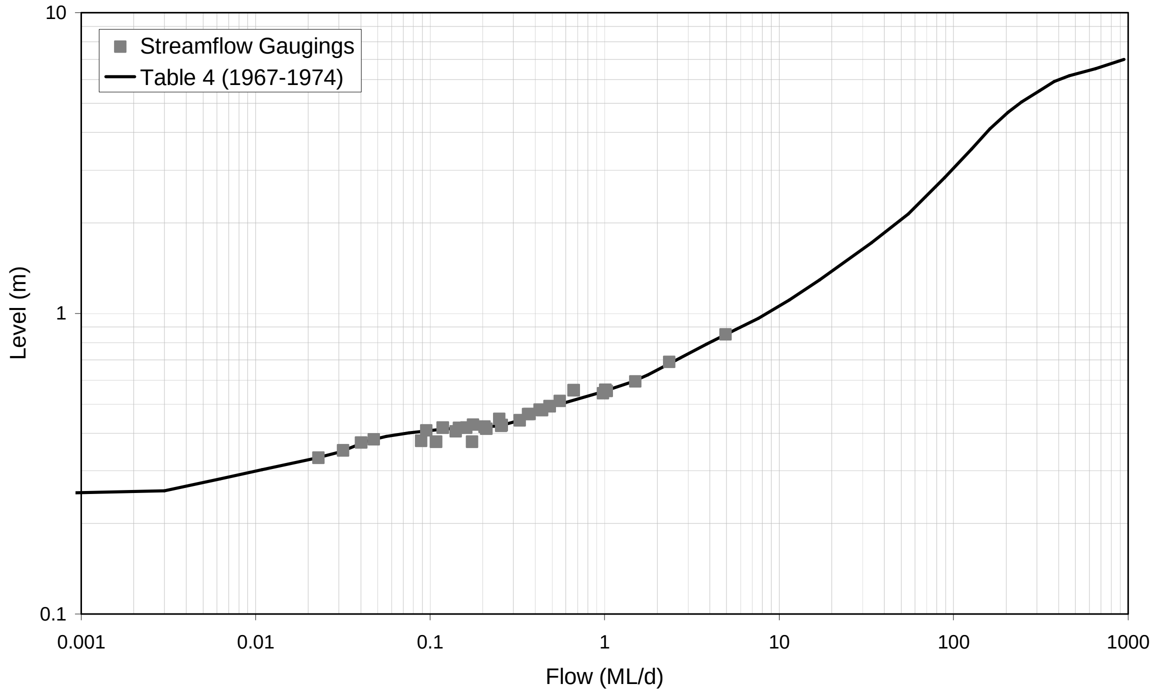
The gauge at 8170084 has had a number of changes in rating tables over the period of interest, as shown in Figure A-86. This indicates that the shape of the channel at this location is relatively unstable and thus there have been several significant changes in the shape of the rating at low flows. However, all of the rating tables shown correspond fairly well with the actual streamflow gaugings. The individual rating tables with their associated streamflow gauging points are shown below.



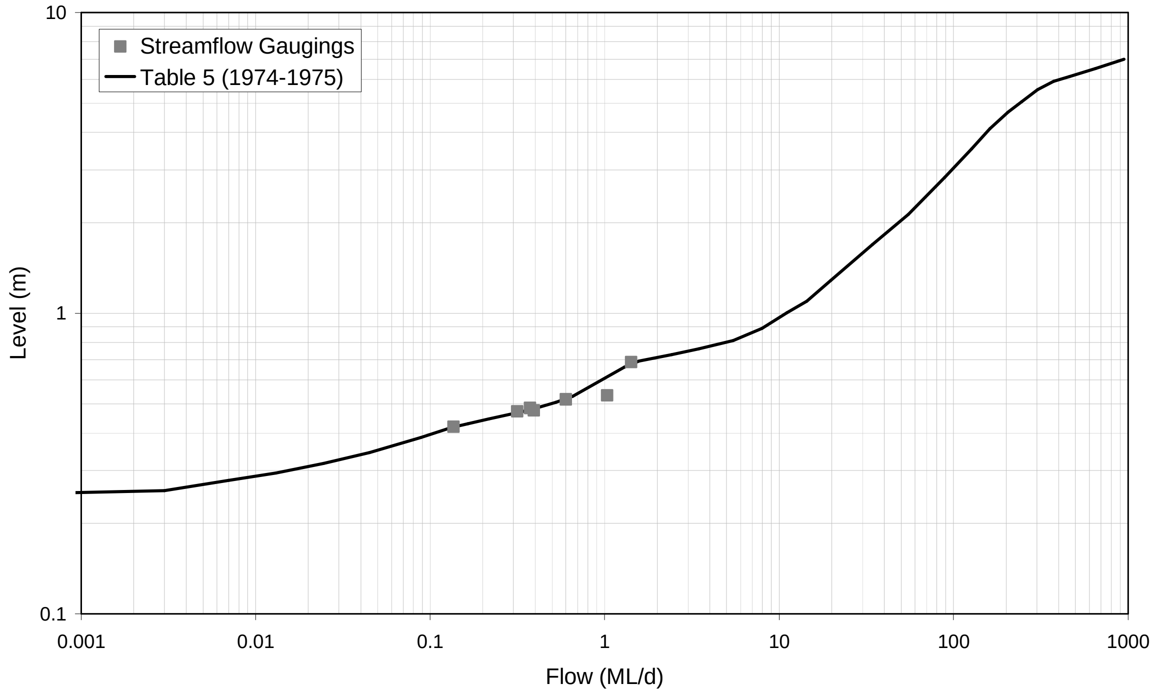

- **Figure A-86: All Rating Tables and Streamflow Gaugings for 8170084**



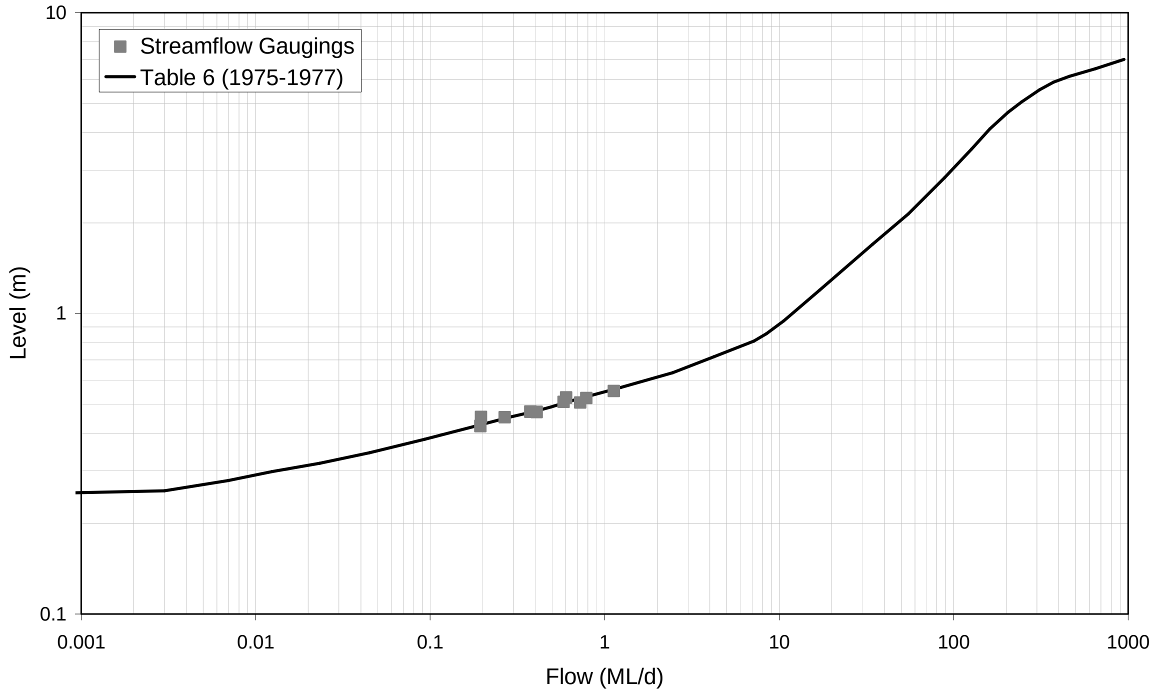

- **Figure A-87: Rating Table 3 and Streamflow Gaugings for 8170084 (1964-1967)**



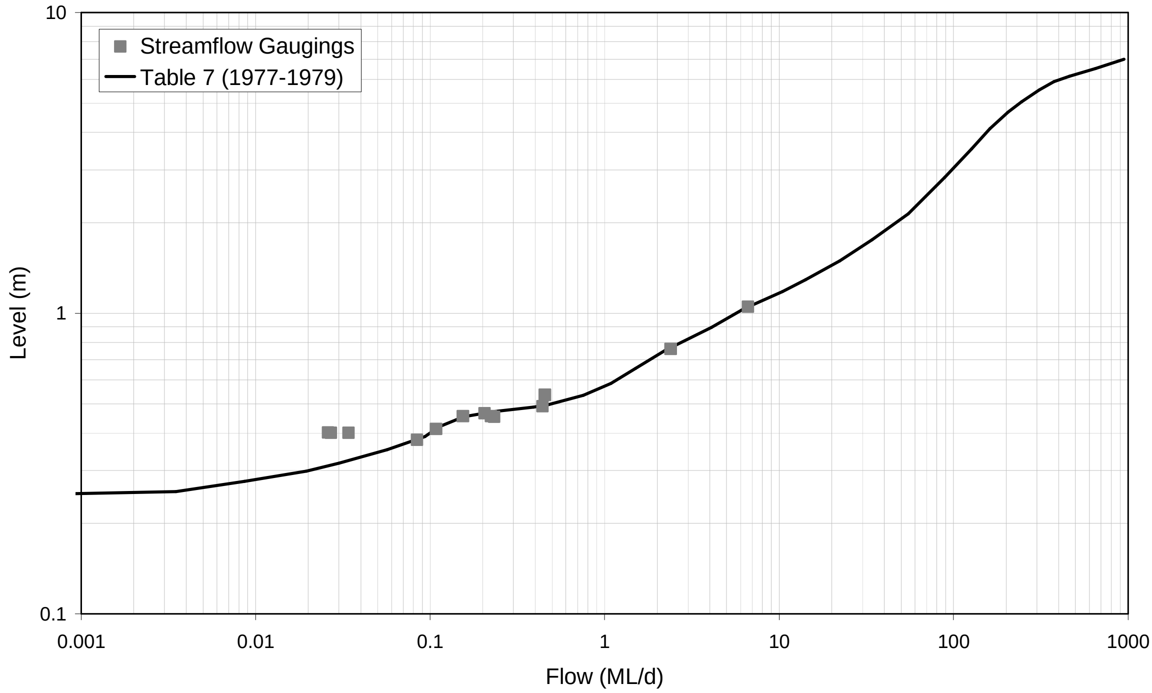

- **Figure A-88: Rating Table 4 and Streamflow Gaugings for 8170084 (1967-1974)**



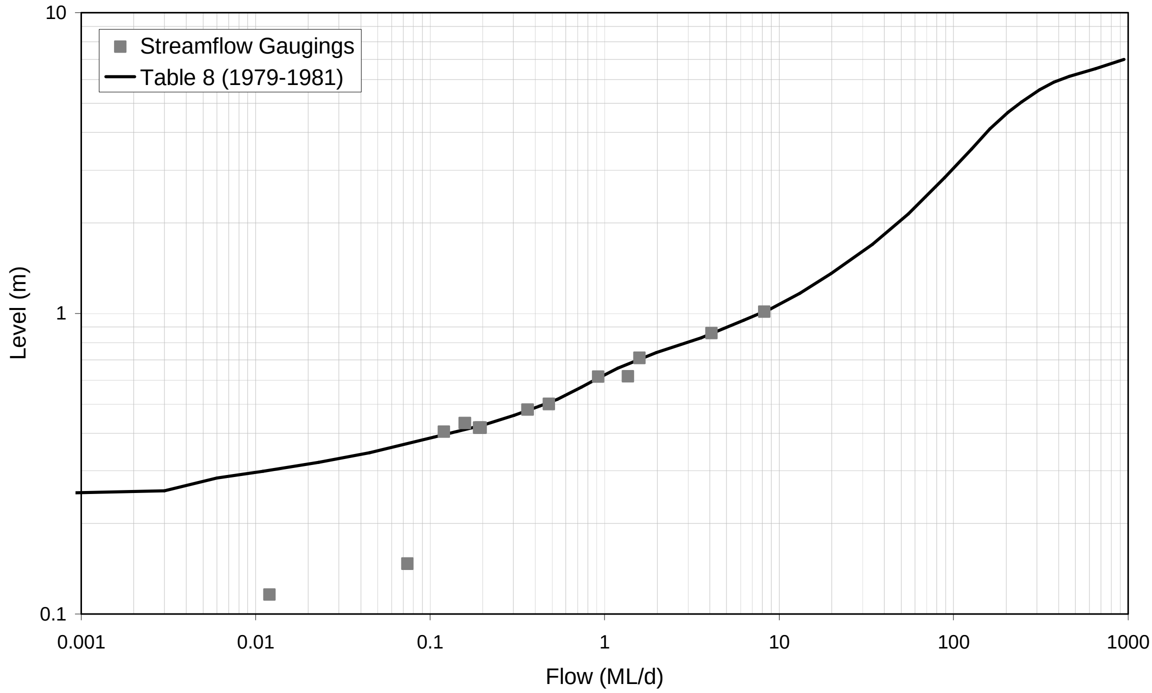

- **Figure A-89: Rating Table 5and Streamflow Gaugings for 8170084 (1974-1975)**



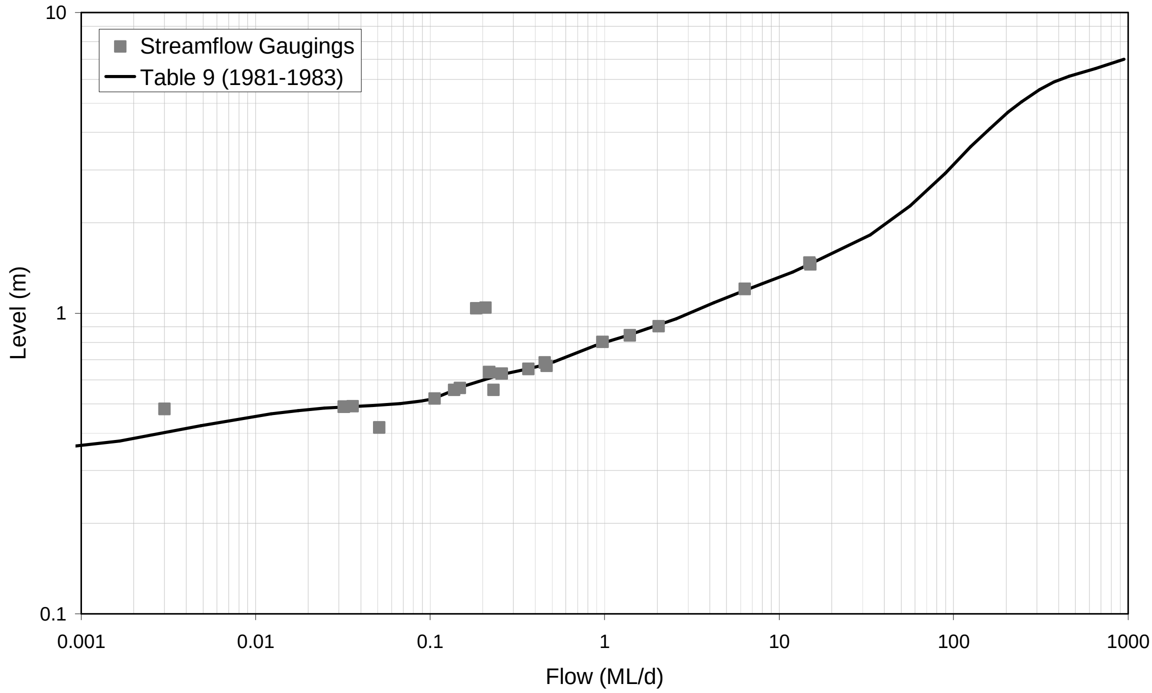

- **Figure A-90: Rating Table 6 and Streamflow Gaugings for 8170084 (1975-1977)**



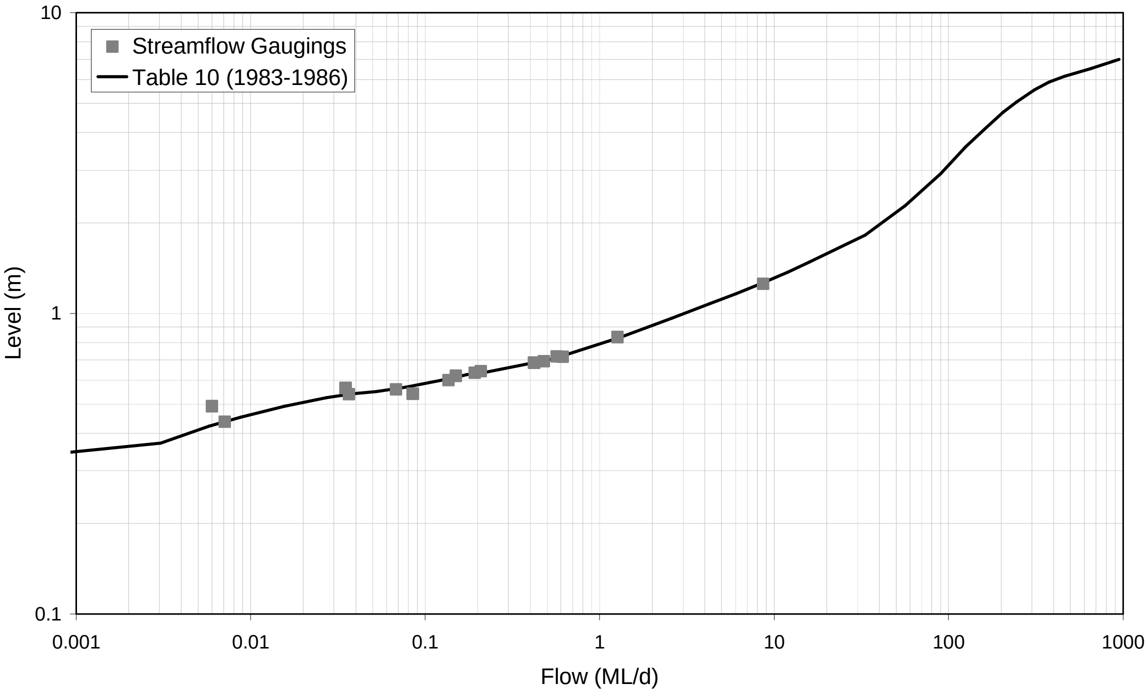

- **Figure A-91: Rating Table 7 and Streamflow Gaugings for 8170084 (1977-1979)**



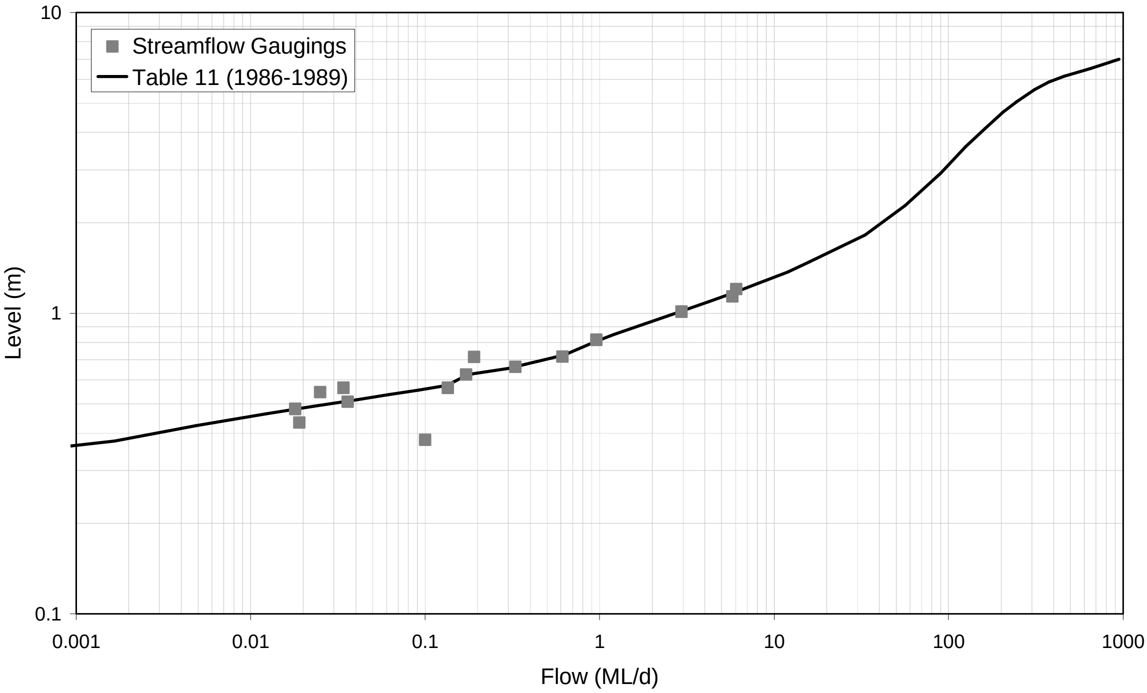

▪ **Figure A-92: Rating Table 8 and Streamflow Gaugings for 8170084 (1979-1981)**



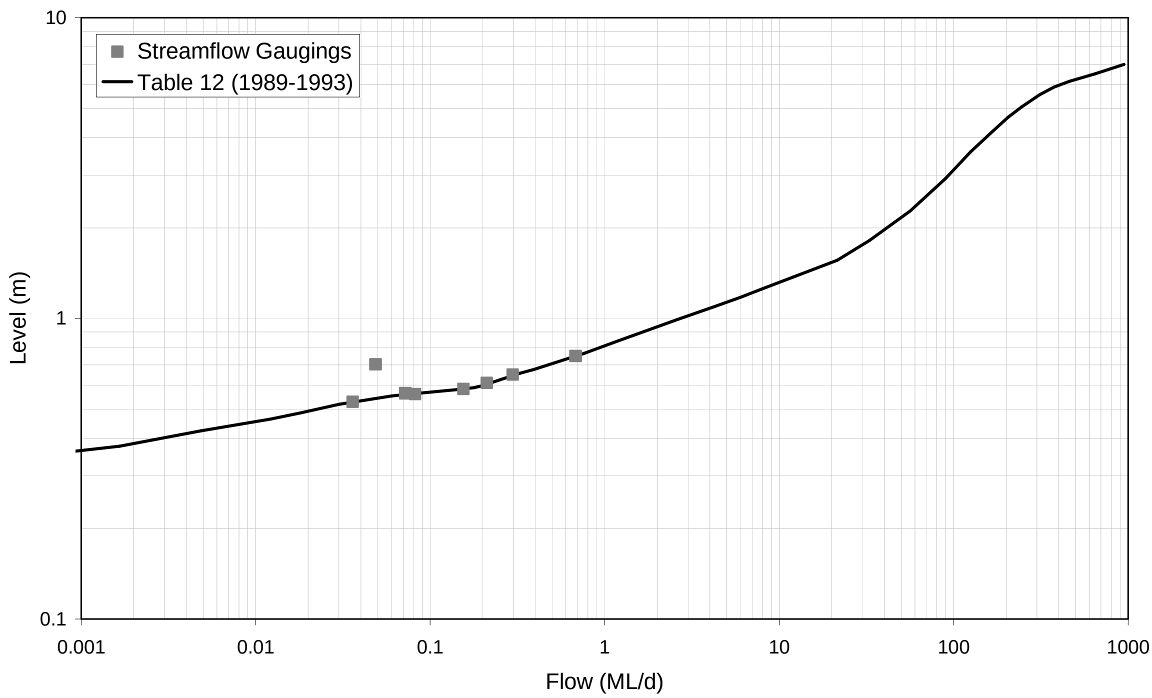

▪ **Figure A-93: Rating Table 9 and Streamflow Gaugings for 8170084 (1981-1983)**



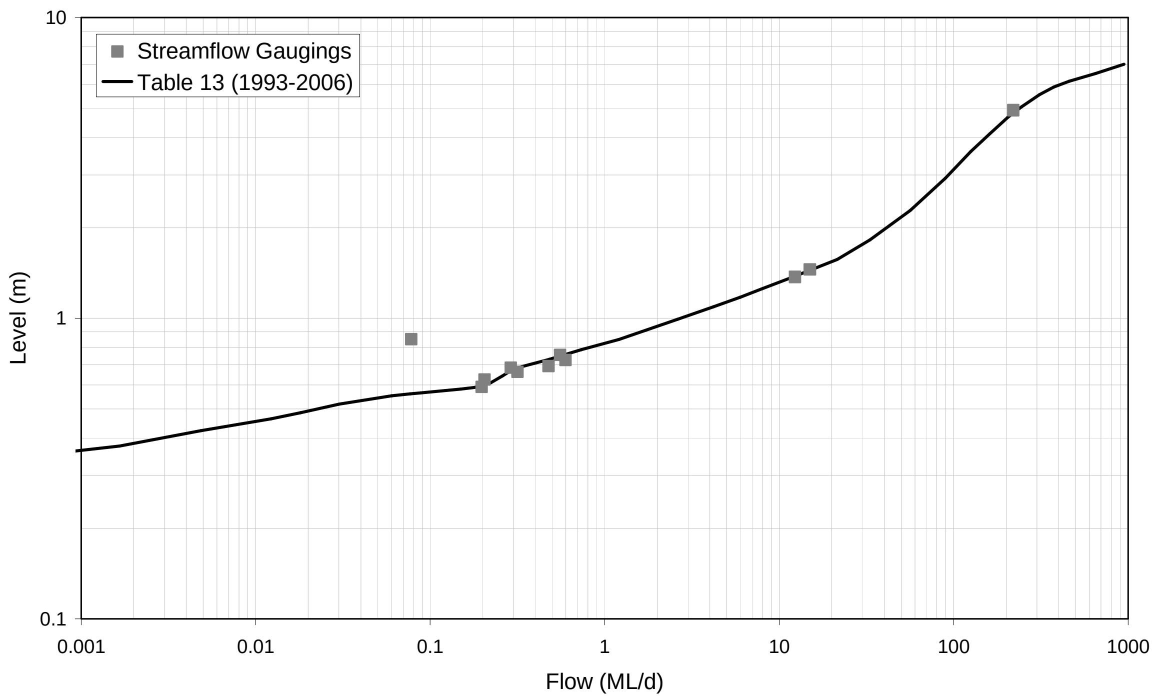

■ **Figure A-94: Rating Table 10 and Streamflow Gaugings for 8170084 (1983-1986)**




■ **Figure A-95: Rating Table 11 and Streamflow Gaugings for 8170084 (1986-1989)**



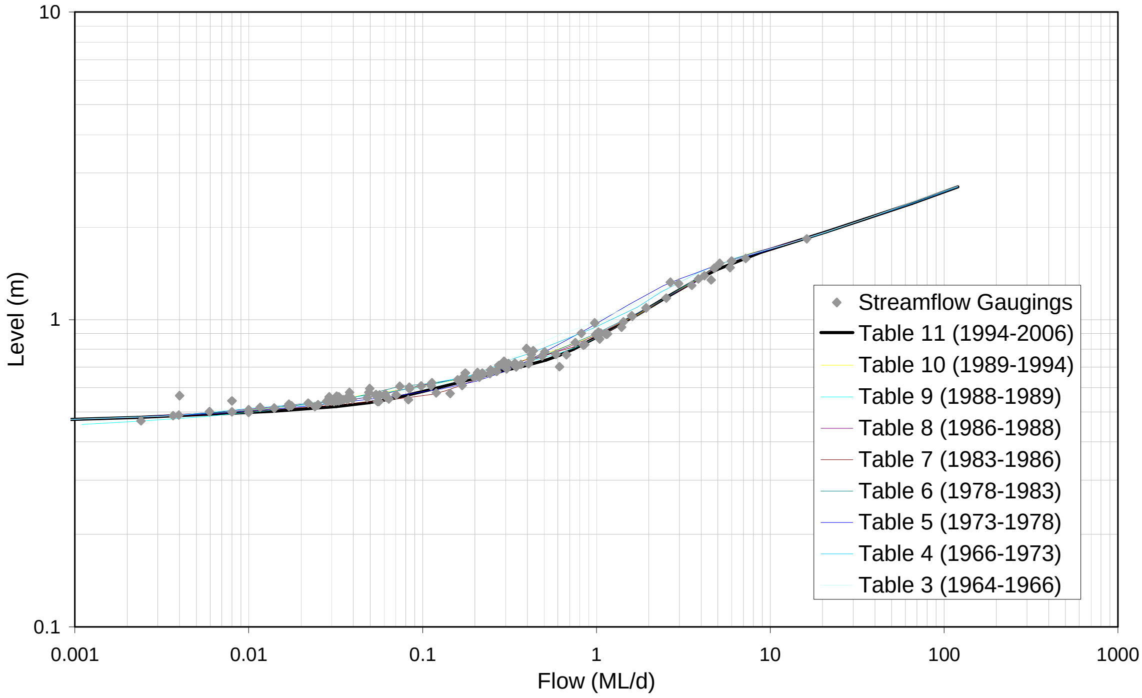

- **Figure A-96: Rating Table 12 and Streamflow Gaugings for 8170084 (1989-1993)**




- **Figure A-97: Rating Table 13 and Streamflow Gaugings for 8170084 (1993-2006)**

## A.11 Acacia Creek at Stuart Highway (8170085)

The gauge at 8170085 has had a number of changes in rating tables over the period of interest, as shown in Figure A-98. It can be seen that there has been little variation in the rating tables, and that they are all based on consistent streamflow gaugings. The individual rating tables with their associated streamflow gauging points are shown below.




- **Figure A-98: All Rating Tables and Streamflow Gaugings for 8170085**

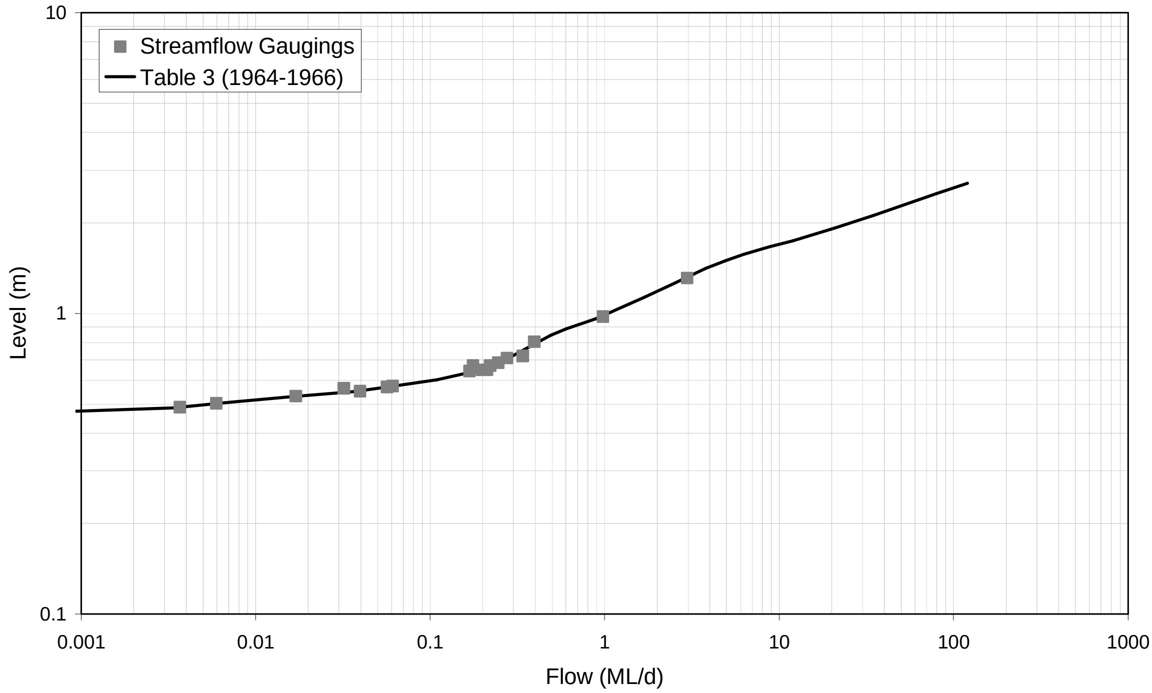



Figure A-99: Rating Table 3 and Streamflow Gaugings for 8170085 (1964-1966)

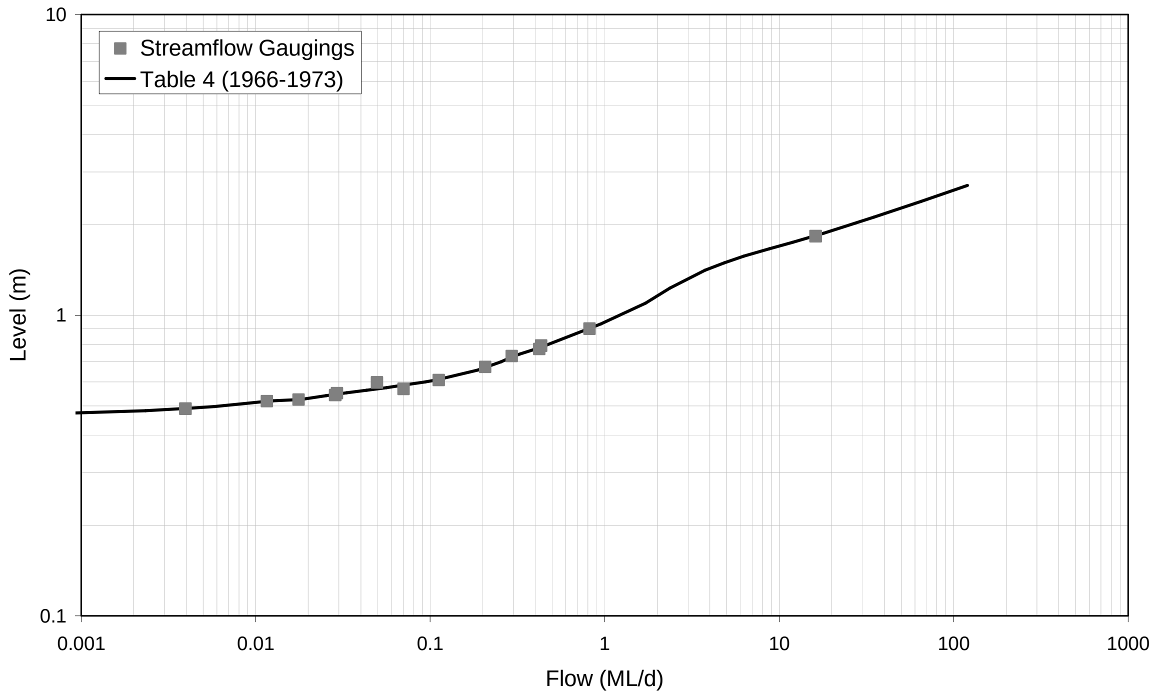
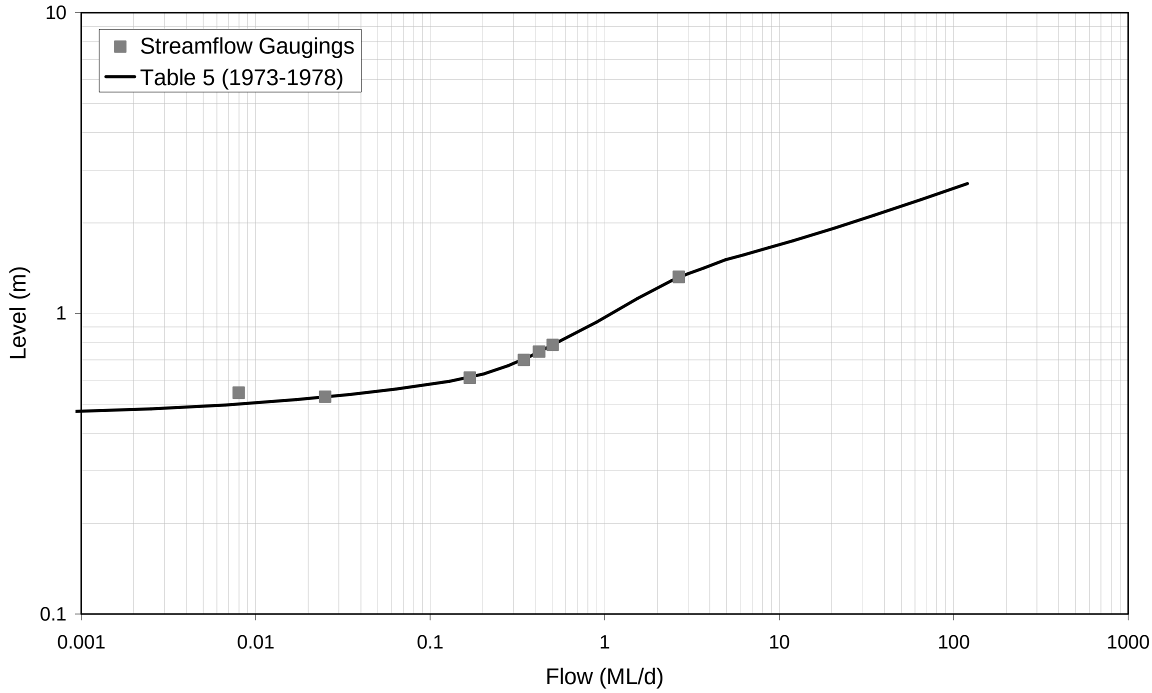
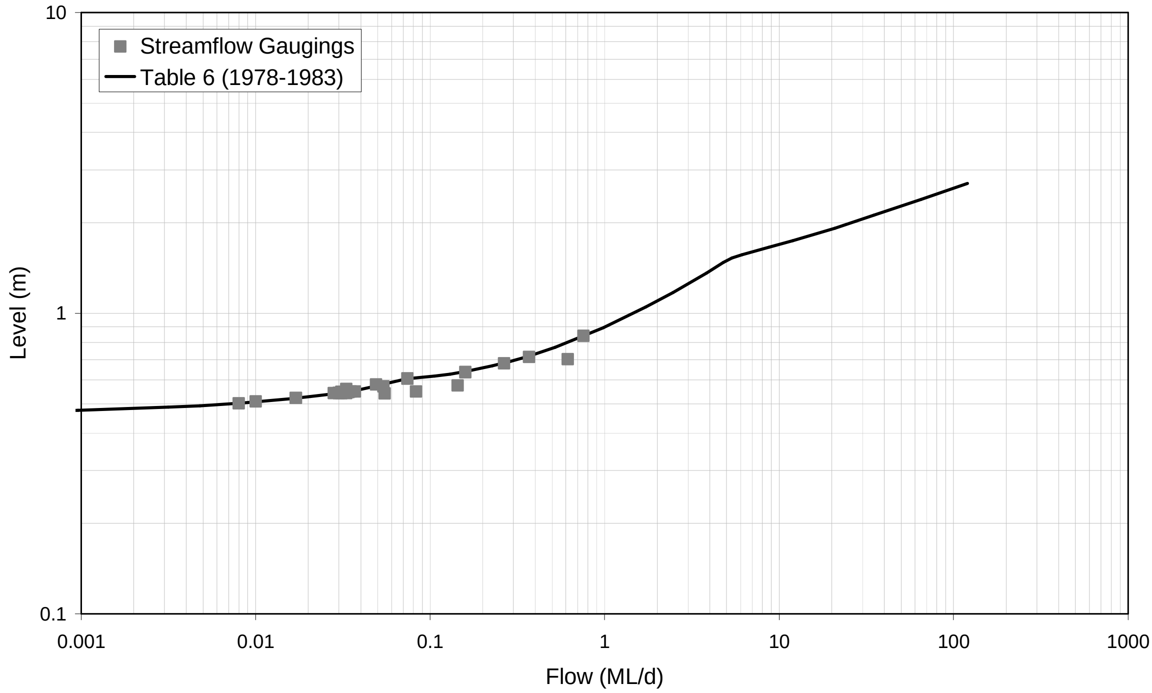


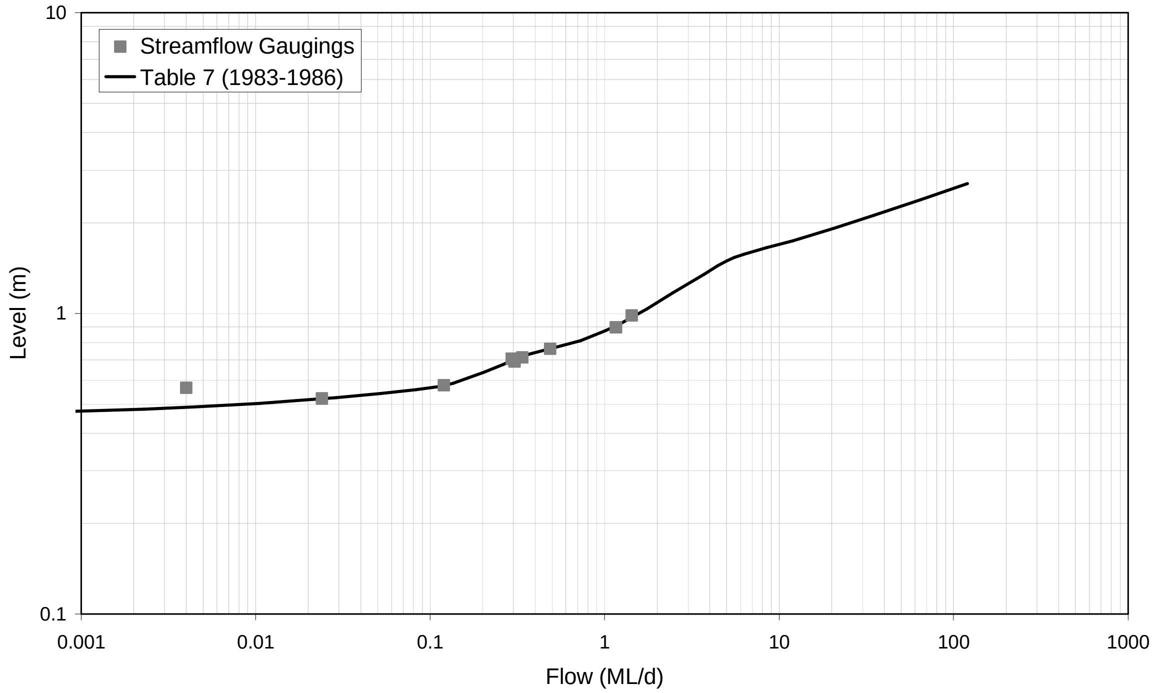

Figure A-100: Rating Table 4 and Streamflow Gaugings for 8170085 (1966-1973)



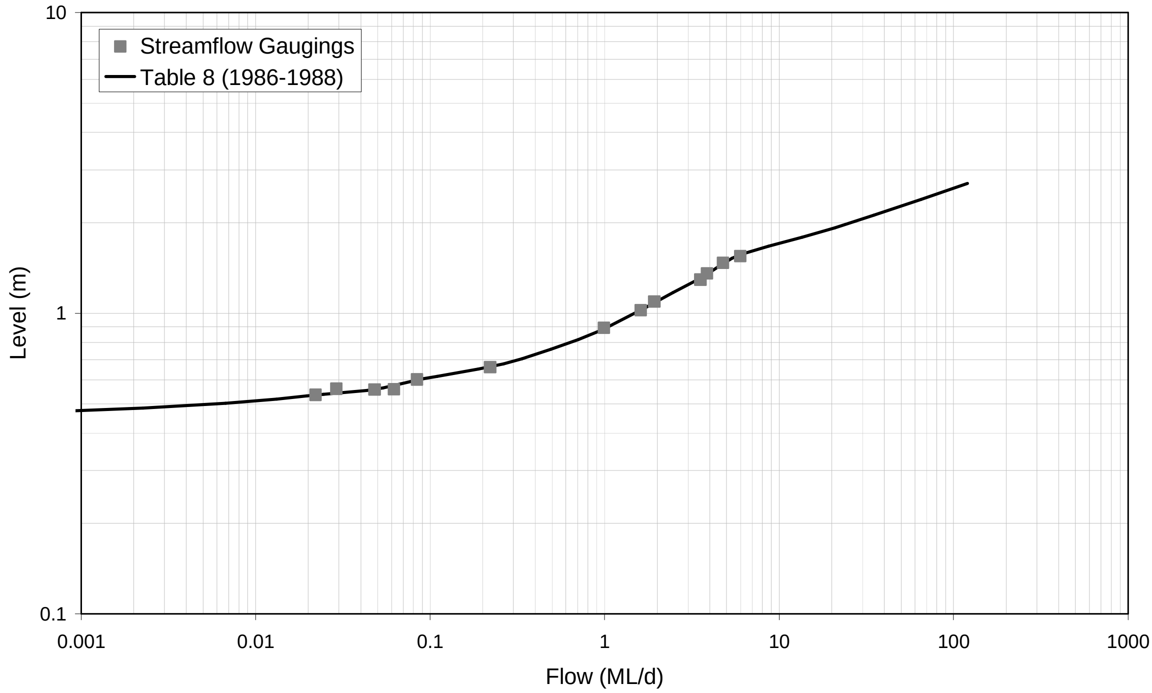

▪ **Figure A-101: Rating Table 5 and Streamflow Gaugings for 8170085 (1973-1978)**



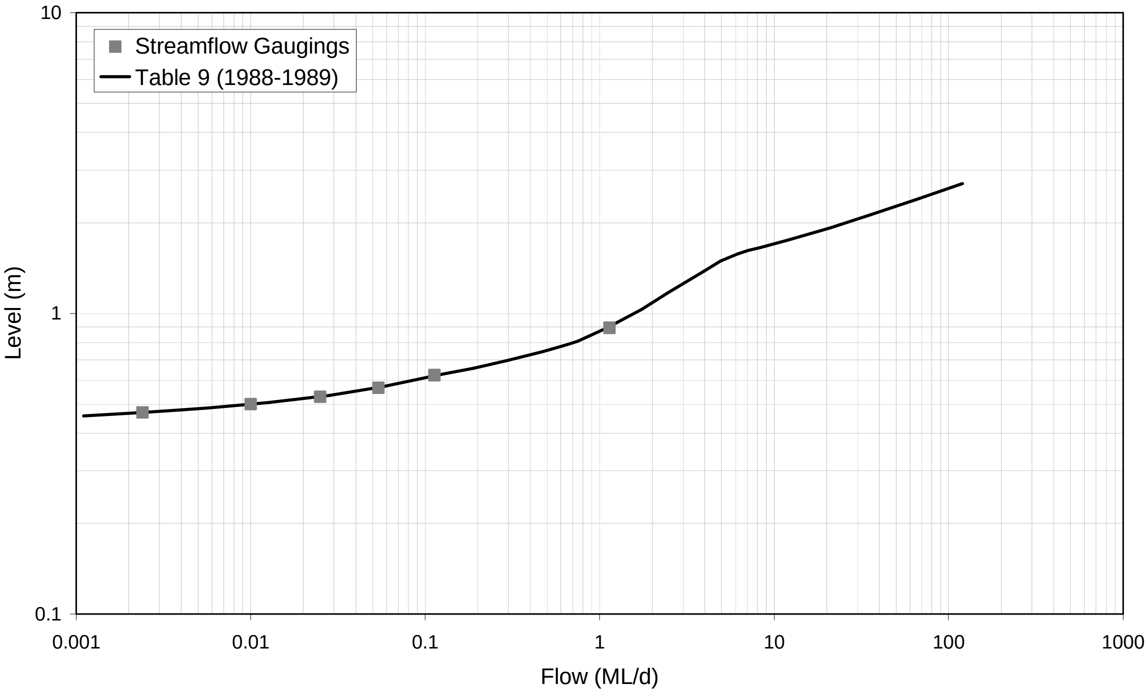

▪ **Figure A-102: Rating Table 6 and Streamflow Gaugings for 8170085 (1978-1983)**



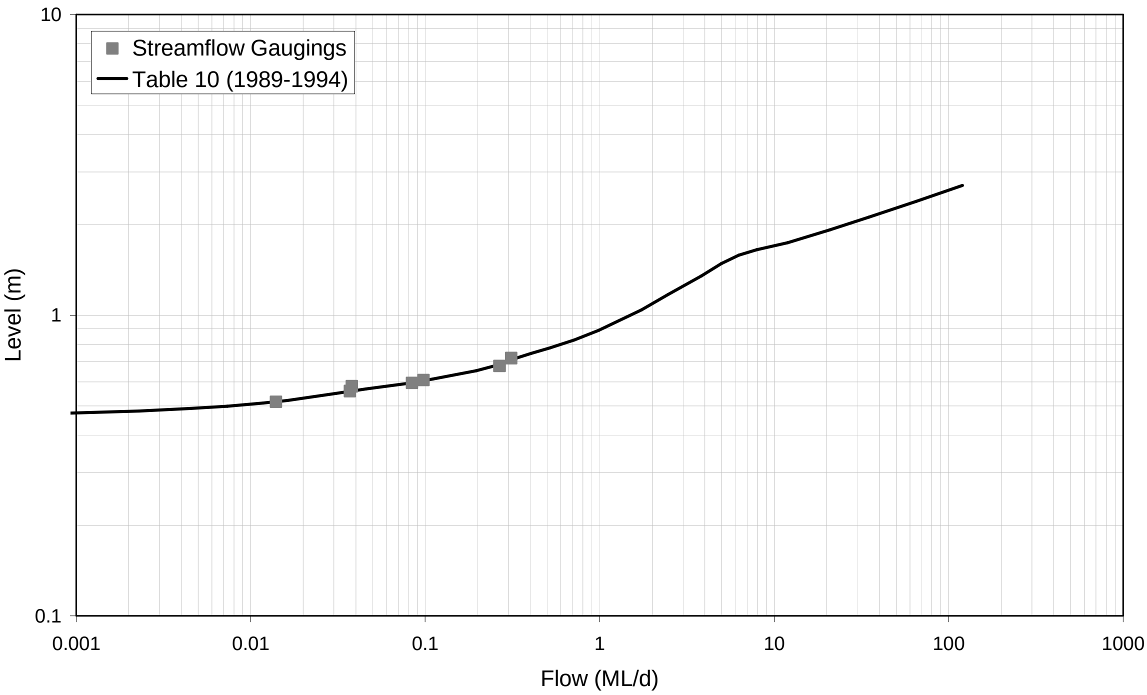

- **Figure A-103: Rating Table 7 and Streamflow Gaugings for 8170085 (1983-1986)**




- **Figure A-104: Rating Table 8 and Streamflow Gaugings for 8170085 (1986-1988)**




■ **Figure A-105: Rating Table 9 and Streamflow Gaugings for 8170085 (1988-1989)**




■ **Figure A-106: Rating Table 10 and Streamflow Gaugings for 8170085 (1989-1994)**

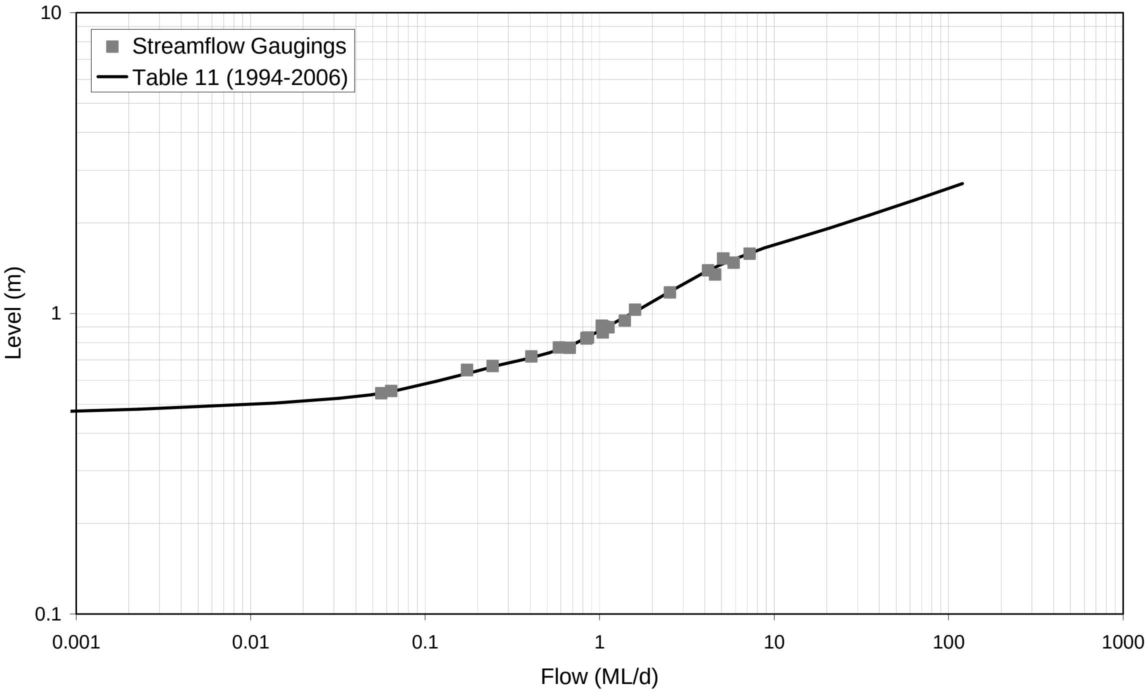



**Figure A-107: Rating Table 11 and Streamflow Gaugings for 8170085 (1994-2006)**

# Appendix B Streamflow Data Availability

## B.1 Data Availability and Gauge Selection

Streamflow data for all available gauges in the Finniss River and Adelaide River basins was supplied by NRETA. Gauges that were downstream of major regulating structures such as the Darwin River Dam were excluded from the analysis. Additionally, tide gauges and gauges on water supply or small drainage channels were also excluded. A thorough review of the data from the remaining 27 gauges was then undertaken to determine which gauges were suitable for use in the analysis.

A summary of the 27 gauges in the Finniss River and Adelaide River basins suitable for use in this analysis is given in Table B-1. The gauges are listed in order of gauge number, with gauges in the Finniss River basin (basin number 815) first, followed by gauges in the Adelaide River basin (basin number 817).

A number of gauges were immediately excluded from any further consideration in this project based on the characteristics of each catchment. This included Sandy Creek at Casuarina Hospital (8150003), which is located on a small coastal stream in an urban area. As such, data recorded at this gauge in unlikely to be representative of the hydrological processes occurring more broadly across the two basins. Also excluded for this reason was Winnellie Drain at Tiger Brennan Drive (8150016).

Investigation of the missing data at each gauge showed there were a number of reasons for missing data. NRETA attaches a quality code to each day of recorded streamflow data that indicates the reliability of the data for that day. These codes range from 1 to 255, with any data coded above 150 considered unreliable. The percentage of missing data in Table B-1 refers to the percentage of data within the start and end dates of each gauge with quality codes greater than 150. On further investigation, it was found that much of the 'missing' data had been quality coded as 175 or 176, which indicates that the water level of the stream was below the sensor orifice. In these cases it is likely that the streamflow on these days was or was very close to zero. This assumption was confirmed with NRETA, and all missing data coded 175 or 176 was replaced with zero.

▪ **Table B-1: Summary of Suitable Streamflow Gauges**

| Gauge No | Name | Start Record | End Record | Missing Data | Missing Data After Replacement of QC Codes 175 and 176 |
|---|---|---|---|---|---|
| 8150003 | Sandy Creek at Casuarina Hospital | 01/09/1979 | 15/09/1981 | 47% | 47% |
| 8150005 | Howard Springs Creek at Sandpits | 30/11/1968 | 11/07/1974 | 9% | 8% |
| 8150010 | Finniss River at Batchelor Dam Site | 23/12/1974 | 16/02/2006 | 4% | 1% |
| 8150016 | Winnellie Drain at Tiger Brennan Drive | 23/11/1995 | 19/12/2003 | 12% | 12% |
| 8150018 | Elizabeth River at Stuart Highway | 01/02/1953 | 28/06/2006 | 44% | 20% |
| 8150027 | Berry River at March Fly Weir | 02/11/1960 | 25/08/1981 | 3% | 3% |
| 8150096 | Carawarra Creek at Cox Peninsula Road | 17/02/1965 | 14/02/2006 | 32% | 20% |
| 8150097 | East Finniss River at Rum Jungle | 20/01/1965 | 26/05/2006 | 19% | 3% |
| 8150098 | Blackmore River at Tumbling Waters | 22/02/1961 | 04/08/2005 | 10% | 7% |
| 8150152 | Beetsons Creek upstream of Darwin River Dam | 06/09/1972 | 26/08/1981 | 0% | 0% |
| 8150179 | Howard River at Koolpinya Stockyard | 30/10/1963 | 22/06/2006 | 53% | 53% |
| 8150180 | Finniss River at Gitchams | 29/10/1960 | 15/02/2006 | 5% | 5% |
| 8150200 | East Finniss River at Rum Jungle Road Crossing | 07/12/1981 | 26/05/2006 | 24% | 20% |
| 8150204 | Finniss River North West of Mount Fitch | 15/12/1981 | 14/09/1995 | 61% | 51% |
| 8170002 | Adelaide River at Railway Bridge | 02/03/1953 | 30/01/2005 | 19% | 19% |
| 8170005 | Adelaide River upstream of Marrakai Crossing | 01/09/1957 | 31/08/2005 | 23% | 17% |
| 8170008 | Adelaide River Downstream Daly Road | 27/08/1981 | 29/01/2005 | 45% | 45% |
| 8170032 | Margaret River upstream of Marrrakai Crossing | 14/01/1957 | 26/07/1978 | 48% | 13% |
| 8170059 | Len Graham Creek upstream of Fogg Dam | 21/10/1958 | 02/04/1962 | 65% | 54% |
| 8170062 | Burrell Creek at Eighty-Seven Mile Jump | 09/11/1957 | 31/08/1986 | 50% | 7% |
| 8170065 | Howley Creek downstream of Brocks Creek Mine | 17/12/1997 | 31/08/2001 | 63% | 45% |

| Gauge No | Name | Start Record | End Record | Missing Data | Missing Data After Replacement of QC Codes 175 and 176 |
|---|---|---|---|---|---|
| 8170066 | Coomalie Creek at Stuart Highway | 01/09/1958 | 26/08/2005 | 4% | 4% |
| 8170076 | Stapleton Creek at Stuart Highway | 01/11/1963 | 27/08/1981 | 60% | 45% |
| 8170084 | Adelaide River at Tortilla Flats | 18/09/1963 | 31/08/2005 | 15% | 6% |
| 8170085 | Acacia Creek at Stuart Highway | 11/11/1963 | 31/08/2005 | 32% | 7% |
| 8170089 | Snake Creek at Stuart Highway | 01/11/1963 | 08/05/1969 | 82% | 80% |
| 8170240 | Margaret River at Bob's Hill | 01/09/1980 | 31/08/1986 | 58% | 23% |

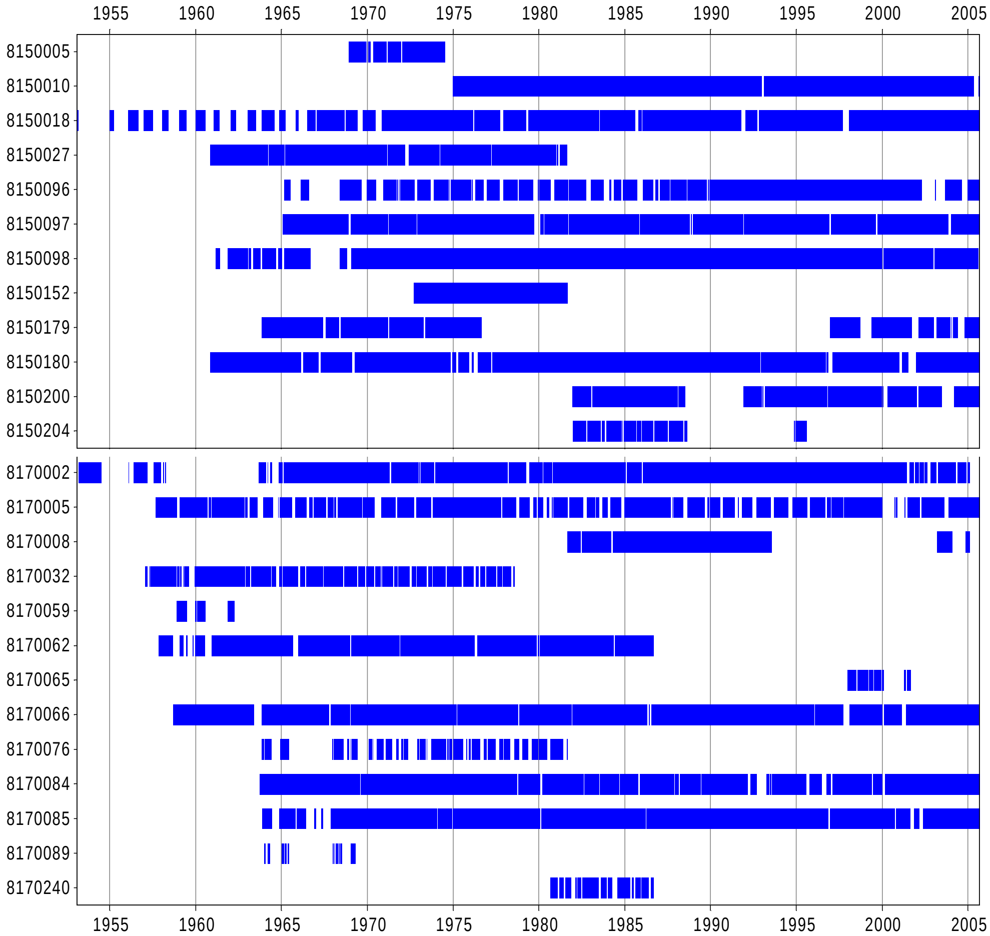
Once all missing data quality coded 175 or 176 had been removed from the time series, a more accurate picture of the percentage of unrecorded or lost data at each gauge could be established. This led to further gauges being deemed unsuitable for inclusion in the analysis, generally because their period of record was too short to contribute meaningfully to the statistical analysis, or because too much of the data was missing.

## B.2 Selection of Analysis Period

Having removed gauges with inappropriate hydrological characteristics and ensuring that all missing data was due to a faulty gauge reading rather than a day of zero flow, the streamflow data time series for all the gauges was investigated to determine a suitable analysis period. Selection of the analysis period was driven by the requirement to have a full record of data from the start to the end of the period at each gauge being analysed. Infilling missing periods of data using streamflow regressions based on neighbouring gauges was used to eliminate short periods of missing data, but this was undertaken sparingly as it has the potential to cross-correlate trends in the data from one gauge to another. Streamflow data was only infilled and used where less than 10% of the data at each gauge used in the analysis could be missing.

Data from all gauges (excluding those previously eliminated) was plotted as a Gantt chart so that gaps in the data could be compared. This is shown in Figure B-1, and it can be seen that there are many periods of missing data at most of the gauges scattered throughout the period of record. This chart was then used to identify likely analysis periods. The aim of the analysis period was to select as many gauges as possible, for as long a period of record as possible, while minimising the amount of missing data requiring infilling. It was found that this could most optimally be achieved for two different analysis periods.

The first analysis period selected ran from 1965 to 2005. The advantage of this period is that it contains a good representation of streamflow variability for a relatively large number of years. However, only 7 of the possible 25 gauges had a sufficient amount of recorded data to be included in the analysis. One of the gauges (8170066) was found to be influenced by discharges from Woodcutters Mine over the period 1985 to 1987. The magnitude of these discharges was in the order of 9 to 17 ML/d, which was a significant component of the dry season flow regime. As a result, this gauge was excluded from the first analysis period. Alternatively, for the period 1968 to 1978 there were 11 gauges with enough data to be included in the analysis, but the length of the period was significantly shorter. As there was insufficient information available at this stage to resolve this trade-off between temporal and spatial variability, it was decided to proceed with the analysis using both analysis periods. The gauges available for each period of analysis are summarised in Table B-2. For each selected streamflow gauge, a catchment boundary was identified using GIS tools.




- **Figure B-1: Gantt Chart For Selected Finniss River and Adelaide River Streamflow Gauges**

**Table B-2: Summary of Streamflow Gauges Selected for Each Analysis Period**

| Gauge No | Name | Catchment Area ($km^2$) | 1965-2005 | 1968-1978 |
|---|---|---|---|---|
| 8150018 | Elizabeth River at Stuart Highway | 94 | ✓ | ✓ |
| 8150027 | Berry River at March Fly Weir | 141 | × | ✓ |
| 8150097 | East Finniss River at Rum Jungle | 74 | ✓ | ✓ |
| 8150098 | Blackmore River at Tumbling Waters | 182 | ✓ | ✓ |
| 8150180 | Finniss River at Gitchams | 1,048 | ✓ | ✓ |
| 8170002 | Adelaide River at Railway Bridge | 655 | ✓ | ✓ |
| 8170005 | Adelaide River upstream of Marrakai Crossing | 1,635 | × | ✓ |
| 8170062 | Burrell Creek at Eighty-Seven Mile Jump | 42 | × | ✓ |
| 8170066 | Coomalie Creek at Stuart Highway | 84 | × | ✓ |
| 8170084 | Adelaide River at Tortilla Flats | 1,173 | ✓ | ✓ |
| 8170085 | Acacia Creek at Stuart Highway | 11 | ✓ | ✓ |

## B.3 Comparison of hydrologic Indices over the two analysis periods

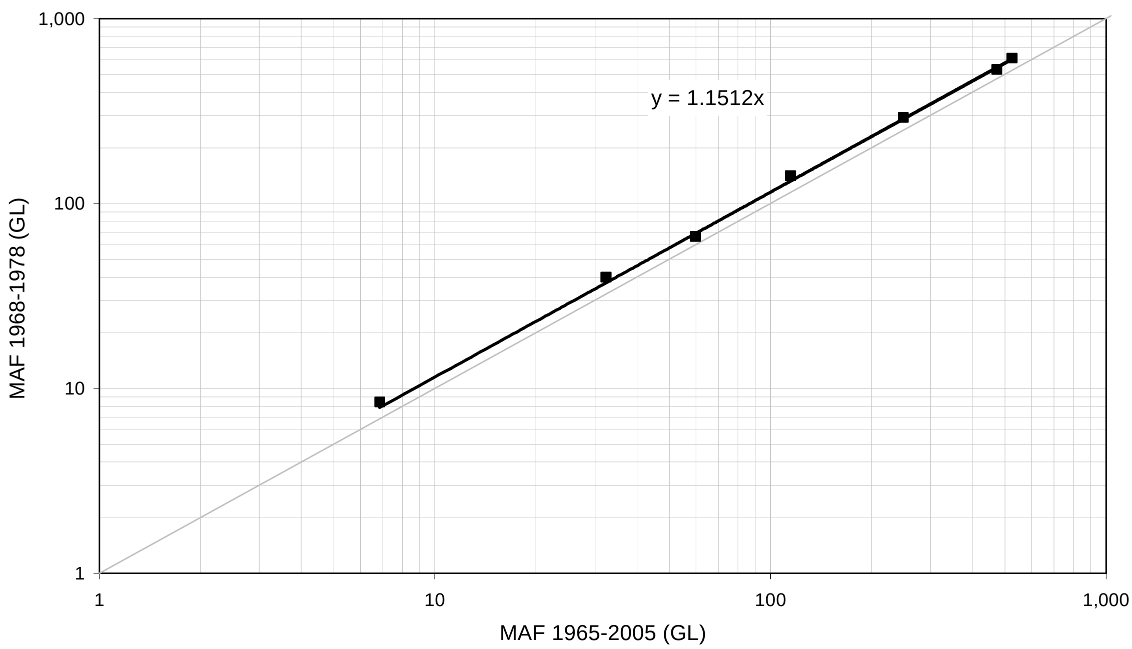
To determine the relative influence of temporal variability across the two different analysis periods, the hydrological indices from those gauges with data for both analysis periods were plotted against each other. A line of best fit passing through the origin was then added to each plot. The slope of this line indicates the degree of difference from one analysis period to another. A high degree of difference indicates that estimates of an index are considerably different from one analysis period to the other, and hence that temporal variability is an important consideration for that variable.

These plots are shown in Figure B-2 to Figure B-10. The calculated percentage bias is shown for each of the indices in Table B-3. These statistics indicate that temporal variability is influential in estimates of hydrological indices in the catchments of interest. It can be seen that estimates of mean annual flow are typically 15% higher when calculated over the shorter analysis period as compared to the longer analysis period. This rises to as much as 20% for the wet season median flow. Some of the indices have differences of less than 5% (for example the wet season 80$^{th}$ percentile flow) but it can be seen from the plot that there is a relatively large degree of scatter around the line of best fit. The low degree of difference calculated for these indices is sometimes due to the fact that there is one larger estimate which corresponds well across both analysis periods. This can be observed in Figure B-7.

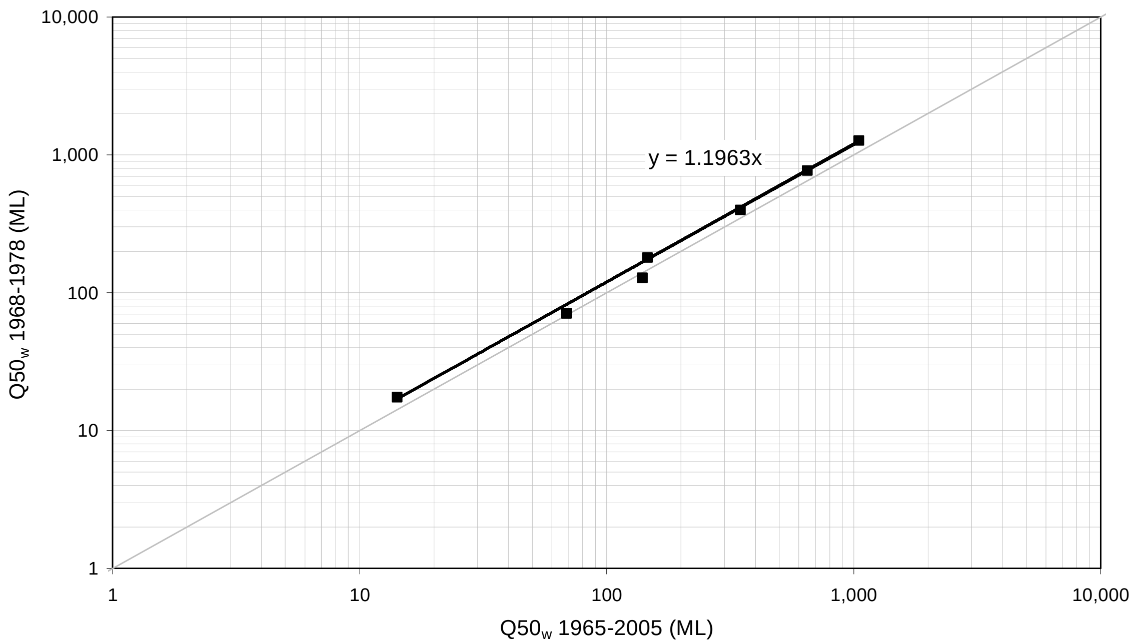
It is also worth noting that indices which describe the low flow portion of the flow regime (eg the dry season indices, the 80$^{th}$ percentile flow indices and the cease to flow) tend to be more variable from one analysis period to another. This indicates that there is more natural variability at the lower range of flows as compared with the larger flows.

## Table B-3: Degree of Difference from Longer to Shorter Analysis Period

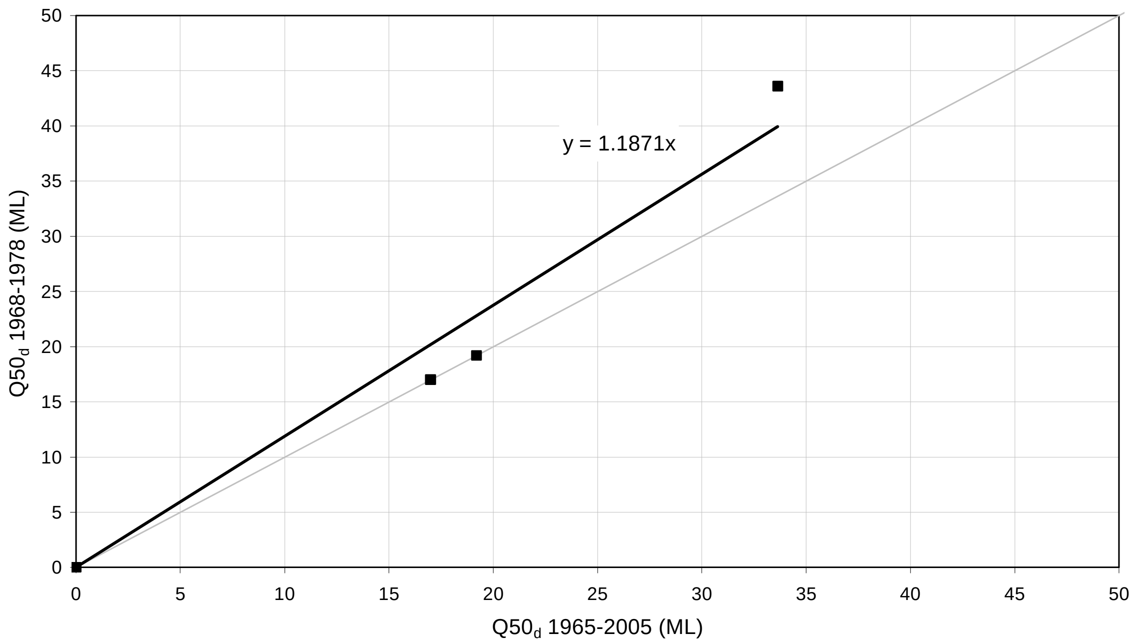
| Index | Percentage Increase in Estimate from Longer Period to Shorter Period |
|---|---|
| MAF | 15% |
| Q50w | 20% |
| Q50d | 19% |
| Q20w | 18% |
| Q20d | 13% |
| Q80w | 2% |
| Q80d | 2% |
| CTF | -10% |
| BFI | -2% |



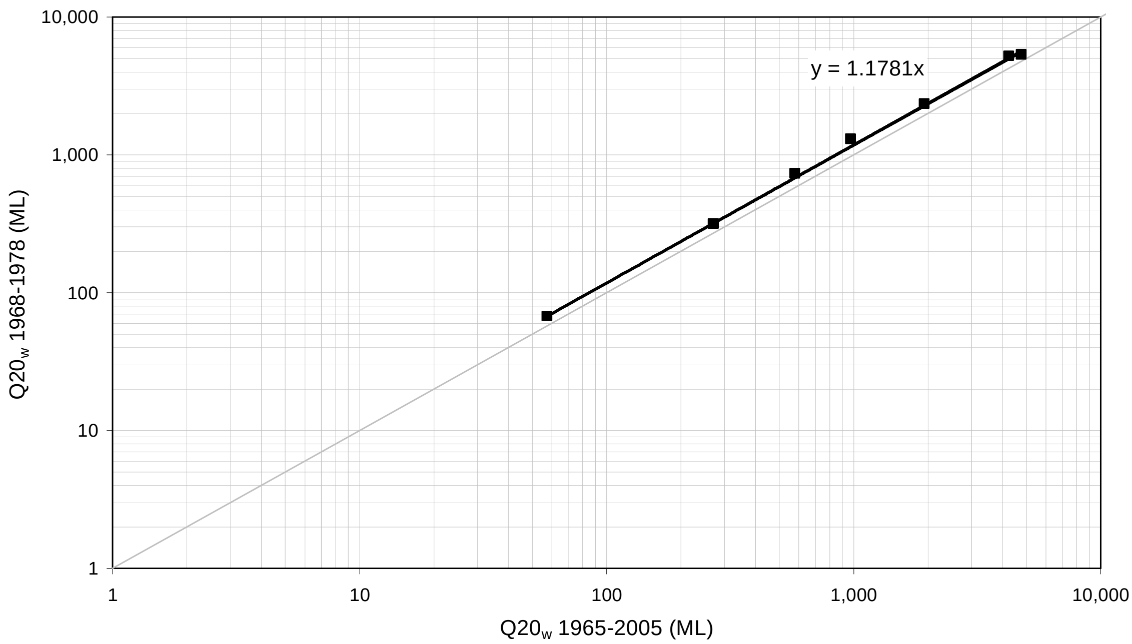

## Figure B-2: Comparison of Mean Annual Flow Estimates



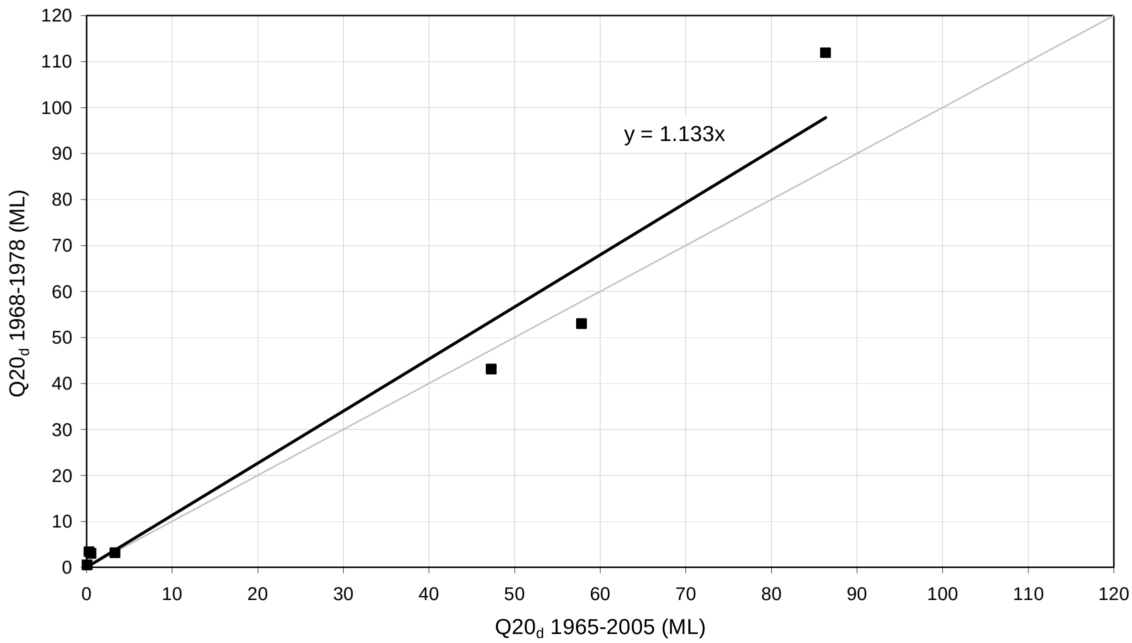

■ **Figure B-3: Comparison of Wet Season Median Flow Estimates**



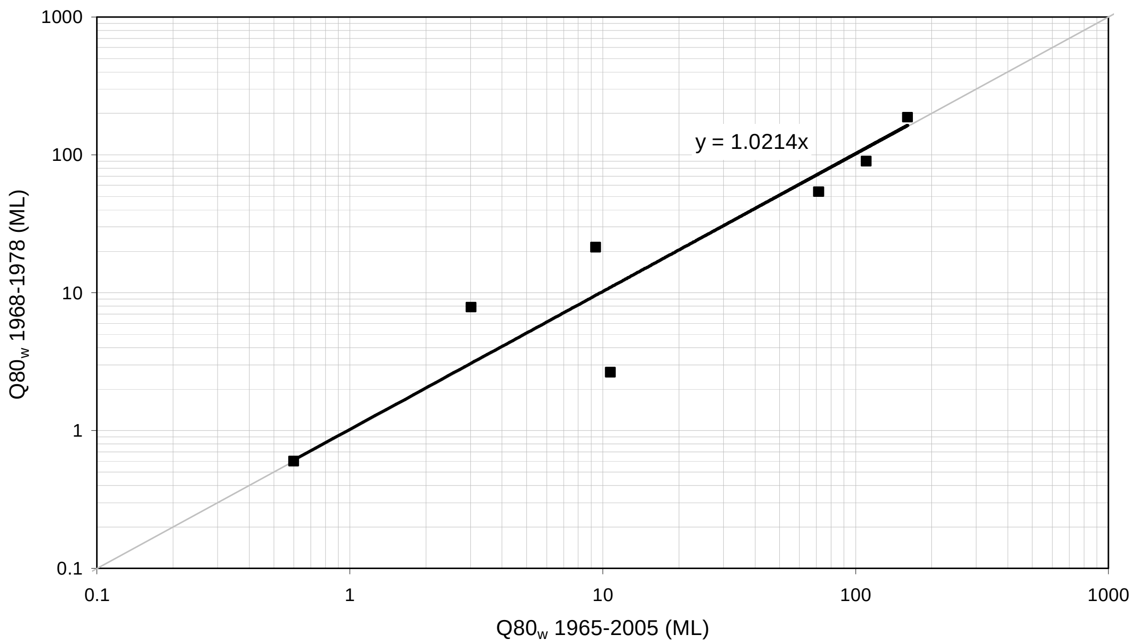

■ **Figure B-4: Comparison of Dry Season Median Flow Estimates**



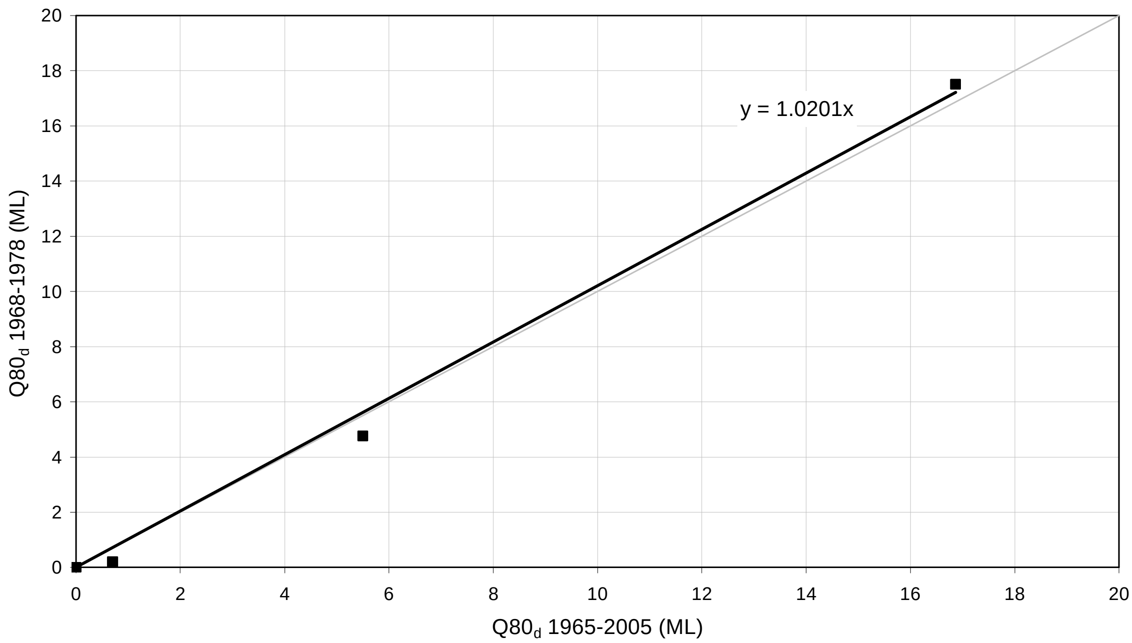

■ **Figure B-5: Comparison of Wet Season 20$^{th}$ Percentile Flow Estimates**



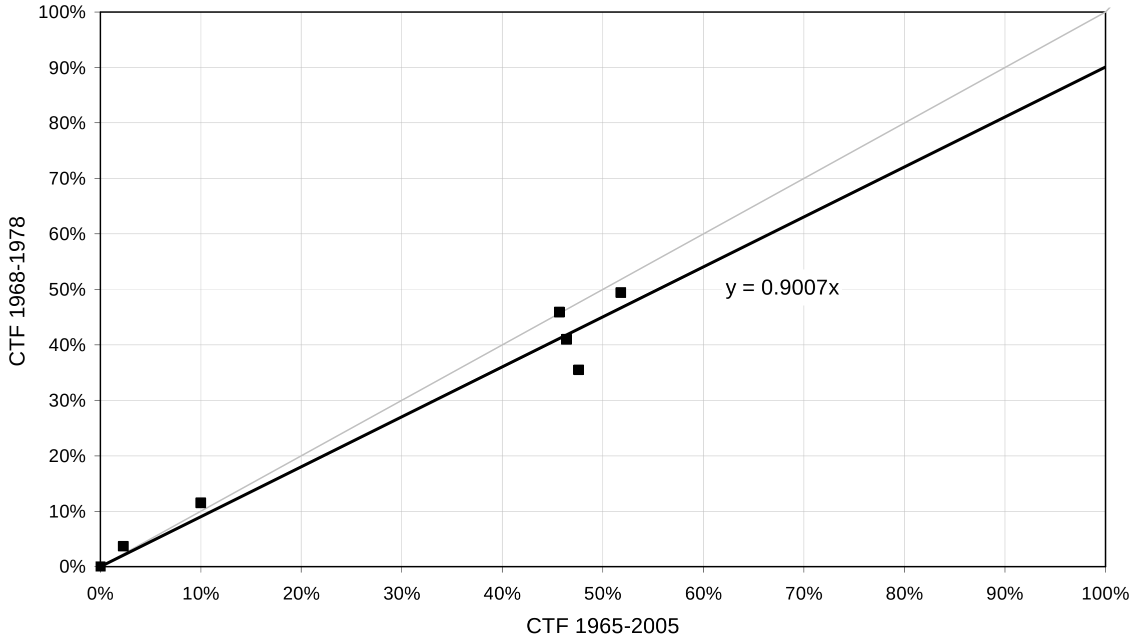

■ **Figure B-6: Comparison of Dry Season 20$^{th}$ Percentile Flow Estimates**



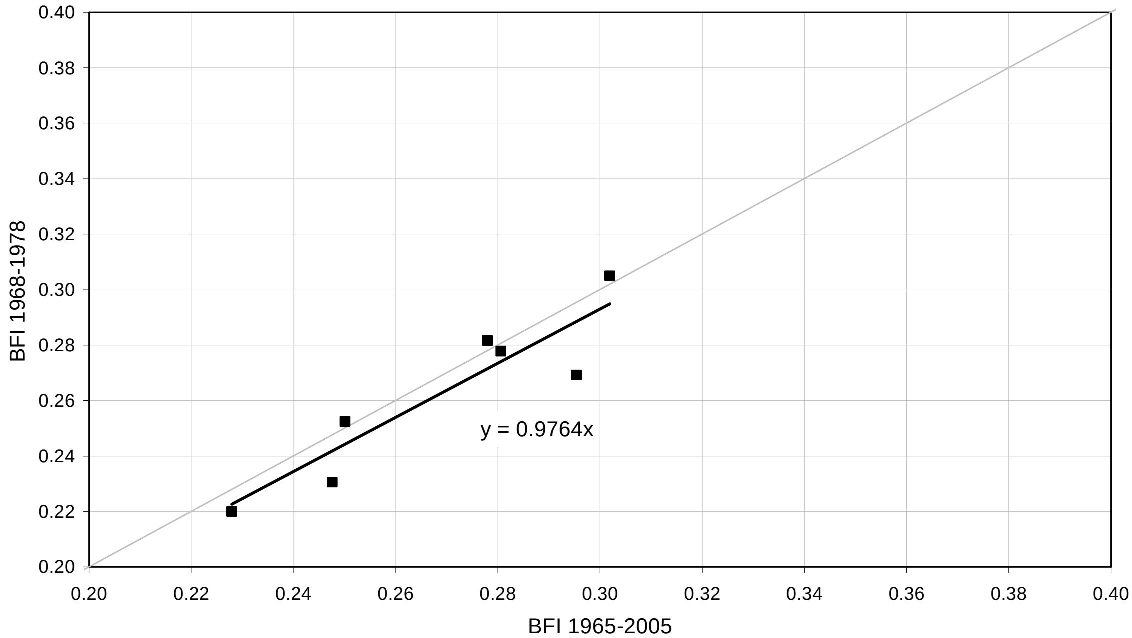

- **Figure B-7: Comparison of Wet Season 80th Percentile Flow Estimates**




- **Figure B-8: Comparison of Dry Season 80th Percentile Flow Estimates**




- **Figure B-9: Comparison of Cease to Flow Estimates**




- **Figure B-10: Comparison of Baseflow Index Estimates**

# Appendix C Streamflow Infilling

## C.1 Data Infilling

Before the streamflow data from the selected gauges could be used for analysis, data infilling was undertaken to remove missing data. The method used for data infilling was development of a regression relationship for streamflow at the gauge of interest with streamflow at a nearby gauge. The two analysis periods selected ensured that infilled data accounted for less than 10% of streamflow data at any given gauge (excluding 8170005, where 12% of missing data for the shorter analysis period was considered acceptable given the quality of the regression relationship developed).

Attempts were made to develop regressions on weekly and monthly time steps, however it was found that these regressions could not maintain the variability observed in the original time series. As a result, all the regressions developed were done so using daily streamflow data. A power transformation of 0.3 or 0.4 was applied to the regressions to improve the fit. In general, the coefficient of determination ($R^2$) and standard error statistics of the regressions were well within the range of acceptable streamflow regression relationships.

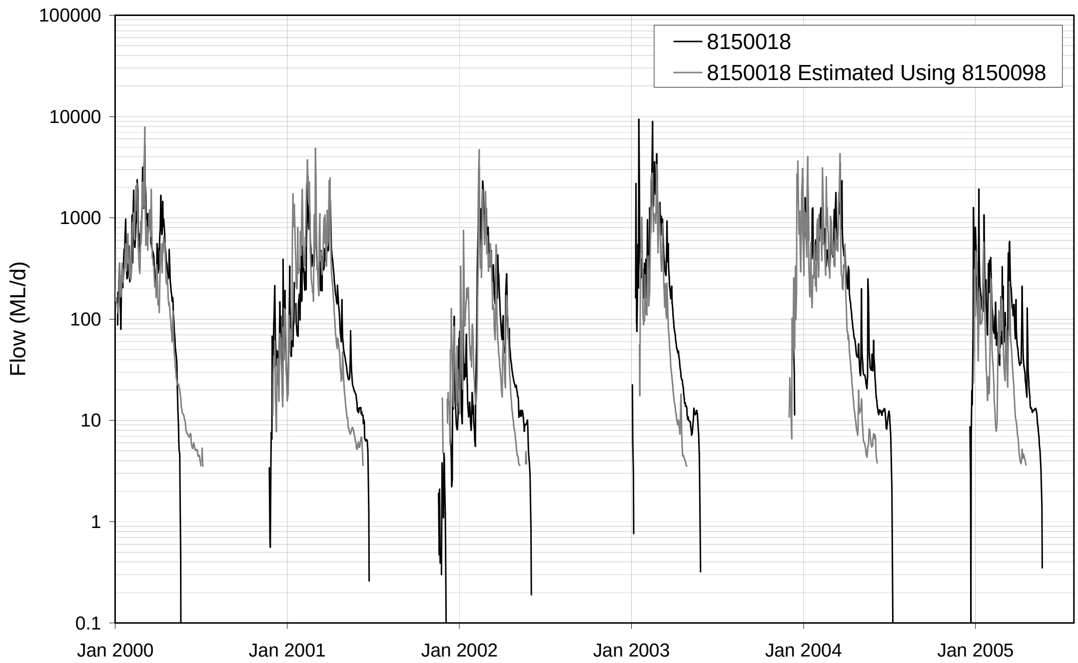
The regression relationships that were developed for these gauges all show a relatively good fit to medium to high flows. However, some of the regressions display a consistent overestimation at low flows (e.g. 8150180). Where this occurred, the distribution of the missing data at that gauge was checked to ensure that the majority of the missing data did not occur at low flows. For the case of 8150180, the missing data mainly consists of wet season events and as such is not affected by the poor quality of the regression at lower flows.

Regressions were generally always developed using all gauged data available. Regressions were not developed using infilled data, but were applied using data previously infilled from another regression. This was done to minimise the number of regressions required to infill all the gauges. One gauge required two separate regression relationships due to the timing of the missing data. A summary of the regressions used is given in Table C-1, while plots showing comparisons of gauged streamflow with estimated streamflow at each gauge are shown in Appendix C.

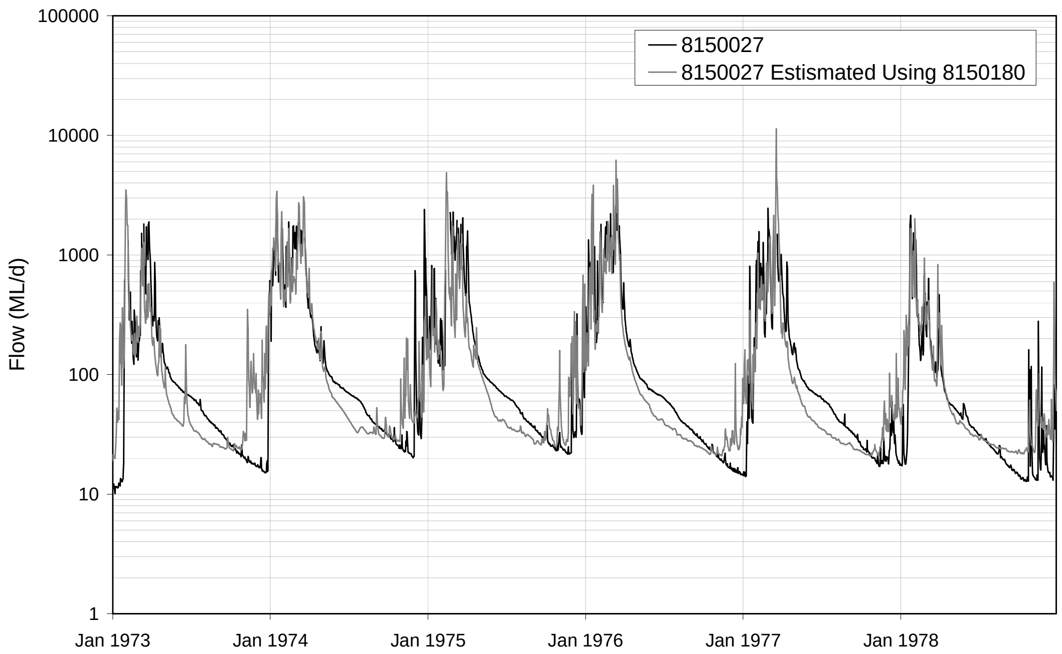
▪ **Table C-1: Summary of Regression Relationships Used to Infill Gauged Data**

| Gauge | Regression With Gauge | Equation | Percentage of Missing Data Infilled | Daily Coefficient of Determination ($R^2$) | Standard Error (% of Mean) |
|---|---|---|---|---|---|
| 8150018 | 8150098 | $y=(0.6284(x^{0.4})+0.9769)^{2.5}$ | 7.43% | 0.77 | 65% |
| 8150027 | 8150180 | $y=(0.3338(x^{0.4})+2.242)^{2.5}$ | 3.31% | 0.77 | 32% |
| 8150097 | 8150096 | $y=(0.8345(x^{0.3})+0.365)^{3.3}$ | 3.29% | 0.75 | 61% |
| 8150098 | 8150097 | $y=(1.3293(x^{0.3})+0.0724)^{3.3}$ | 5.51% | 0.83 | 57% |
| 8150180 | 8170002 | $y=(1.1136(x^{0.3})+0.7582)^{3.3}$ | 5.24% | 0.79 | 36% |
| 8170002 | 8170066 | $y=(2.3315(x^{0.4})-0.649)^{2.5}$ | 5.11% | 0.73 | 58% |
| 8170005 | 8170084 | $y=(1.0244(x^{0.3})-0.0966)^{3.3}$ | 11.82% | 0.94 | 20% |
| 8170062 | 8150097 | $y=(0.5707(x^{0.3})-0.0675)^{3.3}$ | 2.90% | 0.69 | 91% |
| 8170066 | 8170002 | $y=(0.3142(x^{0.4})+1.1457)^{2.5}$ | 3.00% | 0.73 | 46% |
| 8170066 | 8170084 | $y=(0.229(x^{0.4})+1.4087)^{2.5}$ | 0.03% | 0.73 | 45% |
| 8170084 | 8170066 | $y=(3.1841(x^{0.4})-2.0143)^{2.5}$ | 5.80% | 0.73 | 65% |
| 8170085 | 8150097 | $y=(0.4715(x^{0.4})+0.2186)^{2.5}$ | 5.48% | 0.77 | 71% |

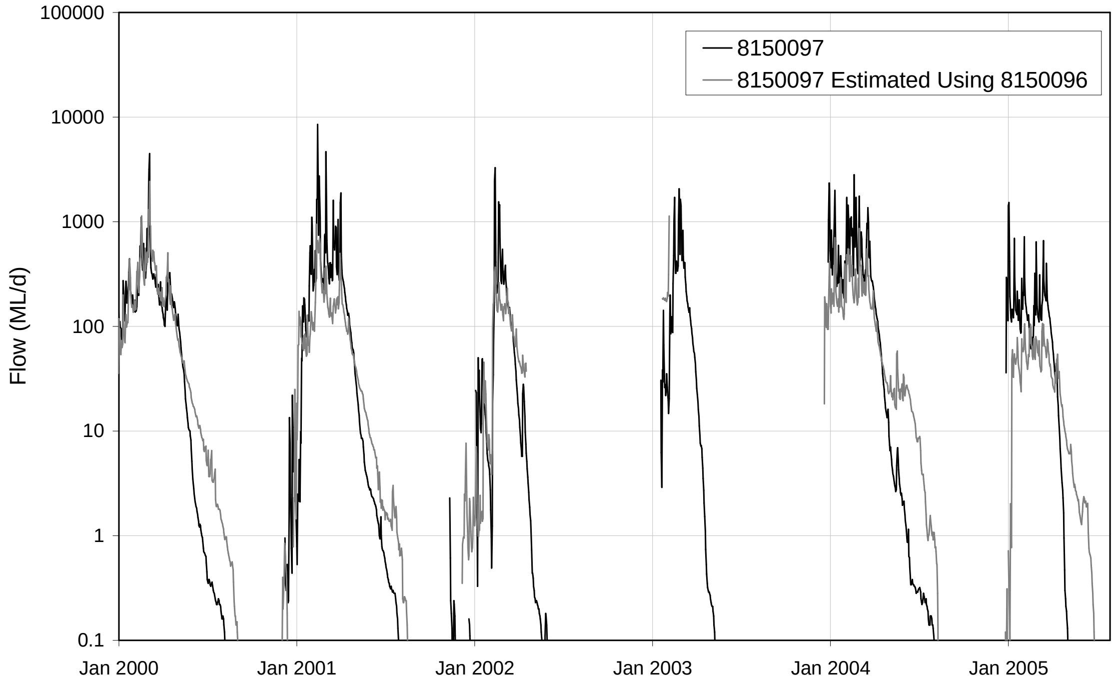
## C.2 Plots of infilled data



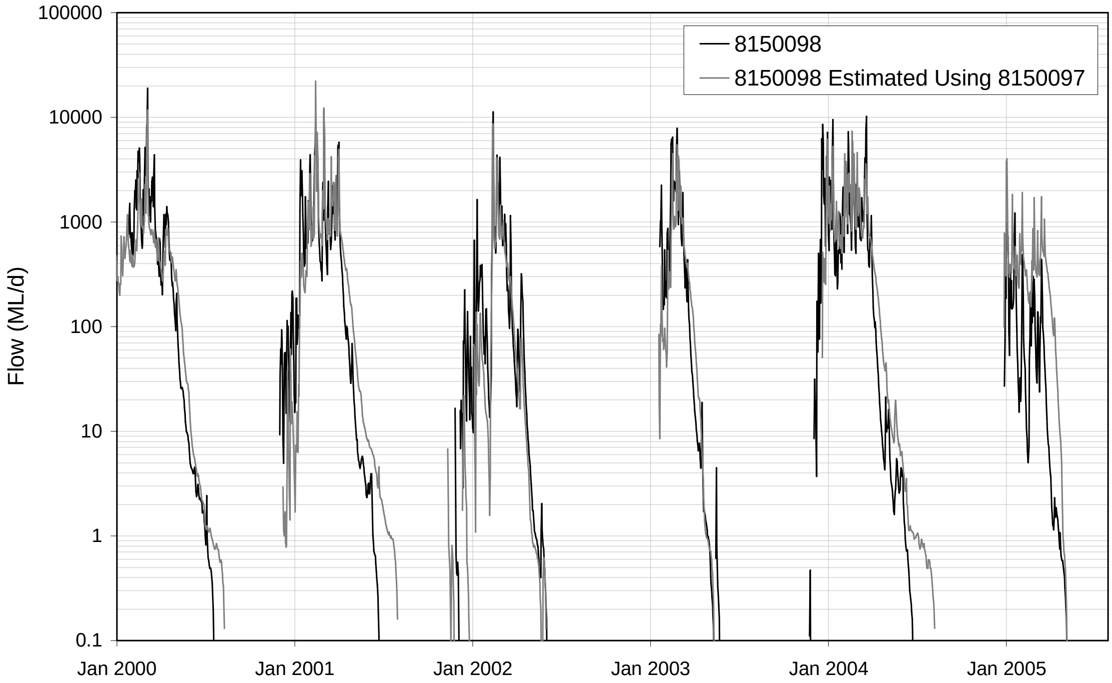

▪ **Figure C-2: Comparison of Gauged and Estimated Flow at 8150018**



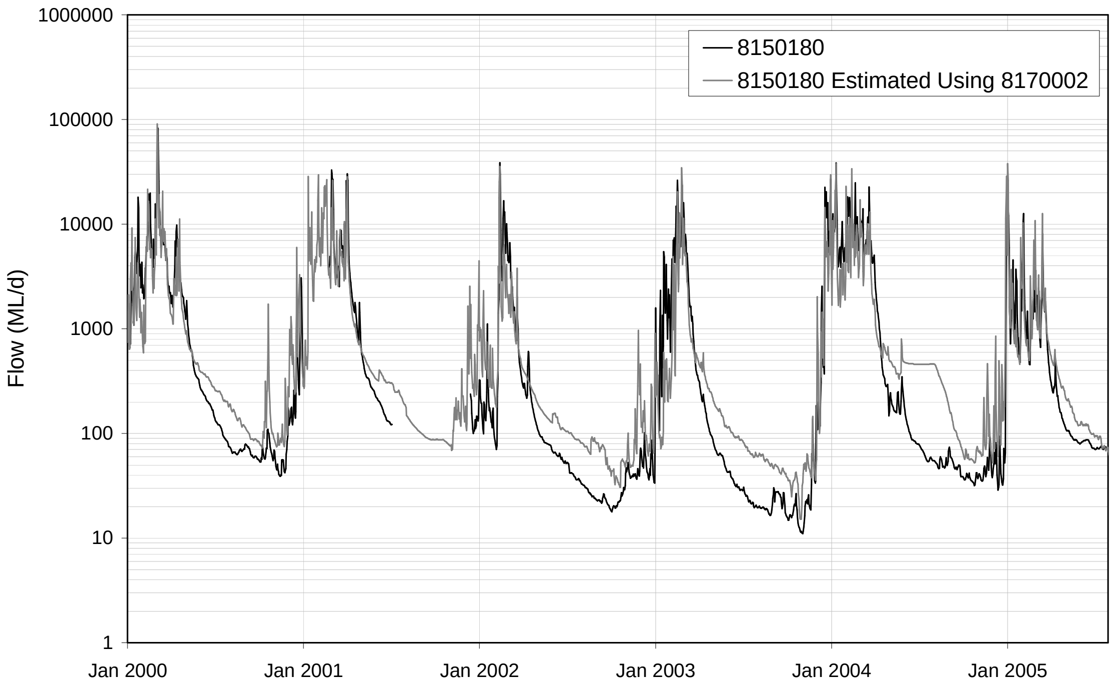

■ **Figure C-3: Comparison of Gauged and Estimated Flow at 8150027**



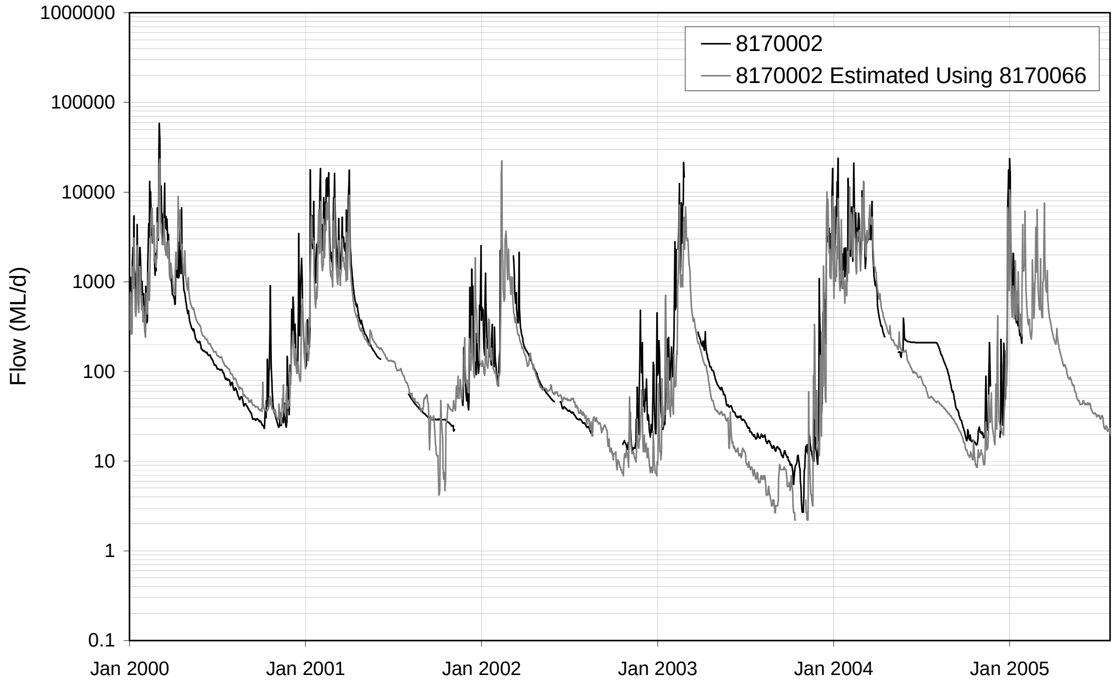

■ **Figure C-4: Comparison of Gauged and Estimated Flow at 8150097**



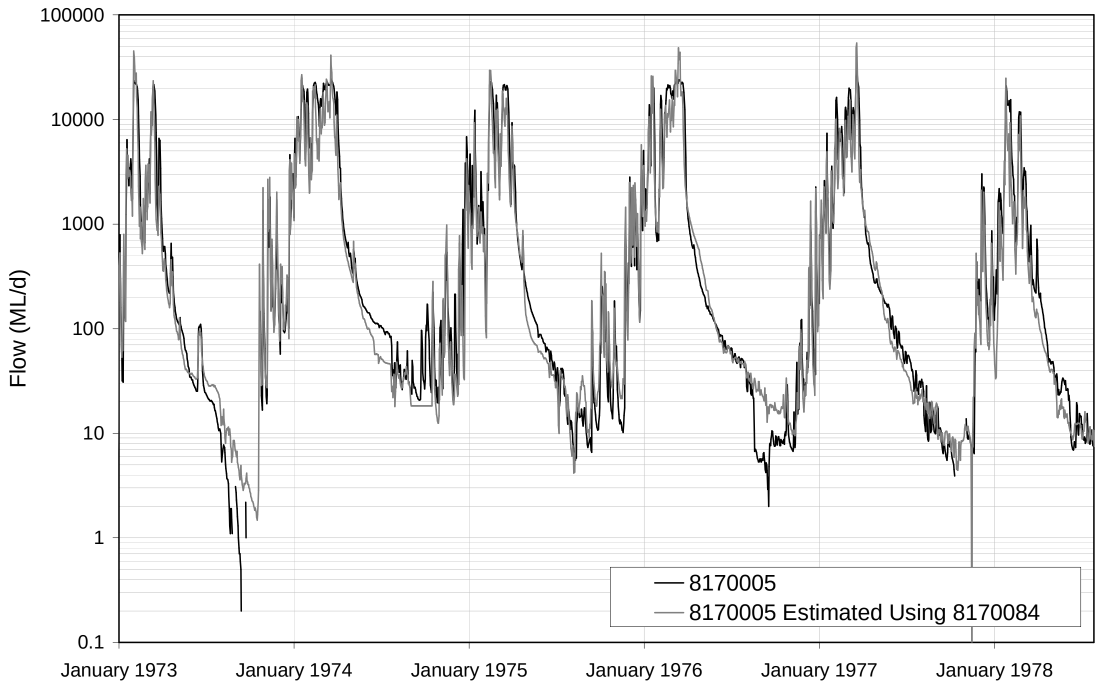

- **Figure C-5: Comparison of Gauged and Estimated Flow at 8150098**



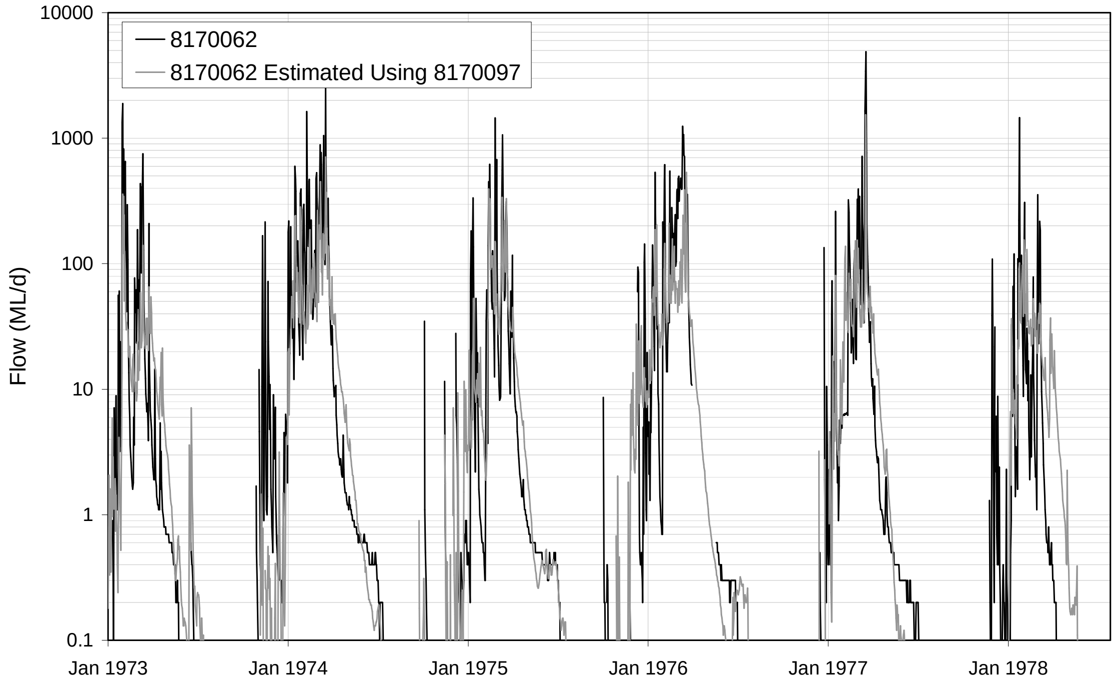

- **Figure C-6: Comparison of Gauged and Estimated Flow at 8150180**



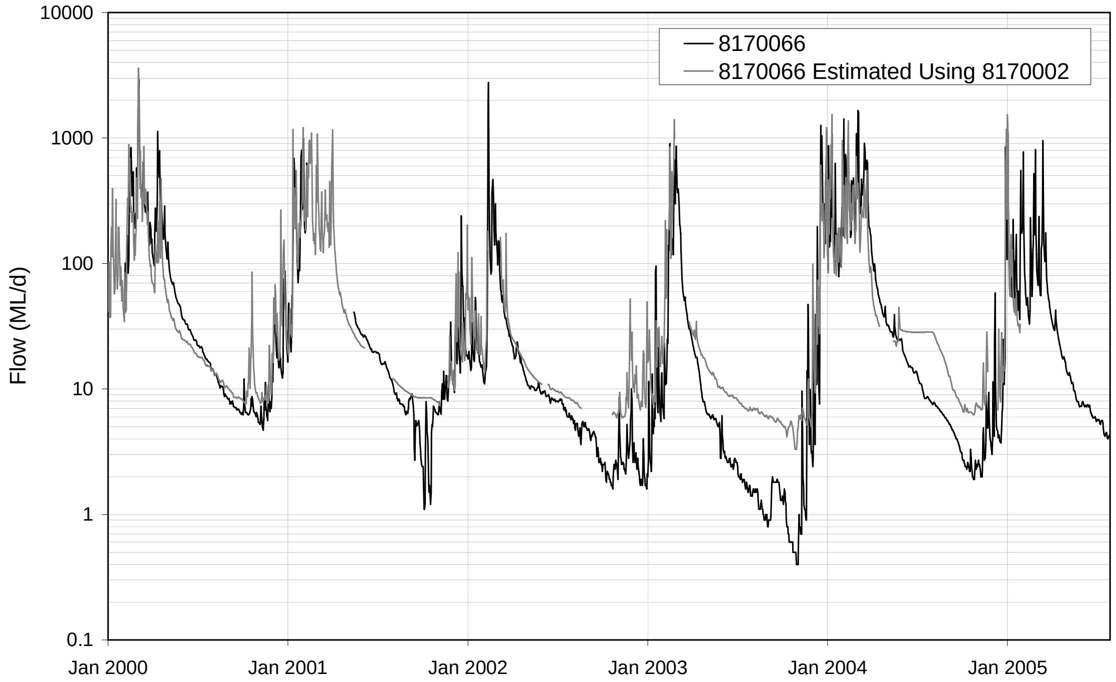

■ **Figure C-7: Comparison of Gauged and Estimated Flow at 8170002**




■ **Figure C-8: Comparison of Gauged and Estimated Flow at 8170005**




■ **Figure C-9: Comparison of Gauged and Estimated Flow at 8170062**




■ **Figure C-10: Comparison of Gauged and Estimated Flow at 8170066 (Regression 1)**

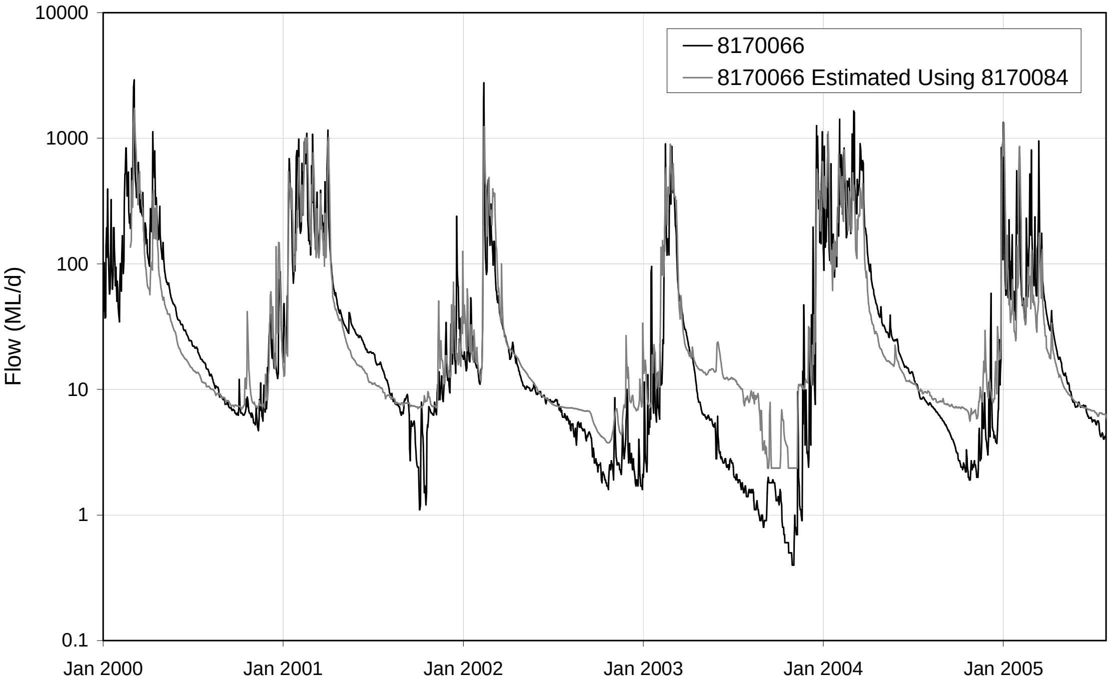



**Figure C-11: Comparison of Gauged and Estimated Flow at 8170066 (Regression 2)**

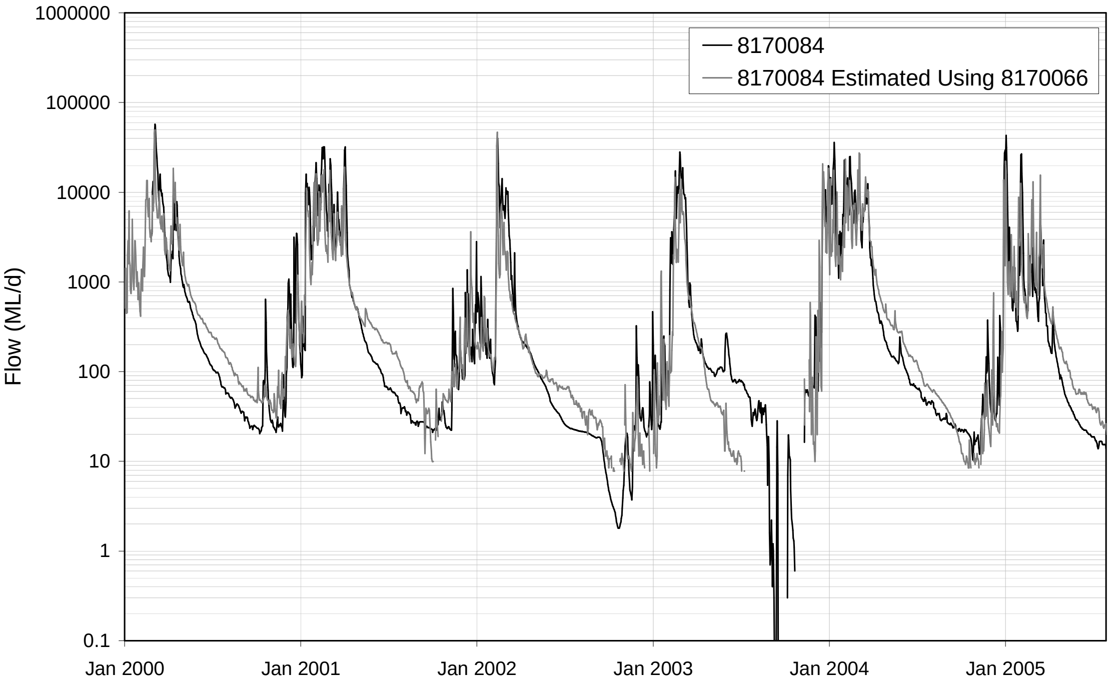
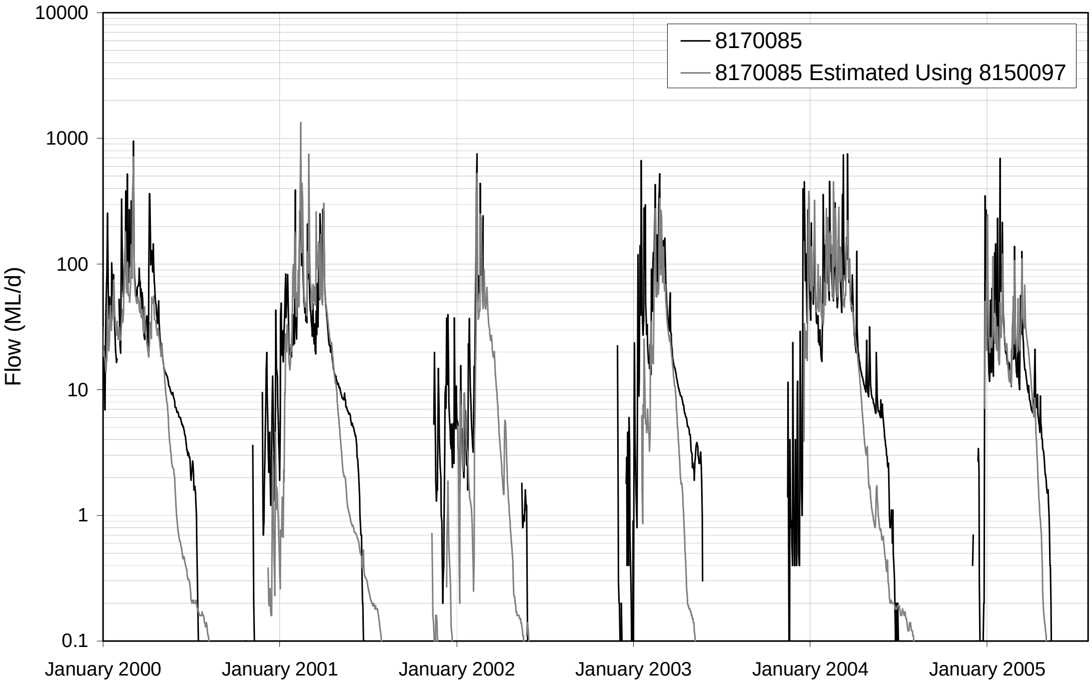



**Figure C-12: Comparison of Gauged and Estimated Flow at 8170084**



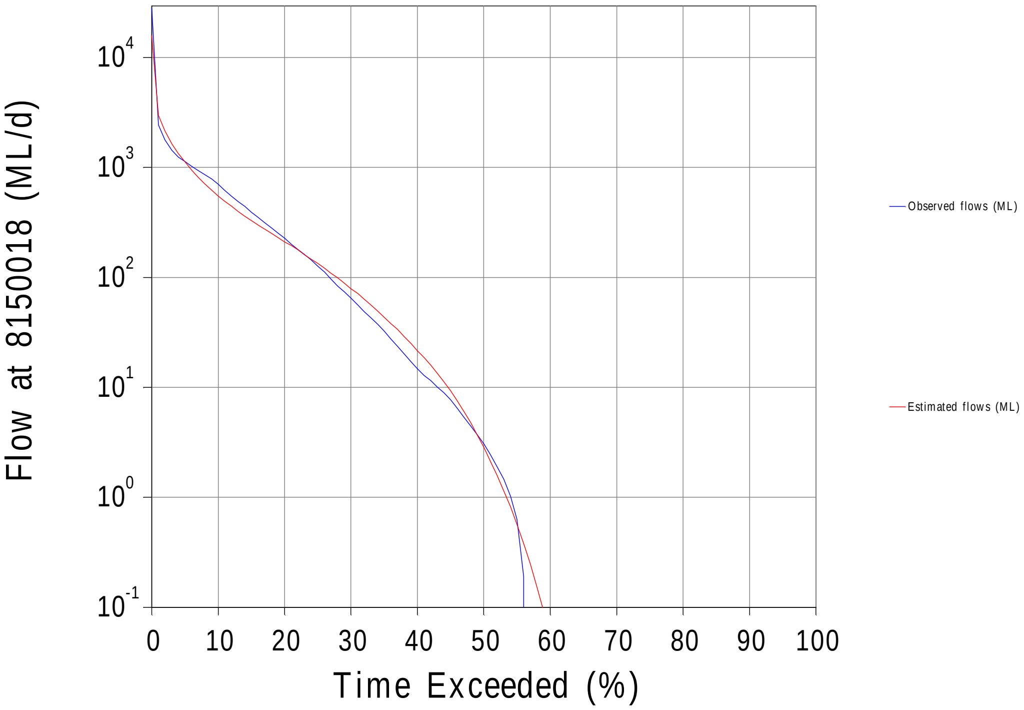

- **Figure C-13: Comparison of Gauged and Estimated Flow at 8170085**

# Appendix D Rainfall-runoff model calibrations

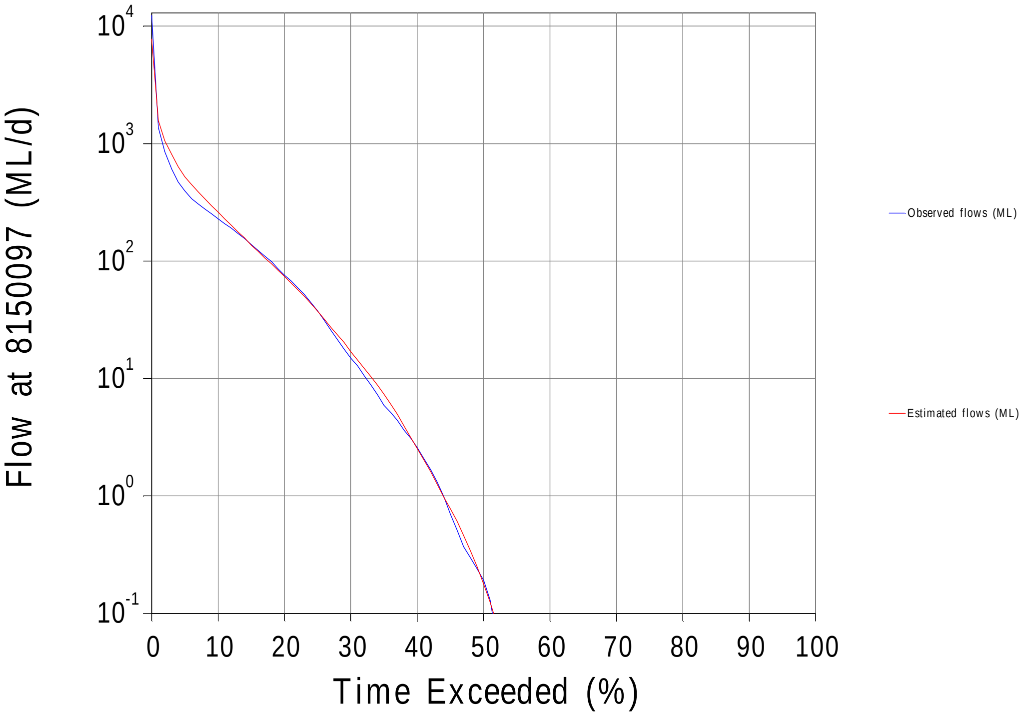
## D.1 Daily SIMHYD models

**Table D-1 Calibration parameters and statistics for daily SIMHYD models**

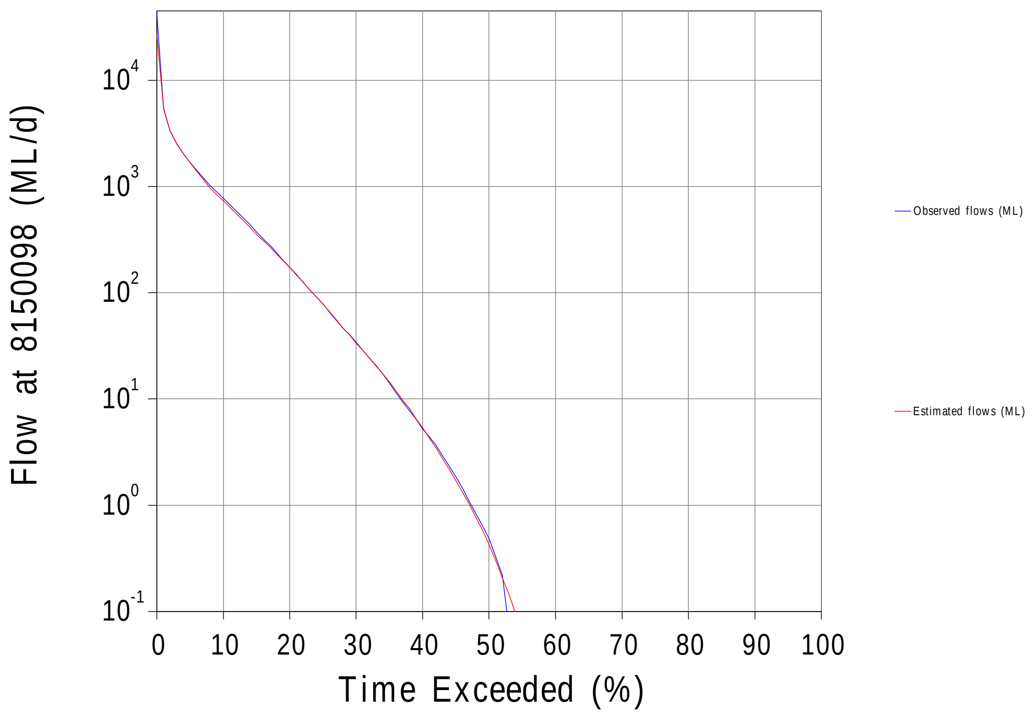
| Parameter | 8150018 | 8150097 | 8150098 | 8150180 | 8170002 | 8170084 | 8170085 |
|---|---|---|---|---|---|---|---|
| Catchment Area ($km^2$) | 94.3 | 74 | 182.1 | 1048.4 | 654.6 | 1172.7 | 11.08 |
| Rainfall Factor | 1 | 1 | 1.1 | 1 | 0.98 | 1 | 1 |
| Evaporation Factor | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| COEFF | 270 | 250 | 270 | 300 | 250 | 170 | 265 |
| CRAK | 0.22 | 0.53 | 0.18 | 0.05 | 0.023 | 0.065 | 0.2298 |
| RK | 0.35 | 0.25 | 0.26 | 0.01 | 0.0145 | 0.0235 | 0.23 |
| INSC | 6 | 20 | 10 | 12 | 1 | 10 | 2 |
| SMSC | 320 | 500 | 280 | 500 | 480 | 400 | 250 |
| SQ | 2 | 3 | 3 | 3.16 | 2.69 | 3 | 2.24 |
| SUB | 0.4 | 0.39 | 0.78 | 0.53 | 0.22 | 0.39 | 0.40891 |
| INIHS | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| INIHG | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| SDK | 0.35 | 0.32 | 0.65 | 0.23 | 0.6405 | 0.37 | 0.82 |
| Percentage difference in means (%) | 0.2472 | 8.5418 | -2.0567 | -2.7702 | -3.9323 | -0.7599 | -1.8821 |
| Coefficient of Determination ($R^2$) | 0.4270 | 0.3356 | 0.6425 | 0.4713 | 0.5016 | 0.5678 | 0.3428 |
| Coefficient of Efficiency (CE) | 0.3107 | 0.2585 | 0.6239 | 0.4451 | 0.4063 | 0.4507 | 0.2241 |



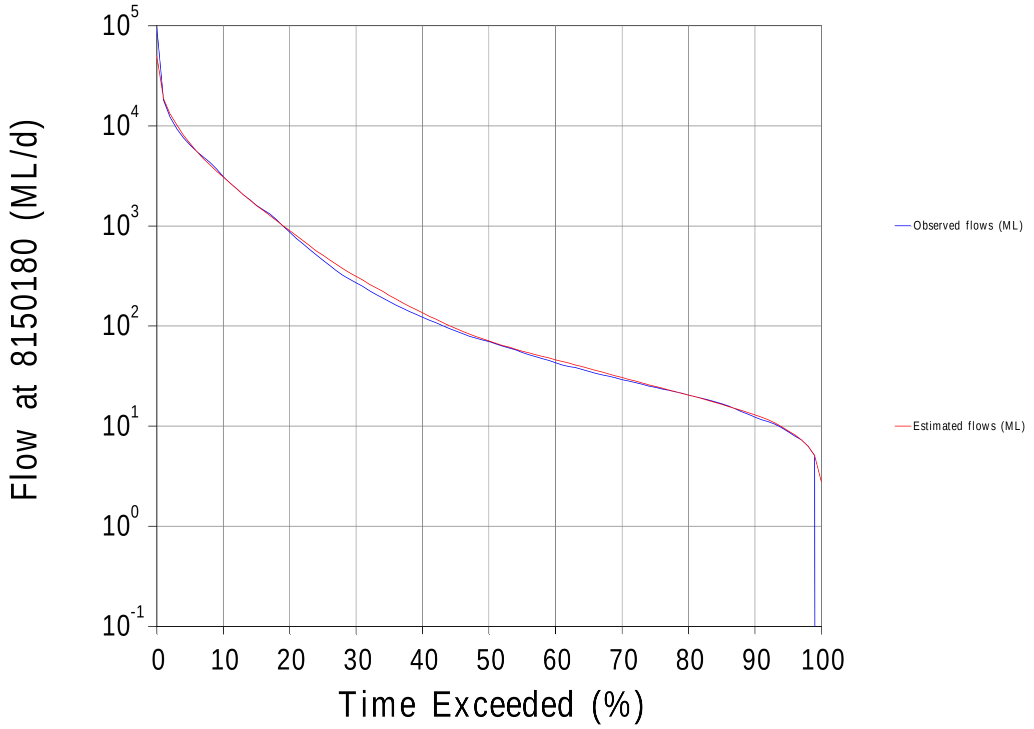

- **Figure D-1 Daily SIMHYD Flow-Duration Curve - Elizabeth River at Stuart Highway (G8150018)**



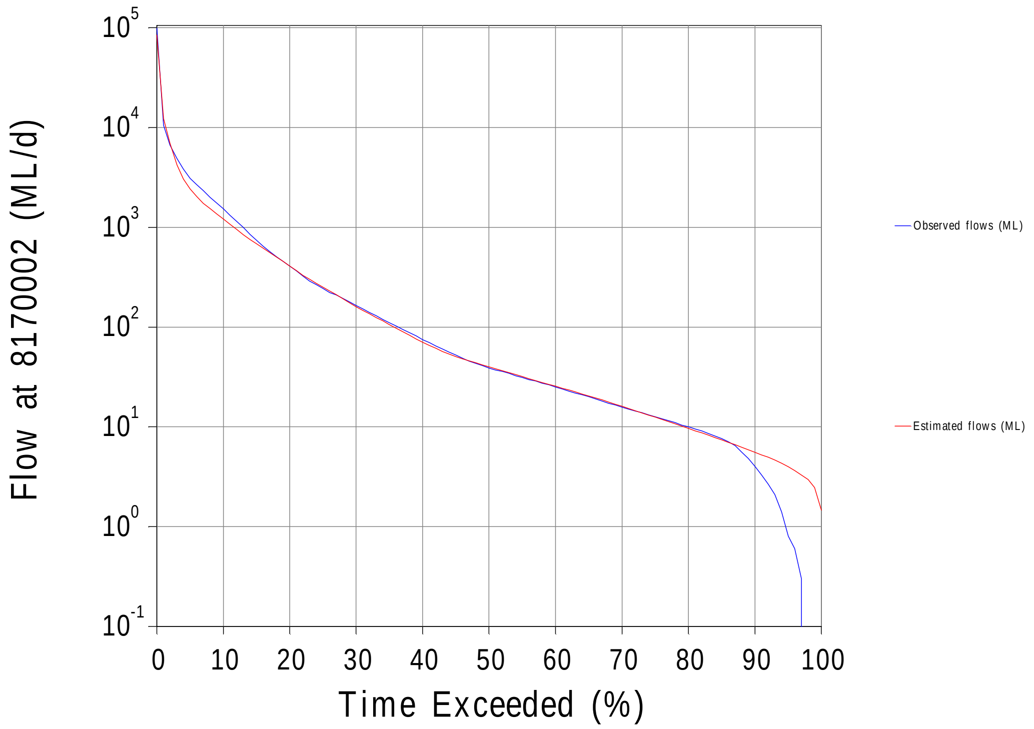

- **Figure D-2 Daily SIMHYD Flow-Duration Curve - East Finniss River at Rum Jungle (G8150097)**



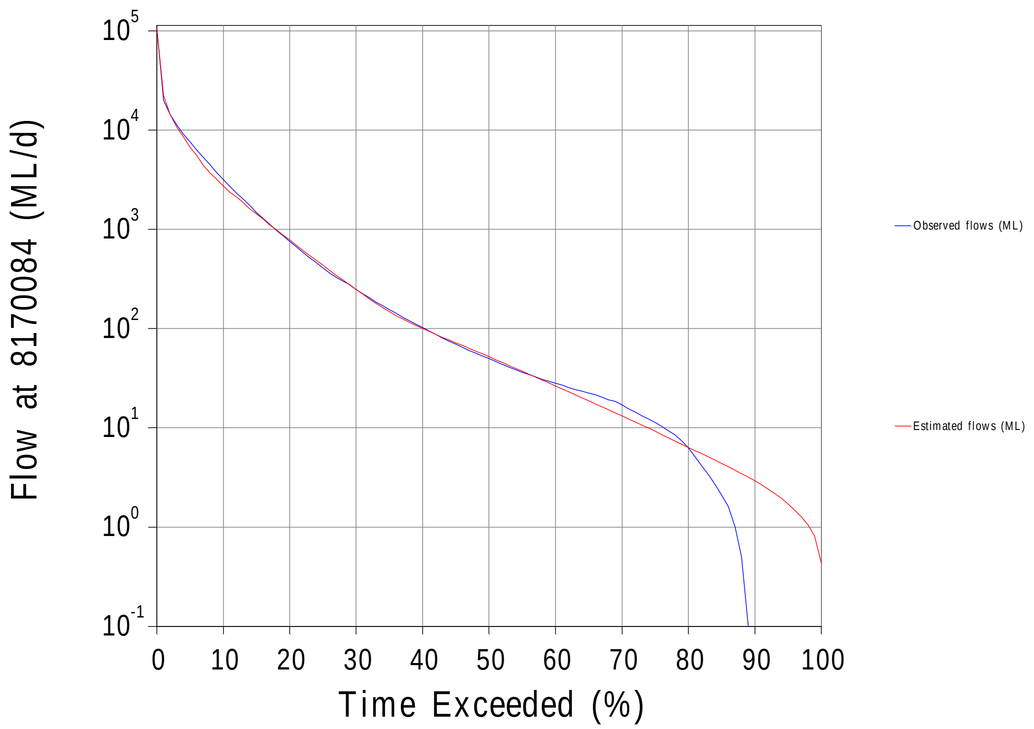

▪ **Figure D-3 Daily SIMHYD Flow-Duration Curve - Blackmore River at Tumbling Waters (G8150098)**



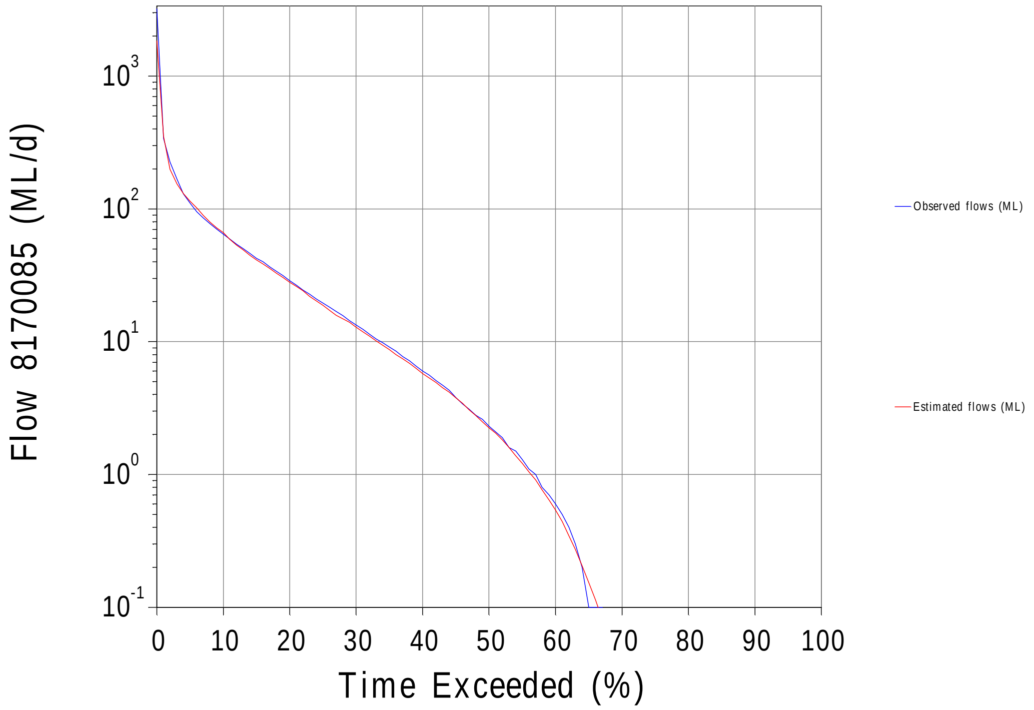

■ **Figure D-4 Daily SIMHYD Flow-Duration Curve - Finniss River at Gitchams (G8150180)**




- **Figure D-5 Daily SIMHYD Flow-Duration Curve - Adelaide River at Railway Bridge (G8170002)**




- **Figure D-6 Daily SIMHYD Flow-Duration Curve - Adelaide River at Tortilla Flats (G8170084)**

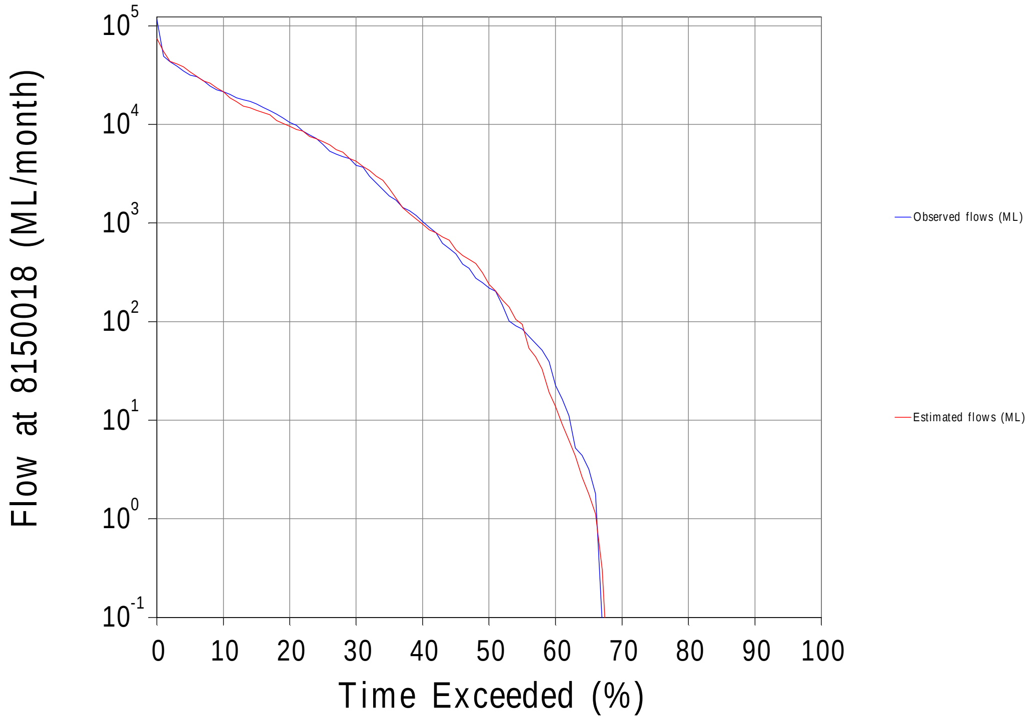



- **Figure D-7 Daily SIMHYD Flow-Duration Curve - Acacia Creek at Stuart Highway (G8170085)**

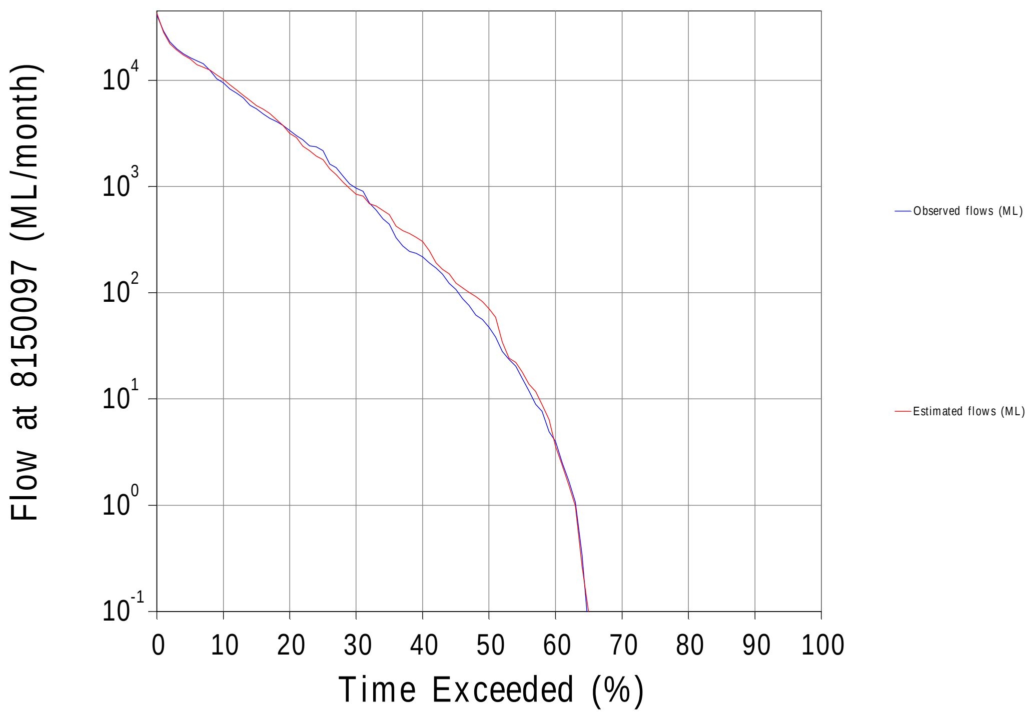
## D.2 Monthly SIMHYD models

### Table D-4 Calibration parameters and statistics for monthly SIMHYD models

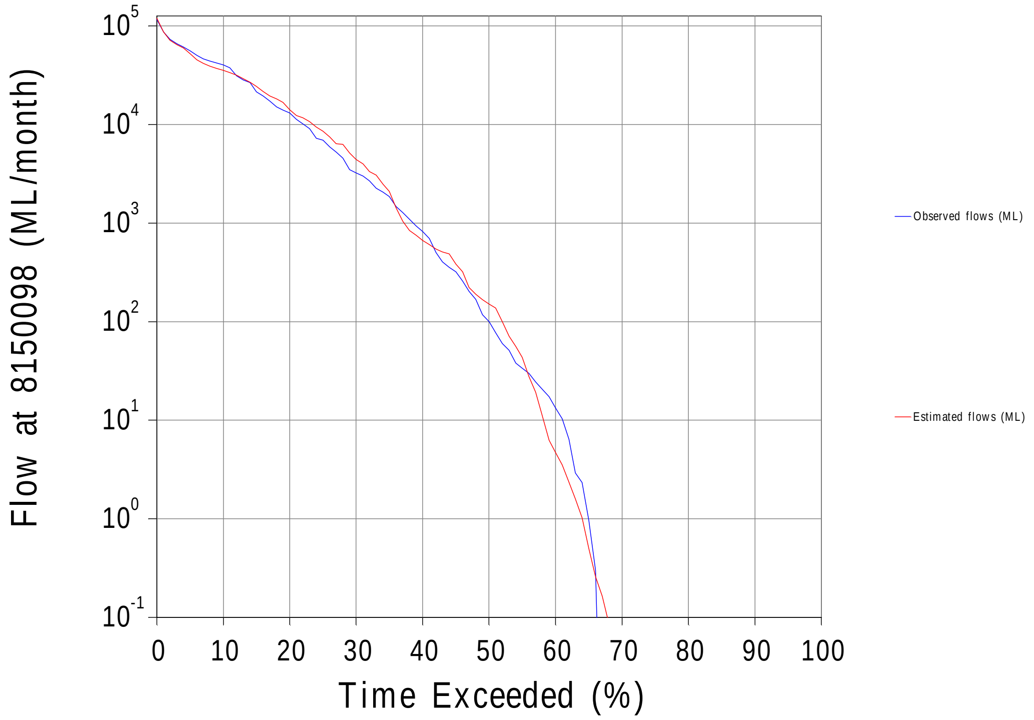
| Parameter | 8150018 | 8150097 | 8150098 | 8150180 | 8170002 | 8170084 | 8170085 |
|---|---|---|---|---|---|---|---|
| Catchment Area ($km^2$) | 94.3 | 74 | 182.1 | 1048.4 | 654.6 | 1172.7 | 11.08 |
| Rainfall Factor | 1 | 0.95 | 1.1 | 0.87 | 0.99 | 1.14 | 1 |
| Evaporation Factor | 1 | 1 | 1 | 1 | 1.1 | 1 | 1 |
| COEFF | 120 | 130 | 90 | 145 | 150 | 150 | 190 |
| CRAK | 0.07 | 0.15 | 0.06 | 0.03 | 0.16 | 0 | 0.0398 |
| RK | 0.52 | 0.395 | 0.6 | 0.012 | 0.019 | 0.034 | 0.1459 |
| INSC | 6 | 10 | 3 | 2.9 | 20 | 20 | 10 |
| SMSC | 350 | 500 | 210 | 200 | 250 | 480 | 130 |
| SQ | 2.33 | 2.5 | 1.5 | 2.7 | 2.51 | 1.71 | 2.5 |
| SUB | 0.25 | 0.26 | 0.04813 | 0.01 | 0.46 | 0.1 | 0.49891 |
| INIHS | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| INIHG | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| SDK | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Percentage difference in means (%) | -0.8846 | -0.7338 | -0.5627 | 0.4160 | 0.2802 | -0.1545 | -0.6605 |
| Coefficient of Determination ($R^2$) | 0.6294 | 0.6470 | 0.8628 | 0.6710 | 0.7429 | 0.7179 | 0.7710 |
| Coefficient of Efficiency (CE) | 0.5954 | 0.6173 | 0.8620 | 0.6343 | 0.7335 | 0.7016 | 0.7635 |



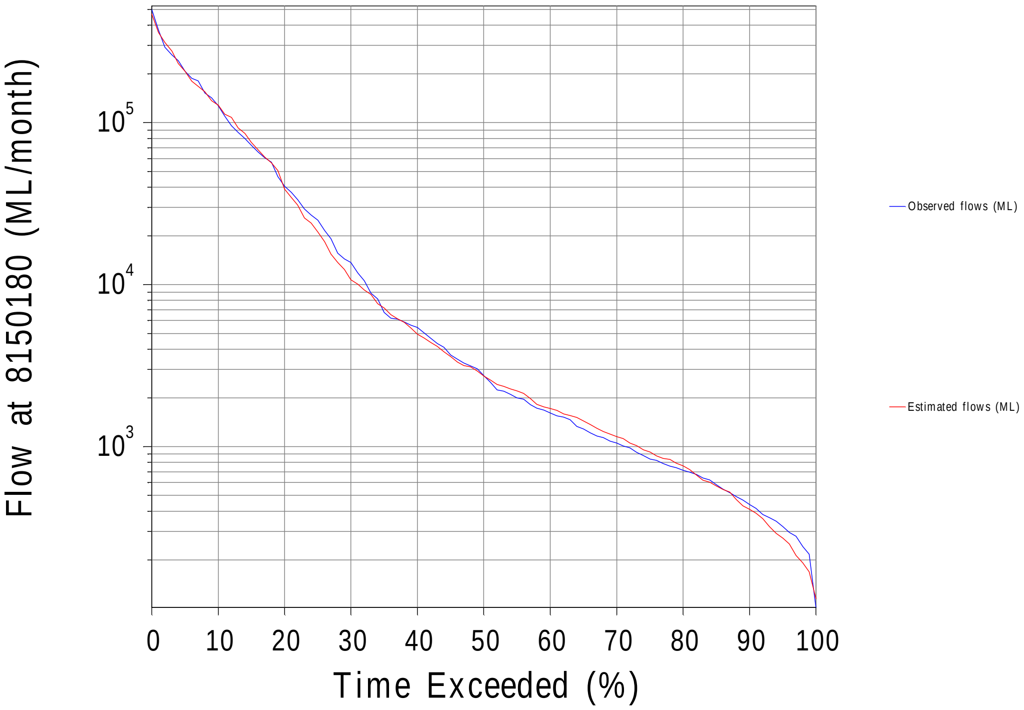

▪ **Figure D-8 Monthly SIMHYD Flow-Duration Curve - Elizabeth River at Stuart Highway (G8150018)**



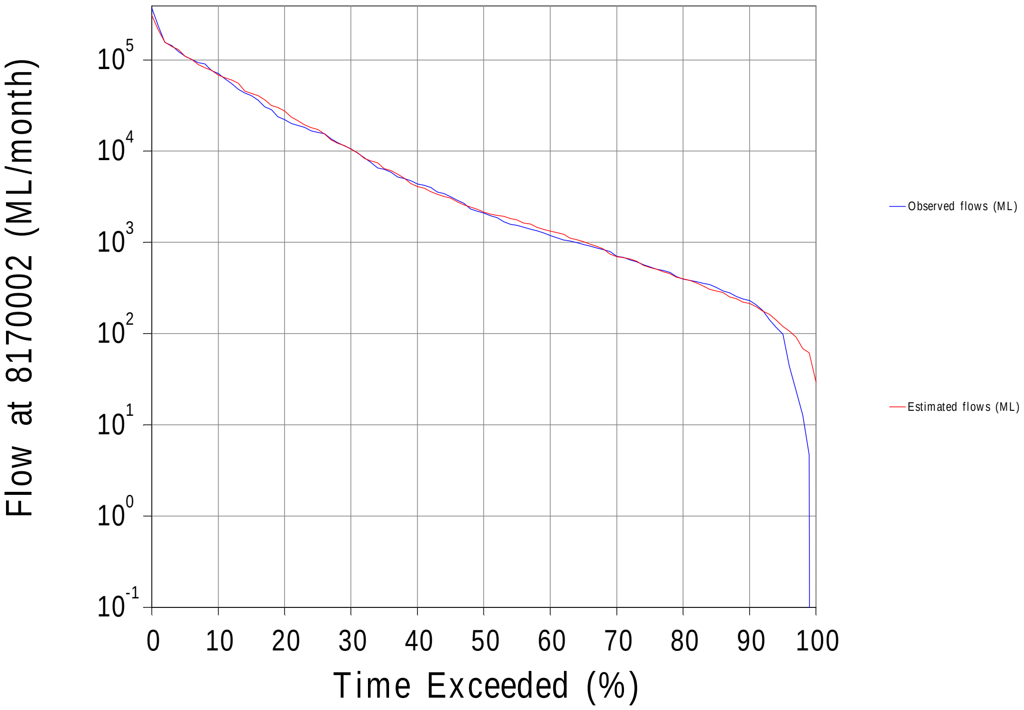

- **Figure D-9 Monthly SIMHYD Flow-Duration Curve - East Finniss River at Rum Jungle (G8150097)**



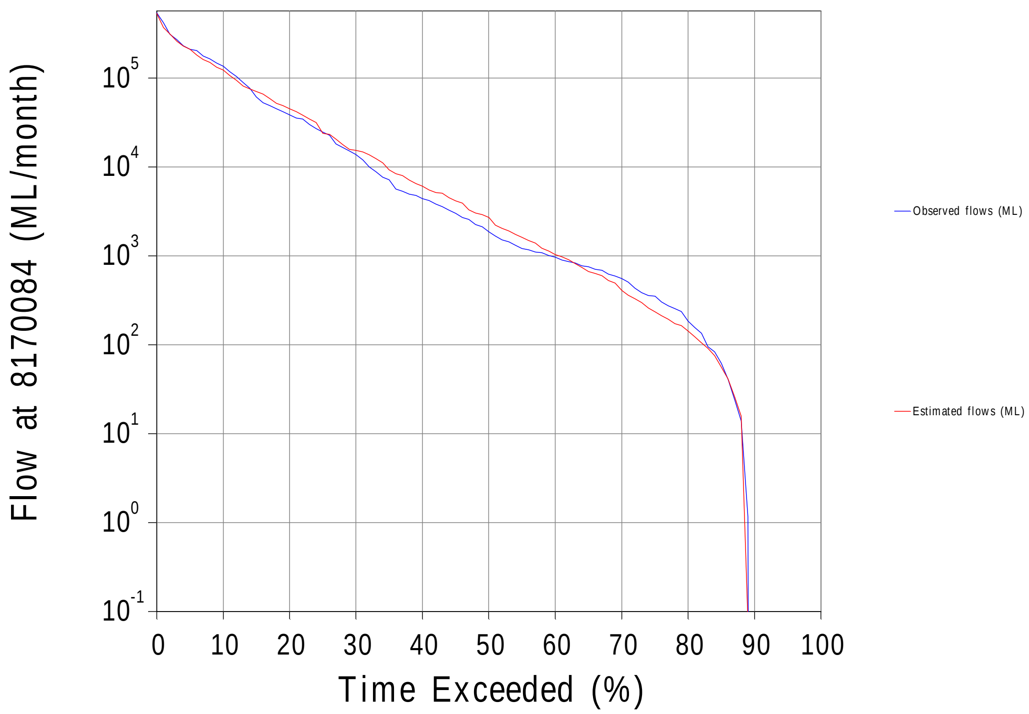

- **Figure D-10 Monthly SIMHYD Flow-Duration Curve - Blackmore River at Tumbling Waters (G8150098)**



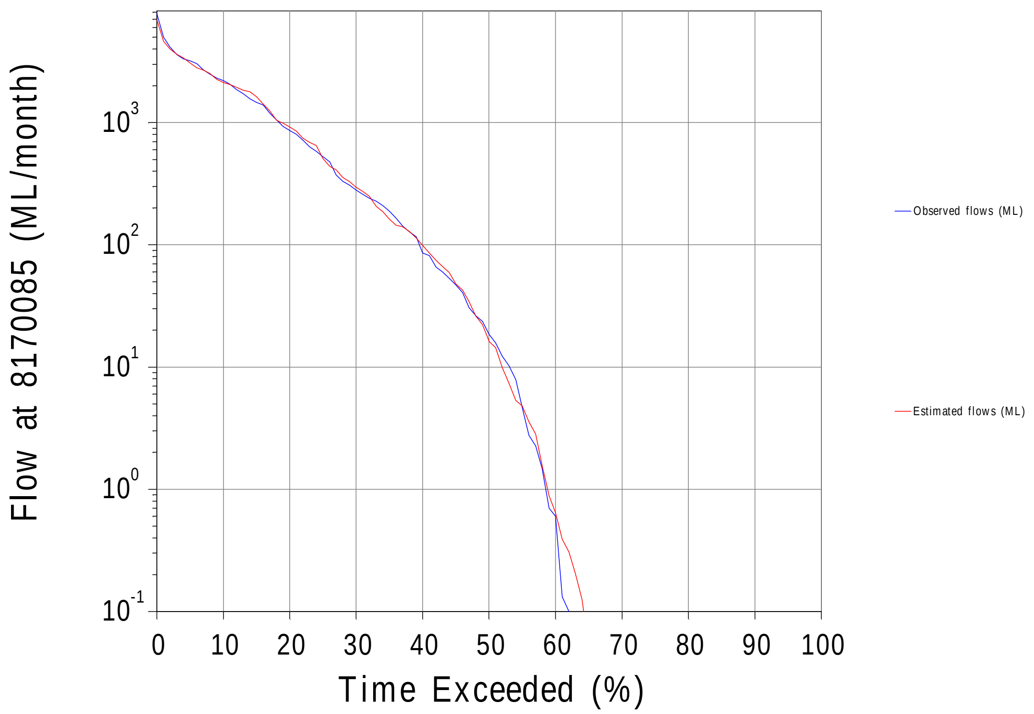

- **Figure D-11 Monthly SIMHYD Flow-Duration Curve - Finniss River at Gitchams (G8150180)**




- **Figure D-12 Monthly SIMHYD Flow-Duration Curve - Adelaide River at Railway Bridge (G8170002)**




- **Figure D-13 Monthly SIMHYD Flow-Duration Curve - Adelaide River at Tortilla Flats (G8170084)**




- **Figure D-14 Monthly SIMHYD Flow-Duration Curve - Acacia Creek at Stuart Highway (G8170085)**

# Appendix E Development of Prediction Equations

## E.1 Multiple Linear Regression

Multiple linear regression is a statistical technique that allows one dependent variable (in this case the hydrological indices) to be predicted from a number of independent variables (the catchment characteristics). The multiple linear regression equations are of the form:

$$Y = a_0 + a_1 X_1 + a_2 X_2 + ... + a_n X_n$$

The dependent variable is denoted by $Y$, while $X_x$ and $a_x$ are the independent variables and coefficients. The multiple linear regression tool in SYSTAT was used to determine the coefficients of the prediction equations, using a method of least squares. The coefficients are selected so that the sum of the square of the residual values (the difference between observed and estimated values) is minimised.

## E.2 Candidate catchment characteristics

For each selected streamflow gauge, a catchment boundary was identified using GIS tools. These boundaries were then used to extract catchment characteristics for use in development of the prediction equations. The catchment characteristics selected were mainly developed from those which have proved successful in previous studies, including SKM (2003), Lowe *et al* (2006) and Nathan *et al* (2000). This list was then supplemented with a number of other characteristics which were considered to be particularly relevant for northern Australia. These characteristics are discussed in more detail below.

*Catchment Area*

Catchment area was derived using GIS tools and the catchment boundaries developed from digital elevation model (DEM) information.

*Location*

A number of characteristics representing the catchment location were derived. These included the shortest distance from the catchment centroid to the coast and latitude of the catchment centroid.

*Elevation*

The minimum, maximum, range of, mean and standard deviation of elevation within each catchment were developed from the DEM.

*Slope*

The minimum, maximum, range of, mean and standard deviation of slope within each catchment were developed from the DEM. The slope for each DEM cell in each catchment was calculated based on the elevations of the eight neighbouring cells.

*Aspect*

The mean and standard deviation of the aspect (the compass direction in degrees that each cell in the catchment is facing) in each catchment was calculated using the DEM.

*Rainfall and Evaporation*

GIS rainfall and actual evaporation grids produced by the Bureau of Meteorology were used to extract minimum, maximum and mean average annual rainfall and actual evaporation for each catchment. These characteristics were calculated for calendar years. Additionally, the average wet and dry season rainfalls at each catchment centroid were also calculated.

*Stream Length and Stream Density*

The total stream length within each catchment was calculated using the 1:250,000 stream network available from Geoscience Australia. This is the best resolution of stream network data available with coverage across the whole of northern Australia. The stream density was then calculated by dividing the stream length in each catchment by the catchment area.

*Number of Stream Junctions and Stream Frequency*

The total number of stream junctions within each catchment was calculated using the 1:250,000 stream network available from Geoscience Australia. The stream frequency was then calculated by dividing the number of junctions in each catchment by the catchment area.

*Vegetation Cover*

The area covered by woody vegetation in each catchment was calculated using a vegetation coverage grid supplied by the Australian Greenhouse Office. This was also expressed as a percentage by dividing the area of woody vegetation by the total catchment area.

*Soil Type*

For each gauged catchment, the percentage of each Northcote soil type present was calculated using GIS tools. These soil types were then converted into useful hydrological characteristics following on from the method proposed by McKenzie and Hook (1992) and subsequently modified in SKM (2001b). The result of this was four sub-characteristics for each catchment:

- Profile permeability ($K_s$);
- Profile water holding capacity (PWHC);
- Depth of soil profile; and
- Texture.

A description of these different rating systems is included in Table E-1.

*Geology*

Information from the hydrogeological assessment was used to extract the total length of stream in each gauged catchment intersecting with carbonate aquifers. This was expressed as absolute and percentage values. Additionally, the area of carbonate aquifer in each catchment (again expressed as absolute and percentage values) was extracted. Refer Section 6.2 for more information on the geology of the study area.

- **Table E-1: Rating System for Soil Type Catchment Characteristics**

| Rating | Physical Property | Description |
|---|---|---|
| | **Profile Permeability** | |
| 1 | <5 mm/day | Very slow |
| 2 | 5 – 50 mm/day | Slow |
| 3 | 50 – 500 mm/day | Moderate |
| 4 | >500 mm/day | Fast |
| | **Profile Water Holding Capacity** | |
| 1 | <50 mm | Very low |
| 2 | 50 -150 mm | Low |
| 3 | 150 – 250 mm | Medium |
| 4 | 250 – 350 mm | High |
| 5 | >350 mm | Very high |
| | **Soil Texture Profile** | |
| 1 | Uniform coarse | |
| 2 | Uniform medium | |
| 3 | Uniform fine | |
| 4 | Uniform cracking | |
| 5 | Gradational calcareous | |
| 6 | Gradational | |
| 7 | Duplex | |
| | **Soil Depth** | |
| 1 | < 0.5 m | Shallow |
| 2 | 0.5 – 1.5 m | Moderate |
| 3 | > 1.5 m | Deep |

## E.3 Independent Variable Selection

The catchment characteristics described in Section E.2 were considered in the development of prediction equations. The stepwise multiple regression tool was used to select appropriate variables. The process was interactive, allowing variables to be added or removed from the model one at a time.

The correlation of independent variables was avoided by use of a correlation matrix to identify catchment variables showing high levels of correlation. The matrix (showing $R^2$ values) is shown in Figure E-1. Variables with $R^2$ values greater than 0.70 were not used together in the prediction equations because of their cross-correlation.

The addition of a variable to the model was based on the F-statistic.  This is a measure of the amount of additional variation (i.e. the variation not explained by variables already in the model) explained by the variable. Variables with the highest F-statistic were added first.

## Figure E-1: Correlation Matrix for Catchment Characteristics

| Perimeter | Woody Area | Woody % | Min Elev | Max Elev | Range Elev | Mean Elev | Std Elev | Min Slope | Max Slope | Range Slope | Mean Slope | Std Slope | Mean Aspect | Std Aspect | Stream Length | Stream Density | # Junctions | Frequency | Min Rain | Max Rain | Mean Rain | Min Evap | Max Evap | Mean Evap | Latitude | Distance to Coast | Wet Season Rainfall | Dry Season Rainfall | Ks | PWHC | Depth | Texture | Pct Length Carb | Pct Area Carb | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.98 | 0.90 | 0.14 | 0.13 | 0.55 | 0.82 | 0.05 | 0.80 | 0.55 | 0.54 | 0.55 | 0.04 | 0.22 | 0.34 | 0.05 | 1.00 | 0.01 | 0.98 | 0.02 | 0.32 | 0.35 | 0.00 | 0.52 | 0.06 | 0.29 | 0.25 | 0.23 | 0.03 | 0.04 | 0.28 | 0.46 | 0.17 | 0.00 | 0.01 | 0.00 | **Area** |
| | 0.88 | 0.17 | 0.16 | 0.55 | 0.84 | 0.04 | 0.79 | 0.59 | 0.52 | 0.52 | 0.03 | 0.20 | 0.33 | 0.10 | 0.98 | 0.03 | 0.96 | 0.05 | 0.31 | 0.39 | 0.01 | 0.52 | 0.05 | 0.29 | 0.25 | 0.22 | 0.03 | 0.05 | 0.28 | 0.47 | 0.18 | 0.00 | 0.03 | 0.00 | **Perimeter** |
| | | 0.05 | 0.11 | 0.57 | 0.82 | 0.06 | 0.80 | 0.51 | 0.56 | 0.56 | 0.04 | 0.23 | 0.29 | 0.07 | 0.91 | 0.01 | 0.96 | 0.06 | 0.32 | 0.34 | 0.01 | 0.48 | 0.06 | 0.27 | 0.22 | 0.17 | 0.04 | 0.03 | 0.17 | 0.43 | 0.23 | 0.03 | 0.02 | 0.00 | **Woody Area** |
| | | | 0.16 | 0.01 | 0.07 | 0.02 | 0.07 | 0.55 | 0.02 | 0.02 | 0.01 | 0.00 | 0.00 | 0.11 | 0.15 | 0.32 | 0.13 | 0.16 | 0.00 | 0.26 | 0.11 | 0.05 | 0.00 | 0.02 | 0.01 | 0.00 | 0.11 | 0.01 | 0.03 | 0.02 | 0.01 | 0.05 | 0.07 | 0.06 | **Woody %** |
| | | | | 0.08 | 0.01 | 0.63 | 0.00 | 0.23 | 0.07 | 0.07 | 0.58 | 0.30 | 0.00 | 0.25 | 0.13 | 0.00 | 0.14 | 0.13 | 0.05 | 0.42 | 0.28 | 0.10 | 0.55 | 0.26 | 0.32 | 0.34 | 0.21 | 0.07 | 0.13 | 0.02 | 0.00 | 0.21 | 0.00 | 0.64 | **Min Elev** |
| | | | | | 0.87 | 0.63 | 0.90 | 0.23 | 0.95 | 0.95 | 0.54 | 0.78 | 0.32 | 0.02 | 0.56 | 0.09 | 0.55 | 0.00 | 0.44 | 0.07 | 0.02 | 0.92 | 0.60 | 0.84 | 0.83 | 0.78 | 0.16 | 0.26 | 0.02 | 0.30 | 0.27 | 0.28 | 0.10 | 0.40 | **Max Elev** |
| | | | | | | 0.27 | 0.98 | 0.46 | 0.83 | 0.83 | 0.23 | 0.51 | 0.35 | 0.11 | 0.83 | 0.09 | 0.83 | 0.01 | 0.37 | 0.27 | 0.00 | 0.77 | 0.28 | 0.57 | 0.54 | 0.49 | 0.06 | 0.18 | 0.08 | 0.38 | 0.30 | 0.14 | 0.10 | 0.13 | **Range Elev** |
| | | | | | | | 0.33 | 0.00 | 0.62 | 0.61 | 0.93 | 0.85 | 0.14 | 0.05 | 0.05 | 0.06 | 0.05 | 0.07 | 0.28 | 0.04 | 0.15 | 0.63 | 0.91 | 0.81 | 0.87 | 0.87 | 0.26 | 0.26 | 0.02 | 0.07 | 0.12 | 0.42 | 0.06 | 0.84 | **Mean Elev** |
| | | | | | | | | 0.44 | 0.89 | 0.89 | 0.30 | 0.60 | 0.34 | 0.06 | 0.81 | 0.09 | 0.81 | 0.00 | 0.38 | 0.24 | 0.00 | 0.80 | 0.32 | 0.62 | 0.59 | 0.54 | 0.07 | 0.21 | 0.06 | 0.36 | 0.29 | 0.16 | 0.08 | 0.15 | **Std Elev** |
| | | | | | | | | | 0.19 | 0.19 | 0.00 | 0.05 | 0.03 | 0.15 | 0.58 | 0.20 | 0.59 | 0.23 | 0.03 | 0.62 | 0.22 | 0.22 | 0.01 | 0.10 | 0.07 | 0.05 | 0.04 | 0.09 | 0.01 | 0.06 | 0.02 | 0.00 | 0.13 | 0.04 | **Min Slope** |
| | | | | | | | | | | 1.00 | 0.60 | 0.87 | 0.44 | 0.01 | 0.56 | 0.09 | 0.55 | 0.01 | 0.41 | 0.08 | 0.02 | 0.89 | 0.59 | 0.82 | 0.81 | 0.76 | 0.11 | 0.27 | 0.02 | 0.34 | 0.39 | 0.31 | 0.05 | 0.39 | **Max Slope** |
| | | | | | | | | | | | 0.60 | 0.87 | 0.44 | 0.01 | 0.56 | 0.09 | 0.55 | 0.01 | 0.41 | 0.08 | 0.02 | 0.89 | 0.59 | 0.82 | 0.81 | 0.76 | 0.11 | 0.27 | 0.02 | 0.34 | 0.39 | 0.31 | 0.05 | 0.38 | **Range Slope** |
| | | | | | | | | | | | | 0.89 | 0.15 | 0.04 | 0.04 | 0.12 | 0.04 | 0.06 | 0.19 | 0.01 | 0.08 | 0.56 | 0.84 | 0.73 | 0.79 | 0.79 | 0.19 | 0.27 | 0.04 | 0.04 | 0.16 | 0.46 | 0.08 | 0.76 | **Mean Slope** |
| | | | | | | | | | | | | | 0.29 | 0.00 | 0.23 | 0.13 | 0.23 | 0.03 | 0.31 | 0.01 | 0.05 | 0.77 | 0.80 | 0.85 | 0.88 | 0.85 | 0.13 | 0.31 | 0.00 | 0.16 | 0.28 | 0.42 | 0.06 | 0.60 | **Std Slope** |
| | | | | | | | | | | | | | | 0.01 | 0.34 | 0.00 | 0.33 | 0.01 | 0.21 | 0.04 | 0.01 | 0.44 | 0.22 | 0.37 | 0.33 | 0.27 | 0.00 | 0.08 | 0.17 | 0.63 | 0.72 | 0.12 | 0.04 | 0.17 | **Mean Aspect** |
| | | | | | | | | | | | | | | | 0.06 | 0.33 | 0.07 | 0.11 | 0.00 | 0.19 | 0.09 | 0.00 | 0.02 | 0.00 | 0.01 | 0.02 | 0.08 | 0.00 | 0.01 | 0.03 | 0.04 | 0.00 | 0.22 | 0.05 | **Std Aspect** |
| | | | | | | | | | | | | | | | | 0.02 | 0.99 | 0.03 | 0.31 | 0.37 | 0.01 | 0.54 | 0.06 | 0.31 | 0.26 | 0.23 | 0.03 | 0.05 | 0.26 | 0.46 | 0.19 | 0.01 | 0.01 | 0.00 | **Stream Length** |
| | | | | | | | | | | | | | | | | | 0.02 | 0.28 | 0.00 | 0.18 | 0.11 | 0.11 | 0.12 | 0.12 | 0.10 | 0.07 | 0.00 | 0.04 | 0.03 | 0.00 | 0.01 | 0.09 | 0.72 | 0.02 | **Stream Density** |
| | | | | | | | | | | | | | | | | | | 0.06 | 0.31 | 0.38 | 0.01 | 0.51 | 0.06 | 0.29 | 0.24 | 0.19 | 0.03 | 0.04 | 0.23 | 0.46 | 0.20 | 0.01 | 0.02 | 0.00 | **# Junctions** |
| | | | | | | | | | | | | | | | | | | | 0.01 | 0.13 | 0.06 | 0.00 | 0.01 | 0.00 | 0.01 | 0.06 | 0.01 | 0.16 | 0.05 | 0.05 | 0.03 | 0.03 | 0.38 | 0.17 | **Frequency** |
| | | | | | | | | | | | | | | | | | | | | 0.06 | 0.51 | 0.50 | 0.32 | 0.45 | 0.41 | 0.33 | 0.48 | 0.04 | 0.45 | 0.68 | 0.02 | 0.01 | 0.02 | 0.09 | **Min Rain** |
| | | | | | | | | | | | | | | | | | | | | | 0.69 | 0.04 | 0.04 | 0.00 | 0.00 | 0.00 | 0.16 | 0.15 | 0.00 | 0.00 | 0.13 | 0.06 | 0.10 | 0.08 | **Max Rain** |
| | | | | | | | | | | | | | | | | | | | | | | 0.05 | 0.15 | 0.09 | 0.10 | 0.09 | 0.48 | 0.18 | 0.24 | 0.18 | 0.05 | 0.10 | 0.04 | 0.10 | **Mean Rain** |
| | | | | | | | | | | | | | | | | | | | | | | | 0.70 | 0.94 | 0.91 | 0.83 | 0.18 | 0.19 | 0.07 | 0.42 | 0.26 | 0.21 | 0.08 | 0.43 | **Min Evap** |
| | | | | | | | | | | | | | | | | | | | | | | | | 0.89 | 0.90 | 0.82 | 0.18 | 0.22 | 0.01 | 0.14 | 0.15 | 0.36 | 0.08 | 0.74 | **Max Evap** |
| | | | | | | | | | | | | | | | | | | | | | | | | | 0.99 | 0.91 | 0.20 | 0.22 | 0.02 | 0.31 | 0.23 | 0.28 | 0.09 | 0.61 | **Mean Evap** |
| | | | | | | | | | | | | | | | | | | | | | | | | | | 0.96 | 0.21 | 0.27 | 0.01 | 0.24 | 0.21 | 0.31 | 0.07 | 0.69 | **Latitude** |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.20 | 0.35 | 0.00 | 0.17 | 0.19 | 0.31 | 0.05 | 0.74 | **Dist to Coast** |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.11 | 0.20 | 0.14 | 0.05 | 0.01 | 0.10 | 0.14 | **Wet Season Rain** |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.34 | 0.03 | 0.29 | 0.65 | 0.00 | 0.34 | **Dry Season Rainfall** |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.64 | 0.00 | 0.39 | 0.01 | 0.05 | **Ks** |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.24 | 0.01 | 0.00 | 0.02 | **PWHC** |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.45 | 0.01 | 0.16 | **Depth** |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.05 | 0.45 | **Texture** |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.01 | **Pct Length Carb** |

$R^2 \geq 0.90$

$0.80 \leq R^2 < 0.90$

$0.70 \leq R^2 < 0.80$

A degree of judgement was also used in the selection of independent variables. For example, variables which appeared to have no causative relationship to the dependent variable under consideration were excluded from the regression. This was necessary as many of the dependent variables under consideration were those found to be useful in similar studies in southern states, and in many cases the different topographical and climatic conditions in northern Australia rendered these variables less influential hydrologically.

Due to the relatively small sample size of the dependent variables (8 to 10 values), it was important that statistical interpretations of the relationship between certain independent and dependent variables could be explained in terms of hydrological processes. This ensured that regression relationships were not based on statistical noise or anomalies in the data, particularly given the small sample sizes being used.

## E.4 Goodness of Fit

The goodness of fit of each regression relationship was evaluated using the coefficient of determination ($R^2$) and standard error of estimate (SEE) parameters. The $R^2$ measures the proportion of the total variation that is explained by the model. A large $R^2$ is associated with a good model or prediction equation. The standard error is an estimate of the standard deviation of the residuals, that is, it measures the degree of scatter of the observed data points around the regression line. Hence a small standard error is associated with an accurate model. The standard error has been expressed as a percentage of the mean of the observed dependent variable in this report.

For each dependent variable, four primary independent variables were selected. Selection of these primary variables was based on the considerations noted above. Taking into account these factors, a final "best" variable was chosen. This "best" variable was then used in a multiple regression with a secondary variable, to determine whether the estimate could be improved. Again, the best four secondary variables were evaluated for each analysis period. If it was found that the $R^2$ and standard error were improved with the addition of a secondary variable, and it was considered that this variable could be physically linked to the dependent variable with some logical explanation, it was added to the prediction equation. Secondary variables that were highly correlated with the primary variable were excluded from the analysis.

The following sections show the best individual and secondary variables for the estimation of each hydrological prediction index. Prediction equations have been shown where they were identified, and recommendations have been given for their use. The various indices are grouped into wet season and dry season indices.

## E.5 Wet Season Indices

### E.5.1 Mean Wet Season Quickflow

The best four predictor variables for mean wet season quickflow are shown in Table E-2.

- **Table E-2 Mean Wet Season Quickflow – Best Primary Predictor Variables**

| Rank | Catchment Characteristic | $R^2$ | SEE | F | p |
|---|---|---|---|---|---|
| | | **1965-2005** | | | |
| 1 | Number of Junctions | 0.979 | 12% | 459 | <0.001 |
| 2 | Area | 0.978 | 16% | 226 | <0.001 |
| 3 | Steam Length | 0.978 | 17% | 220 | <0.001 |
| 4 | Perimeter | 0.945 | 26% | 86 | <0.001 |
| | | **1968-1978** | | | |
| 1 | Number of Junctions | 0.994 | 9% | 1481 | <0.001 |
| 2 | Stream Length | 0.973 | 20% | 326 | <0.001 |
| 3 | Area | 0.963 | 23% | 238 | <0.001 |
| 4 | Woody Area | 0.954 | 26% | 187 | <0.001 |

Each of the four primary variables in Table E-2 is highly correlated with area. For the reasons discussed previously, area was chosen as the primary variable. Table E-3 shows the best secondary variables used with area to predict mean wet season quickflow. The correlation matrix in Figure E-1 shows that number of junctions, stream length and woody area are all highly correlated with area. Of these variables, area would be expected to have the most readily interpretable relationship with mean wet season flow, and its value can be readily estimated for any catchment. Given the restricted number of data points, it is likely that the other three variables are primarily acting as surrogates for area. This is reinforced by the fact that the variables percentage wooded area, stream density and frequency of junctions, all of which have had their areal component removed, were not found to be good predictors of mean wet season flow by themselves. For these reasons, area was selected as the primary predictor variable for mean wet season flow.

**Table E-3: Mean Wet Season Quickflow – Best Secondary Predictor Variables With Area**

| Rank | Secondary Variable | $R^2$ | SEE | F | p (Area) | p (secondary variable) |
|---|---|---|---|---|---|---|
| **1965-2005** | | | | | | |
| 1 | Distance to Coast | 0.997 | 7% | 22 | <0.001 | 0.009 |
| 2 | Number of Junctions | 0.991 | 12% | 6 | 0.405 | 0.074 |
| 3 | Mean Elevation | 0.990 | 12% | 5 | <0.001 | 0.094 |
| 4 | Latitude | 0.990 | 13% | 4 | <0.001 | 0.103 |
| **1968-1978** | | | | | | |
| 1 | Number of Junctions | 0.995 | 9% | 50 | 0.246 | <0.001 |
| 2 | Woody Area | 0.985 | 16% | 12 | 0.003 | 0.009 |
| 3 | Stream Length | 0.981 | 18% | 7 | 0.107 | 0.027 |
| 4 | Frequency of Junctions | 0.978 | 19% | 6 | <0.001 | 0.047 |

The variable distance to coast, when used with area, improves the prediction of mean wet season quickflow for the 1965-2005 analysis period. For the 1968-1978 analysis period, the only variable not correlated with area that improves the prediction of mean wet season quickflow is the frequency of junctions. The relationship between mean wet season quickflow and the frequency of stream junctions in the catchment is not altogether clear, however those catchments with a greater number of stream junctions per square kilometre are likely to have larger volumes of surface runoff. Given the uncertainty associated with this, distance to coast was chosen as the best secondary variable for use in the prediction equation.

The equation using area to predict mean wet season quickflow (derived with data from the 1965-2005 analysis period) is:

$$MQF_w = 8.803 + (0.305 \times Area)$$

where: $MQF_w$ = Mean Wet Season Quickflow (GL/year);

$Area$ = Catchment Area (km$^2$);

$R^2 = 0.978$; and

SEE = 16%

A significant improvement to the estimate of mean wet season quickflow can be made by including the variable distance to coast in the prediction equation:

$$MQF_w = 39.200 + (0.353 \times Area) - (1.140 \times DistToCoast)$$

where: $MQF_w$ = Mean Wet Season Quickflow (GL/year);

$Area$ = Catchment Area (km$^2$);

$DistToCoast$ = Direct distance from catchment centroid to nearest coastal point (km)

$R^2$ = 0.997; and

SEE = 7%

The observed mean wet season quickflows for the 1965-2005 period, and the mean wet season quickflows estimated using the above prediction equations are shown in Figure E-2 below.

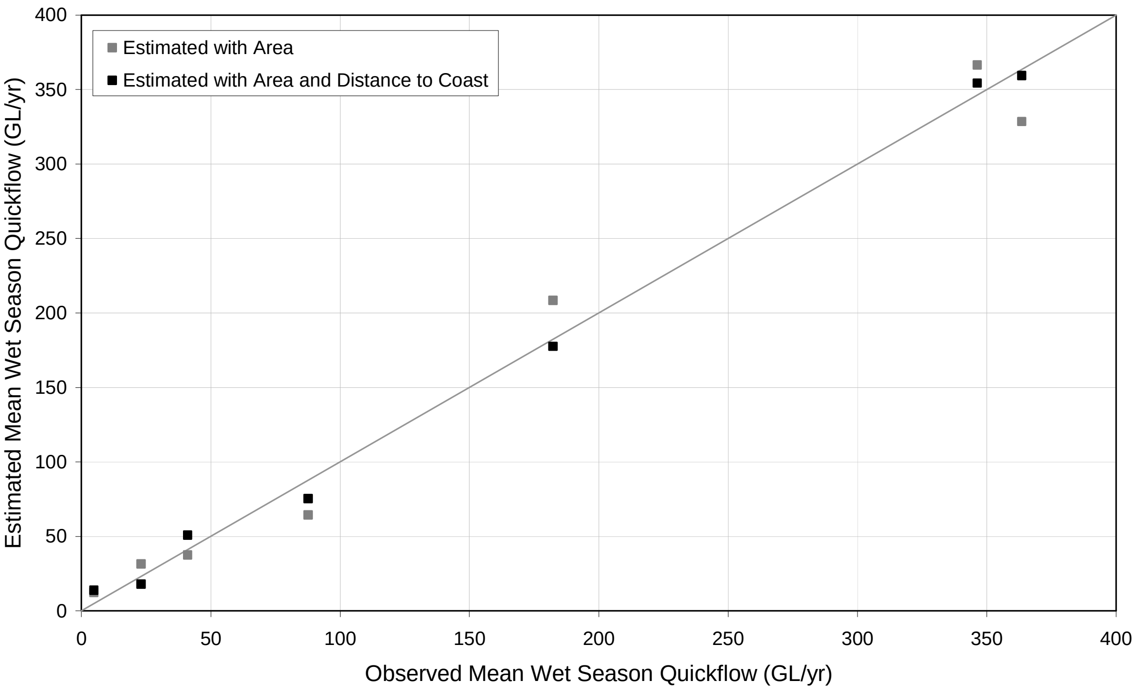



**Figure E-2: Observed and Estimated Mean Wet Season Quickflow for the 1965-2005 Period**

### E.5.2 Mean Wet Season Baseflow

The best four predictor variables for mean wet season baseflow are shown in Table E-4.

- **Table E-4 Mean Wet Season Baseflow – Best Primary Predictor Variables**

| Rank | Catchment Characteristic | $R^2$ | SEE | F | p |
|---|---|---|---|---|---|
| **1965-2005** | | | | | |
| 1 | Number of Junctions | 0.967 | 19% | 174 | <0.001 |
| 2 | Woody Area | 0.969 | 20% | 156 | <0.001 |
| 3 | Area | 0.923 | 32% | 60 | 0.001 |
| 4 | Stream Length | 0.921 | 33% | 58 | 0.001 |
| **1968-1978** | | | | | |
| 1 | Number of Junctions | 0.988 | 14% | 733 | <0.001 |
| 2 | Stream Length | 0.967 | 22% | 268 | <0.001 |
| 3 | Area | 0.964 | 23% | 240 | <0.001 |
| 4 | Woody Area | 0.951 | 27% | 176 | <0.001 |

Each of the four primary variables in Table E-4 is highly correlated with area. For the reasons discussed previously, area was chosen as the primary variable. Table E-5 shows the best secondary variables used with area to predict mean wet season base flow.

- **Table E-5: Mean Wet Season Baseflow – Best Secondary Predictor Variables With Area**

| Rank | Secondary Variable | $R^2$ | SEE | F | p (Area) | p (secondary variable) |
|---|---|---|---|---|---|---|
| **1965-2005** | | | | | | |
| 1 | Distance to Coast | 0.987 | 15% | 19 | <0.001 | 0.012 |
| 2 | Number of Junctions | 0.979 | 19% | 11 | 0.320 | 0.031 |
| 3 | Woody Area | 0.976 | 20% | 9 | 0.342 | 0.041 |
| 4 | Latitude | 0.963 | 25% | 4 | 0.001 | 0.108 |
| **1968-1978** | | | | | | |
| 1 | Number of Junctions | 0.988 | 14% | 16 | 0.813 | 0.004 |
| 2 | Woody Area | 0.984 | 16% | 10 | 0.003 | 0.012 |
| 3 | Distance to Coast | 0.975 | 20% | 4 | <0.001 | 0.092 |
| 4 | Latitude | 0.972 | 22% | 2 | <0.001 | 0.171 |

The variable distance to coast, when used with area, improves the prediction of mean wet season baseflow for both analysis periods. Distance to coast was therefore chosen as the best secondary variable for use in the prediction equation.

The equation using area to predict mean wet season baseflow (derived with data from the 1965-2005 analysis period) is:

$$MBF_w = 2.450 + (0.109 \times Area)$$

where: $MBF_w$ = Mean Wet Season Baseflow (GL/year);

$Area$ = Catchment Area (km$^2$);

$R^2$ = 0.923; and

SEE = 32%

A significant improvement to the estimate of mean wet season baseflow can be made by including the variable distance to coast in the prediction equation:

$$MBF_w = 23.221 + (0.142 \times Area) - (0.779 \times DistToCoast)$$

where: $MBF_w$ = Mean Wet Season Baseflow (GL/year);

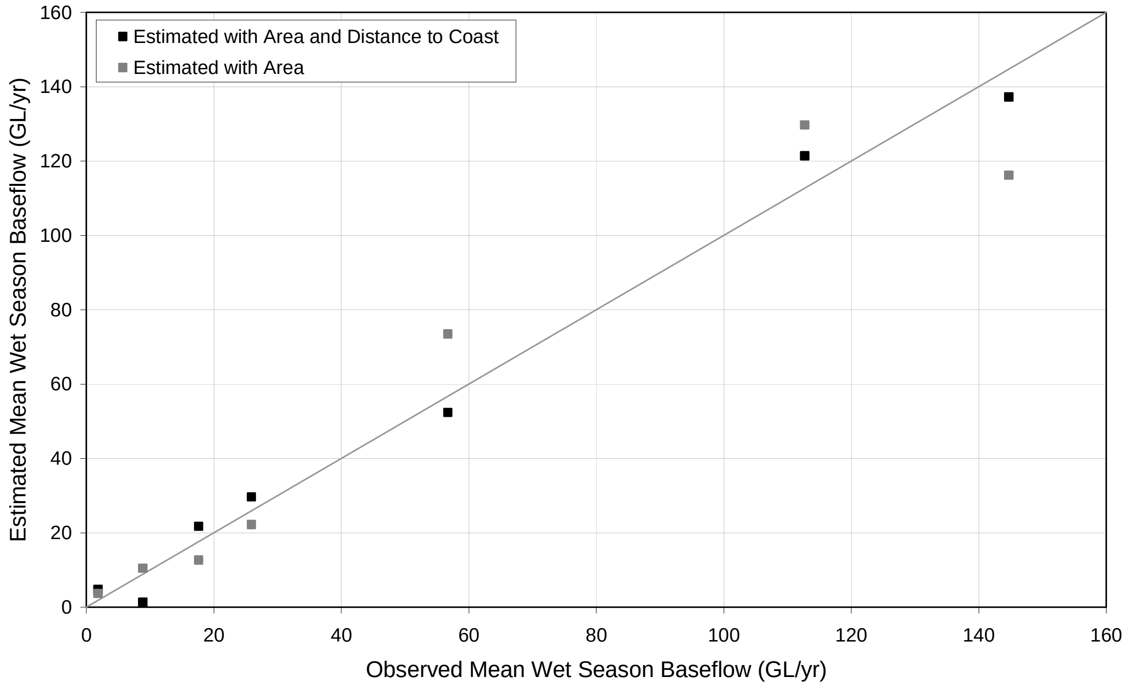
$Area$ = Catchment Area (km$^2$);

$DistToCoast$ = Direct distance from catchment centroid to nearest coastal point (km)

$R^2$ = 0.987; and

SEE = 15%

The observed mean wet season baseflows for the 1965-2005 period, and the mean wet season baseflows estimated using the above prediction equations are shown in Figure E-3 below.




- **Figure E-3: Observed and Estimated Mean Wet Season Baseflows for the 1965-2005 Period**

### E.5.3 Median Daily Flow – Wet Season

The best four predictor variables for wet season median daily flow are shown in Table E-6.

- **Table E-6 Wet Season Median Daily Flow – Best Primary Predictor Variables**

| Rank | Catchment Characteristic | $R^2$ | SEE | F | p |
|---|---|---|---|---|---|
| | | **1965-2005** | | | |
| 1 | Woody Area | 0.965 | 22% | 137 | <0.001 |
| 2 | Number of Junctions | 0.917 | 33% | 55 | 0.001 |
| 3 | Area | 0.831 | 45% | 25 | 0.004 |
| 4 | Stream Length | 0.829 | 45% | 24 | 0.004 |
| | | **1968-1978** | | | |
| 1 | Woody Area | 0.966 | 23% | 254 | < 0.001 |
| 2 | Number of Junctions | 0.919 | 36% | 102 | < 0.001 |
| 3 | Stream Length | 0.849 | 49% | 51 | < 0.001 |
| 4 | Area | 0.836 | 51% | 46 | < 0.001 |

Each of the four primary variables in Table E-6 is highly correlated with area. For the reasons discussed previously, area was chosen as the primary variable. Table E-7 shows the best secondary variables used with area to predict wet season median daily flow.

**Table E-7: Wet Season Median Daily Flow – Best Secondary Predictor Variables With Area**

| Rank | Secondary Variable | $R^2$ | SEE | F | p (Area) | p (secondary variable) |
|---|---|---|---|---|---|---|
| **1965-2005** | | | | | | |
| 1 | Distance to Coast | 0.954 | 25% | 40 | 0.001 | 0.033 |
| 2 | Latitude | 0.904 | 35% | 18 | 0.008 | 0.168 |
| 3 | Minimum Evaporation | 0.885 | 38% | 15 | 0.018 | 0.250 |
| 4 | Mean Evaporation | 0.884 | 38% | 15 | 0.012 | 0.258 |
| **1968-1978** | | | | | | |
| 1 | Frequency of Junctions | 0.870 | 48% | 47 | < 0.001 | 0.189 |
| 2 | Distance to Coast | 0.863 | 50% | 45 | < 0.001 | 0.245 |
| 3 | Latitude | 0.850 | 52% | 38 | < 0.001 | 0.415 |
| 4 | Std Dev of Aspect | 0.848 | 52% | 39 | < 0.001 | 0.453 |

The variable distance to coast, when used with area, improves the prediction of wet season median daily flow for both analysis periods. Frequency of junctions was the secondary variable that resulted in the greatest improvement of estimate over the 1968-1978 analysis period. However, over the longer 1965-2005 analysis period, it produced a larger standard error of estimate (SEE = 52%) than for area alone (SEE = 45%). Distance to coast was therefore chosen as the best secondary variable for use in the prediction equation.

The equation using area to predict wet season median daily flow (derived with data from the 1965-2005 analysis period) is:

$$Q50_w = 21.391 + (0.700 \times Area)$$

where: $Q50_w$ = Wet Season Median Daily Flow (ML/day);

$Area$ = Catchment Area (km$^2$);

$R^2$ = 0.831; and

SEE = 45%

A significant improvement to the estimate of wet season median daily flow can be made by including the variable distance to coast in the prediction equation:

$$Q50_w = 216.529 + (1.009 \times Area) - (7.322 \times DistToCoast)$$

where: $Q50_w$ = Wet Season Median Daily Flow (ML/day);

$Area$ = Catchment Area (km$^2$);

$DistToCoast$ = Direct distance from catchment centroid to nearest coastal point (km)

$R^2$ = 0.952; and

SEE = 25%

The observed wet season median daily flows for the 1965-2005 period, and the wet season median daily flows estimated using the above prediction equations are shown in Figure E-4 below.

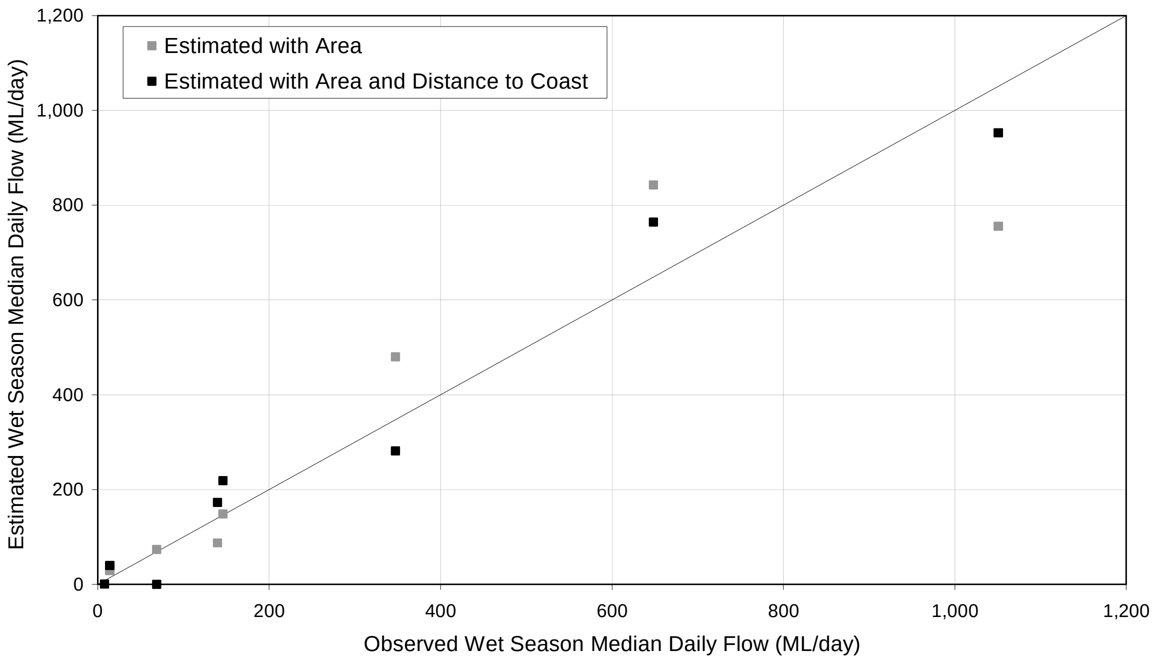



**Figure E-4: Observed and Estimated Wet Season Median Daily Flows for the 1965-2005 Period**

### E.5.4 20th Percentile Flow – Wet Season

The best four predictor variables for wet season 20th percentile flow are shown in Table 8-8.

- **Table 8-8: Wet Season 20th Percentile Flow – Best Primary Predictor Variables**

| Rank | Catchment Characteristic | $R^2$ | SEE | F | p |
|---|---|---|---|---|---|
| **1965-2005** | | | | | |
| 1 | Number of Junctions | 0.976 | 18% | 203 | < 0.001 |
| 2 | Area | 0.953 | 24% | 101 | < 0.001 |
| 3 | Stream Length | 0.949 | 25% | 93 | < 0.001 |
| 4 | Woody Area | 0.943 | 27% | 83 | < 0.001 |
| **1968-1978** | | | | | |
| 1 | Area | 0.984 | 16% | 554 | < 0.001 |
| 2 | Stream Length | 0.982 | 17% | 484 | < 0.001 |
| 3 | Number of Junctions | 0.979 | 18% | 429 | < 0.001 |
| 4 | Perimeter | 0.959 | 26% | 212 | < 0.001 |

Each of the primary variables in Table 8-8 is highly correlated with area. For the reasons discussed previously, area was chosen as the primary variable. Table E-9 shows the best secondary variables used with area to predict wet season 20th percentile flow.

- **Table E-9: Wet Season 20th Percentile Flow – Best Secondary Predictor Variables With Area**

| Rank | Secondary Variable | $R^2$ | SEE | F | p (Area) | p (secondary variable) |
|---|---|---|---|---|---|---|
| **1965-2005** | | | | | | |
| 1 | Distance to Coast | 0.997 | 6% | 682 | < 0.001 | 0.001 |
| 2 | Latitude | 0.986 | 14% | 136 | < 0.001 | 0.040 |
| 3 | Mean Elevation | 0.981 | 16% | 103 | < 0.001 | 0.072 |
| 4 | Minimum Evaporation | 0.979 | 16% | 94 | 0.001 | 0.088 |
| **1968-1978** | | | | | | |
| 1 | Distance to Coast | 0.991 | 13% | 778 | < 0.001 | 0.031 |
| 2 | Latitude | 0.991 | 13% | 697 | < 0.001 | 0.042 |
| 3 | Mean Evaporation | 0.990 | 13% | 620 | < 0.001 | 0.057 |
| 4 | Maximum Evaporation | 0.990 | 14% | 739 | < 0.001 | 0.073 |

The variable distance to coast, when used with area, improves the prediction of wet season 20th percentile flow for both analysis periods. The other secondary variables, latitude, mean elevation and the evaporation variables, are all correlated with distance to coast.

The equation using area to predict wet season 20th percentile flow (derived with data from the 1965-2005 analysis period) is:

$$Q20_w = 60.676 + (3.830 \times Area)$$

where: $Q20_w$ = Wet Season 20th Percentile Flow (ML/day);

$Area$ = Catchment Area (km$^2$);

$R^2 = 0.953$; and

SEE = 24%

A significant improvement to the estimate of wet season 20th percentile flow can be made by including the variable distance to coast in the prediction equation:

$$Q20_w = 661.118 + (4.782 \times Area) - (22.528 \times DistToCoast)$$

where: $Q20_w$ = Wet Season 20th Percentile Flow (ML/day);

$Area$ = Catchment Area (km$^2$);

$DistToCoast$ = Direct distance from catchment centroid to nearest coastal point (km)

$R^2 = 0.997$; and

SEE = 6%

The observed wet season 20th percentile flows for the 1965-2005 period, and the wet season 20th percentile flows estimated using the above prediction equations are shown in Figure E-5 below.

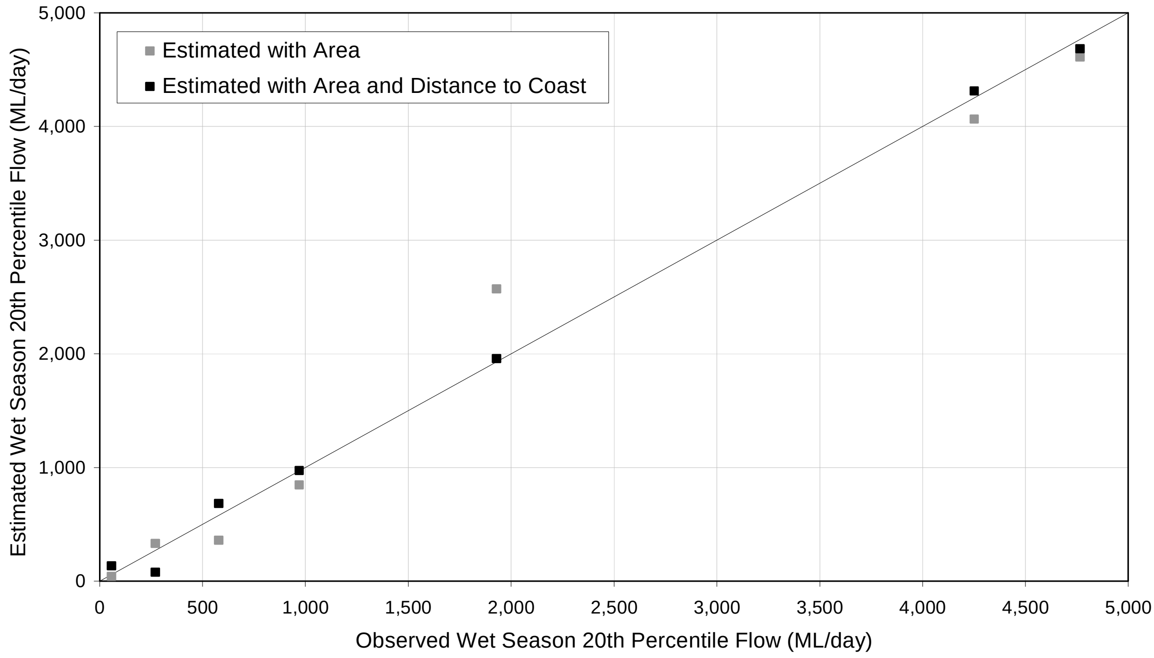



**Figure E-5: Observed and Estimated Wet Season 20th Percentile Flows for the 1965-2005 Period**

### E.5.5 80th Percentile Flow – Wet Season

The best four predictor variables for wet season 80th percentile flow are shown in Table E-10.

**Table E-10: Wet Season 80th Percentile Flow – Best Primary Predictor Variables**

| Rank | Catchment Characteristic | $R^2$ | SEE | F | p |
|---|---|---|---|---|---|
| **1965-2005** | | | | | |
| 1 | Woody Area | 0.998 | 5% | 2625 | < 0.001 |
| 2 | Number of Junctions | 0.971 | 22% | 155 | < 0.001 |
| 3 | Stream Length | 0.908 | 38% | 49 | 0.001 |
| 4 | Area | 0.906 | 38% | 48 | 0.001 |
| **1968-1978** | | | | | |
| 1 | Woody Area | 0.951 | 31% | 175 | < 0.001 |
| 2 | Number of Junctions | 0.909 | 42% | 89 | < 0.001 |
| 3 | Stream Length | 0.838 | 56% | 46 | < 0.001 |
| 4 | Area | 0.830 | 58% | 44 | < 0.001 |

Each of the primary variables in Table E-10 is highly correlated with area. For the reasons discussed previously, area was chosen as the primary variable. Table E-9 shows the best secondary variables used with area to predict wet season 80th percentile flow.

- **Table E-11: Wet Season 80th Percentile Flow – Best Secondary Predictor Variables With Area**

| Rank | Secondary Variable | $R^2$ | SEE | F | p (Area) | p (secondary variable) |
|---|---|---|---|---|---|---|
| **1965-2005** | | | | | | |
| 1 | Distance to Coast | 0.949 | 29% | 35 | 0.003 | 0.153 |
| 2 | % Wooded Area | 0.938 | 32% | 29 | 0.002 | 0.238 |
| 3 | Latitude | 0.925 | 35% | 24 | 0.007 | 0.384 |
| 4 | Minimum Evaporation | 0.919 | 36% | 23 | 0.015 | 0.461 |
| **1968-1978** | | | | | | |
| 1 | Distance to Coast | 0.856 | 56% | 43 | < 0.001 | 0.256 |
| 2 | Frequency of Junctions | 0.855 | 57% | 42 | < 0.001 | 0.265 |
| 3 | Std Dev of Aspect | 0.841 | 59% | 37 | < 0.001 | 0.467 |
| 4 | % Wooded Area | 0.839 | 60% | 38 | < 0.001 | 0.516 |

The variable distance to coast, when used with area, improves the prediction of wet season 80th percentile flow for both analysis periods. Percentage wooded area also appears in the top four secondary variables for both analysis periods, but results in only a slight improvement to the estimate for the 1965-2005 analysis period and a worse estimate for the 1968-1978 analysis period. As was the case with the prediction of wet season median daily flow, frequency of junctions is one of the best secondary variables when used with area for the 1968-1978 analysis period, but produced a higher standard error of estimate (SEE = 45%) for the 1965-2005 analysis period than area used alone (SEE = 38%).

The equation using area to predict wet season 80th percentile flow (derived with data from the 1965-2005 analysis period) is:

$$Q80_w = -4.364 + (0.122 \times Area)$$

where: $Q80_w$ = Wet Season 80th Percentile Flow (ML/day);

$Area$ = Catchment Area ($m^2$);

$R^2$ = 0.906; and

SEE = 38%

A significant improvement to the estimate of wet season 80th percentile flow can be made by including the variable distance to coast in the prediction equation:

$$Q80_w = 14.720 + (0.153 \times Area) - (0.716 \times DistToCoast)$$

where: $Q80_w$ = Wet Season 80th Percentile Flow (ML/day);

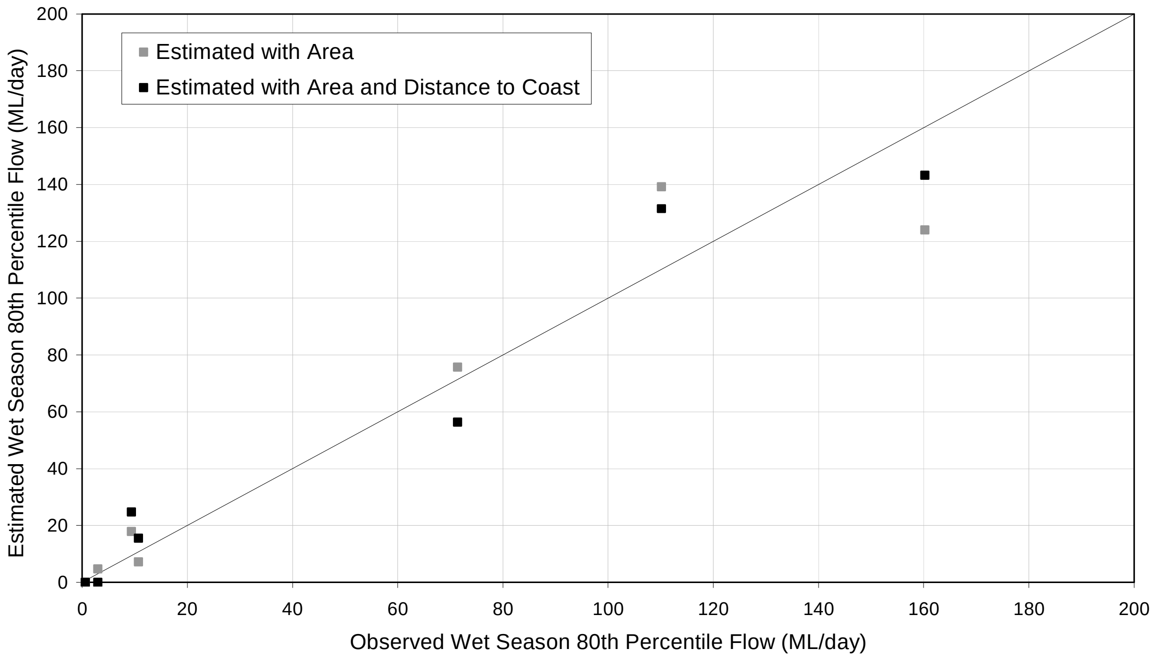
$Area$ = Catchment Area ($km^2$);

$DistToCoast$ = Direct distance from catchment centroid to nearest coastal point (km)

$R^2 = 0.949$; and

SEE = 29%

The observed wet season 80th percentile flows for the 1965-2005 period, and the wet season 80th percentile flows estimated using the above prediction equations are shown in Figure E-6 below.




- **Figure E-6: Observed and Estimated Wet Season 80th Percentile Flows for the 1965-2005 Period**

## E.6 Dry Season Indices

### E.6.1 Mean Dry Season Quickflow

The best four predictor variables for mean dry season quickflow are shown in Table E-12. Although not one of the best four for the 1968-1978 analysis period, area is also included as it is correlated with many of the other variables.

- **Table E-12 Mean Dry Season Quickflow – Best Primary Predictor Variables**

| Rank | Catchment Characteristic | $R^2$ | SEE | F | p |
|---|---|---|---|---|---|
| **1965-2005** | | | | | |
| 1 | Stream Length | 0.987 | 13% | 387 | <0.001 |
| 2 | Area | 0.985 | 14% | 340 | <0.001 |
| 3 | Perimeter | 0.978 | 17% | 225 | <0.001 |
| 4 | Range of Elevation | 0.964 | 22% | 133 | <0.001 |
| **1968-1978** | | | | | |
| 1 | Woody Area | 0.914 | 34% | 96 | <0.001 |
| 2 | Number of Junctions | 0.864 | 43% | 57 | <0.001 |
| 3 | Stream Length | 0.798 | 53% | 36 | <0.001 |
| 4 | Perimeter | 0.790 | 54% | 34 | <0.001 |
| n/a | Area | 0.771 | 56% | 30 | <0.001 |

Four of the six primary variables in Table E-12 are highly correlated with area, excluding the range of elevations, the correlation of which with mean dry season quickflow may be a statistical artefact. For the reasons discussed previously, area was chosen as the primary variable. Table E-13 shows the best secondary variables used with area to predict mean dry season quickflow.

- **Table E-13: Mean Dry Season Quickflow – Best Secondary Predictor Variables With Area**

| Rank | Secondary Variable | $R^2$ | SEE | F | p (Area) | p (secondary variable) |
|---|---|---|---|---|---|---|
| **1965-2005** | | | | | | |
| 1 | Dry Season Rainfall | 0.997 | 7% | 15 | <0.001 | 0.018 |
| 2 | Distance to Coast | 0.996 | 9% | 9 | <0.001 | 0.040 |
| 3 | Mean Elevation | 0.992 | 11% | 4 | <0.001 | 0.126 |
| 4 | Latitude | 0.992 | 11% | 4 | <0.001 | 0.126 |
| **1968-1978** | | | | | | |
| 1 | Number of Junctions | 0.942 | 30% | 24 | 0.011 | 0.001 |
| 2 | Woody Area | 0.921 | 35% | 15 | 0.431 | 0.005 |
| 3 | Stream Length | 0.899 | 39% | 10 | 0.022 | 0.013 |
| 4 | Frequency of Junctions | 0.825 | 52% | 3 | <0.001 | 0.156 |

The variable dry season rainfall, when used with area, improves the prediction of mean dry season quickflow for the 1965-2005 analysis period. The variable distance to coast also improves the prediction of mean dry season quickflow, but given that distance to coast is related the occurrence of intense cyclonic rainfall (which is likely to happen only rarely in the dry season), the average dry season rainfall is felt to be a better predictor of dry season quickflow. For the 1968-1978 analysis period the variable frequency of junctions improves the prediction of mean dry season quickflow slightly, however dry season rainfall provides a greater increase in goodness of fit. Dry season rainfall was therefore chosen as the best secondary variable for use in the prediction equation.

The equation using area to predict mean dry season quickflow (derived with data from the 1965-2005 analysis period) is:

$$MQF_d = 0.012 + (0.007 \times Area)$$

where: $MQF_d$ = Mean Dry Season Quickflow (GL/year);

$Area$ = Catchment Area (km$^2$);

$R^2$ = 0.985; and

SEE = 14%

A significant improvement to the estimate of mean dry season quickflow can be made by including the variable dry season rainfall in the prediction equation:

$$MQF_d = -6.184 + (0.006 \times Area) + (0.025 \times DrySeasonRain)$$

where: $MQF_d$ = Mean Dry Season Quickflow (GL/year);

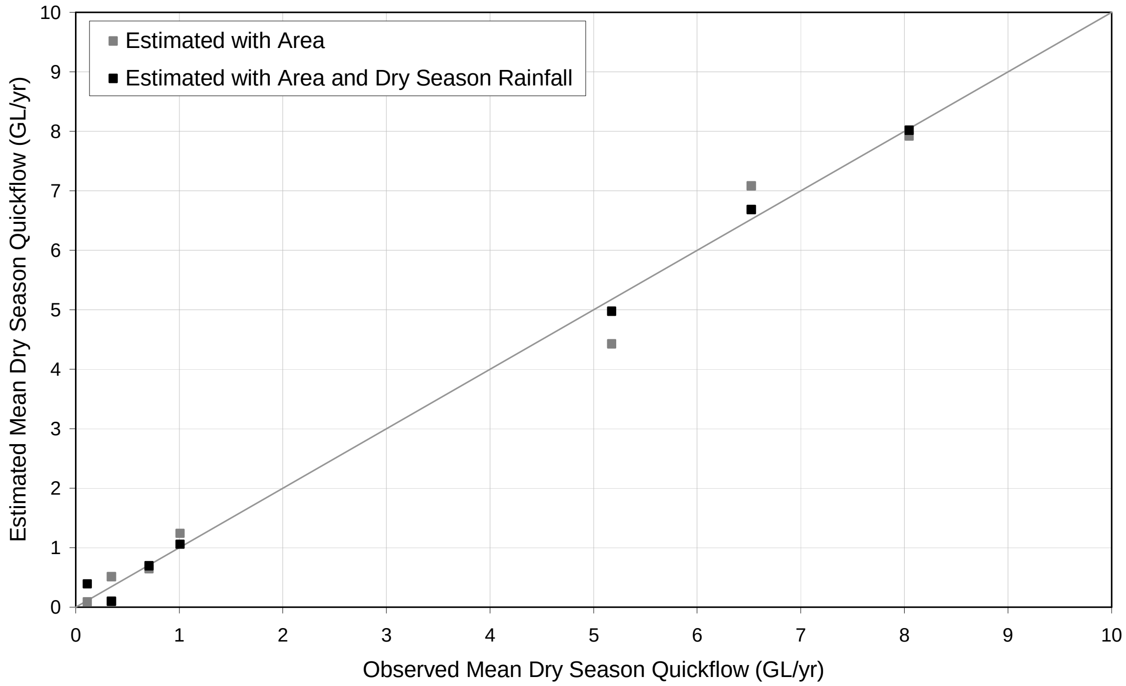
$Area$ = Catchment Area (km$^2$);

$DrySeasonRain$ = Mean dry season rainfall (mm)

$R^2$ = 0.997; and

SEE = 7%

The observed mean dry season quickflows for the 1965-2005 period, and the mean dry season quickflows estimated using the above prediction equations are shown in Figure E-7 below.




- **Figure E-7: Observed and Estimated Mean Dry Season Quickflows for the 1965-2005 Period**

### E.6.2 Mean Dry Season Baseflow

The best four predictor variables for mean dry season baseflow are shown in Table E-14.

- **Table E-14 Mean Dry Season Baseflow – Best Primary Predictor Variables**

| Rank | Catchment Characteristic | $R^2$ | SEE | F | p |
|---|---|---|---|---|---|
| | | 1965-2005 | | | |
| 1 | Woody Area | 0.983 | 18% | 285 | <0.001 |
| 2 | Number of Junctions | 0.918 | 40% | 56 | 0.001 |
| 3 | Standard Deviation of Elevation | 0.854 | 53% | 29 | 0.003 |
| 4 | Area | 0.825 | 58% | 24 | 0.005 |
| | | 1968-1978 | | | |
| 1 | Woody Area | 0.679 | 73% | 19 | 0.002 |
| 2 | Number of Junctions | 0.539 | 87% | 11 | 0.010 |
| 3 | Range of Elevations | 0.502 | 90% | 9 | 0.015 |
| 4 | Standard Deviation of Elevation | 0.472 | 93% | 8 | 0.020 |

Three of the four primary variables in Table E-14 are highly correlated with area, excluding the standard deviation of elevation, the correlation of which with mean dry season baseflow may be a statistical artefact. It can be seen that no variables were able to accurately predict mean dry season baseflow over the shorter analysis period. The fact that variables such as the range and standard deviation of elevation have emerged in the top four independent variables for this period demonstrates the poor temporal variability of the data for the 1968-1978 analysis period.

For the reasons discussed previously, area was chosen as the primary variable. Table E-15 shows the best secondary variables used with area to predict mean dry season baseflow.

- **Table E-15: Mean Dry Season Baseflow – Best Secondary Predictor Variables With Area**

| Rank | Secondary Variable | $R^2$ | SEE | F | p (Area) | p (secondary variable) |
|---|---|---|---|---|---|---|
| **1965-2005** | | | | | | |
| 1 | Woody Area | 0.993 | 13% | 103 | 0.062 | 0.001 |
| 2 | Number of Junctions | 0.975 | 25% | 24 | 0.040 | 0.008 |
| 3 | Percentage of Woody Area | 0.875 | 55% | 2 | 0.006 | 0.279 |
| 4 | Distance to Coast | 0.865 | 57% | 1 | 0.016 | 0.342 |
| **1968-1978** | | | | | | |
| 1 | Woody Area | 0.825 | 57% | 18 | 0.032 | 0.003 |
| 2 | Number of Junctions | 0.766 | 66% | 12 | 0.023 | 0.009 |
| 3 | Standard Deviation of Aspect | 0.639 | 82% | 5 | 0.037 | 0.064 |
| 4 | Stream Length | 0.584 | 88% | 3 | 0.150 | 0.124 |

Of these variables, woody area and number of junctions are correlated with area and so cannot be used in a multiple linear regression where area is already used. The variable percentage of woody area is independent of area and provides some improvement in the prediction of mean dry season baseflow. The hydrological relationship between dry season baseflow and the percentage of the catchment covered by woody vegetation is not altogether clear, however it could be argued that increased tree cover acts to retain water in the soil profile and so promote baseflow. It is worth noting that similar catchment characteristics have been successfully used in baseflow prediction equations in other studies (SKM, 2003). Percentage of woody vegetation was therefore chosen as the best secondary variable for use in the prediction equation.

The equation using area to predict mean dry season baseflow (derived with data from the 1965-2005 analysis period) is:

$$MBF_d = -0.258 + (0.007 \times Area)$$

where: $MBF_d$ = Mean Dry Season Baseflow (GL/year);

$Area$ = Catchment Area ($km^2$);

$R^2 = 0.825$; and

SEE = 58%

An improvement to the estimate of mean dry season baseflow can be made by including the variable percentage of woody area in the prediction equation:

$$MBF_d = -2.788 + (0.007 \times Area) + (9.501 \times PercentWoody)$$

where: $MBF_d$ = Mean Dry Season Baseflow (GL/year);

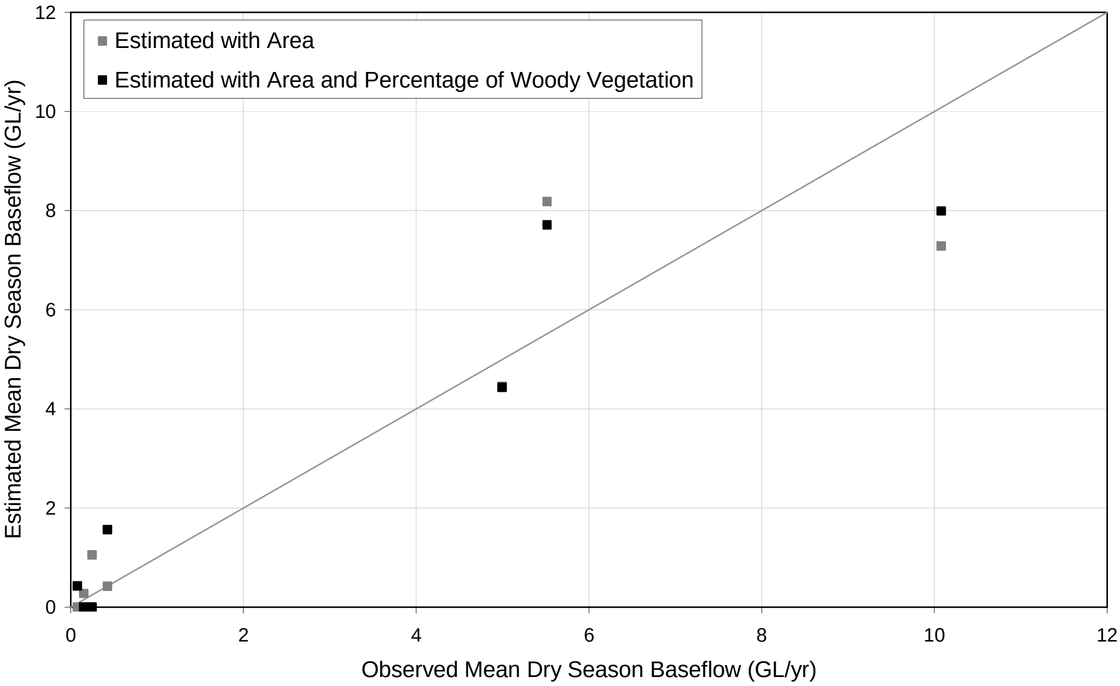
$Area$ = Catchment Area ($km^2$);

$PercentWoody$ = Percentage of catchment covered by woody vegetation (%)

$R^2 = 0.993$; and

SEE = 55%

The observed mean dry season baseflows for the 1965-2005 period, and the mean dry season baseflows estimated using the above prediction equations are shown in Figure E-8 below.




■ **Figure E-8: Observed and Estimated Mean Dry Season Baseflows for the 1965-2005 Period**

### E.6.3 Median Daily Flow – Dry Season

The best four predictor variables for dry season median daily flow are shown in Table E-16. Although not one of the best four, area is also included, as it is highly correlated with the majority of the other variables.

■ **Table E-16: Dry Season Median Daily Flow – Best Primary Predictor Variables**

| Rank | Catchment Characteristic | $R^2$ | SEE | F | p |
|---|---|---|---|---|---|
| | | **1965-2005** | | | |
| 1 | Woody Area | 0.987 | 16% | 304 | <0.001 |
| 2 | Number of Junctions | 0.935 | 35% | 65 | <0.001 |
| 3 | Std Dev of Elevation | 0.880 | 47% | 35 | 0.002 |
| 4 | Range of Elevation | 0.854 | 49% | 26 | 0.004 |
| n/a | Area | 0.847 | 52% | 27 | 0.003 |
| | | **1968-1978** | | | |
| 1 | Woody Area | 0.561 | 84% | 12 | 0.008 |
| 2 | Std Dev of Aspect | 0.525 | 88% | 10 | 0.012 |
| 3 | Range of Elevation | 0.470 | 92% | 8 | 0.020 |
| 4 | Number of Junctions | 0.453 | 94% | 7 | 0.023 |
| n/a | Area | 0.376 | 100% | 5 | 0.045 |

Attempts were also made to correlate the median dry season flow with the geological variables relating to the proportion of carbonate aquifer present in each gauged catchment. This was based on the observation that two catchments in particular with known interaction with carbonate aquifers (8150027 and 8170066) tend to have sustained dry season flows. However, it proved difficult to fit a relationship due to variability in the estimates of carbonate aquifer interaction (refer Section 6) and the very small sample size of gauged catchments available. Five of the eleven catchments have a dry season median daily flow of zero. Four of these catchments are used in the 1965-2005 analysis period, with only three non-zero points used in the regression analyses. This high proportion of zero values makes the significance of any relationship difficult to determine. Therefore, no regression relationship has been recommended and it is concluded that the dry season median daily flow cannot reliably be predicted from the candidate catchment characteristics with the available sample size of gauged data.

### E.6.4 20th Percentile Flow – Dry Season

The best four predictor variables for dry season 20th percentile flow are shown in Table E-17. Although not one of the best four, area is also included, as it is correlated with all of the other variables.

- **Table E-17: Dry Season 20th Percentile Flow – Best Primary Predictor Variables**

| Rank | Catchment Characteristic | $R^2$ | SEE | F | p |
|---|---|---|---|---|---|
| | | **1965-2005** | | | |
| 1 | Woody Area | 0.993 | 12% | 608 | < 0.001 |
| 2 | Number of Junctions | 0.960 | 27% | 110 | < 0.001 |
| 3 | Std Dev of Elevation | 0.923 | 36% | 57 | 0.001 |
| 4 | Range of Elevation | 0.900 | 40% | 39 | 0.002 |
| n/a | Area | 0.896 | 42% | 42 | 0.001 |
| | | **1968-1978** | | | |
| 1 | Woody Area | 0.794 | 54% | 35 | < 0.001 |
| 2 | Number of Junctions | 0.720 | 63% | 23 | 0.001 |
| 3 | Stream Length | 0.664 | 69% | 18 | 0.002 |
| 4 | Perimeter | 0.655 | 70% | 17 | 0.003 |
| n/a | Area | 0.653 | 70% | 17 | 0.003 |

As all variables in Table E-17 are highly correlated with area, and given the reasons discussed previously, area was chosen as the primary variable. Table E-18 shows the best secondary variables used with area to predict dry season 20th percentile flow.

**Table E-18: Dry Season 20th Percentile Flow – Best Secondary Predictor Variables With Area**

| Rank | Secondary Variable | $R^2$ | SEE | F | p (Area) | p (secondary variable) |
|---|---|---|---|---|---|---|
| **1965-2005** | | | | | | |
| 1 | % Wooded Area | 0.935 | 34% | 27 | 0.002 | 0.218 |
| 2 | Maximum Slope | 0.907 | 40% | 19 | 0.339 | 0.556 |
| 3 | Range of Slope | 0.907 | 40% | 19 | 0.338 | 0.557 |
| 4 | Maximum Elevation | 0.905 | 40% | 18 | 0.130 | 0.602 |
| **1968-1978** | | | | | | |
| 1 | Std Dev of Aspect | 0.834 | 52% | 23 | 0.001 | 0.018 |
| 2 | Distance to Coast | 0.703 | 69% | 18 | 0.003 | 0.278 |
| 3 | Minimum Elevation | 0.684 | 71% | 12 | 0.009 | 0.400 |
| 4 | Latitude | 0.681 | 72% | 15 | 0.004 | 0.432 |

It can be seen from Table E-18 that the only secondary variables that may be used to improve the estimate of dry season 20th percentile flow are percentage wooded area over the 1965-2005 analysis period, and standard deviation of aspect over the 1968-1978 period. Standard deviation of aspect (which describes the variability of direction of hill slope faces within a catchment) is relevant to southern Australia where rain shadows and exposure to sunlight can influence hydrological conditions, but this effect is not clearly evident in the Northern Territory. As a result, this variable was excluded as it had a tenuous link to the dry season 20th percentile flow. The percentage of woody area has a better link to dry season flows within a catchment, as it could be argued that a greater coverage of woody vegetation within a catchment is an indication of greater surface water/groundwater interaction in the catchment and thus higher a baseflow component to the gauged flows. As the 20th percentile flow is usually regarded as a 'high' flow, and as such is likely to have little baseflow influence, the fact that in the pilot catchments dry season flows are relatively low (the maximum 20th percentile dry season flow is 86 ML/d) indicates that baseflow is probably an important component of the entire flow regime during the dry season.

The equation using area to predict dry season 20th percentile flow (using data from the 1965-2005 analysis period) is:

$$Q20_d = -3.609 + (0.068 \times Area)$$

where: $Q20_d$ = Dry Season 20th Percentile Flow (ML/day);

$Area$ = Catchment Area (km$^2$);

$R^2 = 0.896$; and

SEE = 42%

A significant improvement to the estimate of dry season 20th percentile flow can be made by including the variable percentage of woody vegetation in the prediction equation:

$$Q20_d = -23.557 + (0.069 \times Area) + (74.902 \times PercentWoody)$$

where: $Q20_d$ = Dry Season 20th Percentile Flow (ML/day);

$Area$ = Catchment Area (km$^2$);

$PercentWoody$ = Percentage of catchment area covered by woody vegetation (%);

$R^2 = 0.935$; and

SEE = 34%

The observed dry season 20th percentile flows for the 1965-2005 period, and the dry season 20th percentile flows estimated using the above prediction equations are shown in Figure E-9 below.

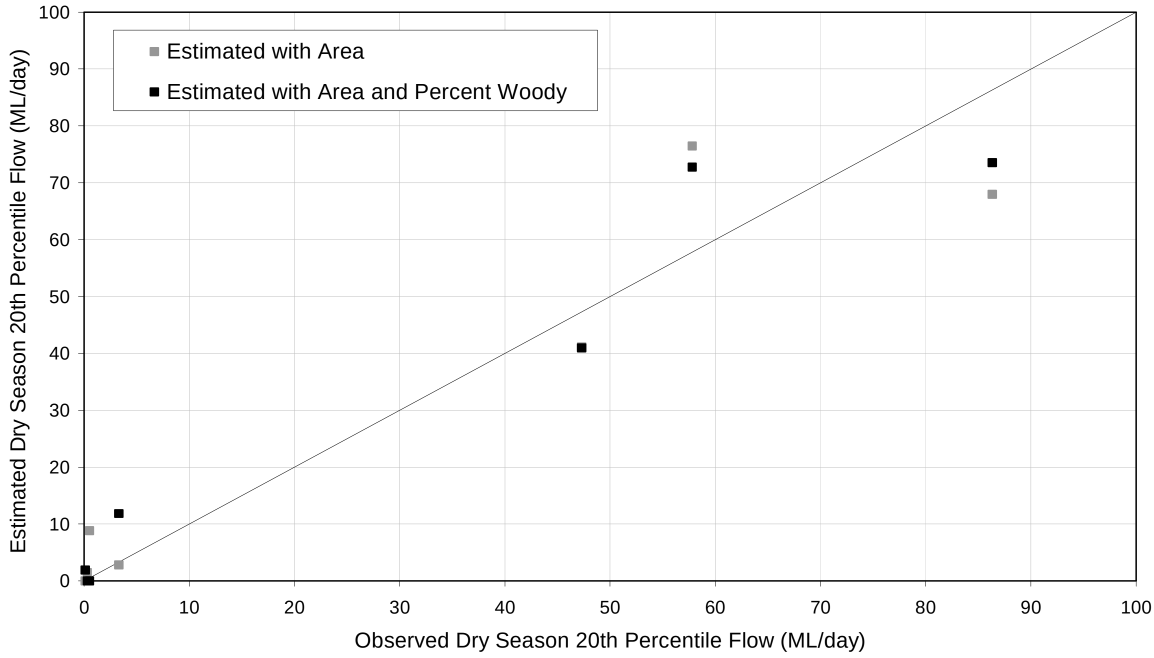



**Figure E-9: Observed and Estimated Dry Season 20th Percentile Flows for the 1965-2005 Period**

### E.6.5 80th Percentile Flow – Dry Season

The best four predictor variables for dry season 80th percentile flow are shown in Table E-19. Although not one of the best four, area is also included, as it is correlated with a number of the other variables.

- **Table E-19: Dry Season 80th Percentile Flow – best predictor variables**

| Rank | Catchment Characteristic | $R^2$ | SEE | F | p |
|---|---|---|---|---|---|
| | | **1965-2005** | | | |
| 1 | Woody Area | 0.695 | 90% | 11 | 0.022 |
| 2 | Number of Junctions | 0.535 | 99% | 6 | 0.065 |
| 3 | Std Dev of Elevation | 0.423 | 101% | 4 | 0.115 |
| 4 | Range of Slope | 0.401 | 97% | 3 | 0.131 |
| n/a | Area | 0.377 | 101% | 3 | 0.143 |
| | | **1968-1978** | | | |
| 1 | Std Dev of Aspect | 0.617 | 109% | 15 | 0.004 |
| 2 | Woody Area | 0.141 | 163% | 1.5 | 0.255 |
| 3 | Minimum Elevation | 0.134 | 164% | 1.4 | 0.269 |
| 4 | Range of Elevation | 0.091 | 168% | 0.9 | 0.367 |
| n/a | Area | 0.034 | 173% | 0.3 | 0.589 |

Five of the eleven catchments have a dry season 80th percentile flow of zero. Four of these catchments are used in the 1965-2005 analysis period, with only three non-zero points used in the regression analyses. This high proportion of zero values makes the significance of any relationship difficult to determine. For this reason no prediction equation has been recommended for dry season 80th percentile flow.

## E.7 Summary

A number of multiple linear regression relationships were developed which can be used to predict the hydrological indices in ungauged catchments. For some indices, two equations were developed representing an additional level of complexity by adding another independent variable to the equation, with a resultant increase in the goodness of fit. A summary of the recommended equations is given in Table E-20, and in all cases the equations with two independent variables are recommended as the most accurate.

- **Table E-20: Recommended Regression Equations**

| Index | Multiple Linear Regression Equation | $R^2$ | SEE (%) |
|---|---|---|---|
| $MQF_w$ | $39.200 + (0.353 \times Area) - (1.140 \times DistToCoast)$ | 0.997 | 7 |
| $MBF_w$ | $23.221 + (0.142 \times Area) - (0.779 \times DistToCoast)$ | 0.987 | 15 |
| Q50w | $216.529 + (1.009 \times Area) - (7.322 \times DistToCoast)$ | 0.952 | 25 |
| Q20w | $661.118 + (4.782 \times Area) - (22.528 \times DistToCoast)$ | 0.997 | 6 |
| Q80w | $14.720 + (0.153 \times Area) - (0.716 \times DistToCoast)$ | 0.949 | 29 |
| $MQF_d$ | $-6.184 + (0.006 \times Area) + (0.025 \times DrySeasonRain)$ | 0.997 | 7 |
| $MBF_d$ | $-2.788 + (0.007 \times Area) + (9.501 \times PercentWoody)$ | 0.993 | 55 |
| Q50d | 0* | NA | NA |
| Q20d | $-23.557 + (0.069 \times Area) + (74.902 \times PercentWoody)$ | 0.935 | 34 |
| Q80d | 0* | NA | NA |

*value may be greater than zero for catchments containing some carbonate aquifer

# Appendix F Geology and Hydrogeology

## F.1 Geology of the Adelaide River Basin

Tertiary and Quaternary sediments form a veneer over most of the Proterozoic and Mesozoic rocks. The surface geology of the Adelaide River valley is characterised by Quaternary-aged alluvium. In the northern part of the basin, on the saline mud flats, the alluvium comprises mud, silt and clay (Black-soil plains), which are bordered by colluvial sand, silt and clay. These flats are inundated during the wet season. Sand, silt and clay dominate the alluvial fill in the southern parts of the basin, which also includes ferruginised gravel (Pietsch and Stuart-Smith, 1987). The average thickness of the Cainozoic sediments is approximately 3 m (Verma, 2002). The higher ground on the floodplain margins and between the smaller drainage lines in the north of the basin is composed of Tertiary-Quaternary laterite and unconsolidated sand and sandy soils.

In the north of the basin, to the west and east of the Adelaide River floodplain, the underlying geology comprises Mesozoic-aged (Cretaceous) flat lying sediments of the Bathurst Island Formation. In the northern reaches of the Adelaide River basin, this formation is at least 80m thick (up to 130 m in thickness) and comprises claystone, medium to coarse grained sandstone and minor conglomerate. The Cretaceous sediments were deposited on an unconformity related to a period of non-deposition between 1800 and 225 million years ago (Ma) (Pietsch and Stuart-Smith, 1987)

Beneath the Mesozoic sediments in the north and directly underlying the Cainozoic alluvium (with limited outcrop) and predominantly outcropping in the south of the basin is the Proterozoic geology. From north to south, the Proterozoic geology comprises: Mount Partridge Group (arenites, lutite, volcanics and dolomites), South Alligator Group (iron-rich and tuffaceous sediments) and the Finniss River Group (interbedded siltstones and sandstones, and more resistant greywackes). There are also some small inliers of granite (Pietsch and Stuart Smith, 1987 and Ahmad *et al.*, 1993).

The Archaean-aged Rum Jungle Complex forms the western boundary of the Adelaide River basin and is located approximately in the middle of the basin. It consists of granites which have intruded gneiss, schist, diorite and banded iron formation. The contact between the overlying Proterozoic metasediments is generally sheared (Pietsch and Stuart Smith, 1987).

The hard-rock geology is heavily folded, with the fold axes trending roughly north-south. There are three major faults in the basin: the Giants Reef Fault, which trends northeast-southwest through the Rum Jungle Complex and terminates just north of the Arnhem highway near Harrison Dam; the Adelaide River Fault which is sub-parallel to the Giants Reef Fault and terminates at the township of Adelaide River; and the north-south trending Mount Shoebridge Fault which divides the Adelaide and Margaret Rivers in the south of the basin.

## F.2 Geology of the Finniss River Basin

### F.2.1 Finniss and Reynolds River Catchments

The geology of the Finniss/Reynolds River catchment is characterised by a thin veneer of fine grained Quaternary-aged alluvium on the river floodplains, generally directly overlying Proterozoic-aged geology. The divide between the two rivers is formed from laterite (ferruginised unconsolidated sands), which is also characteristic of the northern part of the Finniss River catchment. Proterozoic and Archaean-aged hard-rock geology outcrop in the upper reaches of the rivers, with the geological structure forming the north-south trending ridges.

The hard-rock geology comprises sandstone, granite, greywacke, shale, slate and siltstones. There are dolomites in the Arachaean-aged Rum Jungle and Waterhouse Complexes, which form the headwaters of the Finniss and Reynolds Rivers.

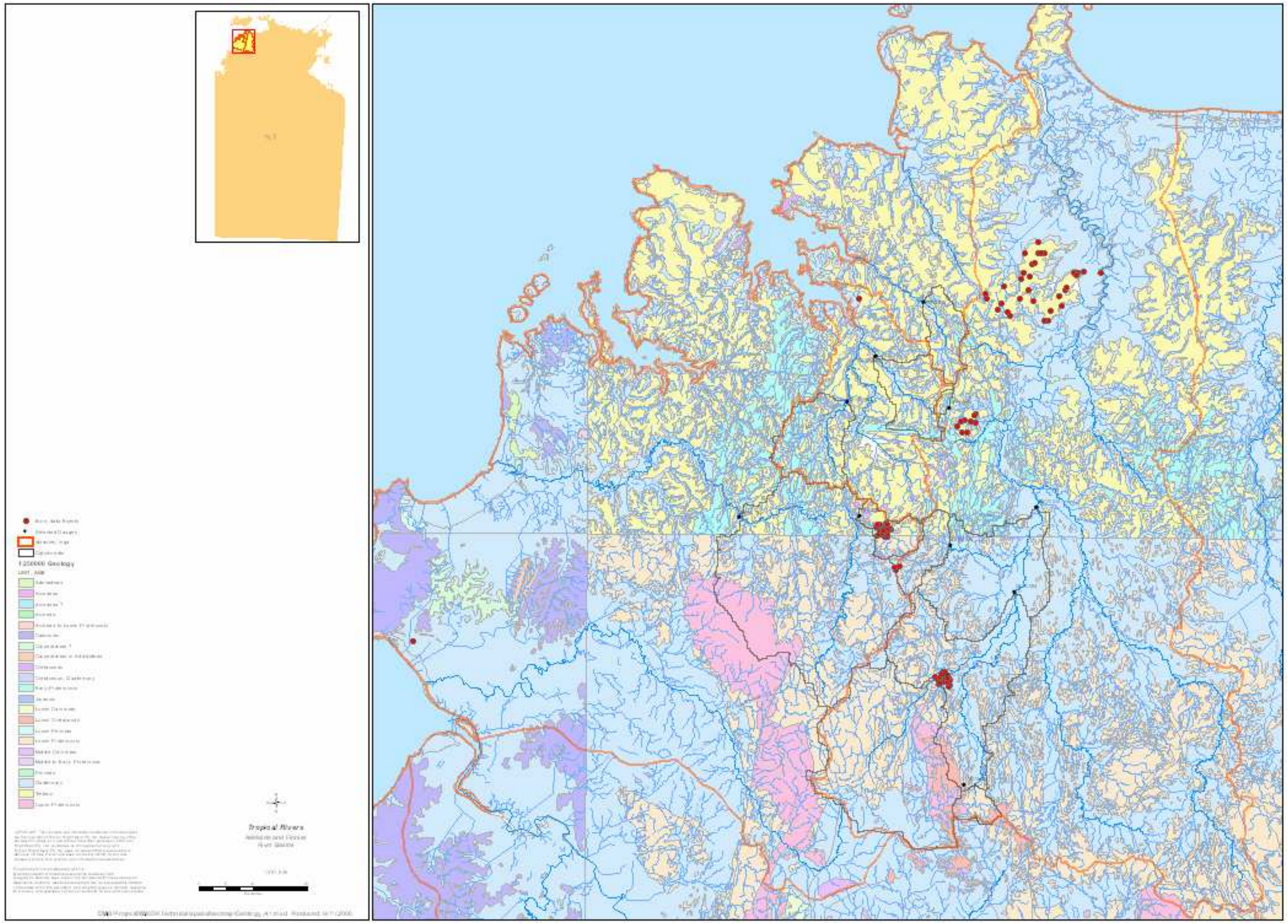
The north-south trending Tom Turners Fault and Giants Reef Faults are present through the catchment, but is generally subsurface beneath the veneer of Quaternary sediments, however it does outcrop through the older geology.

### F.2.2 Blackmore and Darwin River Catchment

The catchment of the Blackmore and Darwin River is underlain by the Cretaceous sediments of the Bathurst Island Formation, which are up to 80m thick at the northern extent of the catchment. The western margin of the catchment is formed by north-south striking deformed metasediments (shale, siltstone and sandstones, with minor conglomerate) of the Proterozoic-aged Finniss River Group. The river valleys are filled with sands and gravels and the coastal plains are characterised by muds and silts.

### F.2.3 Howard and Elizabeth Rivers Catchment

The Howard and River and Elizabeth River catchment is characterised by the thin veneer of Cretaceous sediments overlying predominantly the Proterozoic-aged Koolpinyah Dolomite. The surficial geology in the river valleys is characterised by Quaternary-aged gravel, sand and silt that become finer-grained towards the river mouth.



■ **Figure F-1: Geology of the Study Area (based on GIS 1:250,000 Geological map)**

## F.3 Hydrogeology

The hydrogeological environment can be divided into two major units: the fractured rock aquifer and the overlying sediments. Verma (2002) divides the fractured rock environment into two broad categories: calcareous and fractured weathered rocks; and non-calcareous fractured and weathered and intrusive rocks. The calcareous units tend to have higher transmissivities which are related to secondary porosity developed during the period of non-deposition from 1800 to 225 million years ago (Ma), when erosion of the carbonate surface created karstic topography (i.e. cavernous and highly fractured) prior to the Cretaceous deposition. It is the hydraulic behaviour of the overlying sediments which controls the supply potential as it is this unit which is initially recharged and from which evapotranspiration occurs (Cook *et al.* 1998b). The veneer of Cretaceous sediments have a high enough vertical permeability to transmit surface water downwards (Pietsch and Stuart-Smith, 1987).

## F.4 Aquifer Hydraulic Parameters

Groundwater resource investigations have been undertaken for the township of Batchelor (Jolly, 1982), the township of Adelaide River (Prowse, 1983); the Lambells Lagoon area (Jolly and Yin Foo, 1988) and the Finniss-Dundee Cox Peninsula (Knapton *et al*., 2003). Aquifer hydraulic parameters from these investigations are summarised in Table F-1 and show significant variation, even on a local scale. This is typical of fractured rock aquifers.

- **Table F-1: Summary of Aquifer Hydraulic Parameters from Groundwater Resource Investigations**

| Tested Lithology | Formation | Region | Transmissivity ($m^2$/day) | Storage Coefficient | Leakage ($day^{-1}$) | Specific Yield | Reference |
|---|---|---|---|---|---|---|---|
| Unweathered Dolomite | Coomalie Dolomite | Lambells Lagoon | 1230 to 9000 | $3x10^{-3}$ to $10x10^{-3}$ | $4x10^{-3}$ to $15x10^{-3}$ | 0.1 | Jolly and Yin Foo, 1988 |
| Weathered Dolomite | Coomalie Dolomite | Lambells Lagoon | - | $2x10^{-4}$ | $0.5\ x10^{-4}$ | - | Jolly and Yin Foo, 1988 |
| Cretaceous Sediments | Bathurst Island Formation | Lambells Lagoon | - | - | - | 0.06 to 0.15 | Jolly and Yin Foo, 1988 |
| Interbedded Siltstone and Greywacke | Burrel Creek Formation | Adelaide River | 7 to 87 | $8x10^{-5}$ to $1x10^{-3}$ | $7x10^{-5}$ to $2.3x10^{-3}$ | - | Prowse, 1983 |
| Weathered Dolomite | Coomalie Dolomite | Batchelor | 370 to 2560 | $6x10^{-5}$ to $1.8x10^{-2}$ | - | - | Jolly, 1982 |
| Sandstone | Darwin Member | Cox Peninsula | 47 to 75 | - | - | - | Knapton *et al.*, 2003 |

This information on hydraulic parameters was assigned to each gauged streamflow catchment based on the geology in each catchment. These are summarised in Table F-3. For calculating groundwater outflow, the Finniss River basin was split into three major regions, namely the Reynolds River, the Finniss and Annie Rivers, and the remaining catchments to the north of the Finniss River basin. The adopted transmissivity was generally within the middle of the transmissivity range from the available literature.

- **Table F-2: Transmissivity values used in gauged streamflow catchments**

| Catchment | Subsurface Geology | Transmissivity Range ($m^2/d$) | Adopted Transmissivity ($m^2/d$) |
|---|---|---|---|
| 8150018 | Mount Partridge Group | 500-2000 | 1250 |
| 8150027 | Bathurst Island Formation | 47-75 | 61 |
| 8150097 | Finniss River Group | 7-87 | 47 |
| 8150098 | Finniss River Group | 7-87 | 47 |
| 8150180 | Finniss River Group / Rum Jungle Complex | 7-87 | 47 |
| 8170002 | Finniss River Group | 7-87 | 47 |
| 8170005 | South Alligator Group | 7-87 | 47 |
| 8170062 | Finniss River Group | 7-87 | 47 |
| 8170066 | Mount Partridge Group | 500-2000 | 1250 |
| 8170066 | South Alligator Group | 7-87 | 47 |
| 8170084 | South Alligator Group | 7-87 | 47 |
| 8170085 | Mount Partridge Group | 7-87 | 47 |
| Adelaide basin | n/a | n/a | 50 |
| Reynolds | n/a | n/a | 50 |
| Finniss and Annie | n/a | n/a | 50 |
| Darwin, Corrawarra, Elizabeth, Howard, King, Leaders | n/a | n/a | 50 |
| Total Finniss basin | n/a | n/a | 50 |

## F.5 Water Levels, Potentiometry and Groundwater Flow

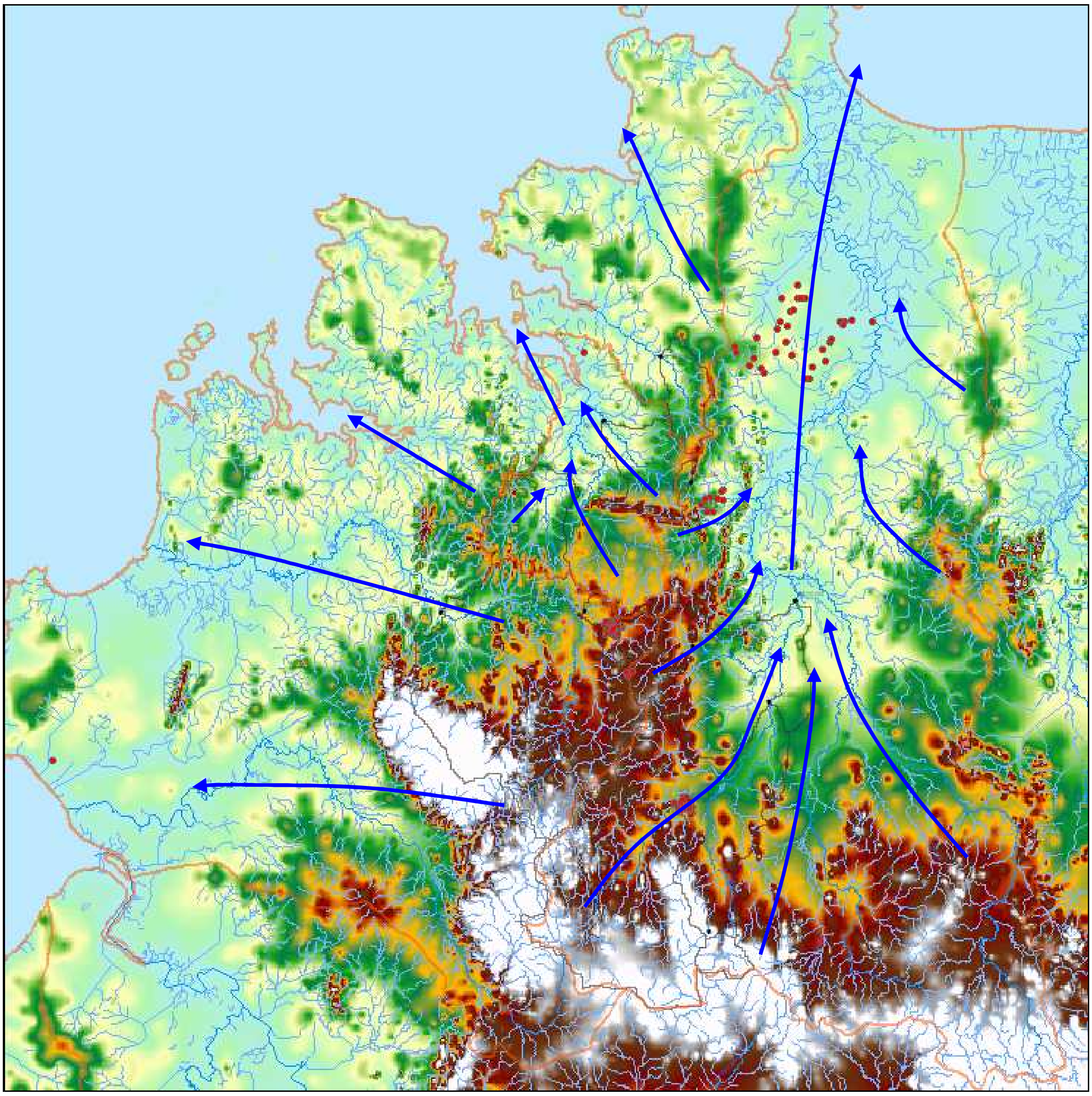
A limited water level dataset exists for the area of interest, with monitoring bores generally clustered in the vicinity of where previous resource investigations have been undertaken and where there is existing extraction, namely: Adelaide River, Batchelor Township, Acacia, Lambells Lagoon, Middle Point and Rum Jungle. The locations of the monitoring bores are shown on Figure F-1. The range of water level fluctuation in the monitoring bores is from 3 m to 11 m between the dry season and the wet season. The shallowest water levels can be artesian during the wet season and during the dry season, the deepest water levels are more than 28 metres below ground level. Bore Hydrographs are presented in Appendix G.

Cross sections shown on the 1:250,000 Hydrogeological Map of Darwin (DIPE, 2004) indicate that the fractured rock aquifers are confined, as the standing water levels are higher than the water strike during drilling. These cross sections also indicate that the potentiometric surface shown is a subdued reflection of topography. According to Jolly and Yin Foo (1998) groundwater movement in the Lambells Lagoon area is generally directed from topographic highs to lows and Prowse (1983) indicated that groundwater flow is towards the river.

In the absence of a potentiometric surface map and sufficient data to prepare one, it is initially assumed that groundwater flow is ultimately from the higher ground around the Rum Jungle complex towards the coast (north to south in Adelaide River basin and Blackmore/Howard/Elizabeth/Darwin catchment; east to west in Finniss/Reynolds catchment), with local flow towards the rivers. This is shown diagrammatically on Figure F-2, which is based on the digital elevation model (DEM).

This groundwater flow diagram relies only on the digital elevation model and does not incorporate local geology.

River gauge data indicate that streamflow ceases during the dry season in catchments 8150018, 8150097, 8150098, 8170085 and 8170062. These catchments are all at the headwaters of their respective river basins, and the existing data suggests that at some point close to the headwaters, the streams change from gaining to losing at the beginning of the dry season.



- Figure F-2: Initial Conceptualised Groundwater Flow Directions Based on DEM

## F.6 Conceptual Hydrogeological Model

A conceptual hydrogeological model has been developed which covers the entire study area. The basis for a single model for both river basins is that the on the broad-scale, underlying aquifers over the study area remain consistent.

The study area is characterised by a monsoonal weather system, with wet summers and dry winters. In the wet season, the floodplains are inundated. Water levels vary by up to 10 m between seasons. On the floodplains the water level is approximately 3 m below ground level during the dry season and the floodplains are inundated during the wet season.

The vegetation is typical of a savannah, with continuous grass coverage and a discontinuous tree canopy. There are some swamps which are likely to be groundwater dependent. Tree water use is related to the mean annual rainfall and is consistent throughout the year, hence either the woody vegetation is groundwater dependent or sufficient water remains in the unsaturated zone during the dry season that tree water use is not limited. The understorey comprises grasses which senesce at the beginning of the dry season. Understorey ET is considered to be groundwater independent, as water levels during the dry season are likely to be too deep for grass species to access.

The study area can be divided into two surface water basins: the Adelaide River Basin and the Finniss River Basin. The watertable is considered to be a subdued reflection of topography, hence groundwater divides are expected to be coincident with the river basin boundaries. The implication of this model is that there will be negligible lateral subsurface movement of groundwater between the basins. There is a seasonal change in the interaction between surface water and groundwater and in the upper reaches of the basins the streams are ephemeral but become perennial at lower elevations where they are sustained by groundwater inflow during the dry season.

The geology consists of fractured Proterozoic rocks overlain by a wedge of unconsolidated fine to coarse grained Cretaceous sediments. On the floodplains and in the drainage lines there is a thin veneer of Quaternary-aged fine-grained alluvial deposits. The fractured rocks and the overlying sediments are considered to be the main hydrogeological units as recharge is either directly into the fractured rock or via infiltration through the sediments. Recharge occurs through vertical infiltration of rainfall, with the fraction of rainfall entering the groundwater system as recharge related to the underlying geology.

Groundwater extraction is generally from the unconformity between the Proterozoic basement and Cretaceous sediments where there was the development of significant secondary porosity, particularly in the dolomites. The unconsolidated Cretaceous sediments provide water storage, which drains into unconformity. It is likely that there is a high degree of connection between the aquifers and the streams, with groundwater extraction already impacting on streamflow records.

Water quality is poorest (>1000 mg/L TDS) where the alluvial sediments are seasonally inundated on the coastal and estuarine plains and is best on the intervening drainage divides and where the fractured rocks aquifer outcrops.

### F.7 Groundwater Extraction

Groundwater is extracted for town water supply, irrigation and stock and domestic use. Limited groundwater extraction data is available for the study area due, in part, to there being no general requirement for extraction bores to be licensed so it is not possible to determine groundwater extraction for individual catchments from readily available data. Estimated groundwater extraction data has been sourced from the Australian Natural Resources Atlas, and is based on the National

Land and Water Resources audit data from 1996 (ANRA, 2006). The atlas indicates that this data has been derived from a number of different methods including the use of licencing systems, information provided as part of the Australian Bureau of Statistics water account (with provider consent) and other information gathered from the State and Territory water agencies. In some cases water use was assumed to be the same as the allocation. These figures should therefore be regarded as a coarse estimate only. The available groundwater extraction data is summarised in Table F-3. The volumes from the 1996 audit are within the range of The National Land and Water Resources Audit of 2006, which estimates extraction covering most of the study area is in the range 10-100 GL/year (AWR, 2006).

**Table F-3: Estimated Groundwater Extraction in the Study Area (ANRA, 2006)**

| Location | Volume (ML/year) |
|---|---|
| Berry Springs Dolomite | 4,761 |
| Koolpinyah Dolomite | 18,920 |
| Proterozoic Sedimentary (Adelaide River) | 17,048 |
| Total | 40,729 |

Groundwater extraction is generally from the unconformity between the Proterozoic basement and Cretaceous sediments where there was the development of significant secondary porosity, particularly in the dolomites. The unconsolidated Cretaceous sediments provide water storage, which drains into the unconformity during pumping (pers. comm. D Yin Foo, NRETA, 2006).

To assess the likelihood of groundwater extraction impacting on baseflow, an analytical model was compiled using the Jenkins (1968) equation. The range of aquifer parameters from the Adelaide River and Batchelor groundwater resource investigations (Prowse, 1983; and Jolly, 1982, summarised in Table F-1) were modelled, using a distance of 500m between the bore and the river, and an extraction rate of 1 ML/day pumped continuously for 365 days. Results of this analysis are shown in Appendix H.

The results indicate at Adelaide River township there would be depletion in excess of 50% of the pumping rate within the first ten days of pumping under most scenarios, with this time extending to a maximum of 40 days. Under all scenarios, there would be streamflow depletion of in excess of 80% of the extraction rate within the first year of extraction.

At Batchelor Township, streamflow depletion ranges from 100% of the extraction rate within 50 days of the commencement of pumping to a minimum approximately 90% at the end of the first year.

The assumptions for the Jenkins equation are as follows:

1. Transmissivity does not change with time. Thus for a water table aquifer, drawdown is considered to be negligible when compared with aquifer thickness;
2. The temperature of the stream is assumed to be constant and to be the same as the temperature of the water in the aquifer;
3. The aquifer is isotropic, homogeneous, and semi-infinite in areal extent;
4. The stream forms a straight boundary, and the stream fully penetrates the aquifer;
5. Water is released instantaneously from storage;
6. The well is open to the full saturated thickness of the aquifer
7. The pumping rate is steady during any period of pumping

The hydrogeology across the study area does not satisfy these assumptions as the aquifer is not isotropic and homogeneous and neither the stream nor the well would fully penetrate the aquifer. The storage values, as well as water level data also indicate that the aquifers from which extraction is occurring are likely to be at least semi-confined. Although the modelling did indicate that groundwater extraction will impact on streamflow, it is expected that the time lag would be longer than predicted due to partial penetration and the presence of the aquitard. However, as much of the groundwater extraction, especially for town water supply, commenced in excess of 20 years ago, it is expected that the gauging records will already be impacted by the extraction.

## F.8 Groundwater Outflow

The fractured rock aquifer system extends beyond the boundaries of the study area. Although surface water catchment boundaries do not necessarily correspond to groundwater flow boundaries (Cook, 2003), in the absence of a potentiometric surface map it is initially considered that the groundwater divides are coincident with the margins of the river basins. This conceptual model suggests that there will be limited lateral groundwater movement between adjacent river basins, however there will be groundwater outflow downgradient through successive catchments and eventually discharging offshore. The difference between the amount of groundwater flowing into the catchment and the amount leaving the catchment is equal to the groundwater outflow.

The amount of groundwater outflow is related to the transmissivity of the aquifer and the hydraulic gradient and can be calculated using Darcy's Law, which can be written as follows:

$$Q = -KiA \text{ or } Q = -TiL$$

Where: K = hydraulic conductivity of the aquifer
i = hydraulic gradient
A = cross-sectional area

T = transmissivity of the aquifer = K * aquifer thickness
L = aquifer width

The negative value would indicate that there is discharge from the system, however for this analysis, because groundwater flow paths are assumed to follow topography, there is no groundwater inflow from adjacent catchments. Although horizontal groundwater flow rates can be estimated in a fractured rock environment using Darcy's Law, the large variability in hydraulic conductivity adds a large degree of uncertainty to the estimates (Cook, 2003).

A range of transmissivity values have been determined during previous groundwater resource evaluations, as provided in Table F-1. Transmissivity ranges were applied to each catchment based on the catchment geology and its geological similarity to the area in which the pumping was undertaken. The range in height of the catchment was obtained from the DEM and the length over which the gradient was calculated was the longest distance parallel to the expected groundwater flow direction in that catchment. The aquifer width was assumed to be the maximum width of the catchment on the down hydraulic gradient direction, perpendicular to the general direction of groundwater flow.

The sensitivity of the calculation of subsurface discharge to these input parameters was investigated. The input parameter with the greatest sensitivity was the transmissivity and as such was regarded as a flexible parameter within the ranges previously specified in Table F-1. It was found that an hydraulic gradient equal to the topographic gradient or 10% of the topographic gradient resulted in the same net daily outflow in mm/day. Doubling or halving the aquifer width resulted in doubling or halving the outflow rate only where there was a high transmissivity (catchments 8150018 and 8170066).

Calculations of the subsurface outflow are summarised in Table F-4, which indicates significant groundwater outflow from catchments 8150018, 8170066 and 8170084 and negligible outflow from remaining catchments. It has been assumed that the amount of subsurface outflow is proportional to the number of days in each of the wet and dry season (150 and 215 days respectively).

**Table F-4: Initial Estimate of Net Subsurface Discharge from Each Catchment**

| Catchment | Elevation range (m) | Down gradient catchment Length (m) | Hydraulic Gradient (m/m) | Down gradient aquifer width (m) | Wet season groundwater outflow (mm) | Dry season groundwater outflow (mm) |
|---|---|---|---|---|---|---|
| 8150018 | 76 | 10500 | 0.007 | 3500 | 50 | 72 |
| 8150027 | 119 | 19500 | 0.006 | 8000 | 3 | 5 |
| 8150097 | 79 | 12000 | 0.007 | 4000 | 3 | 4 |
| 8150098 | 77 | 18000 | 0.004 | 5000 | 1 | 1 |
| 8150180 | 219 | 36000 | 0.006 | 15000 | 1 | 1 |
| 8170002 | 205 | 30000 | 0.007 | 15000 | 1 | 2 |
| 8170005 | 146 | 28000 | 0.005 | 9000 | 1 | 1 |
| 8170062 | 143 | 6000 | 0.024 | 1500 | 6 | 9 |
| 8170066 | 97 | 5500 | 0.018 | 1500 | 59 | 85 |
| 8170066 | 227 | 20500 | 0.011 | 14000 | 2 | 3 |
| 8170084 | 45 | 3000 | 0.015 | 3000 | 29 | 41 |
| 8170085 | 250 | 140000 | 0.002 | 30000 | 0 | 0 |

## F.9 Actual Evapotranspiration

Long-term average actual evapotranspiration data was extracted from the Bureau of Meteorology's GIS layer of the Climatic Atlas of Australia and is shown in Table F-5. All figures are a catchment weighted average value. Actual evapotranspiration is calculated for these layers using Morton's complementary relationship (Wang et al. 2007), which states that:

$$ET_{arealactual} + ET_{pointpotential} = 2 * ET_{arealpotential}$$

Where:

$ET_{arealactual}$ is the evapotranspiration that actually takes place from an area so large that the effects of any upwind boundary transitions are negligible and local variations are integrated to an areal average.

$ET_{pointpotential}$ is the evapotranspiration that would take place if there was an unlimited supply of water from an area so small that the local evapotranspiration effects do not alter local air mass properties. This is calculated by the Bureau of Meteorology by simultaneously solving energy transfer and mass balance equations using a constant energy transfer coefficient.

$ET_{arealpotential}$ is the evapotranspiration that would take place if there was an unlimited supply of water from an area so large that the effects of any upwind boundary transitions are negligible and local variations are integrated to an areal average. This is calculated by the Bureau of Meteorology using the Preistley-Taylor equation with modification to allow for advection.

Wang et al. (2007) note that "Morton's estimates of mean annual areal actual evapotranspiration gave good spatial trend but were not accurate in absolute values". As a result Wang et al. (2007) made adjustment to the dataset based on annual actual ET estimates for 77 large catchments in 9 climate zones across Australia. These adjustments included constraining annual areal actual evapotranspiration to be not greater than annual rainfall. This particular check does not appear to have been carried out by Wang et al. on a monthly or seasonal time step, which is particularly relevant for tropical regions because of the stark contrast in water availability in the dry and wet seasons. Dry season evapotranspiration from the Bureau of Meteorology is greater than the dry season rainfall.

- **Table F-5: Long-term average actual areal evapotranspiration**

| Catchment | Actual areal evapotranspiration from Bureau of Meteorology | | |
|---|---|---|---|
| | Wet season (mm) | Dry season (mm) | Total (mm) |
| 8150018 | 573 | 501 | 1074 |
| 8150027 | 568 | 487 | 1055 |
| 8150097 | 562 | 463 | 1025 |
| 8150098 | 561 | 471 | 1032 |
| 8150180 | 557 | 448 | 1005 |
| 8170002 | 551 | 416 | 967 |
| 8170005 | 554 | 429 | 983 |
| 8170062 | 553 | 411 | 964 |
| 8170066 | 558 | 450 | 1008 |
| 8170084 | 553 | 422 | 975 |
| 8170085 | 569 | 489 | 1058 |
| Adelaide River Basin | 565 | 463 | 1028 |
| Finniss River Basin | 557 | 464 | 1021 |

## F.10 Groundwater Evapotranspiration

For this study total evapotranspiration was split into evapotranspiration sourced from groundwater and evapotranspiration from the land surface and the unsaturated zone. In order to understand these two components, the differing evapotranspiration rates from woody vegetation and the understorey need to be estimated as they have a different degree of access to groundwater.

Hutley *et al.* (2001) undertook a study of evapotranspiration of savannah vegetation in northern Australia at three locations of increasing distance from the northern coastline representing high medium and low rainfall sites, i.e. Howard Springs (1,750 mm/year), Katherine (890 mm/year) and Newcastle Waters (520 mm/year). Note that these rainfall totals used in Hutley et al. (2001) are over a different assessment period to those used in this study from the Bureau of Meteorology, for which rainfall at Howard Springs is approximately 1550 mm/yr. The alluvial plains in the study area  for the current study are characterised by savannah vegetation (continuous grass cover and discontinuous tree cover), and based on rainfall is similar to the conditions at Howard Springs, which is located 35 km south of Darwin in the Finniss River basin.

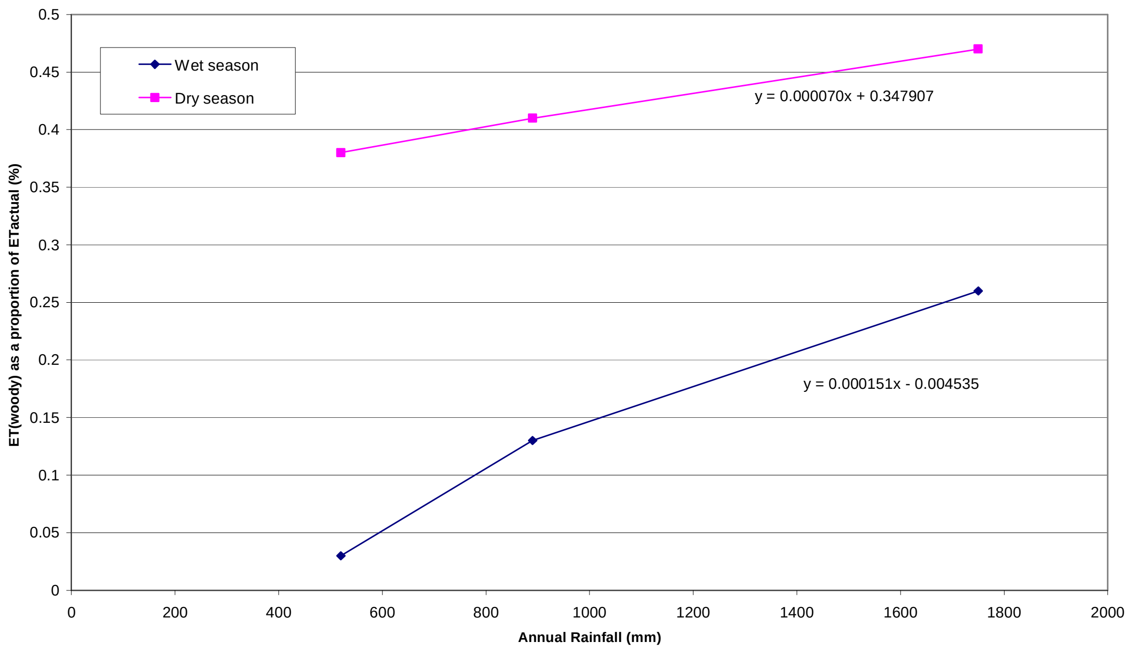
Cook et al. (1998b) undertook an earlier broad-ranging study in the Howard River catchment, which included consideration of evapotranspiration. The composition and structure of the vegetation was relatively homogeneous across the study area and was typical of the more elevated geomorphic zones, with eucalypt woodland (predominantly *Eucalyptus miniata* and *E. tetradonta*) the dominant vegetation type and small areas of paperbark swamps and rainforests in the wetter patches. The understorey consisted of speargrass, which died back during the dry season.

These two studies provide alternative views on evapotranspiration from similar locations, as shown in Table F-6. It can be seen in both cases that the evapotranspiration from the understorey during the dry season is roughly the same proportion (~0.75) of the evapotranspiration from woody vegetation. The relationship between evapotranspiration from these two vegetation types in the wet season however differs markedly, primarily due to Hutley's much lower evapotranspiration rate from woody vegetation during the wet season. Both authors found that the majority of evapotranspiration was from the understorey during the wet season and from woody vegetation in the dry season.

- **Table F-6: Comparison of evapotranspiration in the Howard River area from previous studies**

| Item | Hutley et al. (2001) | Cook et al. (1998b) |
|---|---|---|
| Annual evapotranspiration (mm) | 855 | 1110 |
| Total wet season evapotranspiration (mm) | 510 | 810 |
| Wet season evapotranspiration from woody vegetation (mm) | 135 | 373 |
| Wet season evapotranspiration from understorey (mm) | 375 | 437 |
| Wet season understorey evapotranspiration as a proportion of woody vegetation evapotranspiration | 2.78 | 1.17 |
| Total dry season evapotranspiration (mm) | 345 | 300 |
| Dry season evapotranspiration from woody vegetation (mm) | 195 | 175 |
| Dry season evapotranspiration from understorey (mm) (and percentage of total dry season evapotranspiration) | 150 | 125 |
| Dry season understorey evapotranspiration as a proportion of woody vegetation evapotranspiration | 0.77 | 0.71 |

Hutley et al. (2001) provides a relationship between rainfall and evapotranspiration from woody vegetation or understorey vegetation. This relationship is based on tree density being less in lower rainfall areas. The relationship is shown in Figure F-3 for both the wet and dry season. It can be seen from this figure that over the relatively small rainfall gradients of the study area (1400-1550 mm, which would equate to roughly 1600-1750 mm in Figure F-3), there is little variation in woody vegetation evapotranspiration as a proportion of total evapotranspiration. Hence it is reasonable to assume a constant seasonal relationship between evapotranspiration from woody vegetation and understorey vegetation. The relationship derived by Hutley et al. (2001) for Howard Springs was used throughout the Adelaide and Finniss River basins, which was that evapotranspiration from woody vegetation is 26% of total evapotranspiration during the wet season and 47% of total evapotranspiration during the dry season.




- **Figure F-3: Variation of evapotranspiration from woody vegetation with annual rainfall (adapted from Hutley et al., 2001)**

The next part of the analysis involves estimating the degree of access of each vegetation type to groundwater. Hutley *et al*. (2001) found that tree stand water use was constant throughout the year despite the monsoonal water availability, suggesting that the trees are able to extract water from the water table throughout the year. Cook et al. (1998a) suggests that woody vegetation did not depend on groundwater during the dry season, but notes in Cook et al. (1998b) that groundwater may be accessed by woody vegetation during times of drought. Root depths of up to 10 m have been found, but root density decreases significantly with depth. On the basis of these previous assessments, it is assumed for this study that 100% of wet season evapotranspiration from woody vegetation is sourced from groundwater and that 50% of dry season evapotranspiration from woody vegetation is sourced from groundwater, with the remainder coming from the unsaturated zone.

Cook *et al*. (1998b) found that at the beginning of the dry season, soil moisture and transpiration from the understorey resulted in an increased evaporation rate, following which the tree canopy transpired at a relatively constant rate throughout the remainder of the dry season. It was inferred that by the end of May, evaporation was almost completely evapotranspiration from woody vegetation, and suggested that the woody vegetation may be sustained by water in the unsaturated zone during the dry season. On this basis, it was assumed that understorey evapotranspiration occurred from groundwater in the wet season only, with all evapotranspiration in the dry season being sourced from the unsaturated zone. It is assumed during the wet season that the water table is close to the natural surface (ie within a metre or so) and hence both transpiration by woody vegetation and evaporation from very shallow groundwater will be high. However during the wet season the distinction between the unsaturated zone and the fully saturated zone (ie groundwater) becomes less clearly defined.

The proportion of woody vegetation was calculated using a vegetation coverage grid supplied by the Australian Greenhouse Office. It is not possible to determine the nature of the woody vegetation from this data to determine the areal extent of groundwater dependent ecosystems. Consistent with the definition of a savannah, the area of understorey used was equal to the total catchment area. A summary of estimated evapotranspiration based on the above approach is contained in Table F-7 and Table F-8. It should be noted that the dry season evapotranspiration from the unsaturated zone was restricted by the available rainfall after allowing for recharge to groundwater.

- **Table F-7: Estimated wet season evapotranspiration**

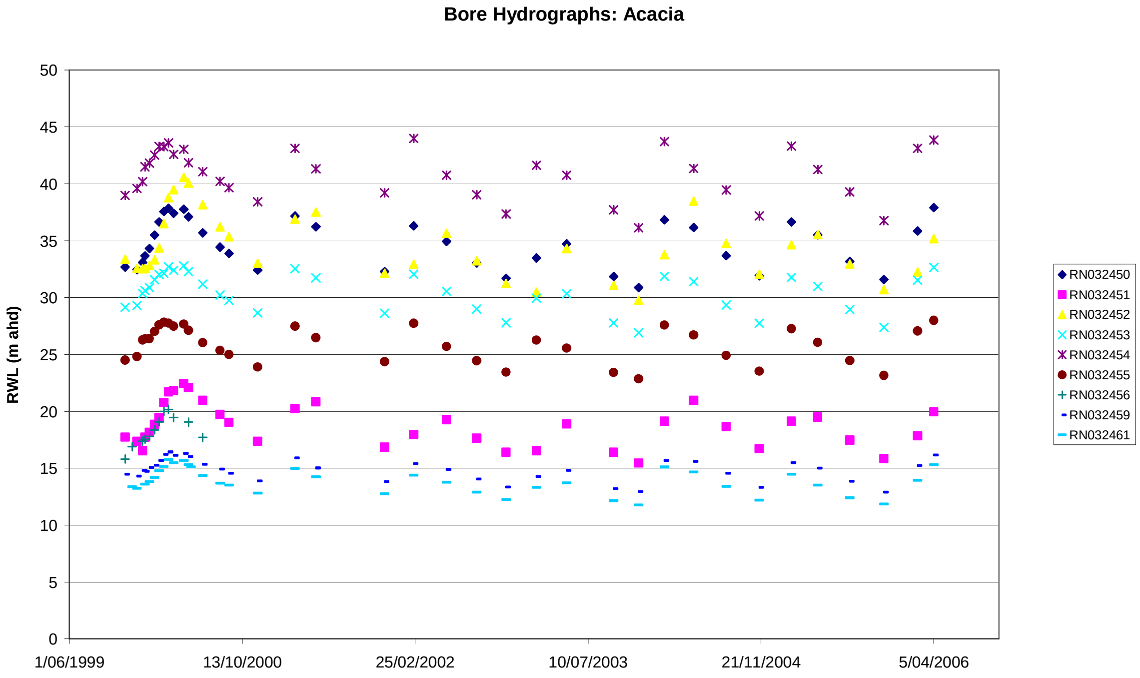
| Catchment | Wet Season Woody ET (mm) | Wet Season Understorey ET (mm) | Wet season groundwater ET (mm) | Wet season unsaturated zone ET (mm) |
|---|---|---|---|---|
| 8150018 | 149 | 424 | 573 | 0 |
| 8150027 | 148 | 420 | 568 | 0 |
| 8150097 | 146 | 416 | 562 | 0 |
| 8150098 | 146 | 415 | 561 | 0 |
| 8150180 | 145 | 412 | 557 | 0 |
| 8170002 | 143 | 408 | 551 | 0 |
| 8170005 | 144 | 410 | 554 | 0 |
| 8170062 | 144 | 409 | 553 | 0 |
| 8170066 | 145 | 413 | 558 | 0 |
| 8170084 | 144 | 409 | 553 | 0 |
| 8170085 | 148 | 421 | 569 | 0 |
| Adelaide River Basin | 147 | 418 | 565 | 0 |
| Finniss River Basin | 145 | 412 | 557 | 0 |

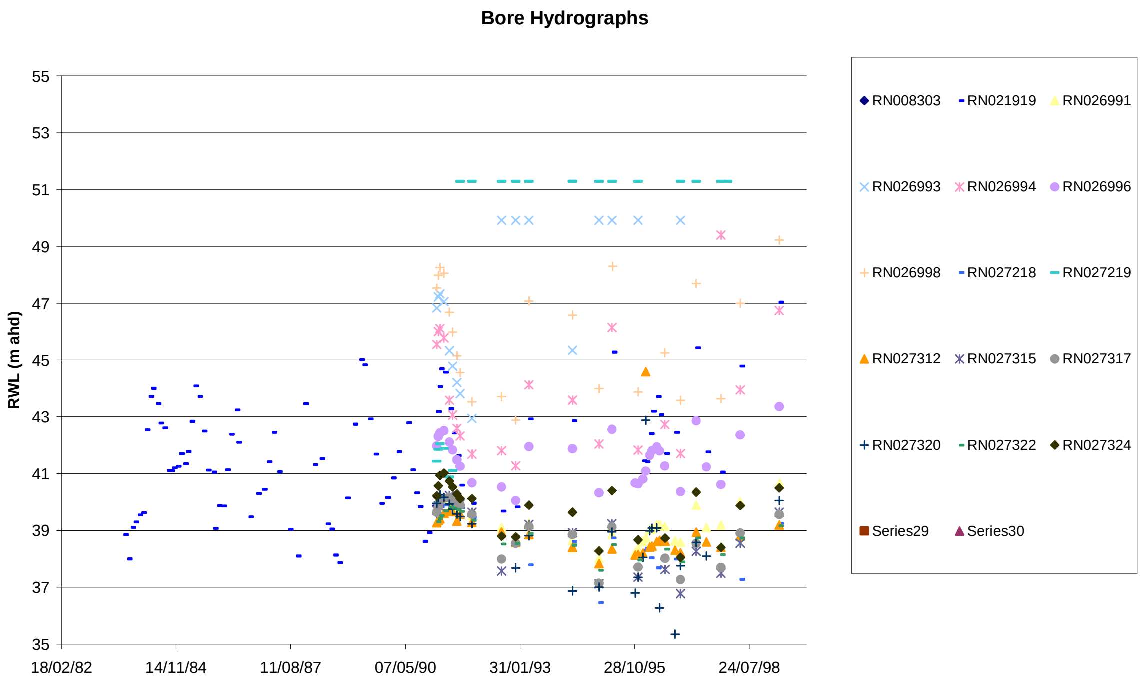
▪ **Table F-8: Estimated dry season evapotranspiration**

| Catchment | Dry Season Woody ET (mm) | Dry Season Understorey ET (mm) | Dry season groundwater ET (mm) | Dry season unsaturated zone ET (mm)* |
|---|---|---|---|---|
| 8150018 | 235 | 266 | 118 | 238 |
| 8150027 | 229 | 258 | 114 | 242 |
| 8150097 | 218 | 245 | 109 | 221 |
| 8150098 | 221 | 250 | 111 | 235 |
| 8150180 | 211 | 237 | 105 | 232 |
| 8170002 | 196 | 220 | 98 | 262 |
| 8170005 | 202 | 227 | 101 | 244 |
| 8170062 | 193 | 218 | 97 | 254 |
| 8170066 | 212 | 239 | 106 | 223 |
| 8170084 | 198 | 224 | 99 | 251 |
| 8170085 | 230 | 259 | 115 | 249 |
| Adelaide River Basin | 218 | 245 | 109 | 228 |
| Finniss River Basin | 218 | 246 | 109 | 231 |

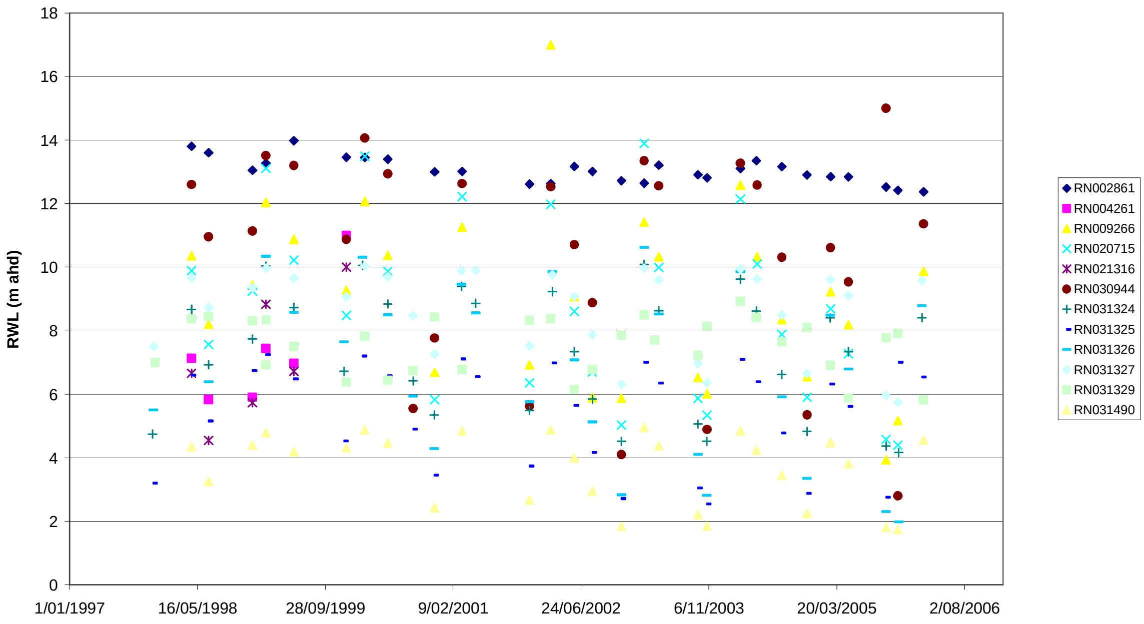
*limited by dry season rainfall minus recharge

# Appendix G Groundwater bore hydrographs

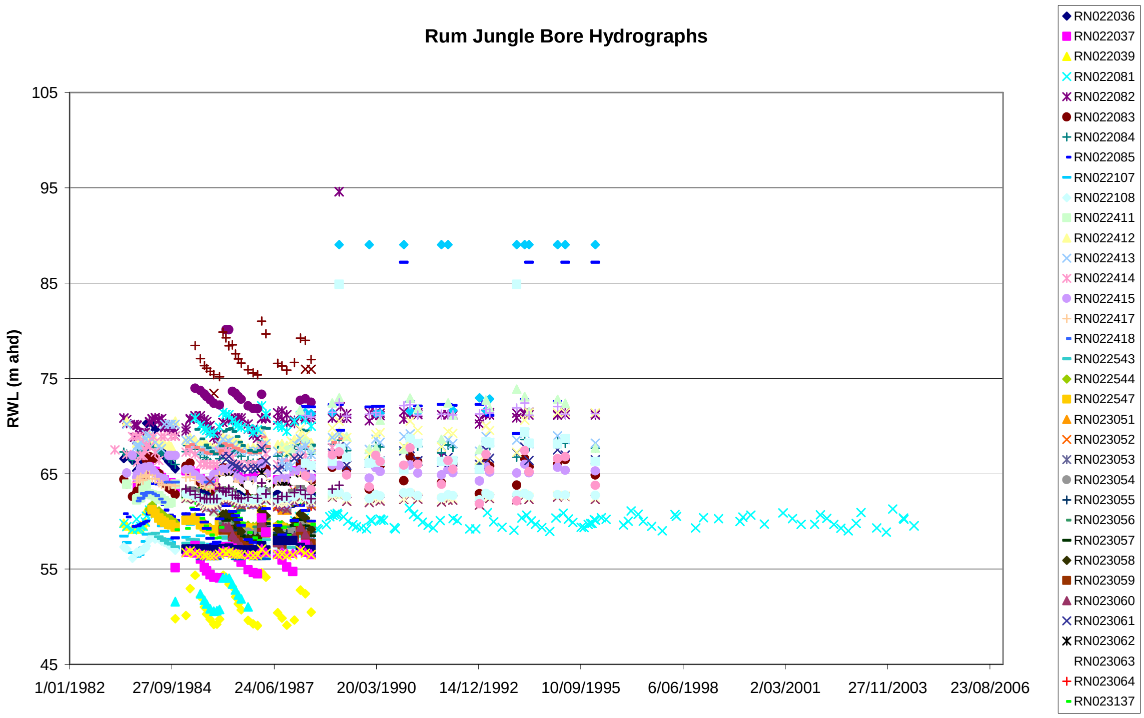


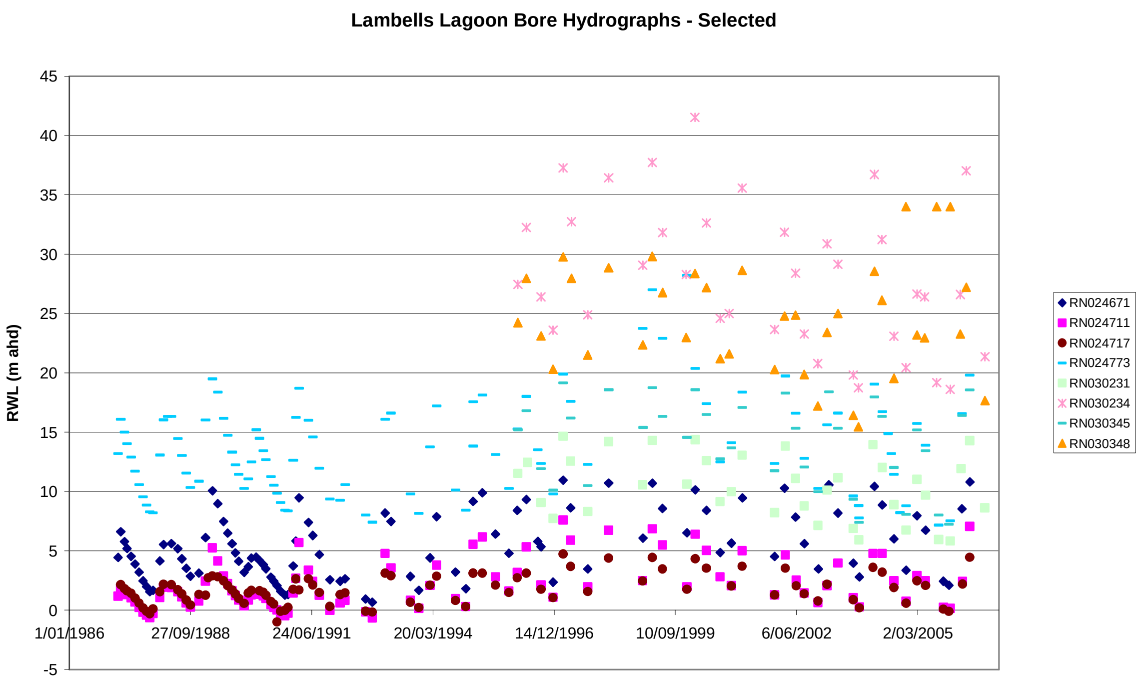



Middle Point Bore Hydrographs



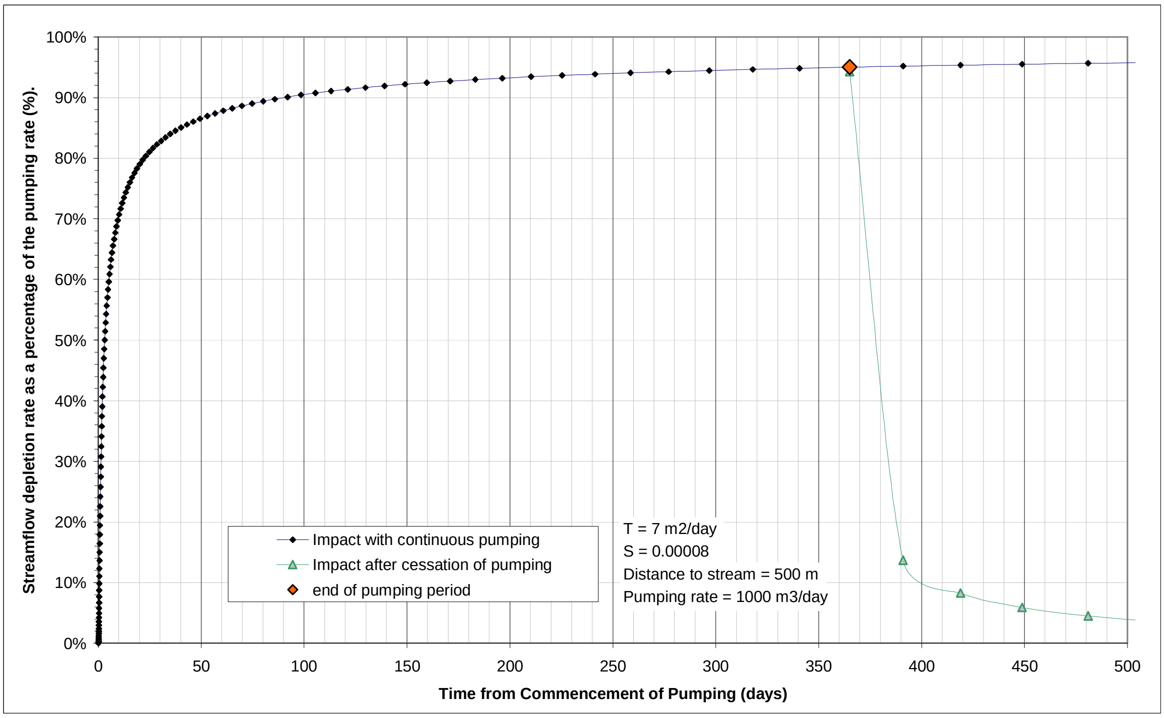

Rum Jungle Bore Hydrographs

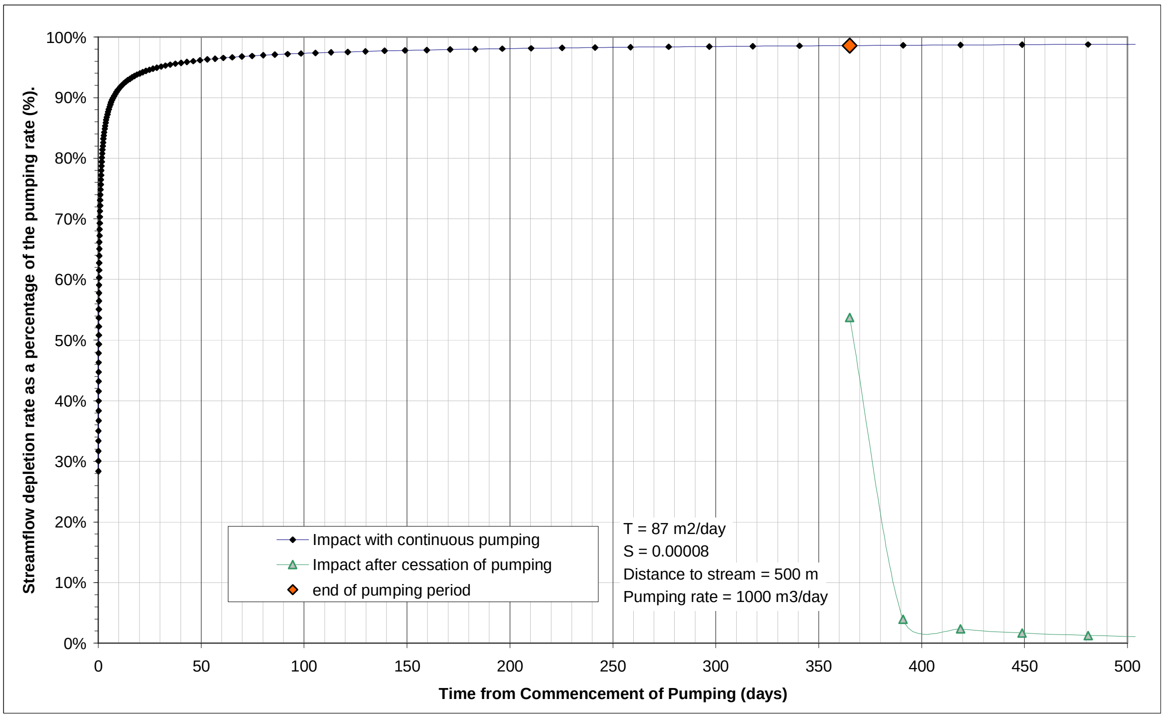


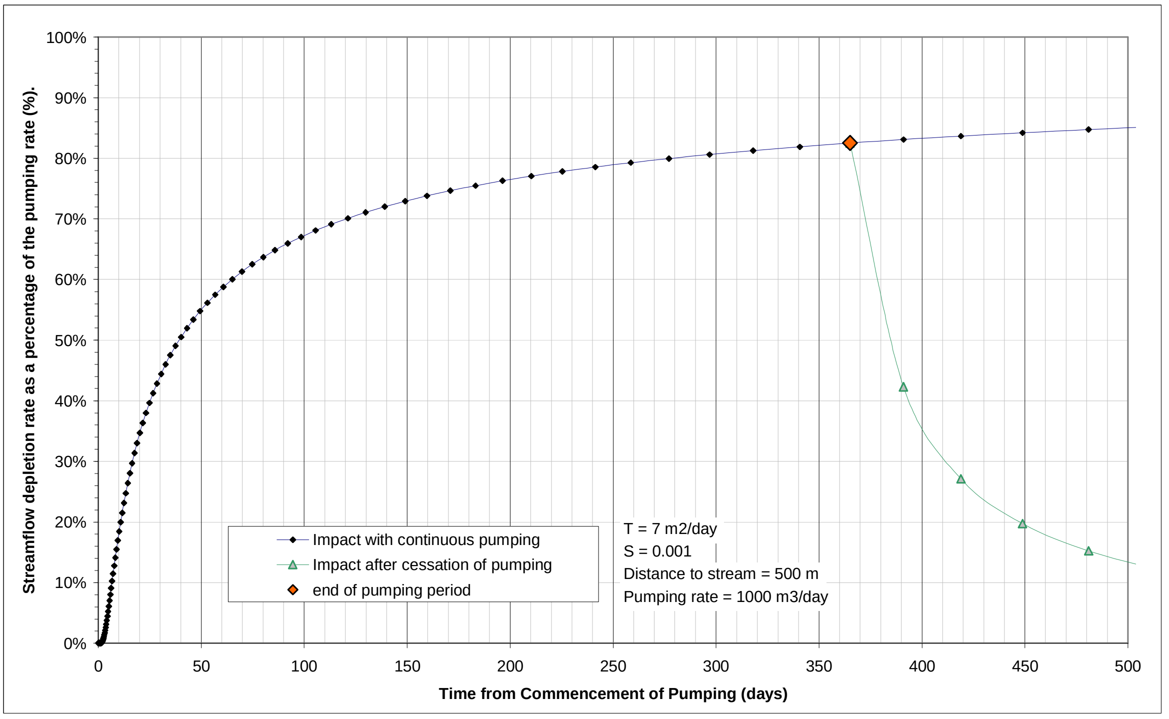

Lambells Lagoon Bore Hydrographs - Selected
RWL (m ahd)
45
40
35
30
25
20
15
10
5
0
-5
1/01/1986
27/09/1988
24/06/1991
20/03/1994
14/12/1996
10/09/1999
6/06/2002
2/03/2005
RN024671
RN024711
RN024717
RN024773
RN030231
RN030234
RN030345
RN030348

# Appendix H Groundwater extraction impacts on streamflow

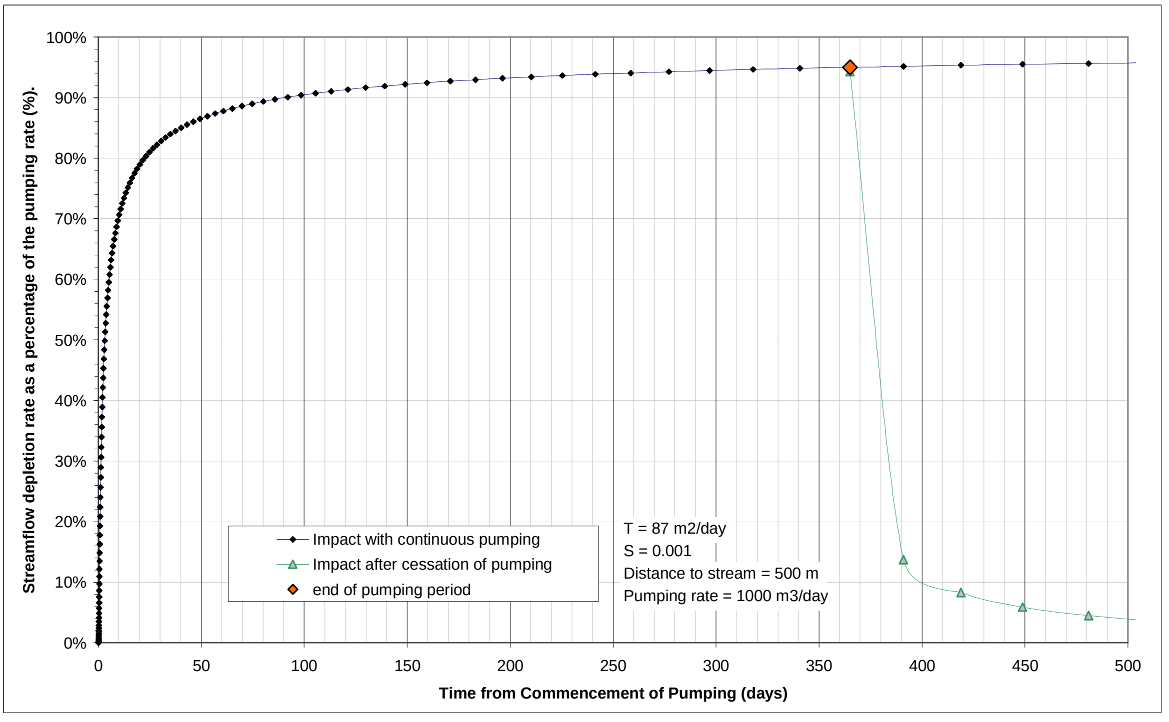
## H.1 Adelaide River Township



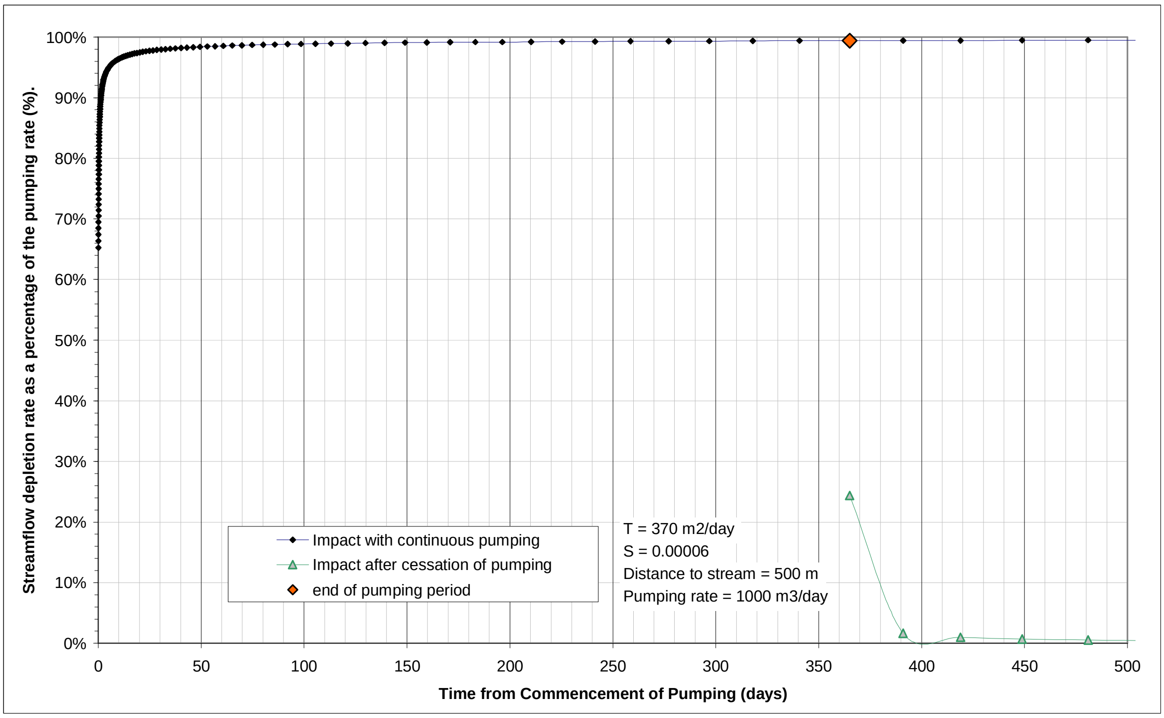


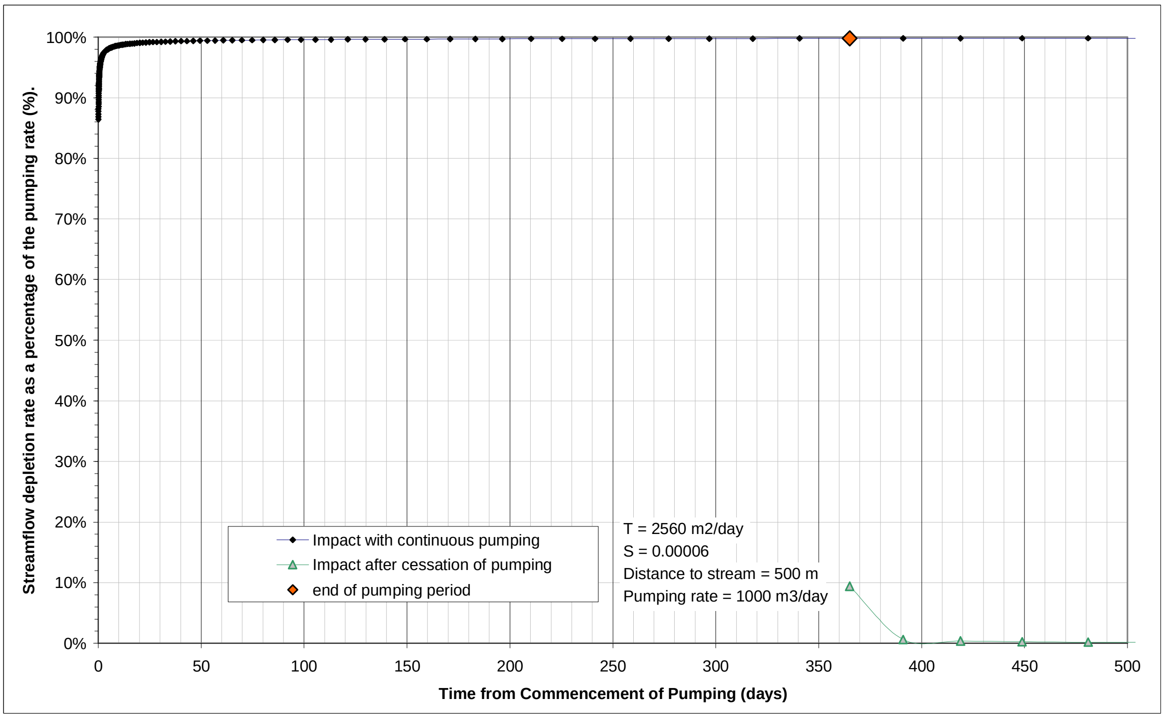
Streamflow depletion rate as a percentage of the pumping rate (%).
Time from Commencement of Pumping (days)
Impact with continuous pumping
Impact after cessation of pumping
end of pumping period
T = 7 m2/day
S = 0.001
Distance to stream = 500 m
Pumping rate = 1000 m3/day

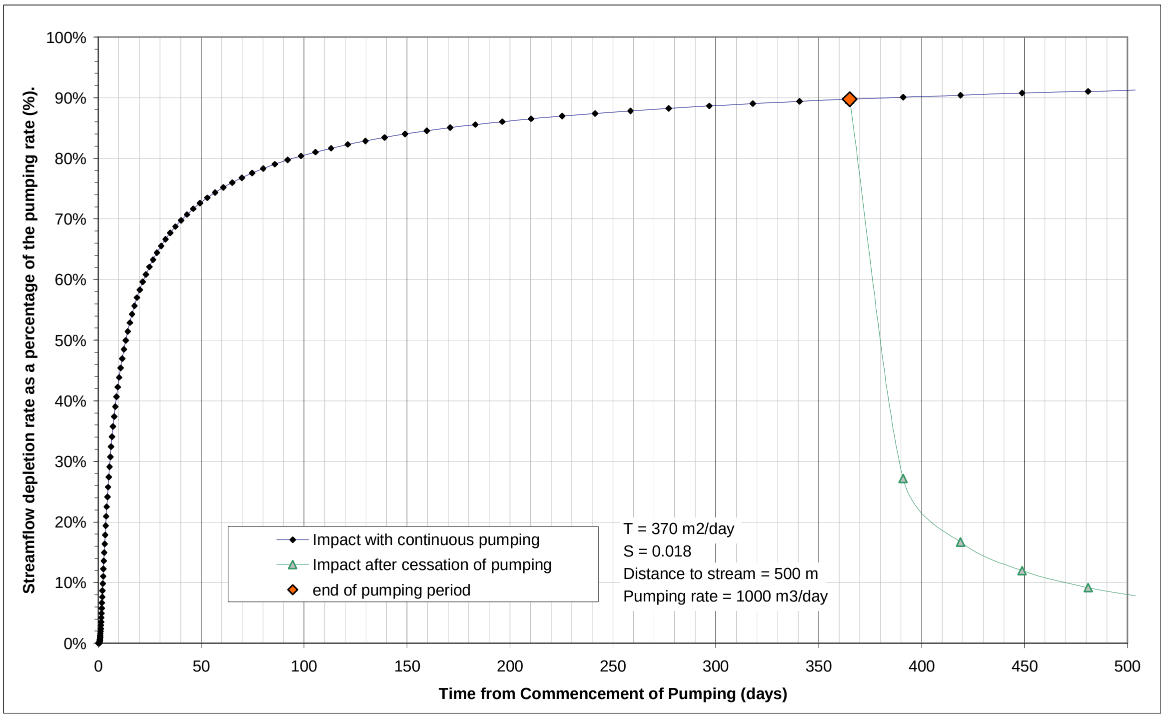



Streamflow depletion rate as a percentage of the pumping rate (%).
Time from Commencement of Pumping (days)
Impact with continuous pumping
Impact after cessation of pumping
end of pumping period
T = 87 m2/day
S = 0.001
Distance to stream = 500 m
Pumping rate = 1000 m3/day

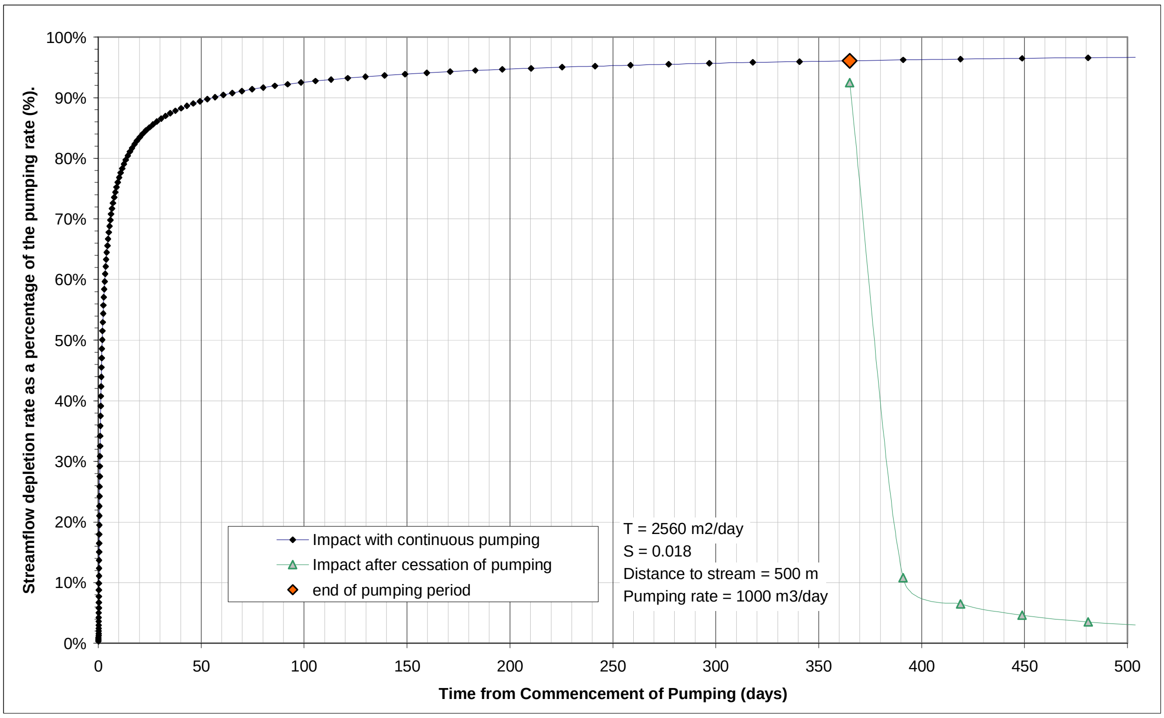
## H.2 Batchelor Township





Streamflow depletion rate as a percentage of the pumping rate (%).
Time from Commencement of Pumping (days)
Impact with continuous pumping
Impact after cessation of pumping
end of pumping period
T = 370 m2/day
S = 0.018
Distance to stream = 500 m
Pumping rate = 1000 m3/day

Streamflow depletion rate as a percentage of the pumping rate (%).
Time from Commencement of Pumping (days)
Impact with continuous pumping
Impact after cessation of pumping
end of pumping period
T = 2560 m2/day
S = 0.018
Distance to stream = 500 m
Pumping rate = 1000 m3/day