Developing guidelines for the selection of streamflow gauging stations

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1. Introduction

This report for the Bureau of Meteorology provides advice on the selection of high quality streamflow gauges across Australia. The aim of this study is to develop guidelines to allow the Bureau to identify these high quality gauges. The guidelines and their subsequent application are intended to support the Bureau's streamflow gauging network modernisation and extension program and its seasonal (weeks to seasons) streamflow forecasting and long-term (multi-decadal) streamflow prediction studies. It is assumed that the focus of the guidelines is not to identify high quality sites for the purposes of flood event (daily and sub-daily) or short-term flow (7-10 days) monitoring and forecasting.

The study was conducted in three phases:

- A literature review of previous regional studies where streamflow gauges have been selected for their quality from all available streamflow gauges (Section 2);
- Develop guidelines for the selection of high quality streamflow monitoring stations for monitoring changes due to climate change, climate variability, land use and related factors such as plantations, forest harvesting and bushfire impact on water yield (Section 3 and 4); and
- Two example applications of the guidelines in the Campaspe River in Victoria and the Adelaide River in the Northern Territory (Section 5).

An appendix to the study includes a list of sites previously selected as being suitable for past hydrologic investigations.

This version of the report is a work in progress and documents the outcomes of the literature review, draft guidelines and part of the application to the case studies.

1.1. Preliminary criteria for seasonal forecasting site selection from the Bureau

An internal file note produced by the Bureau (2010b) outlined some draft criteria for the selection of sites at which its seasonal streamflow prediction service would ideally be provided. The following were draft selection criteria for sites:

- Key user stakeholder(s) will likely derive benefit from forecasts at that site;
- Site used or needed for flood warning, short term flow or multi-decadal as well as seasonal;
- Length of record – greater than 25 years is required for statistical modelling and useful for dynamic modelling;
- Historical data accessible;
- Historical data has a low number of periods of zero flow. The more perennial the stream the more likely it is suitable for seasonal forecasting;

- High quality data without long period gaps;
- Good metadata including accurate catchment boundary;
- Optimally the site should have a fixed location in record – the streamflow gauge has not been relocated either upstream/downstream or left/right bank. This may not be necessary if good ratings are available at both sites and there is a reasonable period of overlapping record;
- Commitment from owner for ongoing maintenance and support into the future;
- Quality of rating table at both low flow and high flow and quality/stability of the cross section;
- Climate data also collected at site or nearby;
- Real time data availability – need to be able to generate previous months streamflow on the first of each month;
- Unregulated stream; and
- Main tributary catchment to a major water supply storage (dam, weir) with a high contribution to total storage inflows.

This project aims to refine these criteria, particularly where they relate to the quality of data at the site of interest. The Bureau (2010b) highlighted that this current study by SKM would assist in refining the above criteria.

1.2. Preliminary criteria for climate change and land use change site selection from the Bureau

No specific criteria for the selection of streamflow monitoring sites for climate change and land use change were provided by the Bureau prior to this study. This project aims to develop criteria that suit this end use.

1.3. Preliminary criteria for modernisation and extension funding site selection from the Bureau

In addition to the above criteria for seasonal forecasting, the Bureau (2010b) outlined draft criteria for supporting modernisation and extension funding. In funding rounds to date, proposals were considered for funding where:

- The site is located upstream of a major water supply storage;
- The site has an existing record greater than 25 years (or at least 15 years and the funding would help it to reach 25 years in the future); and
- There is an ongoing commitment to maintain the station into the future.

2. Literature Review

2.1. Introduction

This section of the report documents the outcomes of a literature review of previous regional hydrology studies where streamflow gauges have been selected for their quality from a broader list of available gauges. This section focuses on the criteria used for selecting gauges to see whether there are any common criteria between studies. Past studies have been grouped according to the theme or region of the study wherever possible to avoid duplication of the discussion. Criteria which are not relevant to the quality of the gauge are ignored in this review, such as the requirement for catchments to be below a certain size for small catchment dam inflow studies.

By way of introduction, the preparation of a list of high quality rainfall gauges by the Bureau is also discussed. This is then followed by a discussion of measures of quality in raw streamflow data, which is an input to the selection criteria used in other studies.

2.2. High Quality Climate Data

The Bureau is already familiar with the concept of high quality data from the identification of high quality climate data for daily temperature, annual temperature, daily rainfall, monthly rainfall, monthly pan evaporation and monthly cloud amount (Bureau of Meteorology 2010a). Primary references for the derivation of these site lists and data are Trewin (2001), Della-Marta et al. (2004), Torok et al. (1996), Lavery et al. (1992), Lavery et al. (1997), Jovanovic et al. (2006), Jovanovic et al. (2009).

Key features of note for the high quality climate data are:

- **Adjustments** have been made to some datasets (e.g. temperature) to standardise its quality, whilst an inhomogeneity or data quality problem in other variables (e.g. rainfall) was not adjusted and the site was rejected. The adjustments included adjustments for discontinuities caused by changes in location, exposure, instruments and observation practice;
- Some data sets from **different sites have been merged** where sites were observed to be correlated and contained a minimum period of overlap;
- The list of high quality sites is different when using data at **different time scales** and there are more sites for high quality data presented at longer time steps;
- **Statistical tests** formed part of the selection process for some variables. For example, a cumulative deviation measure for annual rainfall was used to detect abnormal drift from mean rainfall conditions;
- The high quality sites have **data periods of varying length;**
- **Missing data** is still evident in some datasets;

- The data for each site is accompanied by **metadata** which enables users to readily select a subset of gauges from the high quality list for specific purposes. Climate data in urban areas, for example, was denoted as such;
- The list of high quality sites was **a very small subset of the total available sites**. For example for daily rainfall, 191 high quality sites were selected from 2100 candidate sites. Since identification of the high quality sites in 1992, the number that are still high quality has declined to 152, indicating that **the list of high quality sites can change over time** if sites do not continue to meet the necessary standard or are discontinued.

2.3. Measures of quality in gauged streamflow data

Measures of quality in raw streamflow gauge data are considered an input to the selection of high quality streamflow sites. This information relates only to the quality of data as collected by the hydrographer and does not consider other catchment or water management processes which could affect the quality of the data for specific purposes, which are discussed subsequently.

2.3.1. Streamflow Quality Codes

Streamflow data is typically collected by converting continuous water level data into a stream flow using reference velocity measurements at given water level depths. These reference velocity measurements are taken at varying intervals, depending on the stability of the control section for the particular streamflow gauge.

The quality of streamflow data records is assessed by hydrographic data collection agencies. There are many differences between State and Territory jurisdictions, however the general principle usually applies that the higher the quality code, the poorer the data quality. These quality codes identify how the data was collected or estimated on a given time step and take into account the quality of the rating table used and the magnitude of the water level value being measured.

An example list of quality codes from different jurisdictions around Australia is contained in Appendix A. Other quality codes may exist for locally collected data. It is clear from this list that currently there is not a standard set of quality codes that can be considered to form high quality data across all data collection agencies of Australia.

2.3.2. Measurement uncertainty

The uncertainty in measuring streamflow at a site is a combination of the uncertainty in measuring the stream water level and the uncertainty in relationship which converts the water level to a streamflow volume. An Australian Standard (ASA 3778.2.3) specifies a method to quantify the uncertainty associated with streamflow measurements (Australia Standards International 2001).

Some recent studies have applied this standard at sites across Australia, including the analysis of uncertainty in annual flow in 2005/06 at 71 sites across Gippsland in Victoria by Ozbey et al (2008) and 14 sites in the Werribee River catchment in Victoria by Lowe (2009). This approach provides a measurement of uncertainty over different flow ranges as well as an integrated measurement of uncertainty across all flow ranges for a given site. This technique is considered to provide a reasonably robust and comparable measure of the quality of streamflow data collected at a site. Unfortunately this technique is neither widely nor routinely applied across Australia. The application of this technique as part of routine streamflow data collection activities would significantly improve the ability to separate high quality streamflow data sites from lower quality sites and would help to drive investment in gaugings in particular parts of the flow regime where uncertainty is high.

2.4. Selection of Suitable Sites for Regional Hydrologic Studies

A number of studies in regional hydrology have been undertaken across Australia which have selected high quality gauges suitable for use in these analyses from a wider list of available sites. These include studies of baseflow, hydrologic index regionalisation, rainfall-runoff model parameter regionalisation, flow homogeneity, land use change impacts on hydrology, seasonal forecasting and climate change impacts on hydrology. The criteria used to select sites from these previous studies are discussed below.

2.5. Baseflow separation studies

A survey of baseflows in unregulated streams of the Murray-Darling Basin was conducted by SKM (SKM 2002a; Neal et al. 2004) in 2002 and repeated in as yet unpublished work by SKM (2010a) for the Basin Plan that identified 3 criteria for selection of gauging sites. A total of 178 streamflow data sites were selected based on the following criteria:

- The flow should be unregulated, where an unregulated catchment is defined as one with **less than 10% of the catchment area affected by regulation** by major on-stream impoundments or known major discharges. The definition of a major on-stream impoundments was subjective, but was generally restricted to those operated to deliberately release water downstream for environmental or consumptive purposes and did not include on-stream farm dams. Major discharges focussed on checking whether there were sewage treatment plant discharges upstream of the site which generated a consistent baseflow.
- The flow should cover a **minimum concurrent period of 10 years**. In SKM (2002a) this period spanned from 1990-1999 inclusive, but was extended to 2009 in the more recent unpublished work.
- Raw data should contain **not more than 5% missing data**. Beyond this amount the baseflow signal at the site was considered to be unduly influenced by the infilling technique.

This resulted in 178 streamflow data sites being selected for this project across the Murray-Darling Basin, of which 91 were located in NSW, 26 were located in Qld, 5 located in SA and 56 located in Victoria.

A more recent baseflows study covering all of Australia is being undertaken as part of the update of Australian Rainfall and Runoff. The project is estimating baseflow contribution to flood peaks (SKM 2009b). This study identified four criteria for the selection of sites:

- **Unimpaired (unregulated flow) sites** – sites that are unimpaired from flow management conditions;
- **Availability of hourly data** – data is required at a high frequency time step, i.e. sites that record instantaneous flow;
- **Availability of 30 years of record** – to ensure that a range of flood events are captured within the time series; and
- **Less than 10% missing data** – to maximise the usefulness of the data.

These criteria were developed through examining previous studies in which sites were selected based on similar criteria. These studies were the National Land and Water Resources Audit (Peel et al. 2000), other projects for the Australian Rainfall and Runoff Revision project and the Victorian Sustainable Yields Project (SKM 2003). This resulted in 274 sites being applied for this project.

2.6. Hydrologic regionalisation projects

Hydrologic regionalisation involves estimating the hydrology in ungauged catchments from a selection of gauged catchments using regressions between recorded streamflow indices and catchment characteristics.

The Victorian Sustainable Diversion Limit project (SKM 2003; Voorwinde et al. 2003) determined the volume of diversion that could sustainably be taken from the catchment. Seven criteria were used to select sites:

- **Unregulated;**
- Area between 10 km^2 and 1000 km^2;
- **Gauged with more than 10 years of data with less than 5% of missing records;**
- **Free from the effect of large reservoirs;**
- **Largely non-urban and unaffected by channel and drainage networks** – based on analysis of topographic maps that show large reservoirs, urbanisation and the extent of channel and drainage networks; and

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- **Relatively unaffected by upstream diversions** – based on whether summer diversions were less than 10% of the mean summer flow. Where Summer is between December and April, and diversions are to urban and rural users. Diversions over the winter period generally do not exceed 1% of the mean winter flow and the largest diversion was estimated to be less than 3.5% of the mean winter flow.

This resulted in the selection of 165 sites.

The Sustainable Diversion Limit technique was also applied in south-west Western Australia (Lang et al. 2008; SKM 2008a) and used 4 criteria for the selection of sites:

- Catchment area of greater than $10km^2$;
- **A flow record of at least 10 years, post 1975 – due to the shift in climate in 1975**;
- Minimal percentage of missing data; and
- Impacts of regulation should be negligible;

This resulted in the selection of 142 gauges. The second criterion above is of key importance for south-west Western Australia, because earlier data is considered unrepresentative of current climate conditions. To ensure a good spatial range of gauges were included in this analysis, gauges were not excluded based on a specific percentage of missing data (third criteria above) allowed but were assessed for suitability of infilling and their importance in representing regional trends.

The Northern Australia Sustainable Yields Project included regionalisation of ecologically relevant hydrologic indices (SKM 2009a) from gauged to ungauged catchments. Several criteria were developed in consultation with CSIRO and State and Territory agencies for the selection of sites:

- Data assessment period from 1/9/1972 to 31/8/1987 (15 years) for annual indices and 1/11/1972 to 31/10/1987 for wet/ dry season indices;
- **No more than 10% missing data**. Data was infilled using Sacramento rainfall-runoff models;
- **No sites impeded by upstream impoundments (i.e. unregulated flow)**;
- **No more than 60% of the gauged streamflow record above the maximum gauged stage height** (relevant to the analysis of average, median and high flow indices, and wet season indices);
- **No sites with known unstable rating tables at low flows** (relevant to the analysis of low flow and dry season indices only.

This study differed from the hydrologic regionalisation studies conducted in southern Australia because of known difficulties in measuring flows at very high and low flows. It involved thorough examination of rating table stability from the gauging history, as well as examination of the number of gauging within designated flow ranges. At high flows there are difficulties with access to

remote areas of tropical northern Australia, where road access can be cut off for several months during the wet season. There can also be significant shifts in channel morphology due to the high flow volumes generated, which can also affect low flow readings in the following dry season if the gauge is not re-rated. At low flows there are difficulties at some sites due to the presence of carbonate aquifers discharging to streams and creating a natural build up of calcium carbonate (limestone) on control sections. This is evident as an increase in rated discharge as the dry season progresses.

The Northern Australia Sustainable Yields Project drew upon pre-cursor studies by Petheram et al (2008), SKM (2007b) and SKM (2008b). Petheram et al (2008) also noted that a minimum period of less than 10 years would be unsuitable because the El Nino Southern Oscillation, which is driver of climate variability, operates on a 2-7 year climate scale. Petheram et al. (2008) selected 99 sites whilst the SKM work was restricted to the Adelaide and Finniss River basins only.

Moliere et al (2006) used one criteria for streamflow gauge selection in their study of flow characteristics of streams in the tropical rivers region – that gauges must have at least 20 years of complete annual flow data. In a related study to classify the flow regime of data-limited streams in the wet-dry tropical region of Australia (Moliere et al. 2009) the same criterion was applied to select 27 sites – 13 within the Daly River catchment, 6 within the Fitzroy River catchment, and 9 within the Flinders River catchment.

2.7. Regionalising rainfall-runoff model parameters

Similar to the above studies of hydrologic regionalisation of gauged data, a number of studies have investigated the regionalisation of rainfall-runoff model parameters.

This technique is known to have been applied in Australia in the mid-1990s in Nathan et al. (1996), which regionalised the four MOSAZ rainfall-runoff model parameters using catchment characteristics. The streamflow sites selected for the analysis, which was limited to Victoria, was based on the list of sites prepared in the Low Flow Atlas of Victorian Streams (Nathan et al. 1993). The criteria used by Nathan and Weinmann (1993) were:

- A minimum length of record of 15 years;
- Within each drainage division, **catchments should be representative of a range of gauged catchment sizes and climatic conditions**;
- No appreciable artificial regulation (**≤5% of the catchment is regulated**) or **diversion (≤5% of the mean annual flow)** upstream of the point of gauging; and
- Catchments should be free from appreciable dense urban development (**≤5% of the catchment is densely urbanised**).

This resulted in 117 catchments being selected by Nathan and Weinmann (1993), with a further 78 being added in Nathan et al. (1996) possibly due to additional data collected between the two studies and because of additional sites sourced from Nathan and McMahon (1992).

Chiew et al. (undated) took a similar approach but for the estimation of SIMHYD parameter values for application in ungauged catchments across Australia. This study drew upon a list of 331 unimpaired catchments derived for the National Land and Water Resources Audit by Peel et al.. They used several parameters to select appropriate catchments for analysis, ensuring that there were no inconsistencies in the data series. Inconsistent data was identified by one or more of the following:

- Runoff coefficient greater than 0.8;
- Actual evapotranspiration (mean annual rainfall minus mean annual runoff) greater than 0.8 times the mean annual areal potential evapotranspiration; and
- Clear inconsistencies between monthly rainfall and runoff data.

This resulted in 293 catchments being used for Chiew et al. (undated).

The study to estimate streamflow in ungauged catchments by Peel et al. (2000) selected sites based on the following criteria:

- At least 10 years (120 months) of unimpaired streamflow data;
- Area between 50 km^2 and 2000 km^2;
- **Unimpaired catchments with no upstream regulation or diversion**;
- **Missing data was allowed as long as 120 months of data was available**;
- **When a catchment has greater than 20% of its area represented by another catchment(s), then the sub-catchment(s) are used, while the larger catchment is not used**; and
- Available data from various federal, state and territory agencies.

This resulted in 331 gauging stations being applied for this study. This study appears to be the only one which has considered the issue of nested catchments duplicating information.

2.8. Regional land use change studies

Many studies have been undertaken in Australia examining the effect of land use change on hydrology. The majority of these studies are local catchment studies, however there have been a number of regional investigations focussed on the hydrologic impact of farm dams.

2.8.1. Farm Dams

A project undertaken to assess the impacts and implications of farm dams on catchment yield (ICAM et al. 1999) used a two step process for identifying high quality gauges for assessing trends in streamflow:

1) Selection critera that had to be satisfied:
   a) 10 years of streamflow, rainfall and temperature
   b) **Reasonable quality of streamflow gauging according to AWRC rating**.
2) **Liaison with local State agency officers** for provision of essential background information on land use development, key issues and concerns.

This resulted in the selection of 11 key catchments.

Gan et al. (1988) estimated yield from farm dams from 71 catchments across Victoria. Catchments were in the range of 0.1 km^2 to 250 km^2 with **no appreciable urban area** and **no large storages upstream**.

Nathan et al (undated) undertook a study to estimate farm dam yield in small agricultural catchments in south-eastern Australia. The catchments were required to broadly represent the range of agricultural catchments found in the regions; the following selection criteria were used:

- Less than 20km^2 in area;
- Rural, with **no appreciable urban development;**
- Have **no significant impoundments** upstream of the point of interest;
- Are **not influenced by snowmelt** (thus have an elevation of less than 1000 mAHD);
- Have dense to medium forest covering less than 90% of the total catchment area;
- Have a mean annual rainfall of less than 1400mm;
- Exhibit the highest mean monthly streamflow during Winter (May – October) months; and
- Have at least three years record of reasonable quality streamflow.

This resulted in 37 catchments being used in the study (31 in Victoria and 6 in NSW).

SKM is currently undertaking a study to model the impacts of farm dams at 168 sites across the Murray-Darling Basin. The criteria being used to select streamflow gauges for the analysis include:

- Minimum 15 year record;
- **End of the 15 year record must be after 1995**;
- Gauge must be **free from significant regulation or major storages / offtakes**;

- Overall choice of gauges must provide **good spatial coverage**;
- 1 gauge in SA was excluded due to an excessive baseflow component, which was not representative of farm dam inflows; and
- Several gauges were excluded because they required **excessive periods of infilling**.

The effect of farm dams on streamflows in south-west Western Australia was undertaken by SKM (2009c). Selection of catchments was undertaken by the Western Australia Department of Water based on local knowledge of the extent of farm dam development in the catchments. Streamflow gauges were then assigned to those catchments.

2.8.2. Plantations, Forest Harvesting and Bushfires

A number of studies examining the effects of plantations, forest harvesting and bushfires have been undertaken around Australia, however the majority of these have been local investigations rather than regional scale ones. Examples include studies into the impact of blue gum plantations on baseflows in five catchments in south-west Victoria (SKM 2008c).

Regional studies of the effects of plantations, forest harvesting and bushfires are less common. The assessment of the 2003 and 2006/07 alpine bushfires on streamflows was undertaken in several studies (SKM 2007c; SKM 2008c; SKM 2009d). No specific criteria for selecting streamflow gauges were identified in those reports, as gauging information was simply used when and where it was available. The effect of changing from forested catchments to pasture was assessed at 1 km by 1 km grids across Victoria in SKM (2008f) however streamflow gauges were not used as part of that assessment. Outputs were expressed as a percentage change without specifying the baseline conditions from which the results were changed.

Historical trend analyses were undertaken on one forested catchment for NSW State Forests, from a selection of six candidate catchments. The criteria for selection were "on the basis of long, reliable hydrologic records (rainfall and streamflow) and a significant proportion of the catchment having been historically planted with pines" (SKM 2002b). The remaining five candidate catchments in the study area did not meet these criteria.

The effect of potential future plantations on streamflows was estimated in Sustainable Yields projects for the Murray-Darling Basin (CSIRO 2008a), Tasmania (CSIRO 2009a) and South-West Western Australia (CSIRO 2008b). This scenario was not prepared for the Northern Australia Sustainable Yields project.

A recent study led by SKM for the NWC has identified catchments where intercepting activities are expected to increase in the future (SKM et al. 2010). The study was a national baseline look at unregulated intercepting activities including plantations, land use change, stock and domestic

bores, farm dams and periurban development. This information could be used as an overlay to prioritise gauges. In addition meteorological data sets and climate change scenarios should be reviewed as well. The Bureau and CSIRO are expected to be sources of such data.

2.9. Climate change studies

Chiew et al (2008) undertook a study that assessed the impact of climate change on runoff throughout the Murray-Darling Basin using rainfall-runoff models. This study used the following criteria to select sites:

- **Unregulated catchment**;
- Areas between 50 and 2000km^2;
- Most gauges have **70% of daily streamflow data considered as good quality** over the study period; and
- Dates range between 1975 and 2006.

The same criteria as listed in Section 2.6 were used for the Northern Australia Sustainable Yields project. For the south-west Western Australia Sustainable Yields project, the selection criteria for selecting the 106 streamflow gauges for calibration of rainfall-runoff models were that catchments had to (CSIRO 2009b):

- be at least 10 km^2 in area;
- have at least 10 years of recent, good quality and continuous streamflow record; and
- contain streams with potable or near potable brackish quality water.

For the Tasmanian Sustainable Yields project, a total of 60 streamflow gauges were used for the calibration of rainfall-runoff models but the criteria for selecting these sites were not reported (CSIRO 2009a).

Each of the sustainable yields projects across Australia assessed water availability under a recent climate scenario which repeated data from the last 10-11 years, typically from 1997-2007. The selection of this period was based on the analysis of climate data, not streamflow data.

McMahon et al. (2007) have done extensive work with a global data set for assessing characteristics of annual streamflows. This data base consists of 1221 sites worldwide that were selected based on the following criteria:

- 10 years or more of continuous historical annual and monthly flows;
- **Not impacted by major water withdrawals or upstream reservoirs**; and
- **Data is free from errors**.

In more recent work that McMahon and Peel are undertaking, a sub-set of the data used for McMahon et al. (2007) was applied. In addition to those criteria outlined for McMahon et al (2007), sites that did not satisfy checks were removed. These checks were for:

- **Transcription errors;**
- **Errors relating to catchment area and location;** and
- **Impacts of major water withdrawals and upstream reservoirs.**

This results in 861 streamflow records being applied for this study. Median streamflow record length is 32 years (ranging between 10 and 172 years); median area is 1,620 km^2 (ranging between 3.6 and 4,640,300 km^2).

Kiem and Verdon-Kidd (2010) identified statistically significant break points in historical climate at 8 gauged streamflow sites across Victoria. The streamflow data were not used for the statistical analysis, but were used to support conclusions drawn from the analysis of rainfall data. These 8 sites had a **desirable length of record of 60 years, representative of natural flow conditions** and were **spatially distributed across Victoria**. In the Goulburn and Yarra River catchments they were unable to find suitable sites and utilised modelled data in their analysis in those two catchments.

A climate shift scenario has been adopted in each of the Victorian State Government's Sustainable Water Strategies. This scenario is based on setting the mean annual runoff in the pre-July 1997 period equal to the mean annual runoff in the post-July 1997 period. The individual streamflow gauges used in these adjustments are not listed in the Sustainable Water Strategies, however having at least ten years of data from 1997 onwards is necessary to undertake the calculation.

In south-west Western Australia the shift in climate was observed to occur earlier and only data collected after 1975 is used in current water planning (CSIRO 2009b).

2.10. Seasonal hydrologic forecasting studies

A project that undertook seasonal forecasting of Victorian Streamflows selected high quality gauges to undertake the analysis, the selection criteria were (SKM 2007a):

- Natural streamflow conditions (or as close as possible) that are **not impacted by upstream impoundments or diversions** – Identified using the Flow Stressed Ranking scores and Sustainable Diversion Limit statistics;
- Long streamflow records (preferably at least 60 years to capture multi-decadal variability);
- **Spatially distributed** across Victoria to ensure several different regions are analysed;
- Relatively large catchment;

- Streamflow gauges that are "useful" to DSE (the client) for operational purposes; and
- **Minimal % of missing data**.

2.11. International Precedents for Designating High Quality Streamflow Sites

The selection of high quality streamflow sites around the world was previously reported in Section 2.9 for the global climate change study by McMahon et al. (2007). Further information was available on the selection of high quality streamflow sites in the United States. The United States Geological Survey (USGS) has established a hydro-climatic data network for use in the study of long-term climate variations (Slack et al. 2006). The process by which the USGS selected its sites is similar to that being undertaken in this study, namely by compiling sites selected and the criteria used to select them from a range of previous studies. The criteria adopted by the USGS are as follows:

- Availability of data in electronic form;
- Breadth of coverage – records from any station were considered if it had any data over the assessment period from 1874-1988;
- Length of record of at least 20 years, however sites with less than 20 years were considered if their type of catchment or location was underrepresented in the data set;
- Accuracy of records – records had to be predominantly "good" where good was defined as having **95% of the daily mean discharge values to be within 10% of the true value**, but with an allowance for "professional judgment of the office that obtains and prepares the record";
- **Unimpaired** (unregulated) basin conditions – this included no upstream impoundments or significant changes in land use, but also included **no reduction in baseflow due to extreme groundwater pumping**;
- Measured discharge values should **not include an excessive number of estimated values**. No attempt was made to infill the data.

Of note in the USGS hydro-climatic data network site selection was the flexible approach adopted. There were a number of exceptions to the criteria adopted, such as including part of the record only if it was unimpaired at an earlier point in its history and allowing sites with constant upstream diversions or small hydropower storages which would have no impact on longer time step climate variability studies.

Carlisle et al. (2009) used spatial datasets and hydrologic models to select 1272 reference sites across the United States from 5271 candidate gauges. The aim of the analysis was to identify sites which were undisturbed from flow regulation or land use change. The analysis used a range of modelling techniques to identify deviation from modelled conditions in the historical records as an

indicator of undisturbed flow conditions. Thirteen hydrologic metrics were combined to evaluate deviation from historical conditions.

The World Meteorological Organisation (2004) developed criteria for selecting streamflow gauges in pristine river basins for use in climate change studies. These criteria were the same as those used in Slack et al. (2006). The dataset was to be known as a *Reference Climate Variability and Change Hydrological Station Network*. More information on this network could not be located and the absence of any reference to this in McMahon et al. (2007) suggests that the network has not been established yet.

2.12. Supporting spatial datasets

Spatial analysis utilising available National and State/Territory data sets will support the identification of high quality stream gauges. A review of available spatial datasets was undertaken to examine whether there were any key datasets missing at a National or regional scale which could inhibit the ability to identify high quality streamflow sites. This list of useful spatial characteristics was derived by examining the spatial datasets utilised in the previous studies outlined above.

It can be seen from Table 2-1 that most datasets are available uniformly at a National or State/Territory scale, and hence could be readily adopted if needed for use in developing selection criteria. The exceptions to this are the point source discharges, such as from mine sites, irrigation drains and sewage treatment plants, and point source diversions. Both of these datasets are typically held by water utilities and are not readily available at a State/Territory or National scale.

Particular opportunities exist with national mapping programs. This includes the Department of Climate Change NCAS – LCCP (National Carbon Accounting System – Land Cover Change program), which can provide current and retrospective views of tree cover and bushfire. It also includes the national plantations inventory on the extent and location of current plantations (Bureau of Rural Sciences) and farm dam mapping programs such as the Murray Darling Basin Authority / Geosciences Australia initiative to update waterbodies and farm dams in the Murray-Darling Basin.

Table 2-1 Supporting Spatial Datasets

Data set	Source	Coverage
Streamflow gauge sites	State/Territory agencies	State/Territory
Stream network	Geoscience Australia	National (1:250k)
River basin boundaries	Geoscience Australia	National
Major river catchment boundaries	Geoscience Australia	National
Streamflow gauge catchment boundaries	State/Territory agencies	State/Territory
Geology	Geoscience Australia	National
Rainfall	Bureau of Meteorology	National
Evapotranspiration	Bureau of Meteorology	National
DEM (to extract stream order)	Bureau of Meteorology / GA	National
Land use	BRS	National
Farm dams	State and Commonwealth Agencies / GA	Regional
Tree cover (includes logging)	DCCEE, LCAS, State/Territory agencies	National, 1972 - 2009
Bushfire extent	State agencies / DCCEE, LCAS	Regional / National
Water bodies	Geoscience Australia	National (1:250k)
Point Source Discharges	Water authorities	Local
Diversions	Water authorities	Local

2.13. Summary

This literature review highlighted the following:

1) Streamflow data quality codes around Australia vary between each State and Territory and there is no commonly accepted definition of "high quality" data based on quality codes;
2) Estimating streamflow gauge uncertainty using Australian Standard ASA 3778.2.3 has been undertaken at a small selection of sites in southern Victoria, but is not routinely applied there or elsewhere in Australia. The use of this standard to measure streamflow gauge uncertainty over time could improve the ability to transparently and robustly identify high quality sites;
3) Regional hydrologic studies have been undertaken throughout Australia that identified streamflow gauging stations suitable for use in those studies. The selection criteria were somewhat similar. Key points to note from these studies were:
    a) Sites are usually unimpaired. The definition of unimpaired typically involved less than 10% of the catchment by area affected by flow regulation. Some studies added that they should be non-urban and unaffected by major discharges and diversions;
    b) Sites usually contain less than 5-10% missing data. The way in which missing data was specified was not readily available, however in the tropical northern Australia an analysis

of rating tables and gauging was undertaken to limit the percentage of the flow record above the maximum gauged value;

c) Sites usually had a minimum period of record, which varied from 10 to 30 years depending on the study, with one study designed to capture inter-decadal climate variability specifying a minimum of 60 years of data. In south-west Western Australia this period had to be after the climate shift around 1975. In one study this period of record was specified to include a recent date;

d) Some studies specified that sites should be representative of a range of catchment sizes and climate conditions;

e) One study applied tests to eliminate sites with inconsistencies between observed climate data and observed streamflow data; and

f) Some studies included liaison with State and Territory agency hydrographers to ensure that there were no local factors affecting the gauges.

4) A similar exercise undertaken by the United States Geological Survey (USGS) adopted a flexible approach within broad selection criteria to ensure that all types of sites were represented. Additional criteria adopted by the USGS that have not been mentioned in Australian studies were the exclusion of sites where baseflow was affected by excessive groundwater pumping and the inclusion of sites where upstream diversions were constant over the period of record.

5) A range of supporting spatial datasets is available for assisting with the selection of high quality sites and assessing their representativeness. None of these datasets were considered to prohibit the selection of sites, with the exception of point source discharges and diversions, which are not readily available in a single repository at each State/Territory level.

The list of gauges used in the above studies has been compiled into a spreadsheet which will allow an empirical check of any selection criteria developed in this study.

3. Discussion of Guideline Selection Criteria

3.1. Introduction

After completing the literature review there are a number of possible approaches to selecting sites. This section of the report discusses some of the issues surrounding the approach and selection criteria for identifying high quality streamflow gauges, including:

- Pros and cons of an empirical selection of sites and the potential use of the empirically selected dataset of gauges from previous studies;
- Criteria for identifying unimpaired sites;
- Comments on how to incorporate land use change into the assessment;
- Selection criteria based on available data quality for unimpaired sites;
- Selection criteria based on an estimate of measurement uncertainty for unimpaired sites;
- Comments on how to incorporate climate stationarity into the assessment; and
- Assessing representativeness of the sites selected.

3.2. Empirical Selection of Sites

The literature review identified a list of sites across Australia which had been selected in previous studies in hydrology for seasonal streamflow forecasting, land use change and climate change investigations. One approach to selecting sites would be to compile this list into a consolidated dataset on the assumption that if a site has been specifically selected for one or more of these previous studies, then it must have value for these types of investigations and would be suitable for the Bureau's purposes.

The advantages of this approach are that:

- It is fast and simple to implement; and
- The data can still be supplemented with information about the quality of data at the site for users of the data.

The disadvantages of this approach are that:

- The criteria used in those previous studies vary, resulting in inconsistent selection criteria;
- In some regions there may have been no or only one study undertaken, which limits the confidence that a particular site is high quality for the purposes of the Bureau and that all high quality sites have been selected;

- The length of available data and its quality changes over time. Sites which were not suitable for previous studies may now meet the selection criteria applied in those studies because of additional data since collected.

For these reasons, it is recommended that the list of sites used in previous studies should only be used for reference purposes by the Bureau to sanity check its own selection of sites.

3.3. Defining Unimpaired Catchments

A common feature of all of the catchments identified in previous studies for investigating seasonal streamflow forecasting, land use change and climate change impacts on hydrology was that they were unimpaired. The definition of unimpaired varies slightly from study to study, however there are some common features. There is also some redundancy in defining unimpaired catchments in previous studies, because in many cases the definition of an unimpaired catchment has been carried from one study to the next rather than being derived independently.

The following definition of an unimpaired catchment is proposed:

A stream gauging station is in an unimpaired catchment if not more than 10% of the catchment by area is affected by flow regulation, and with major discharges and diversions being less than 10% of the mean annual flow.

The figure of 10% by area for flow regulation acknowledges that some form of flow regulation would be likely to exist in most catchments around Australia, but that any more than 10% is likely to compromise the integrity of the dataset. A figure of 5% could equally have been chosen and in some applications no flow regulation may be desirable. Similarly the figure of 10% of the mean annual flow being diverted or discharged is arbitrary and could be tightened to a smaller volume, particularly where mean annual flow volumes are large, such as in tropical areas. In some instances, seasonal patterns of discharge or diversion may adversely affect streamflows in low flow months, even if less than 10% of the mean annual flow is diverted or discharged. The threshold of 10% for the volume of diversions or discharges relative to mean annual flow may need to be more stringent for climate change investigations than seasonal forecasting. The magnitude of the change being detected may be within 10% of the mean annual flow in some climate zones, although it is noted that in south-east Australia climate induced changes in mean annual flow post-1994 have been well in excess of this figure.

The effect of intercepting activities such as small catchment dams (farm dams), bushfire regrowth and plantation forestry lie outside of the diversion licensing regime in some jurisdictions and to different regimes and would be in addition to licensed diversions. Discussion of these intercepting activities occurs in Section 3.6.

The degree to which a catchment is impaired may change over time. It is assumed in the analysis that sites are still useful where data exists prior to a flow regulating structure being constructed or after its decommissioning.

For some applications, the selection criteria by which a catchment is designated as unimpaired may be relaxed or tightened. For this reason, it is recommended that the data in Table 2-1 be collated with each site to allow end users to restrict their selection of sites if needed. The approach to collecting the data in Table 3-1 would be to focus on the most readily accessible sources of information which would exclude a site as being impaired (e.g. the presence of a major on-stream dam) and only to collect the remaining data for sites where the most readily accessible data does not exclude the site.

Table 3-1 Metadata for degree to which catchments are unimpaired

Item	Comments and Definitions
Proportion of the catchment upstream of a flow regulating structure - Name - Storage Capacity (if applicable) - Area upstream of structure - Proportion of catchment upstream of structure - Date of construction of flow regulating structure - Date of decommissioning of flow regulating structure	A flow regulating structure is defined as any on-stream storage that deliberately releases water for environmental use, consumptive use or electricity generation purposes. This assessment should be undertaken for each flow regulating structure if the proportion of the catchment upstream of the structure is less than 10% by area. Electricity generation storages may be acceptable if they only regulate flows on a daily basis and do not affect flows on a seasonal basis.
Point source discharges within the catchment - Name - Description of Location (tributary name, nearest urban centre or spatial co-ordinates) - Average annual discharge volume (ML) - Period of record affected by the discharge	This information must currently be sourced from individual water utilities and would include sewage treatment plant discharges, industrial discharges (e.g. from mine dewatering) and irrigation drains. It should include any inter-basin transfers to rivers associated with water supply operations.
Current annual diversions upstream of streamflow gauge: - Surface water licence volume (ML) - Groundwater licence volume (ML) - Total licence volume (ML) - Licence volume as % of mean annual flow at gauge (%) - Period of record affected by the diversions (if known)	The period of record of diversions may only be known approximately. There are known commencement dates for some major irrigation diversions such as the Ord River scheme and Thomson River diversions to Melbourne. The groundwater licence volume would be collected for all production bores in the first instance and would be refined to include only those in connection with the surface water system if this criteria is critical for the selection of a site.

3.4. Use of quality codes

After removing any impaired sites, quality codes can be used as a first order assessment of the amount of missing data. Table 3-2 presents quality codes previously identified as missing data in a current SKM project to assess baseflow contribution to flood peaks around Australia. These missing data criteria were provided by state agencies. When comparing these codes for missing data against the complete list of quality codes in Appendix A, it can be seen that there are some quality codes which could be considered missing but which are not listed as such in Table 3-2. For example code 104 used by Thiess in Victoria is defined as "Records estimated", code 77 is "correlation with other station" and code 119 is "unregistered Ecowise code", which either suggest that data was missing and has been infilled or gives little clue to the accuracy of the data. However, it should be noted that in practice very few of the quality codes listed in Appendix A are actually used and the likelihood of encountering the more obtusely defined codes is rare. Sometimes these codes exist for water quality variables and are not applicable to flow data at all, such as code 90 "salinity interpolation" used by Thiess.

- **Table 3-2 Quality codes for missing data**

Jurisdiction	Missing data quality codes
Vic, NSW, SA, NT	> 150
Qld	> 125
Tas	> 30, except for codes 32 and 34, which were assumed to not be missing data
WA	> 4, except for codes 11 and 12, for which were considered missing if the level data has a quality code > 4.

When selecting a threshold for missing data, this is somewhat arbitrary. The threshold adopted was to retain sites with at least **one continuous period of 15 years with not more than 5% of days with missing data.** The period of 15 years was selected because it is a typical interval for major drought and flood events and aligns with naturally occurring climate cycles in Australia. For example, major droughts in south-east Australia occurred in 1967/68, 1982/83, 1997/98 and 2006/07, which is roughly around every 15 years. A period of 15 years is likely to contain sufficient climate variability to reliably calibrate a rainfall-runoff model for use in seasonal forecasting. The 5% of days with missing data was arbitrarily selected and was based on a typical value from the literature review in the previous chapter of this report.

The selection of a site based on the availability of one period of 15 years of data indicates that it will potentially be useful for applications by the Bureau. For example, a site with 15 years of data in the 1950s and 1960s could be useful for assessing the effects of land use or climate change, particularly if comparative data exists in a more recent period. If a site does not have 15 years of data in a recent period then it may not necessarily be representative of current climate conditions.

Consideration of whether the period of available data is representative of current climate will affect its use by the Bureau and is discussed further in Section 3.7.

The quality of data can be differentiated from whether data is simply present or missing. The quality of data is a reflection of the stability and therefore certainty of the rating table used to convert water levels into streamflow. A complex measure of uncertainty in the data collected is presented in Section 3.5. A simpler approach using quality codes was considered to minimise the degree of effort required to classify streamflow gauges according to their quality. One simple but key measure of data quality is the extent to which streamflow data has been generated using water levels above or below the highest or lowest water levels at which streamflow gaugings exist. This indicates that the rating table has been extrapolated beyond the range of reliable recorded values. This is a common issue in remote areas with poor access, particularly where these areas are inaccessible over parts of the flow regime, such as in tropical Australia during the wet season. It would also include low flow data collected in a drought worse than that which has previously been gauged, however low flow data is typically more reliably extrapolated than high flow data.

Establishing a threshold for selecting high quality data based on rating table extrapolation is arbitrary and may need to be relaxed in areas where no other data exists, which is likely to be the case in some river basins in remote tropical areas. A notional threshold has been selected of only retaining sites which have not more than 20% of data outside of the range of gauged data. This may be revised by the Bureau after considering the effect that this threshold has on the number of sites selected in river basins across Australia. It may also be revised if it can be correlated with the more meaningful measure of data uncertainty discussed in Section 3.5.

3.5. Use of uncertainty from Australian Standard

The previous section discussed the use of quality codes to reflect the stability and therefore certainty of the rating table used to convert water levels into streamflow. A more complex approach incorporates a statistical analysis of uncertainty associated with the streamflow measurements. This procedure is time intensive and is presented as an alternative to using quality codes. While this approach may time consuming, it provides the only reliable measure of uncertainty across the whole flow range that is independent of subjective quality code classifications.

At each streamflow gauging site the water level is measured on a regular (or continuous) basis and converted to a flow rate using a rating curve. The rating curve is constructed based on a sample of measured streamflows and their corresponding water level (a concurrent streamflow and water level data sample is termed a ‘gauging’). The rating curve can be fitted to the gaugings either using statistical techniques or can include some subjective judgment that may take into account the influence of the shape of the river cross section and downstream obstructions. Details of these

methods can be found in standard hydrology text books or the relevant Australian Standard (Standards Australia 1990).

The Australian Standard number AS3778 (*Measurement of water flow in open channels*) specifies a method to quantify the uncertainty associated with streamflow measurements and considers the uncertainty due to measurement error associated with the water level and uncertainty in the rating curve. Specific information regarding the water level measurement uncertainty is generally contained in the manufacturer's specifications. Alternatively the uncertainty can be estimated by comparing the continuous measurements with more accurate spot readings. The uncertainty in the rating curve is based on a statistical analysis of the variation in the individual gaugings used to construct the rating curve and follows these general steps:

- The historical gaugings that are representative of the current conditions at the site are selected.
- The rating curve is divided into segments which, in the log domain, can be characterised with a straight line.
- The uncertainty estimate is based on the scatter of historical gaugings around the rating curve within each segment.

Further details of these steps, including the relevant equations, can be found in the Australian Standard or the descriptions given by McMillian (2008) or Ozbey et al. (2008).

It should be noted that when applying the Australian Standard that 20 gaugings are required in each segment to ensure a statistically valid estimate of the uncertainty in flow. Ozbey et al. (2008) found that this was not possible for several sites in the Gippsland region of Victoria due to limited gaugings.

Establishing a threshold for selecting high quality data based on uncertainty analysis is arbitrary, and the acceptable level of uncertainty will depend on the use of the data and the alternatives available. A notional threshold has been selected of only retaining sites which have an uncertainty in the mean annual flow (MAF) of less than 10%. This figure is based on the Ozbey et al (2008) study of the Gippsland regions, which found that at the majority of monitoring sites, uncertainty in mean annual flow estimates ranged from +/- 5% to +/- 15%. The chosen threshold of 10% MAF may require review by the Bureau after the method has been applied to more sites. The Bureau may also wish to include a threshold for uncertainty around particular flow ranges (for example low flows).

3.6. Land Use Change

Land use information can be useful for deciding the extent to which a particular site is suitable for a particular investigation. A catchment with a high proportion of a particular land use may still be useful for seasonal forecasting activities or climate change studies, especially if that land use is

stationary over time. Where land use is changing, this has the potential to affect the ability to derive comparable statistics between catchments and over time, and could affect the quality of rainfall-runoff models calibrated to the data.

The majority of catchments in the developed areas of Australia will be subject to some form of land use change such as logging, afforestation, bushfire or farm dam development. In a study of streamflow trends in the Murray-Darling Basin due to climate change, Cai and Cowan (2008) resorted to examining trends in modelled streamflow due to the absence of sufficient long-term gauged streamflow datasets which were unaffected by land use change and flow regulation. Most of the river basins in southern New South Wales, Victoria and the Mount Lofty Ranges in South Australia will have been affected by bushfires at some time over the period of available streamflow gauge data. Black Friday (1939), Ash Wednesday (1983), the Alpine fires of 2003 and Black Saturday (2009) are examples of major fire events contained within the hydrologic record of streamflow gauges in south-east Australia, for example.

Rainfall-runoff models have been developed which endeavour to dynamically model the effects of land use change, such as the WaterCast model of the Googong River catchment near Canberra, which explicitly included changes in farm dam volumes, groundwater pumping and forest cover over the model calibration period (SKM 2010c). The application of such models could obviate the need to exclude streamflow gauging sites due to land use change, however their application is in its infancy and is still subject to high uncertainty.

A threshold for acceptable land use change is difficult to readily incorporate into the selection of high quality streamflow sites because information on land use change is generally not available as a continuous time series. This makes statistical trend analysis of the land use data difficult or impossible. An example of this would be farm dam information, which is only available when aerial photography or satellite imagery of sufficient quality has been collected. In many catchments this data would consist of snapshots that are 10-20 years apart and may not be available earlier than a few decades ago. The quality of the information itself is also subject to change over time, particularly where the techniques for deriving land use change have improved. This means that any comparison against a specified threshold for land use change would be subject to high uncertainty and could not be uniformly applied using the same land use change estimation procedures around Australia.

The approach taken in these guidelines to land use change is to collate data associated with land use change in each catchment and then use this to inform the judgement of the hydrologist in deciding whether to use the high quality dataset for a particular purpose. The current land use provides a good indication of whether land use change is likely to have occurred historically. A summary of the metadata which can be used to identify land use change is contained in Table 3-3.

Some rules of thumb which can be applied to indicate the potential change in mean annual flow arising from land use change are as follows:

- For every megalitre of farm dam, mean annual flows are reduced in the order of one megalitre (SKM 2004). Impacts vary climatically and are affected by the purpose of the dam and the presence of bypass structures.
- The change in runoff anticipated from change in vegetation is related to the change in evapotranspiration from the vegetation at different ages and for different vegetation types. The range of impact is wide and is affected by climate conditions, as well as the species type. For bushfires it is also affected by the fire intensity. The effect of vegetation change on hydrology will change over time. After trees have been removed by fire or logging, runoff will initially increase in the first few years and then decrease to a peak reduction in around 10-20 years. When this peak reduction is reached, runoff will begin to increase again to return to the long-term average runoff over subsequent decades. A summary of bushfire impact modelling in Victoria presented in (SKM 2010b) indicated maximum average annual reductions in runoff from bushfire of between 0-1 ML/ha/yr with an average impact of 0.4 ML/ha/yr (or 40 mm/yr). The increase in runoff immediately after bushfire ranged from 0.7-3.0 ML/ha/yr and averaged 1.7 ML/ha/yr (or 170 mm/yr).
- For urban areas, urbanisation could have a range of impacts, including increasing runoff in wet periods due to the increase in impervious area and the increase in baseflow in dry periods due to garden watering using water imported from other catchments. In previous studies presented in the earlier literature review, an urban area of around 5-10% of the catchment was regarded as an indicator that streamflow gauges could be non-stationary due to urbanisation.
- There may be local land use changes which also affect hydrology. For example in south-west Western Australia, land salinisation has been shown to increase runoff (Bowman et al. 2000). The root fungus disease *Phytophthora cinnamomi* has also been linked to changes in hydrology in this region (CSIRO 2009b). Local knowledge of the catchments is required to obtain insights such as these, hence the recommendation in the guidelines to consult with state and territory agency hydrologists before finalising the list of high quality streamflow gauges.

The effects of land use change on streamflows can be likened to any other diversion or flow regulating activity and as a guide, any land use change which is estimated to change the mean annual flow at a site by more than 10% could be regarded as potential grounds for excluding the site. This single threshold would apply to the sum of land use change and direct diversions and discharges discussed in the previous section. Double mass curves against nearby sites that are unaffected by the same land use change could also indicate the suitability of a site for subsequent investigations where high quality data is required. Using double mass curves instead of collecting land use data may simplify the application of the guidelines.

Table 3-3 Metadata for Land Use Change Assessment

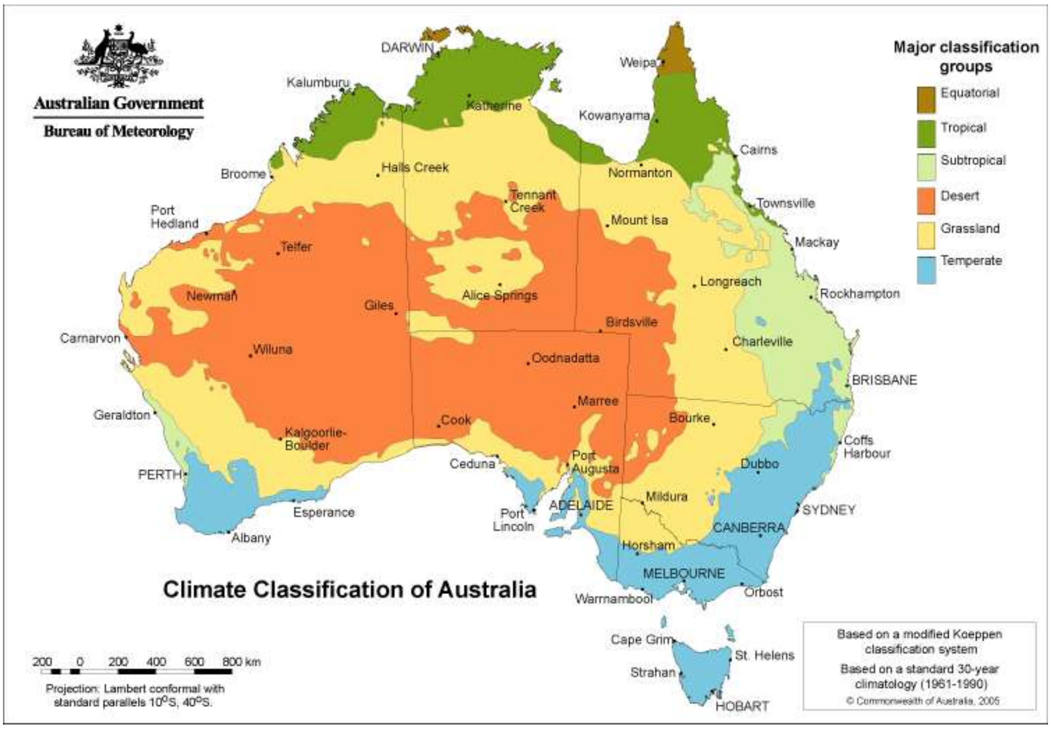
Item	Comments and Definitions
% of catchment forested over time	A national coverage of the % forested is available at intervals over the period 1972-2009
Volume of small catchment dams in catchment (ML)	Geoscience Australia compiled farm dam data for the Murray-Darling Basin. Earlier snapshots are generally only available from State agencies at irregular intervals.
Years of significant bushfires affecting the catchment	List the years when the catchment was partially or fully burned. In Victoria this is maintained by DSE at http://www.dse.vic.gov.au/DSE/nrenfoe.nsf/childdocs/-D79E4FB0C437E1B6CA256DA60008B9EF?open Other states would need to be contacted directly.
Years of significant logging within the catchment	List the years, name and area of logging coops.
Area of forest plantations over time	Information on the extent of forest plantations and their harvesting cycle…
% of the catchment with urban area	Current urban land use is defined by the Bureau of Rural Sciences GIS layer of land use with type "urban".

3.7. Climate stationarity

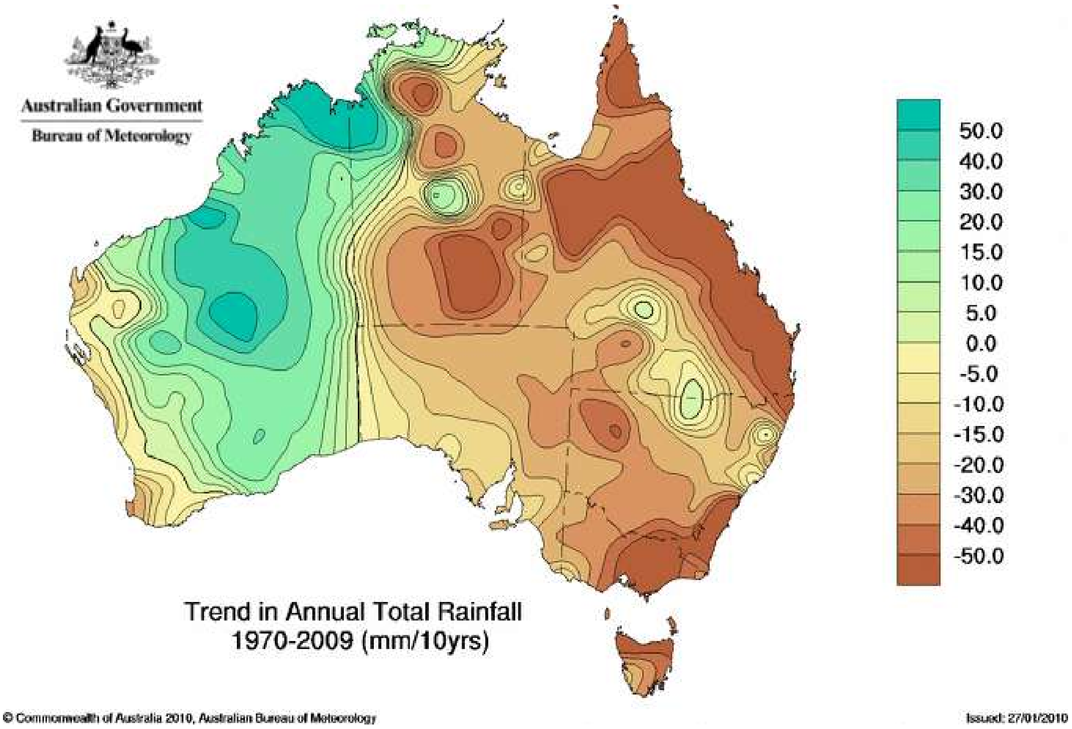
In many parts of Australia, there has been a significant climate shift and streamflow gauges need to be selected that have adequate data to represent each climate step. The following discussion outlines the timing of climate shifts in different regions across Australia, and the streamflow gauge requirements to represent these shifts.

When dividing parts of Australia into climate regions for the purposes of the guidelines, a pragmatic approach has been adopted based on available hydrologic literature examining this issue. The four regions identified broadly correspond to subsets of the major Köppen climate classes (Figure 3-1) and the Bureau's major seasonal rainfall zones. Hydrologic studies documenting climate shift such as the CSIRO sustainable yields reports have generally aligned with these climate classes. Trends in annual rainfall total from 1970 to date are shown in Figure 3-2, which suggests that climate shift does not however necessarily align with these climate classes. For example there is a clear difference in trend in historical rainfall on either side of the Western Australia border. The line of no trend cuts through several climate classes, with isolated pockets of no trend also occurring in eastern Australia and in the middle of the Northern Territory. Further work could be undertaken to better define stationary climate periods in different parts of Australia, which may require a departure from traditionally adopted climate and hydrologic regions.

- **Figure 3-1 Climate Classification of Australia**



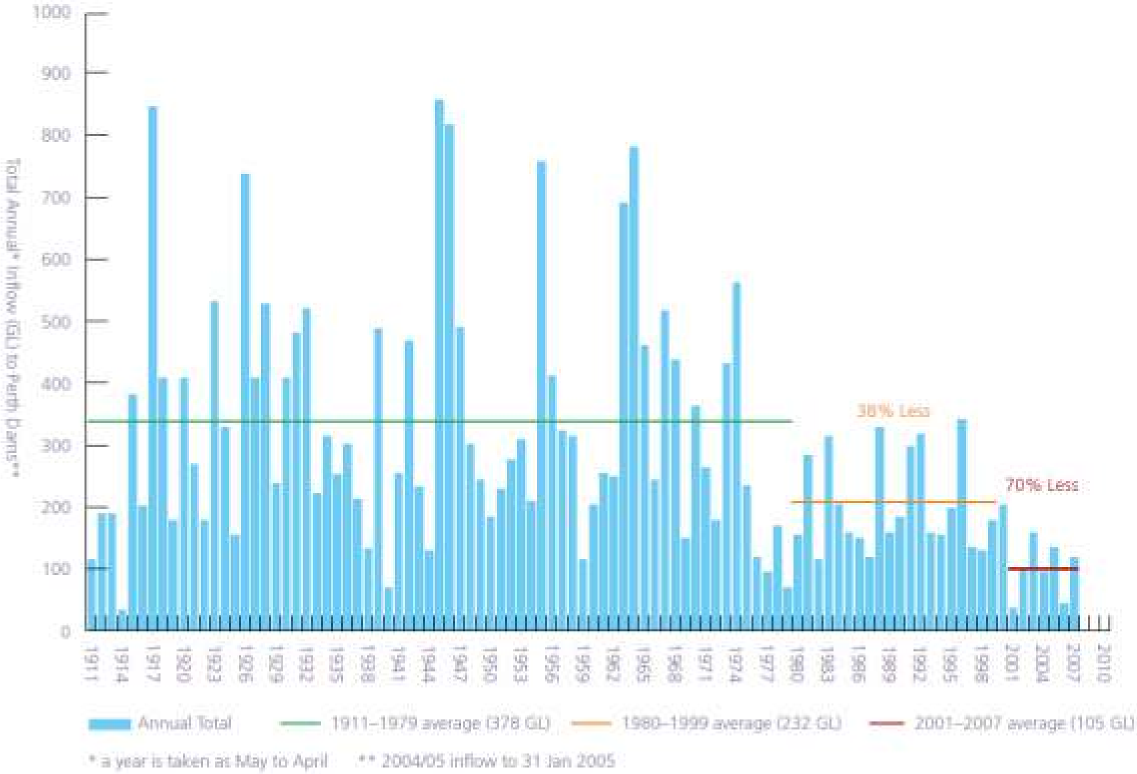
- **Figure 3-2 Trend in Annual Total Rainfall**



Literature discussing climate in the s**outh east region of Australia** has recognised a recent dry period, with reference to the shift beginning anywhere from 1990 to 1998. Kiem et al (2010) applied a statistical test to rainfall records across nine study sites and indentified 1994 as the first year of the current dry phase. The exceptions were the two far eastern stations, Buchan and Mitta Mitta (where 1996 was identified as the start of the dry phase) and Goulburn (where 1993 was identified). Chiew et al (2008) supported this, and showed that the 1997 to 2006 mean annual rainfall and the 1895 to 1996 long-term mean annual rainfall are significantly different for southern catchments including the Eastern Mount Lofty Ranges, Wimmera, Loddon, Avoca, Campaspe, Goulburn-Broken, Ovens, Murray and Murrumbidgee regions. Importantly, this corresponds to reduced streamflows. In Victoria, over the past decade, streamflows in the east of the State have typically been around 25-50% below average, and in the west of the State they have been more typically around 60-90% below the long term average (SEACI 2001). A number of studies have also recognised that the mid-1930s to mid-1940s were drier than average, while the mid-1940s to mid-1990s were wetter than average, which is believed to be linked to longer term climate cycles (Kiem et al. 2010). Streamflow gauges selected in this region should include at least 15 years of record post 1994 and 15 years of record prior to 1994. Ideally, records should also include 15 years of data representing the dry period of the 1930s and 1940s. Tasmania has exhibited a similar climate shift to that identified for the South Eastern region of mainland Australia. In general, the climate over the recent period (1997 to 2007) has been drier than that over the historical period (1924 to 2007) (Post et al. 2009).

In **south-west Western Australia** an earlier shift in climate was observed, with the period post 1975 significantly drier than the historical period (CSIRO 2009b). A major decline in rainfall was apparent in the mid 1970s, with another more recent shift in the late 1990s (IOCI 2009). The WaterCorporation has included this later shift in its water planning (WaterCorporation 2008). The magnitude of this shift for inflows into Perth's water supply dams is shown in Figure 3-3. Annual rainfall variability in this area has been correlated with variation in the Southern Oscillation Index, however the causes of longer term trends in the relationship between the Southern Oscillation Index and rainfall in south-west Western Australia are less clear. At least part of the shift in climate in south-west Western Australia has been attributed to climate change and some has been attributed to natural climate variability and the relative contribution of each is unknown (IOCI, 2002).

▪ **Figure 3-3 Yearly inflow to Perth's Dams including Southern Sources (WaterCorporation, 2008)**



A number of studies have examined the historical climate sequence from **Northern Australia** and found that rainfall since the mid-1960s is above average compared to the long term average (Jolly et al. 2007; SKM 2007b). The CSIRO (2009) report on sustainable yields in the Timor Sea Drainage Division found that recent years (back to 1996) have been slightly wetter than the historical record. However, the recent past does not exhibit the full range of climatic variability seen in the historical record. CSIRO suggested that for this region there is considerable risk in using only recent conditions to guide future water planning as a single very wet year can significantly bias the historical mean.

Information on the **arid region** of Australia was not available. Given the absence of long-term high quality streamflow data in this region and the absence of hydrologic studies on historical climate shift, no climate phases have been specified. Figure 3-2 suggests that climate trends have varied widely in this region, however changes in runoff are likely to be small because runoff is historically low anyway.

A summary of the recommended requirements for selecting high quality streamflow gauges which can represent all periods with climate shift is listed in Table 3-4.

Table 3-4 Requirements for streamflow gauges to ensure adequate representation of climate shifts

Region	Representation of Climate shifts
South East Australia	Include at least 15* years of data post 1994 Include at least 15 years of data between 1940 and 1994 Ideally, include 15 years of data prior to 1940
South West Australia	Include at least 15* years of data post 1996 Include at least 15 years of data between 1975 and 1996 Include at least 15 years of data prior to 1975
Northern Australia	Include at least 15 years of data post 1960 Include at least 15 years of data prior to 1960
Arid region	Include at least 15 years of data in any historical period

* or the length of the climate phase where the period of the climate phase is less than 15 years

3.8. Assessing representativeness

After applying rigid selection criteria to prepare a candidate list of high quality streamflow gauges, it is recommended that three checks should be undertaken on the data. The first is to plot daily flow duration curves and daily time series data and examine these plots for any anomalies. Typical anomalies include flow data with the same reading on consecutive days, which is a potential indicator of flow regulation or flow discharges, or atypical rates of rise or fall on flood hydrographs.

The second recommended check is to prepare double mass curves against other candidate high quality stations in the same area. This will help to identify any regional anomalies caused by historical climate or land use change. Double mass curves against climate data have not been recommended due to the lack of consistency in rainfall-runoff relationships in some catchments as part of natural catchment processes.

The third recommended check is for the Bureau to consult with State agency representatives to confirm that there have been no peculiarities at the selected high quality sites that would affect their use in subsequent applications. These could include industrial discharges over part of the flow record for industrial sites which have since been decommissioned, for example.

The literature review identified that previous studies generally initially applied rigid criteria for selecting high quality streamflow gauges, but then applied some flexibility if there were no available sites in certain areas or over certain periods of time. This is likely to occur in data poor parts of Australia. The guidelines include a step to relax selection criteria in specific river basins if needed to ensure that some datasets are available for seasonal or long-term forecasting.

The availability of companion datasets will help to define the usefulness of the particular high quality data set for specific purposes. It is recommended that the following metadata be associated with each site for reference purposes.

- **Table 3-5 General metadata**

Item	Comments and Definitions
High quality rainfall gauges located within catchment	A pointer to another Bureau high quality data product to encourage consistency in use of datasets
Gauge elevation (mAHD)	Can be an indicator of the presence of snowmelt or problems with icing of the gauge.

4. Proposed Guidelines

The process for selecting high quality streamflow gauging stations is proposed as follows. The order in which steps are undertaken may be varied and the process has been designed to try and minimise the effort required to classify sites. The option to adjust selection thresholds when applying these guidelines more widely can be undertaken if required. Other local selection criteria may be added where they can be demonstrated to affect the quality of streamflow data.

1) Identify all streamflow gauges within a river basin from the Bureau's water resources station catalogue at http://www.bom.gov.au/hydro/wrsc/. Extract information on the station number, river name, station name, latitude, longitude and catchment area. Where the catalogue identifies sites with duplicate numbers but a different suffix, separately list each site and suffix, because this may indicate a change in location of the site or a significant gap in the period of record at the site.
2) Check this list of gauges against state agency lists to ensure that all available streamflow gauges are covered. State agency lists include those on published registries such as the Victorian Data Warehouse, the NSW Pineena Database, the Water Information System of Tasmania. It is envisaged that this step will become redundant once the Bureau's water resources station catalogue contains all State and Territory information. Fill in any gaps about the period of record and catchment area of streamflow gauges where they are readily available from state agency lists.
3) **Exclude any sites clearly identifiable as drains, channels, outfalls, lakes or other non-river sites**. The flow recorded at drains, channels and outfalls will be a function of water management activities and will not be suitable for seasonal or long-term prediction. Data recorded in lakes, lagoons, dam intake towers, etc. will not contain streamflow data.
4) **Exclude any sites clearly identifiable as affected by tidal movement**. The flow recorded at these sites will be affected by tidal movements and will not represent streamflow generated from upstream catchments.
5) Identify the approximate period of record at each streamflow gauge from the Bureau's water resources station catalogue and state agency lists after excluding sites in previous steps above.
6) Identify the most downstream flow regulating structure upstream of the gauge. Major reservoirs can be identified from the ANCOLD register (http://www.ancold.org.au/content.asp?PID=10005), which also has the construction date of the reservoir. Other smaller flow regulating structures can be identified through local knowledge, state agency publications and topographic maps. Determine the area upstream of the structure and calculate the proportion of the gauged catchment that is regulated.
    a) If the area upstream of the structure is more than 10% of the gauged catchment area, then the site is considered regulated over the period for which the structure was in place.

b) For each site considered to be regulated, determine whether there is any data available prior to the construction of the structure or after its decommissioning by comparing these dates with the period of record from Step 5.

c) **Exclude any sites where all data at the site is considered to be regulated**.

d) Repeat the above steps a) to c) for subsequent upstream flow regulating structures if a site is subject to flow regulation from more than one structure. This only needs to be repeated for sites identified as potentially flow regulated at step a).

7) Estimate the mean annual flow at each streamflow gauge – This can be sourced from the data itself, if available at this stage of the assessment, or it may be sourced from previously published information.

8) Estimate the volume of any point source discharges upstream of the streamflow gauges – This includes wastewater treatment plants discharging to rivers, industrial discharges, any irrigation drains and any transfers to rivers from elsewhere as part of water management activities. A site is not considered suitable if the average annual volume of point source discharges upstream of the gauge is more than 10% of the mean annual flow. If annual volumes of discharge are low but there is considered to be a significant shift in the seasonality or low flow characteristics of streamflows due to the discharges, then this may also be justification for the exclusion of a site. **Exclude any sites where flow is considered to be impaired.**

9) Estimate the volume of diversion licences upstream of streamflow gauges. A site is not considered suitable if the average annual volume of licensed diversions upstream of the gauge is greater than 10% of the mean annual flow. Groundwater licences should be included in the total licensed diversions in areas where groundwater volumes are high and are considered to potentially deplete stream baseflows. **Exclude any sites where flow is considered to be impaired.**

10) Combine the data records of any duplicated streamflow gauges corresponding to a single site and note any changes in location for a given streamflow gauge which could create a discontinuity in the data.

11) Determine the proportion of missing data over the period of record. The proportion of missing data is based on an assessment of streamflow data quality codes in each jurisdiction shown in Table 4-1. **Only retain sites which have at least one continuous period of 15 years with not more than 5% of days with missing data**.

- **Table 4-1 Quality codes for missing data**

Jurisdiction	Missing data quality codes
Vic, NSW, SA, NT	> 150
Qld	> 125
Tas	> 30, except for codes 32 and 34, which were assumed to not be missing data
WA	> 4, except for codes 11 and 12, for which were considered missing if the level data has a quality code > 4.

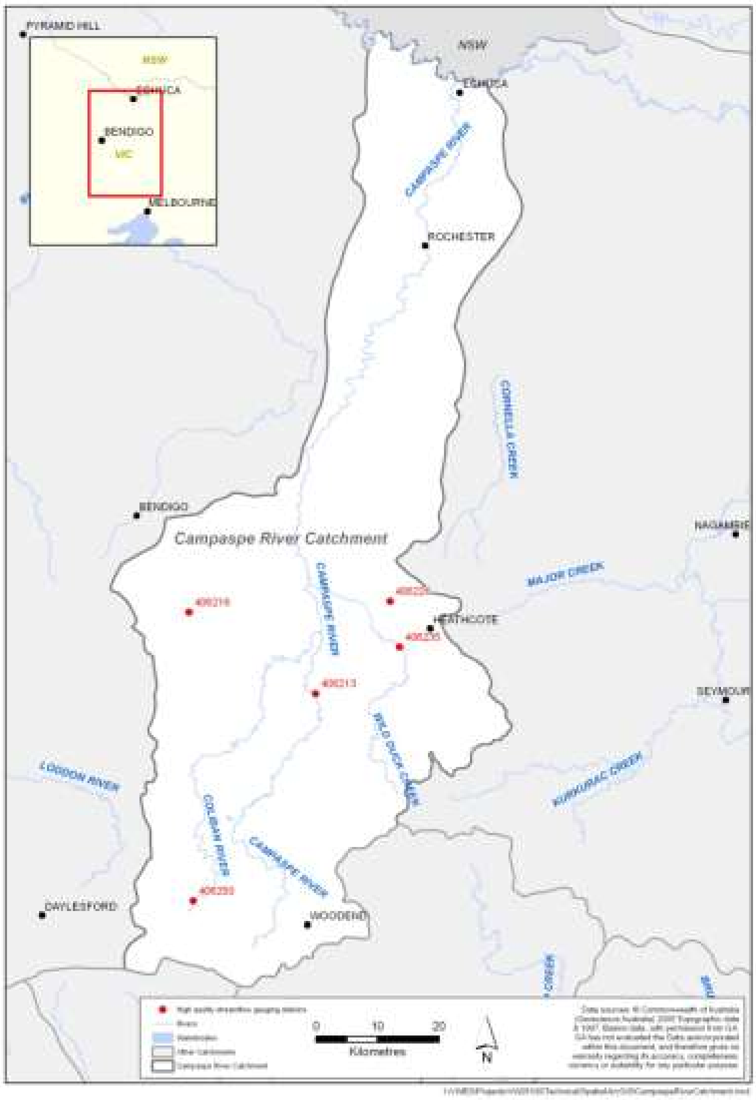
12) Determine the proportion of data above the highest gauged streamflow or below the lowest gauged streamflow. The highest and lowest gauged values can be obtained from rating tables and may vary over different parts of the flow record if rating table versions change over time. **Only retain sites which have not more than 20% of data outside of the range of gauged data**.
13) As an alternative to the previous step, calculate the uncertainty associated with all streamflow data collected at a site using Australian Standard ASA 3778.2.3. **Only retain sites which have not more than ±10% average uncertainty in flow data over the period of record**.
14) Collect and report on land use change data for each selected site. This includes the percentage of urban area over time, the percentage of forest cover over time, the volume of small catchment dams over time, the area of forest plantations over time, a list of historical bushfire events and a history of coops logged in the catchment. Coops are the named areas logged at any given time. Consider excluding sites subject to significant land use change, particularly for long-term climate change investigations.
15) Check the spatial and temporal representativeness of high quality streamflow sites and consider relaxing the constraints if needed to be able to identify a site with slightly lesser quality but with the potential to become a high quality site in the future. Assign a climate region and classify sites according to whether they have at least 15 years of data with not more than 5% missing in each climate phase. Check the list against those used in previous studies.
16) Plot a daily flow-duration curve for each site over each climate period and visually inspect a plot of the daily time series data to ensure that there are no data anomalies or unusual flow patterns which are potential indicators of poor quality data. Also prepare double mass curves of streamflow relative to other candidate high quality streamflow sites in the same region. This step should be undertaken by an experienced hydrologist.
17) Present the list of selected high quality sites to a State agency representative to ensure that there are no other factors influencing the streamflow data at these sites which could cause them to be considered not high quality.
18) Document other supporting information, such as preparing a catchment map, identifying any high quality rainfall sites located within the catchment and presenting the elevation of the gauge.

5. Case Studies

5.1. Campaspe River, Victoria

This section of the report presents the outcome of the application of the guidelines at each step for the Campaspe River Basin. The Campaspe River is a tributary of the River Murray in northern Victoria. It is part of the Murray-Darling Drainage Division. It includes several major flow regulating structures which supply both rural and urban users. There is significant irrigation in the vicinity of Rochester and private diverters downstream of Lake Eppalock. The majority of the catchment is cleared of native vegetation. A map of the catchment is shown in Figure 5-1.

- **Figure 5-1 Campaspe River Catchment**



The steps involved in assessing streamflow data in the Campaspe River basin are outlined as follows:

1) *Identify all streamflow gauges* - A total of 57 streamflow gauges were listed for the Campaspe River catchment on the Bureau's water resource station catalogue. One site was excluded because it was named as being on the River Murray and did not have an associated stream gauging station number.
2) *Check against state agency lists* - A further 5 sites were identified on the Victorian Data Warehouse, a further 9 sites were identified in RWC (1990) and a further 6 sites were identified in SRWSC (1984), resulting in a total of 76 streamflow gauges identified for the Campaspe River Basin. No additional sites were identified in SRWSC (1971). A number of queries are available in the data warehouse. The query used for this project was Standard Warehouse Reports → Catchment and Basin Reports → Select Streamflows by Basin.
3) *Exclude any sites clearly identifiable as drains, channels, outfalls, lakes or other non-river sites* – This included 29 sites in the Campaspe River basin, leaving a remaining list of 47 sites. These 29 sites were mainly located in the Campaspe Irrigation District and drains/channels outfalling directly into the River Murray. Two sites on Sheepwash Creek were excluded because a spur of the Emu Valley No. 1 Channel in the Coliban system was located directly upstream of these sites. The Woodend water treatment plant outfall was also excluded.
4) *Exclude any sites clearly identifiable as affected by tidal movement* – no sites in the Campaspe River basin are affected by tidal movement. Some sites may be affected by backwater from the River Murray, however this is assessed in subsequent steps.
5) *Identify the approximate period of record* – there were some differences in the periods of record reported in the Bureau's water resource station catalogue and the State agency sources, so both sources were used and the maximum periods of record was adopted for assessing flow regulation. For example, for the site 406214 Axe Creek at Longlea, the Bureau's water resource station catalogue notes the data as commencing from January 1965 for site 406214B, but does not include the period of record for site 406214A, which commenced in 1933.
6) *Identify the most downstream flow regulating structure upstream of the gauge* – Five structures were identified on the ANCOLD register in the Campaspe River Basin and are listed in Table 5-1. A total of 15 sites were considered to be regulated due to the most downstream structure upstream of the gauge and a further 5 sites were excluded because they had data available prior to Lake Eppalock being constructed, but not prior to Malmsbury Reservoir being constructed further upstream. A total of 26 sites remained after checking for flow regulation.

- **Table 5-1 Flow regulating structures in the Campaspe River Basin**

Storage Name	Capacity (GL)	Construction Date	Decommission Date	Area upstream of structure (km^2)
Lake Eppalock	312	1964	N/a	2028
Campaspe Weir	2.7	1892	N/a	3269
Malmsbury Reservoir	18	1870	N/a	306
Upper Coliban Reservoir	37.5	1903	N/a	193
Lauriston Reservoir	20	1941	N/a	219

A check was undertaken to see the extent to which the sites designated as regulated in the water resource station catalogue (denoted as “f” in the is_regulated field) correlated with sites identified as regulated in the above analysis. A total of 6 sites were not regulated in both analyses and 3 sites were regulated in both analyses. A total of 11 sites showed inconsistencies between the outcomes of the two analyses. For the sites that were inconsistently classified, the water resource station catalogue reported these sites as regulated, whilst the analysis in this project concluded that these sites were not regulated for at least part of the their flow record. In the water resource station catalogue there were also some internal inconsistencies, for example, with site 406224A (Mount Pleasant Creek at Runnymede) being reported as regulated and site 406224 being reported as not regulated, even though they are at the same location. Through inspection of aerial imagery there do not appear to be any flow regulating structures on this tributary of the Campaspe River. For this reason it is recommended that this field in the water resource station catalogue should not be used to classify high quality streamflow gauges.

7) *Estimate the mean annual flow at each streamflow gauge* – For this case study, mean annual flow information was sourced from the Sustainable Diversion Limit viewer (SKM et al. 2002), which previously presented mean annual flow data for catchments across Victoria.
8) *Estimate the volume of point source discharges* – The volume of wastewater discharged to the Campaspe River was sourced from the Victorian Water Accounts for the years 2007 and 2008 (DSE 2010). The only treatment plant which currently discharges to rivers in the Campaspe River basin is the Kyneton treatment plant, which discharges some of its water to the Campaspe River. This discharge affected several of the remaining streamflow gauges, however the volume of the discharge is very small relative to the flow in the Campaspe River and was not considered to be of sufficient volume to exclude these gauges from the list of candidate sites. The Campaspe River also receives transfers from the Waranga Western Channel in its lower reaches, however this did not affect any remaining sites.
9) *Estimate the volume of diversion licences* – The volume of diversion licences was sourced from the Sustainable Diversion Limit viewer (SKM et al. 2002). A total of 10 sites were excluded due to a volume of diversion licences greater than 10% of the mean annual flow.

These included sites on Axe Creek (17-21%) and Mount Pleasant Creek (12%). Remaining sites on the Campaspe and Coliban Rivers below flow regulating structures but with data which existed prior to those structures being built were also excluded. The current volume of licences is 33-50% of the mean annual flow at these sites. The volume of diversions over the period prior to flow regulation is unknown, but is still likely to have been high on these major streams. The number of sites remaining at this stage of the analysis was 16.

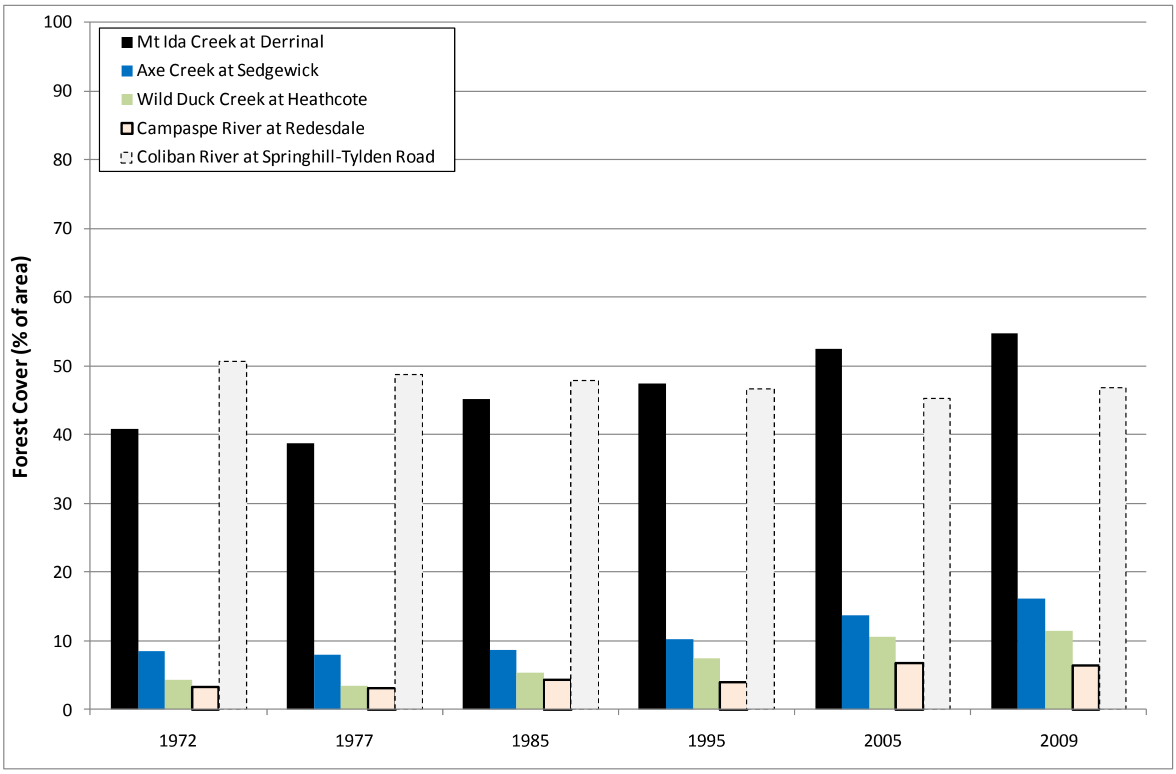
10) *Combine the data records for duplicated streamflow gauges* – Data at the two sites on the Campaspe River at Redesdale (406213 and 406213 C) were amalgamated, as was data at the two sites on Wild Duck Creek at Heathcote (406235 and 406235A). Site locations were assessed and deemed to be consistent for the period of record for each gauge (i.e. not upstream and downstream of an inflow). The number of sites remaining at this stage of the analysis was 14.
11) *Determine the proportion of missing data* – Quality codes and flow data were assessed at each site. For codes greater than 150, data was considered to be missing and therefore did not contribute to the continuous period of data. Quality codes were also assessed to ensure that at least 1 period of 15 years of good quality data existed with less than 5% of missing days. Flow data could not be obtained for 4 sites to undertake the missing data analysis (406254, 406257, 406259, 406260). These sites were assigned 100% missing data as the data could not be obtained. The three sites on Five Mile Creek had a minimum period of missing data over a 15 year period of 23-91%. Only five sites remained after this step.
12) *Determine proportion of data outside the gauging limits* – Gauging information was requested from the Department of Sustainability and Environment but was not forthcoming. Historic maximum and minimum gauged flows up to 1987 were obtained from RWC (1990) for the purposes of the case study only to provide an indication of the effect of applying this step of the guidelines. It was found that all sites had sufficient high flow gaugings. A number of the sites ceased to flow and a high proportion of the data was below the minimum gauged flow because cease to flow events had not been gauged. It was assumed for the case study that if the minimum gauged stage height was close to zero, then the level of extrapolation on the rating curve is small and the site should not be excluded. No sites were excluded at this stage of the analysis.
13) *Uncertainty associated with streamflow data collected* – Rating table information was requested from the Department of Sustainability and Environment but was not forthcoming, therefore this analysis could not be undertaken for the case study.
14) *Report on land use change* – Information on land use and land use change is presented below. Table 5-2 shows that the current urban area in the five candidate catchments is low, hence any historical changes in urbanisation are expected to be small.

Table 5-2 Urban area

Site number	Site name	Current urban area as a % of total catchment area
406213	Campaspe River at Redesdale	2%
406216	Axe Creek at Sedgewick	1%
406226	Mt Ida Creek at Derrinal	5%
406235	Wild Duck Creek at Heathcote	1%
406250	Coliban River at Springhill–Tylden Road	6%

Forest cover is highest in the Mt Ida Creek and Coliban River catchments, as shown in Figure 5-2. Over time, forest cover has increased for four of the five candidate streamflow gauges, however the changes are relatively small. The percentage of forest cover by area increased from 41% to 55% in the Mount Ida Creek catchment. The reason for this increase is unknown and would require further investigation.

Figure 5-2 Change in forest cover over time



Historical information on farm dam capacity is not available. The approximate current farm dam capacity from the SDL Viewer (SKM et al. 2002) is shown in Table 5-3, which indicates that for three of the sites, the capacity of farm dams is greater than 10% of the mean annual flow. This

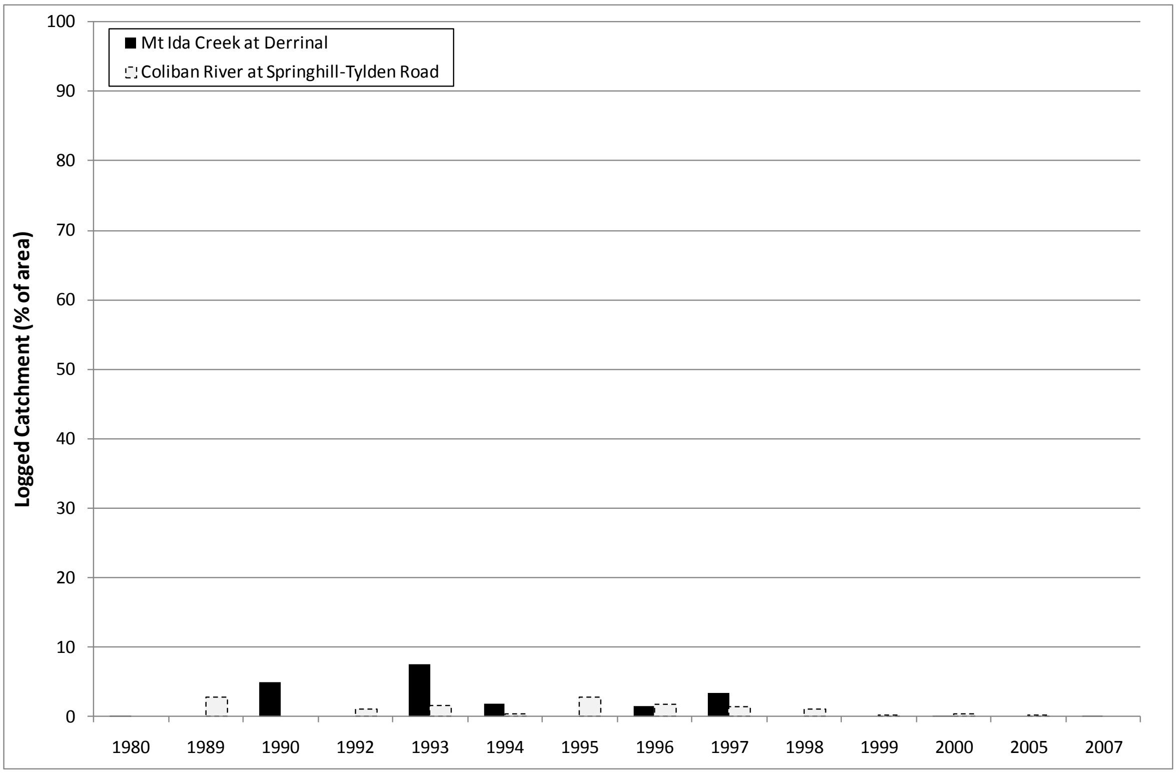
highlights the potential for historical changes in farm dam capacity to significantly alter hydrology in these catchments.

Table 5-3 Farm dam capacity

Site number	Site name	Current farm dam capacity	
		ML	% of mean annual flow
406213	Campaspe River at Redesdale	7,525	11.2%
406216	Axe Creek at Sedgewick	406	10.0%
406226	Mt Ida Creek at Derrinal	1,889	13.6%
406235	Wild Duck Creek at Heathcote	1,395	5.8%
406250	Coliban River at Springhill–Tylden Road	2,092	8.9%

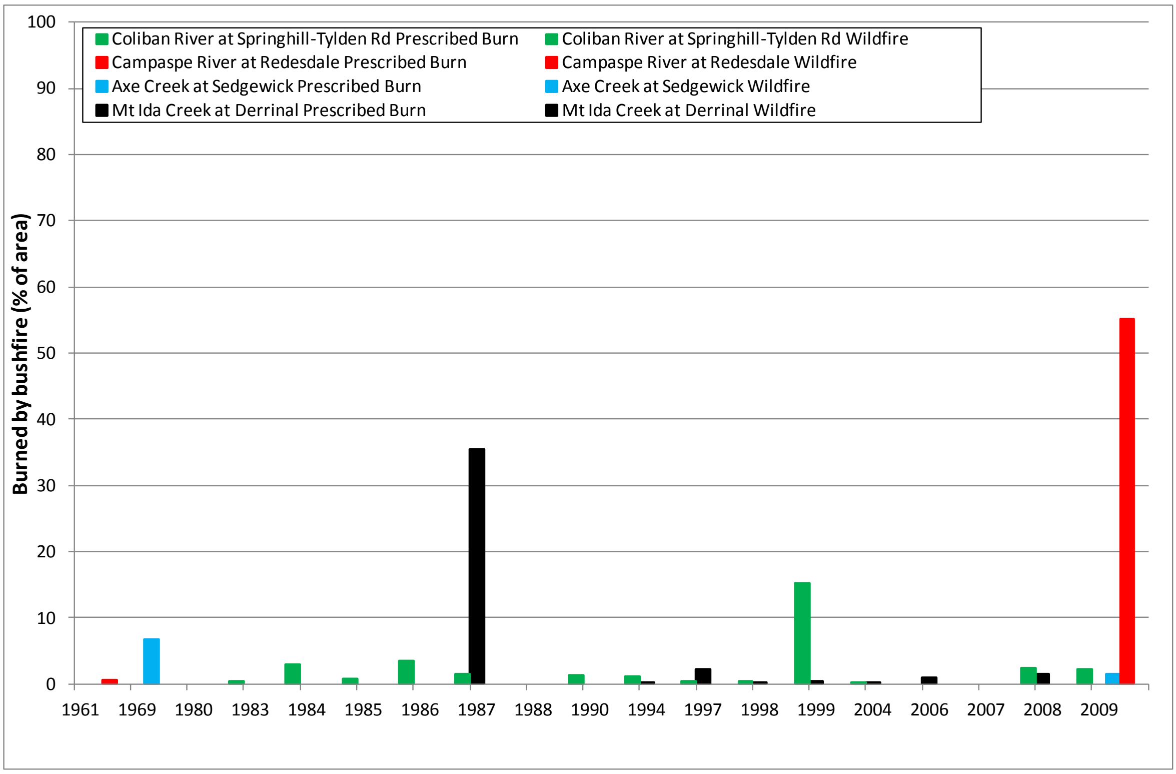
The extent of logging in the five candidate catchments is relatively small, with logging only occurring in the Mt Ida Creek and Coliban River catchments. Less than 10% by area was logged in any one year for these two catchments, as shown in Figure 5-3, with no significant changes in area logged over time. Logging in the Axe Creek catchment, which is not shown in Figure 5-3, was only recorded in 1964, when only 0.2% of the catchment area was logged.

Figure 5-3 Change in logged area over time



Parts of the Campaspe River basin were burnt in historical bushfires, as shown in Figure 5-4. Bushfires affected typically less than 5% of the total catchment area, particularly for all prescribed burns. Significant wildfires occurred in the Mount Ida Creek catchment in 1987, the Coliban River catchment in 1998 and the Campaspe River catchment in 2009. For the Campaspe River upstream of Redesdale, average annual streamflow is around 107 mm/yr, so a typical peak increase in runoff after bushfire of around 170 mm/yr and a peak reduction of 40 mm/yr could create significant non-stationarity in the streamflow data over time. A double mass curve is presented in Figure 5-7, which highlights a change in catchment yield in Mt Ida Creek relative to the Campaspe River in the mid 1980s, however the timing of the short-term increase in runoff is around 12-24 months earlier than the recorded bushfire event. The historical effect of this bushfire event on the Mount Ida Creek catchment would warrant further investigation, particularly in relation to the precise timing of the fire. An increase in yield is evident in the Coliban River gauge relative to the Campaspe River following the 1998 bushfire in the Campaspe River catchment.

- **Figure 5-4 Historical bushfire events over time**



15) *Spatial and Temporal representativeness* – The period of record of the selected gauges is listed in Table 5-4. This shows that all selected gauges have a long record with minimal missing data in the most recent climate phase. In the climate phase from 1940 to 1994, only two sites had data with less than 5% missing over a 15 year period. The site on Wild Duck Creek had

9% missing and could be considered for some applications by the Bureau if more data from this period is needed. No sites had data in the pre-1940 period. Whilst no data exists prior to 1940, the availability of data in the two more recent climate phases indicates that the data provides good temporal representation across the Campaspe River Basin.

The catchments are located on five different tributaries and range in catchment area from 34 km^2 to 629 km^2. It includes sites in both the southern and mid latitudes of the catchment. The elevation of sites ranged from 200 m to greater than 250 m and includes two catchments which drain from the Great Dividing Range. These catchments are therefore considered to provide good spatial representation across the Campaspe River Basin.

From the five selected catchments, sites 406213, 406235 and 406250 had been used in previous regional hydrologic studies (Nathan et al. 1993; SKM 2002a; SKM 2003).

Table 5-4 Period of record and availability of data in different climate phases

Site number	Site name	Catchment Area (km^2)	Period of record	Availability of > 15 years of data with < 5% missing		
				Pre-1940	1940-1994	Post-1994
406213	Campaspe River at Redesdale	629	1953-2009	No	Yes	Yes
406216	Axe Creek at Sedgewick	34	1975-2010	No	No	Yes
406226	Mt Ida Creek at Derrinal	174	1978-2009	No	Yes	Yes
406235	Wild Duck Creek at Heathcote	214	1980-2009	No	No*	Yes
406250	Coliban River at Springhill–Tylden Road	78	1983-2009	No	No	Yes

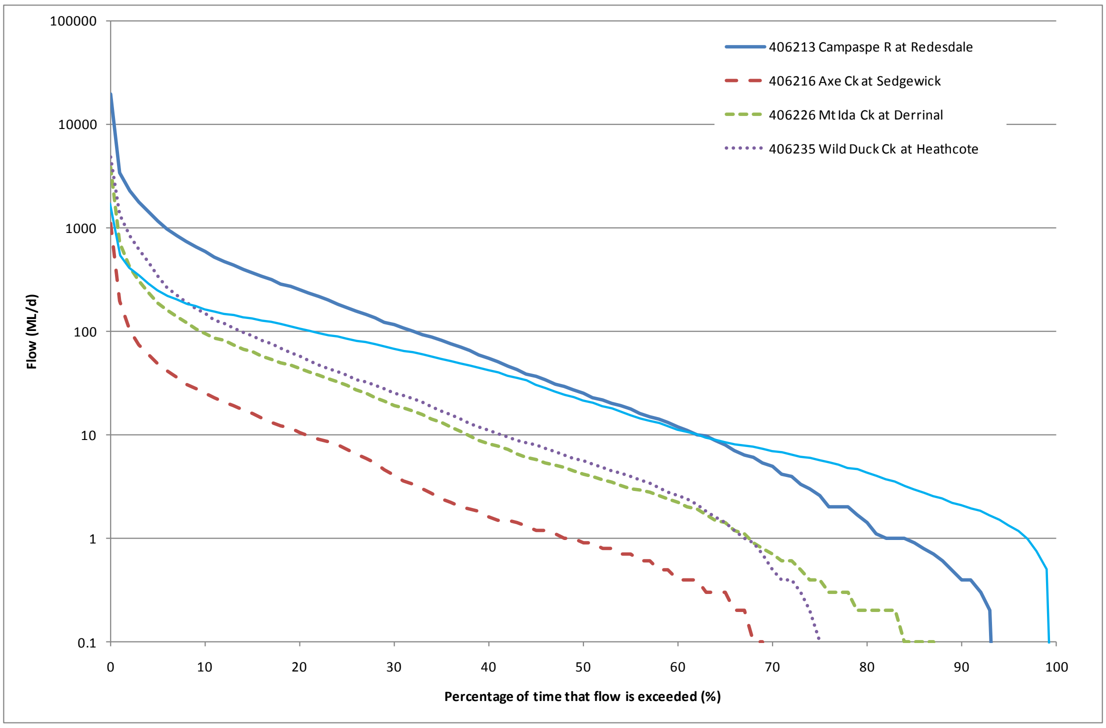
*minimum of 9% missing over a 15 year period in this climate phase at this site

16) *Plot daily flow duration curves and double mass curves* – Flow duration curves for each site are shown in Figure 5-5 for the climate period up to the end of June 1994 and in Figure 5-6 for the climate period from July 1994 onwards. Whilst there is some rounding of flow data at flows below 1 ML/d, there is no clear evidence of non-natural patterns of flow behaviour such as periods of sustained low flows. In addition to the previous analysis at Step 6, a topographic map of the site on Coliban River was checked to ensure that there are no flow regulating structures above this site. The flow-duration curves for the post-1994 climate period illustrate that this period was drier than the pre-1994 period. Interestingly the proportion of time with cease to flow conditions remained the same for the site on Axe Creek in both climate periods.

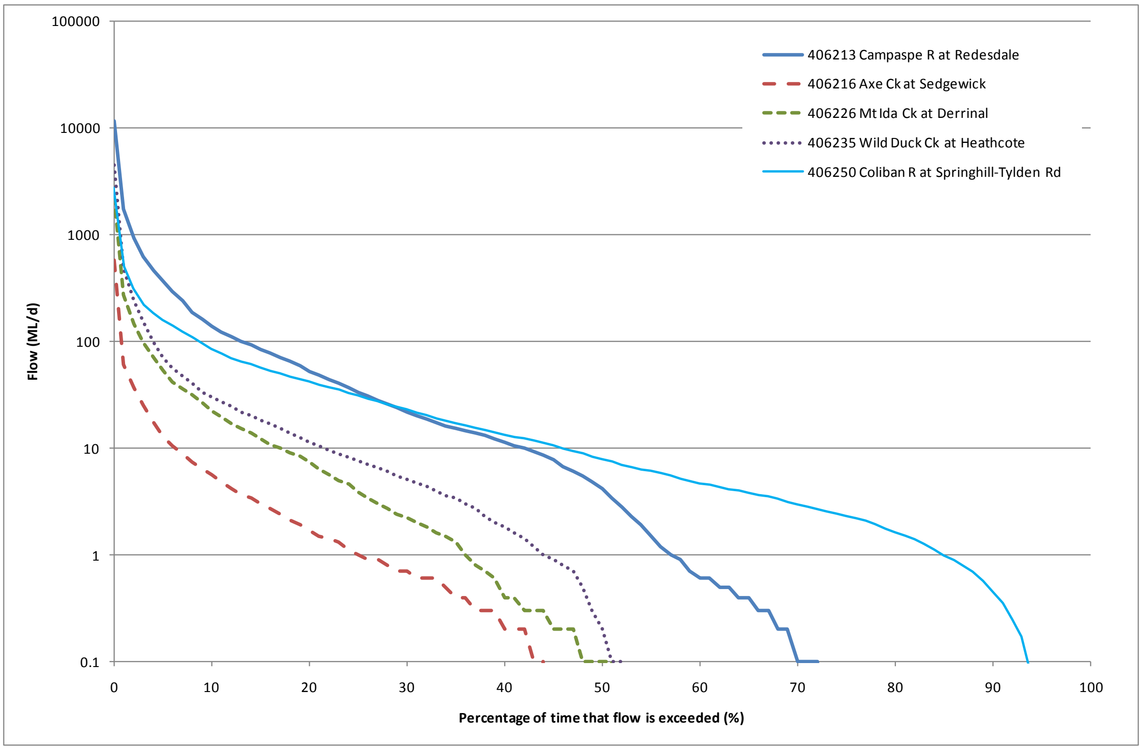
Data from gauges 406216, 406226 and 406235 show a reasonable degree of stationarity when plotted as double mass curves against data from gauge 406213. Data from gauge 406250 (Coliban River) shows a change in slope at around September 1996, which potentially suggests that the streamflow response at this site in the post-1994 drier climate phase is

different to the other sites. This is consistent with the observation in Figure 5-5 that baseflow is more sustained at site 406250 in the Coliban River catchment, because baseflow decline would be expected to lag runoff decline due to climate change and may not be evident yet. This effect is likely to have been exacerbated by the occurrence of a bushfire in the Coliban River catchment in 1998. There is around 6 years of data missing for gauge 406216 on Axe Creek between November 1982 and November 1988. This has been omitted for plotting purposes, with an estimated cumulative flow used for the point at which the data resumes.

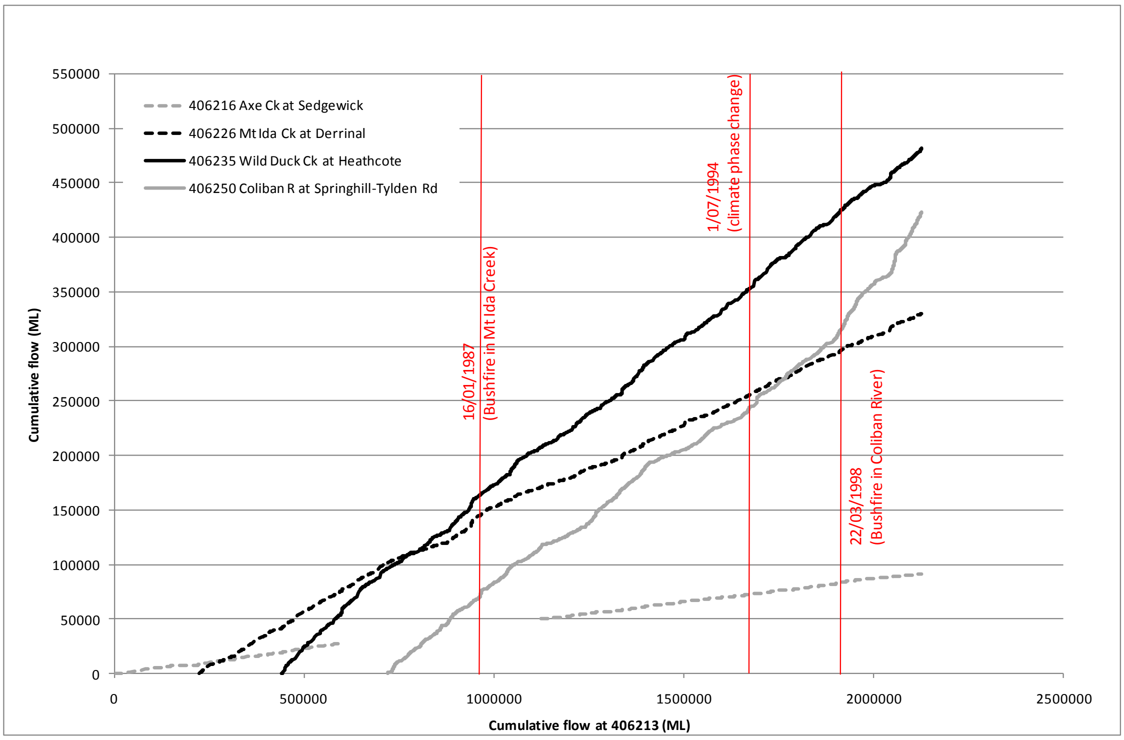
- **Figure 5-5 Flow duration curves prior to 1 July 1994**



■ **Figure 5-6 Flow duration curves post 30 June 1994**



■ **Figure 5-7 Double mass curves against site 406213 Campaspe R at Redesdale**



17) *Present the list of sites to State agency representatives* – For the case studies, this step has not been undertaken.

18) *Other supporting information* - There are no high quality rainfall stations within the Campaspe River catchment. The nearest high quality rainfall stations are 088060 Wallaby Ck Weir, 086117 Toorourong and 086131 Yan Yean, all of which are south of the Great Dividing Range, around 80 km south-east of Heathcote. Elevation data was previously presented at Step 15.

5.2. Summary of Campaspe River case study outcomes

In summary, **five streamflow gauges were selected as high quality streamflow gauges in the Campaspe River basin suitable for seasonal forecasting**. These are:

- 406213 Campaspe River at Redesdale;
- 406216 Axe Creek at Sedgewick;
- 406226 Mt Ida Creek at Derrinal;
- 406235 Wild Duck Creek at Heathcote; and
- 406250 Coliban River at Springhill-Tylden Road

These sites are considered to provide good spatial and temporal representation of streamflow data in the Campaspe River basin. All of the data at these streamflow gauges are affected by a high proportion of small catchment dams in the catchments upstream of the gauges. Significant wildfires occurred in the Mount Ida Creek catchment in 1987, the Coliban River catchment in 1998 and the Campaspe River catchment in 2009. For the 1987 and 1998 fire events, changes in streamflow relative to the Campaspe River gauge are evident, although the timing of the yield response in the Mount Ida Creek catchment appears to occur 12-24 months earlier than the recorded bushfire event and would warrant further investigation.

Two streamflow gauges were selected as high quality streamflow gauges in the Campaspe River basin suitable for long-term climate change investigations because they include at least 15 years of good quality data from two climate phases. These were the site on the Campaspe River and the site on Mt Ida Creek. The use of these two sites is subject to the same limitations in relation to land use change discussed above, particularly with regard to past bushfires.

Whilst there was insufficient data at gauge 406250 on the Coliban River to be regarded as high quality in the pre-1994 climate phase, the data at this site shows a change in slope at around September 1996, which potentially suggests that its streamflow response in the post-1994 drier climate phase is different to the other sites. This is consistent with the observation that baseflow is

more sustained in the Coliban River catchment, because baseflow decline would be expected to lag runoff decline due to climate change and may not be evident yet. This relative increase in yield is likely to have been exacerbated by the occurrence of a bushfire in the Coliban River catchment in 1998.

5.3. Adelaide River, Northern Territory

This section of the report presents the outcome of the application of the guidelines at each step for the Adelaide River Basin. The Adelaide River is located east of Darwin in the Timor Sea Drainage Division and covers an area of around 7,500 km^2. The river drains directly to the Timor Sea. The river and its tributaries are mostly unregulated. A map of the catchment is shown in Figure 5-8.

- **Figure 5-8 Adelaide River Catchment**

The steps involved in assessing streamflow data in the Adelaide River basin are outlined as follows:

1) *Identify all streamflow gauges* - A total of 51 streamflow gauges were listed for the Adelaide River catchment on the Bureau's water resource station catalogue. The downloadable csv file of the list of sites did not contain any data for this river basin.
2) *Check against State agency lists* – NRETAS previously provided a list of available streamflow data in the Adelaide River Basin for SKM (2008g). This list included 103 sites, however of these only 18 sites had both available data and a rating table. All of these 18 sites were included in the Bureau's water resource station catalogue.
3) *Exclude any sites clearly identifiable as drains, channels, outfalls, lakes or other non-river sites* – This included 4 sites in the Adelaide River basin, leaving a remaining list of 47 sites. These 4 sites included Beatrice Lagoon, the Manton Dam inlet tower, Harrison Dam and Lake Finniss.
4) *Exclude any sites clearly identifiable as affected by tidal movement* – This included 3 sites on the lower Adelaide River at Middle Point, Beatrice Hill and Arnhem Highway, which were described as tide gauges. Any gauges on the Adelaide River with a latitude further north than these three gauges (latitude less than -12.658 degrees) were also considered to be affected by tidal movement, which included a further 5 sites. Other streams with a latitude further north than these gauges were not excluded, except for one site described as "salt arm" on the Adelaide River plains. A total of 38 sites remained after excluding sites known to be affected by tidal movement.
5) *Identify the approximate period of record* –the Bureau's water resource station catalogue and NRETAS data generally aligned. One exception was site G8170008 on the Adelaide River 8 km downstream of Daly Road, which the catalogue listed as ceasing in 1993 but NRETAS had data extending to 2008.
6) *Identify the most downstream flow regulating structure upstream of the gauge* – One structure (Manton Dam) was identified on the ANCOLD register and is listed in Table 5-5. Manton Dam provided urban water supply to Darwin from 1942 until the Darwin River Dam was constructed in 1972 in the adjacent Finniss River Basin. The dam is still in place but is only used for recreational purposes. Only one site was excluded because of the effect of Manton Dam, namely Manton River at Acacia Gap (G817033). A number of smaller reservoirs are located in the basin which are not large enough to be registered on ANCOLD. These include Lake Bennett in the upper part of the catchment and a number of dams and lagoons on the Adelaide River plains. None of these smaller dams are considered to significantly affect streamflows at the candidate streamflow gauge locations.

- **Table 5-5 Flow regulating structures in the Adelaide River Basin**

Storage Name	Capacity (GL)	Construction Date	Decommission Date	Area upstream of structure (km^2)
Manton Dam	15.9	1942	N/a	81

A check to see the extent to which the sites designated as regulated in the water resource station catalogue (denoted as "f" in the is_regulated field) correlated with sites identified as regulated in the above analysis could not be undertaken because the data downloaded from the catalogue had not been populated for this river basin.

7) *Estimate the mean annual flow at each streamflow gauge* – For this case study, mean annual flow information was sourced directly from the data. Mean annual flow could only be calculated for 17 sites due to the absence of recorded flow data the other sites. Five of these sites had been eliminated for reasons above, leaving 12 remaining sites.

8) *Estimate the volume of point source discharges* – No point source discharges were identified in the Australian Natural Resources Atlas (http://www.anra.gov.au) or the Australian Water Resources Assessment 2005 (http://www.water.gov.au). According to NT Power and Water's website, sewerage services are provided at the townships of Adelaide River and Acacia Gap, however both of these towns are small and would not generate significant volumes of water if discharged to local rivers.

9) *Estimate the volume of diversion licences* – The estimated water consumption for the whole of the Adelaide River basin from all water sources (surface and groundwater) was 4,155 ML/yr in 2005 in the Australian Water Resources Assessment 2005. The majority of this water was used for agriculture, which from land use maps appears to be distributed across the Adelaide River catchment. The distribution of diversions was not identified for the case study. The mean annual flow in the Adelaide River at upstream of Marakai Crossing (G8170005) is approximately 507 GL/yr, which indicates that if diversions are distributed evenly across the catchment upstream of this location, then diversions would be less than 1% of the mean annual flow.

10) *Combine the data records for duplicated streamflow gauges* – No sites had duplicated data records.

11) *Determine the proportion of missing data* – Quality codes and flow data were assessed at each site. For codes greater than 150, data was considered to be missing and therefore did not contribute to the continuous period of data. Quality codes were also assessed to ensure that at least 1 period of 15 years of good quality data existed with less than 5% of missing days. Most sites had very little continuous data. Only two sites had less than 5% missing data over a 15 year period. These sites were Adelaide River at Railway Bridge (G8170002) and Coomalie

Creek at Stuart Hwy (G8170066). Two further sites had less than 10% missing data over a 15 year period and were retained in the analysis to endeavour to preserve some spatial representativeness in the data. These sites were Manton River upstream of Manton Dam (G8170075) and Adelaide River at Tortilla Flats (G8170084). All other sites had significantly more than 10% missing over any 15 year period.

12) *Determine proportion of data outside the gauging limits* – Gauging information was provided by NRETAS. It was found that all sites had sufficient low flow gaugings. For high flow data, the proportion of the dataset above the maximum gauged flow ranged from 3-17%. No sites were excluded at this stage of the analysis.

13) *Uncertainty associated with streamflow data collected* – Adelaide River at Railway Bridge (G8170002) was selected as a representative site to undertake an uncertainty analysis. This site has 3 rating tables that are relevant over the period of available flow data. The average uncertainty (flow weighted) for this gauge over its whole period of record was estimated to be 21%, which is outside of the range recommended in the guidelines of ±10%. This is not unexpected, as uncertainty is expected to be higher in tropical northern Australia relative to the available reference studies of uncertainty in southern Australia. Uncertainty was estimated to have reduced in this gauge over time, with most recent flows being the most reliable. It should be noted that this analysis has used some segments with less than 20 gaugings, which is fewer than that recommended in the Australian Standard. This uncertainty analysis highlighted that results are very sensitive to the delineation of rating table segments and the distribution of gaugings within those segments. Plots of the uncertainty expected for different flow ranges is presented in Appendix B for each rating table.

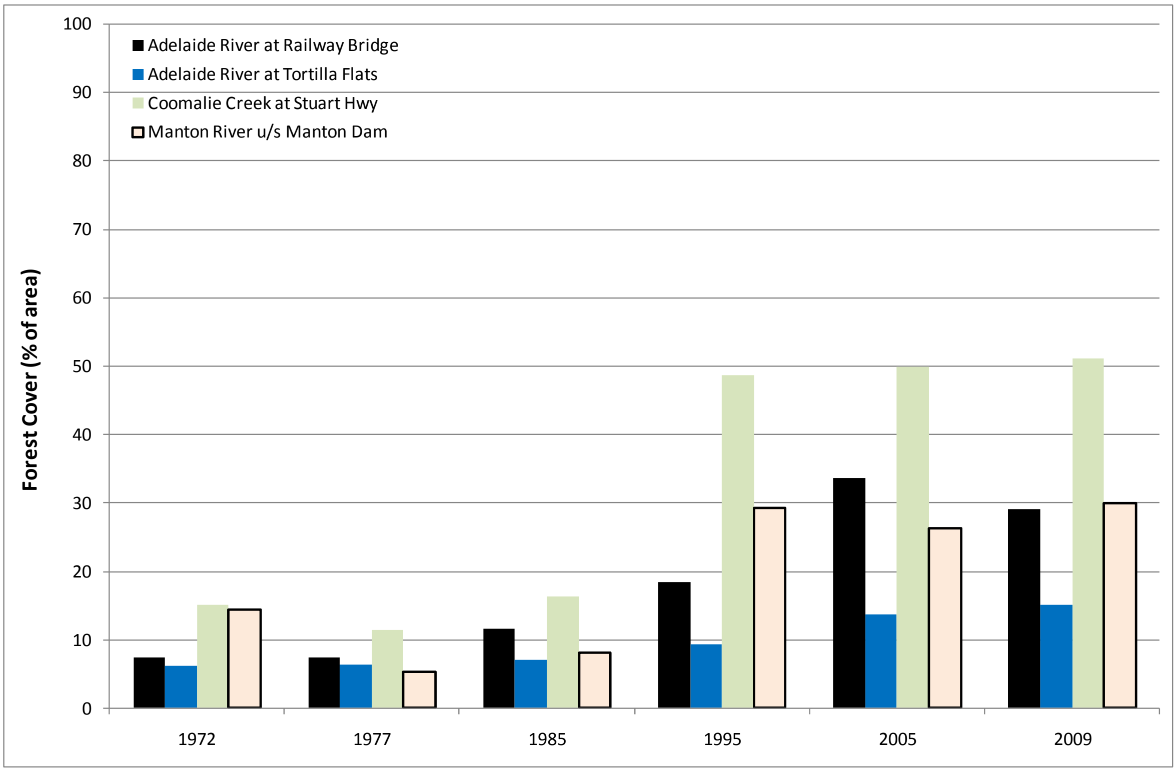
14) *Report on land use change* – Information on land use and land use change is presented below. There is currently no urban area upstream of each of the four candidate high quality sites, as shown in Table 5-6, hence any historical changes in urbanisation are expected to be negligible.

- **Table 5-6 Change in urban area over time**

Site number	Site name	Current urban area as a % of total catchment area
G8170002	Adelaide River at Railway Bridge	0%
G8170066	Coomalie Creek at Stuart Hwy	0%
G8170075	Manton River u/s Manton Dam	0%
G8170084	Adelaide River at Tortilla Flats	0%

Forest cover is highest in the Coomalie Creek catchment. Over time, forest cover is increasing at each gauge, as shown in Figure 5-9. The reasons for this are unclear and may reflect the method of data collection rather than a change in forest cover. This would warrant further investigation.

Figure 5-9 Change in forest cover over time



Historical information on small catchment dam (farm dam) capacity is not available, although it is understood that given the relatively low slopes and high evaporation rates, small catchment dams are not a popular form of water storage in the Northern Territory. A visual inspection of aerial imagery indicated that there was not a high prevalence of small catchment dams in the study area.

According to the Northern Territory Fire and Rescue Service (undated), bushfires are a ubiquitous feature of the Northern Territory dry season, with the territory having the most frequent, largest and most poorly documented vegetation fires of any part of the continent. In the higher rainfall savanna woodlands of the northern Kimberley, the Top End and Cape York up to half of the total area may be burned either every year or every second year. The area burnt is not mapped because of the prevalence of fires, rather the change in forest cover reflects any changes in area burnt from year to year.

15) *Spatial and Temporal representativeness* – The period of record of the selected gauges is listed in Table 5-7. This shows that all selected gauges have a long record with minimal missing data in the most recent climate phase. In the climate phase prior to 1960, there was very little data available and no sites had 15 years of data with less than 5% missing. Whilst no data

exists prior to 1953, the availability of data in the most recent climate phase indicates that the data provides good temporal representation across the Adelaide River Basin.

The gauges are located on five different tributaries and range in upstream catchment area from 28 km^2 to 1246 km^2. It includes sites in both the southern and mid latitudes of the catchment. The elevation of sites ranged from 28 m to 69 m, and whilst this difference in elevation is low, it should be recognised that the Adelaide River catchment is not characterised by high mountain ranges at its watershed boundary. These catchments are therefore considered to provide good spatial representation across the Adelaide River Basin.

From the four selected catchments, the sites on the Adelaide River at Tortilla Flats and the Coomalie Creek site had been used in previous regional hydrologic studies (SKM 2009a; SKM 2009b).

- **Table 5-7 Period of record and availability of data in different climate phases**

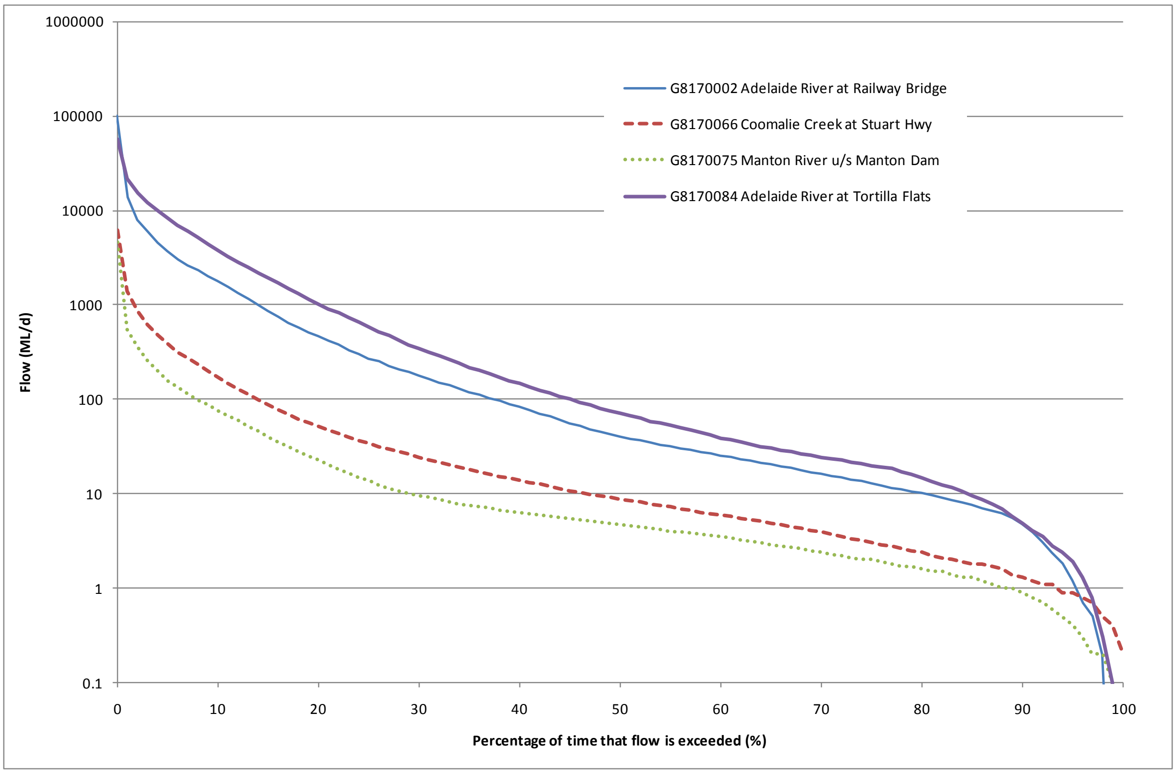
Site number	Site name	Catchment Area (km^2)	Period of record	Availability of > 15 years of data with < 10%# missing	
				Pre-1960*	Post-1960
G8170002	Adelaide River at Railway Bridge	632	1953-2007	No	Yes
G8170066	Coomalie Creek at Stuart Hwy	82	1958-2008	No	Yes
G8170075	Manton River u/s Manton Dam	28	1965-2007	No	Yes
G8170084	Adelaide River at Tortilla Flats	1246	1958-2007	No	Yes

*assessed from 1945, which is 15 years to 1960. No data existed in this river basin prior to 1953.
#criterion for missing data relaxed from 5% to 10% for this river basin to ensure spatial representativeness.

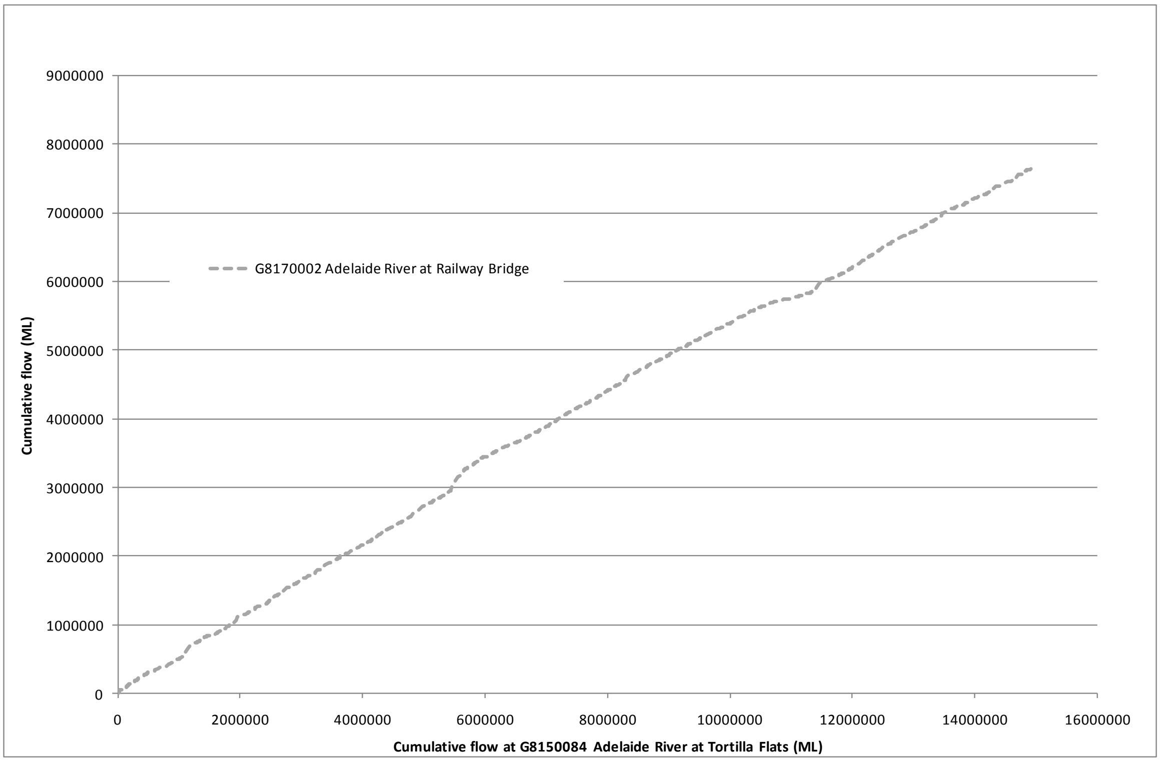
16) *Plot daily flow duration curves and double mass curves* – Flow duration curves for each site are shown in Figure 5-10. The curves illustrate similar behaviour at the two Adelaide River sites and a slightly higher baseflow in the two tributaries. There is no clear evidence of data anomalies in these curves. The flow duration curves are plotted for the whole period of available record and not for individual climate phases because there was insufficient data prior to 1960 to create a flow duration curve representative of this early period. There was a significant amount of missing data at the site at Railway Bridge (G8170002) prior to 1960.

Data from gauges G8170002, G8170066 and G8170075 show a high degree of stationarity when plotted as double mass curves against data from gauge G8170084. The data plotted covers the period 1965 to 2007, which is all within the one climate phase. There is some missing data at all sites, which has been omitted for plotting purposes. The double mass curve for the Adelaide River site is shown in Figure 5-11, whilst the remaining two sites are shown on Figure 5-12, which is plotted on a smaller scale.

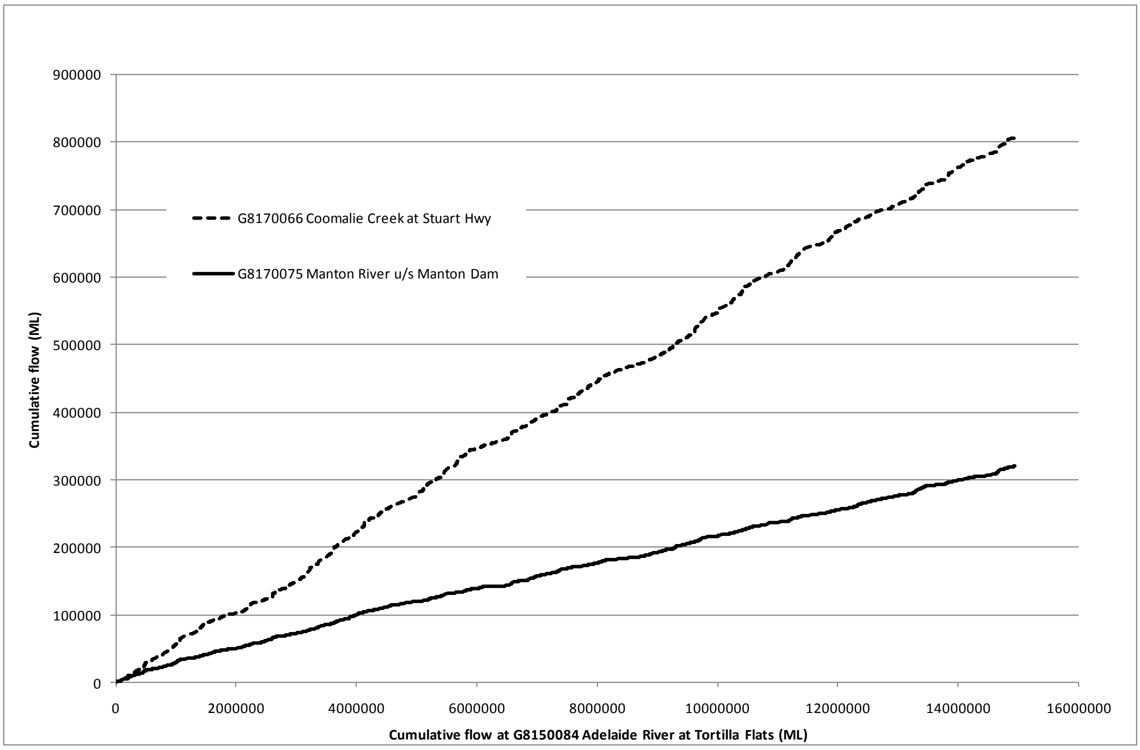
■ Figure 5-10 Flow duration curves for whole period of record



▪ Figure 5-11 Double mass curve 1965-2007 for Adelaide River at Railway Bridge



▪ Figure 5-12 Double mass curve 1965-2007 for Coomalie Crek and Manton River



17) *Present the list of sites to State agency representatives* – For the case studies, this step has not been undertaken.

18) *Other supporting information* - There are no high quality rainfall stations within the Adelaide River catchment. The nearest high quality rainfall station is site 014015 at Darwin, which is around 30 km to the west of the Adelaide River catchment boundary. Elevation data was previously presented at Step 15.

5.4. Summary of Adelaide River case study outcomes

In summary, **four streamflow gauges were selected as high quality streamflow gauges in the Adelaide River basin suitable for seasonal forecasting**. These are:

- G8170002 Adelaide River at Railway Bridge;
- G8170066 Coomalie Creek at Stuart Hwy;
- G8170075 Manton River u/s Manton Dam; and
- G8170084 Adelaide River at Tortilla Flats.

These sites are considered to provide good spatial and temporal representation of streamflow data in the Adelaide River basin. All of the data at these streamflow gauges are affected by regular burning, however the frequency of that burning is so often that it is not expected to affect the stationarity of streamflow data. This would need to be confirmed with the Northern Territory Government. There was also an increase in forest cover observed at all sites since the 1990s, which again would warrant further investigation.

No streamflow gauges were selected as high quality streamflow gauges in the Adelaide River basin suitable for long-term climate change investigations because none of the sites included at least 15 years of good quality data from two climate phases.

6. Conclusions and Recommendations

This study for the Bureau of Meteorology prepared guidelines for selecting high quality streamflow gauges around Australia. It included undertaking a literature review of previous studies, which were then used to inform the development of the guidelines. The guidelines are intended to provide direction to the Bureau but also allow flexibility in adjusting thresholds in the future to preserve some spatial and temporal representativeness in the datasets when applied around Australia. The guidelines were tested with two case studies. For the Campaspe River basin five high quality streamflow sites were identified as suitable for seasonal forecasting and two of those were considered suitable for historic climate change investigations. For the Adelaide River basin, four high quality streamflow sites were selected for seasonal forecasting and no sites were suitable for historic climate change investigations.

Some steps in the guidelines were not followed for the case study, notably the consultation on the selected sites with state agency representatives. It is therefore recommended that the Bureau revisit these two river basins prior to finalising any national datasets of high quality streamflow sites.

In undertaking the guidelines, a number of observations can be made which may assist the Bureau in deciding the future direction of its identification of high quality streamflow gauging stations:

- The order in which tasks were undertaken may need to be varied in some river basins in order to minimise the effort required. For example, given the lack of sites with data in the Adelaide River, starting with the elimination of sites with insufficient data may be preferable to examining flow regulation or diversion information. In the Campaspe River basin, given the ease of identifying flow regulation and the relatively longer lengths of available data, the order of application of the guideline steps is probably the most efficient approach.
- In the Adelaide River basin, the threshold for the proportion of missing data allowed was relaxed from 5% to 10% in order to achieve greater spatial representation across the basin. Such flexibility would ideally be retained by the Bureau for other river basins. Applying the guidelines rigidly in all cases is unlikely to lead to the best outcome for the Bureau.
- Land use change information was often difficult to obtain and in both case studies there were land use changes which occurred throughout the catchments. In the Adelaide River basin bushfires are prevalent across the basin, whilst in the Campaspe River the volume of farm dams has grown rapidly over recent decades. The occurrence of major bushfires in the Campaspe River basin was also evident in the historical streamflow record. The double mass curves were quick to prepare and helpful in identifying land use changes specific to any individual catchment within a river basin, but were unable to identify land use changes affecting the data where it affects all sites within a river basin equally. The Bureau will need

to carefully consider its approach to dealing with land use change in different parts of Australia.

- Forest cover information at both case study locations indicated an increase over time, which appears counter-intuitive. This could be attributable to a change in method in data collection. The Bureau should investigate this issue in the two case study catchments prior to using the forest cover information more widely.
- The estimation of streamflow data uncertainty using the Australian Standard was quite sensitive to the delineation of rating table segments. The case study site did not meet the minimum number of gauging per segment recommended by the Australian Standard, which is likely to be a data constraint at many sites around Australia. The benefit of using this standard appears to be low given the effort involved, unless the Bureau can automate this calculation. The use of quality codes and the proportion of data outside of the gauged stage range would appear to be more practical measures of data quality for nationwide application of the guidelines.
- Automation of many of the steps in the process by the Bureau may help to reduce the potential for manual errors in data processing and increase flexibility in adjusting thresholds in particular river basins to achieve good spatial and temporal representation.
- Some aspects of the guidelines are arbitrary and will need to be refined by the Bureau after wider application. This includes the setting of thresholds for missing data, thresholds for data above and below the gauged flow range, thresholds for data uncertainty and the delineation of climate phases in different regions of Australia. The threshold of 10% for the volume of diversions or discharges relative to mean annual flow may need to be more stringent for climate change investigations than seasonal forecasting. The magnitude of the change being detected may be within 10% of the mean annual flow in some climate zones, although it is noted that in south-east Australia climate induced changes in mean annual flow post-1994 have been well in excess of this figure.

After preparing the guidelines and applying them to the two case studies, the following recommendations are made:

1) The Bureau should apply these guidelines more widely to test their broader applicability and adjust the various thresholds in the guidelines accordingly if required.
2) The “stn type” field in the Bureau’s water resources station catalogue should be expanded to differentiate between rivers, drains, channels and pipes. This would allow the Bureau to more readily exclude streamflow gauging sites that are impaired because they are actually located on irrigation drains, irrigation channels or wastewater treatment plant discharge outfalls.

3) The "is_regulated" field on the Bureau's water resources station catalogue should have an expanded description in the help file to illustrate the criteria by which the site has been designated as regulated. The regulation for sites 406224 and 406224A should be checked for consistency in the catalogue.
4) The water resources station catalogue's csv file of the list of sites for the Adelaide River basin did not contain any data. This should be updated by the Bureau.
5) Further work should be undertaken to classify periods of stationary streamflow data with respect to climate in the different parts of Australia. This is because regional hydrologic studies have examined climate shift in climate classes which are not homogenous in relation to the magnitude and direction of historical climate shifts.
6) The Bureau should consider whether it can automate many of the steps in the guidelines, including the uncertainty analysis. It is recommended that the uncertainty analysis is not used in the application of the guidelines unless this calculation can be automated.
7) The Bureau should investigate whether the forest cover data used in the case studies is affected by the data collection method prior to using this data more widely.
8) The Bureau should endeavour to standardise quality codes for streamflow gauging around Australia. This would make the interpretation of quality codes by data collectors and users much easier.

7. Abbreviations

Abbreviation	Meaning
AWRC	Australian Water Resources Council
FSR	Flow stress ranking; which provides an indication of the relative 'naturalness' of the streamflow and incorporates a number of indices to describe the difference between the current and unimpacted streamflow regime. Scores range from 1 to 10, with 10 representing the smallest difference between current and natural conditions
SDL	Sustainable Diversion Limits; this project calculated man annual flow and total upstream water use. The ratio of total upstream water use and the man annual flow was calculated to provide an indication of the magnitude of diversions.

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Appendix A Example streamflow data quality codes

A.1 Thiess Environmental Services in Victoria

Quality Code	Description
1	Good continuous records
2	Good quality edited data
3	Linear infill to first value in block (no data lost)
4	Temporary coded for currumbeene data
5	Drawdown - chart rating applies
6	Phased Rating Applicable-gradual changing of control&channel
8	Pool reading only
9	Pool dry - no data collected
10	Data transposed from recorder chart
11	Operational data/abnormal data from op. or natural extremes
12	Routine sampling for calibration purposes
13	Accurate derived data from multiple sources (level & flow)
14	Telemetry data not stored in archive
15	Minor editing
20	Edited to measurements
26	Daily read records (MW - Good periodic data)
27	MW - Good periodic data (Other Authority)
30	Good Meas. - mult. point\044 40 sec timing (Good acc. data - MW)
31	Good Meas. - Adeq. verts & obs\044 40 sec timing (Good acc. data - MW)
32	Fair Measurement - Weighted mean gauge hieght\044 turbulent flow\044 flow angle extreme
33	3 Point Measurement - Applicable in narrow sections eg. sewers etc.
34	Bucket Measurement - Applicable to weirs\044 pipe outflow etc.
35	Composite Measurement - Segments taken from several gaugings to create a composite
36	Measurement for sampling purposes. Rough estimate
39	Catchment area defined
40	Catchment area not defined
41	MW - Good data not validated by other means - No editing required
42	Low velocity acoustic record affected by wind or gate opening
50	Medium editing >Q=15 (1996 on & MW) or HYMAN data import (pre1996)
54	Unregistered Ecowise code
55	Unregistered Ecowise code
56	Unregistered Ecowise code
60	LATROBE VALLEY DATA

65	Other authorities data
75	Height correction applied
76	Reliable interpolation
77	Correlation with other station\044 same variable
78	Reliable Daily Read Data (MW)
80	Accumulated
81	Wet day within accumulated rainfall period
82	Linear interpolation across gap in records.
83	BCC Below Instrument Range
90	Salinity interpolation
92	PROJECT SITE U/S DATA USED
95	Irregular time rate data - weekly/monthly read.
100	Irregular data use with caution.
101	Reliable Data Estimate (MW)
104	Records estimated
119	Unregistered Ecowise code
120	Estimated data not using correlation (MW)
130	Estimated periodic data (MW)
140	Estimated Accumulated Data (MW)
142	Unregistered Ecowise code
146	Drawdown - no rating applies
148	Theoretical rating table applied
149	Raw data as received from Serco (MW)
150	Rating extrapolated due to insufficient gaugings (Unrel. data - MW)
151	Data lost due to natural causes - NRE approved loss
152	Refer station file
153	PROBE OUT OF WATER/BELOW INSTRUMENT THRESHOLD
155	ABOVE INSTRUMENT THRESHOLD
160	Backed-up by d/s influence. (Unreliable periodic data - MW)
161	Debris Effecting Sensor.
165	Suspect or bad data supplied by other authority
166	Unregistered Ecowise code
170	Raw unedited data stored in archive (Unrel. accum. data - MW)
180	Equipment malfunction
190	Data unavailable station discontinued
200	Data available but not digitised
201	Data not rec. - no correlation available (Station not op. - MW)
205	Unregistered Ecowise code
235	Poor Measurement - Not enough verticals or observations\044 not enough information
236	Suspect or Incomplete Measurement - Equipment suspect or giving problems causing measurment to be aborted.

237	Surface Velocities - Velocity measurements taken on surface only.
238	Control Leaking - Control leaking\044 either as noted on measurement or chart.
239	Backed up Flow Measurement - Measurement is affected by backup.
240	Not Coded Measurement - Measurement not coded as per HYDSYS System.
250	Rating table suspended
253	Brisbane Quality code
254	Rating table exceeded
255	No Data Exists (Lost data - MW)

A.2 Melbourne Water – Victoria

Quality	PrintQual	Text	Active
1		Very Good data - no editing required (or 1-5mm error)	T
2		Good quality edited data, minor editing only	T
3		Linear infill to first value in block (no data loss - Thiess Quality)	T
4		Excellent Sewerage data or unknown quality from another agency	T
5		Excellent Sewerage data with minor editing or unknown quality from another agency	T
6		Excellent Sewerage data with major editing or Phase rating applicable - gradual changing of control and channel	T
7	B	Very Good data, rating not applicable due to backwater effect	T
8		Pool reading only (Thiess Quality)	T
9		Pool dry - no data collected (Thiess Quality)	T
10		Unknown Quality (perhaps introduced from another agency)	F
11		Unknown Quality (perhaps introduced from another agency)	F
12		Unknown Quality (perhaps introduced from another agency)	F
15		Minor editing only (Thiess Quality)	T
16		Unknown Quality (perhaps introduced from another agency)	F
19		Good quality rating extrapolation	T
20		Unknown Quality (perhaps introduced from another agency)	F
23		Unknown Quality (perhaps introduced from another agency)	F
25		Unknown Quality (perhaps introduced from another agency)	F
26		Good periodical data (MWH)	T
27	!	Good periodical data (Others - not continuous reading)	T
29		Unknown Quality (perhaps introduced from another agency)	F
30	+	Good accumulated data (MWH - continuous reading), Good measuement - multi point 40 sec timing	T
31	#	Good accumulated data (Others - continuous reading), Good measurement - adeq. verts & obs -40sec timing	T
32		Fair measurement - weighted mean gauge height, turbulent flow, flow angle extreme	T
33		3 point measurement - applicable in narrow sections eg. sewers	T
34		Bucket measurement - applicable to weirs, pipe outflow etc.	T
35		Composite measurement - segments taken from several gaugings to create a composite	T
36		Measurement for sampling purposes - rough estimate	T
38		Unknown Quality (perhaps introduced from another agency)	F

40		Unknown Quality (perhaps introduced from another agency)	F
41		Good Data not validated by other means	T
50	Z	Good or Reliable data (5-10mm error), medium editing required	T
54		Good Sewerage data or unknown quality from another agency	T
55		Good Sewerage data with minor editing or unknown quality from another agency	T
56		Good Sewerage data with major editing or unknown quality from another agency	T
57	B	Good/Reliable data, rating not applicable due to backwater	T
65		Other authorities data (Thiess Quality)	T
69		Fair quality rating extrapolation	T
70		Unknown Quality (perhaps introduced from another agency)	F
75		Fair data (10-15mm error), major editing required	T
76	*	Fair data, edited by correlation with another site, gaps <0.5day filled by interpolation	T
77	&	Reliable data correlation with aother station same variable	T
78	%	Reliable daily read data - MWH private raingauge operator	T
79	B	Fair data, rating not applicable due to backwater effect	T
80		Unknown Quality (perhaps introduced from another agency)	F
82		Linear interpolation across gap in records	T
90		Salinity interpolation	T
91		Unknown Quality (perhaps introduced from another agency)	F
92		Unknown Quality (perhaps introduced from another agency)	F
100		Comms failure for Sewerage data - exclude from KPI or Unknown Quality (perhaps introduced from another agency)	T
101	R	Reliable data estimate using good correlation with other variable, Estimated Rating or regenerated velocity sewerage data	T
103		Unknown Quality (perhaps introduced from another agency)	F
104	~	Estimated data edited using a reasonable correlation or fair quality sewerage data	T
105		Fair Sewerage data with minor editing or unknown quality from another agency	T
106		Fair Sewerage data with major editing or unknown quality from another agency	T
110		Unknown Quality (perhaps introduced from another agency)	F
120	I	Estimated data not using correlation (ave. dry weather hydrograph used) or Rating extrapolated	T
130	P	Estimated periodical data, slightly suspect staff gauge readings	T
135		Unknown Quality (perhaps introduced from another agency)	F
140	A	Estimated accumulated data, slightly suspect check bottle reading etc	T
144		Poor Sewerage data or unknown quality from another agency	T
145		Poor Sewerage data with minor editing or unknown quality from another agency	T
146		Poor Sewerage data with major editing or Drawdown - ratings not applicable	T
148	@	Theoretical rating table applied	T
149		Raw data as recieved from contractor, only quality codes changed	T
150	U	Poor data, historical rating or rating not verified, use with caution at clients discretion	T
151	^	Poor Data (15-25mm error) or data yet to be verified. Use with caution	T

153		Probe out of water or outside instrument threshold	T
155		Poor data due to reasons beyond the control of hydrographic contractor	T
157	B	Poor data, rating not applicable due to backwater effect	T
160	U	Unreliable data (>25mm error) or unrelaible periodical data	T
161		Unreliable data due to reasons beyond the control of hydrographic contractor	T
165		Unknown Quality (perhaps introduced from another agency)	F
170	S	Unreliable accumulated data, suspect check reading	T
180		Unknown Quality (perhaps introduced from another agency)	F
200		Unknown Quality (perhaps introduced from another agency)	F
201	?	Station not commissioned - instrument not installed or known not to be working or no sewerage data	T
202		No Sewerage data or unknown quality from another agency	T
204		Unknown Quality (perhaps introduced from another agency)	F
205		Sewerage data lost or unknown quality from another agency	T
235		Poor measurement - not enough verticals or observations	T
236		Suspect or incomplete measurement - equipment problems causing measurement to be aborted	T
237		Surface velocities - velocity measurement taken on surface only	T
238		Control leaking as noted on measurement or chart	T
239		Backed up flow measurement - measuement affected by back water	T
240		Data lost due to reasons beyond the control of hydrographic contractor	T
250	M	Unreliable data due to SCADA system error	T
254	X	Rating table exceeded, data is above or below rating table limits	T
255	N	Invalid or lost data, instrument or operator error, unusable bad data	T

A.3 NRETAS – Northern Territory

Quality		Description data type	
1		Good - continuous data	T
2		good quality - continuous data - some minor editing	T
6		Good Point data-manually entered which adequately represents continuous record	T
7		Good Isolated Point	T
11		Good Gauging	T
31		Reserved For WQ 31-40	T
32		Good - imported from WQ Branch spreadsheets	T
41		Good Rating	T
45		Good Rating Extrapolated	T
51	S	Satisfactory - continuous data	T
52	S	Satisfactory - estimated continuous data	T
56	S	Satisfactory Point data-manually entered which adequately represents data	T
57	S	Satisfactory Isolated Point	T
61	S	Satisfactory Gauging	T

81	S	Satisfactory WQ Result - uncontrolled sampling\044 lab results manually entered	T
82	S	Satisfactory WQ result - uncontrolled sampling\044 Lab analysis	T
83	S	Satisfactory WQ Result - uncontrolled sampling\044 lab results rechecked against lab sheets	T
85	S	Satisfactory WQ Result - uncontrolled sampling\044 lab results transferred from LIMS electronically	T
87	S	Satisfactory WQ Result - uncontrolled sampling\044 lab results transferred from VAX	T
91	S	Satisfactory Rating	T
95	S	Satisfactory Rating - extrapolated	T
101	P	Poor - continuous data	T
102	P	Poor - estimated continuous data	T
106	P	Poor Point data manually entered	T
107	P	Poor Isolated Point	T
109	P	Estimated Data - original lost	T
111	P	Poor Gauging	T
131	P	Reserved For WQ 131-140	T
141	P	Poor Rating	T
142	*	Telemetry data. No visual verification. Final quality code not yet assigned.	T
145	P	Poor Rating - extrapolated	T
146	B	Rating based on theoretical method\044 use with caution	T
150	?	Rating under Review - not Quality Coded	T
151	N	Blank or no data (Met. Bureau rainfall only)	T
155	A	Accumulated Rainfall - over a period	T
157	R	Rain day - in accumulated period	T
162	T	Severe tidal influence - not to be integrated	T
170	?	Data not processed [Historic\044 Q=Y]	T
171	?	Data awaiting editing and quality coding.	T
172	?	Isolated point - no integration/not quality coded	T
173	T	Tidal influence- Orig. data (VAR=100)+ Integrated data (VAR=102	T
174	?	Vax conversion code: data to be Edited to another Qual. code	T
175	D	Dry - below orifice	T
176	W	Wet - below orifice	T
181	?	WQ manually entered	T
183	?	WQ re-checked against lab sheets	T
185	?	WQ transferred from LIMS electronically	T
187	?	WQ transferred from VAX	T
192	X	Lookup Table - exceeded	T
250	N	NON-sensible record - used for Time or below Inlet\044 above CTF	T
252	N	Sensor broken	T

253	N	Logger broken	T
254	N	No Recorded Data (Instrumentation removed)	T
255	N	No Record or Record Lost	T

A.4 DERM – Queensland

```
                              Qualcode.txt
      Qld NRW SWDB

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       Quality Codes Report

      Quality PrintQual Text

           1            Good (actual)
           9            CITEC - Normal Reading
          10            Good
          15 B          Water level below threshold (no flow)
          19 !          CITEC - No Flow Reading
          20 F          Fair
          26            BOM data - Good Daily Read Records
          30 P          Poor
          31            gauging temp - Good
          32            gauging temp - Fair
          33            gauging temp - Poor
          34            gauging temp - composite
          35            gauging temp - equipment problems, causing incomplete
gauging, suspect procedures and methods. Possible inflow between gauging and
station.
          36            gauging temp - Velocity measurements taken on surface
only or velocity measurements with floats.
          37            gauging temp - Discharge correlated from U/S or D/S
stations.
          38            gauging temp - Interim code for data transferred from
CITEC. Data not yet Quality Coded.
          39            gauging temp - Data of No Value
          59 *          CITEC - Derived Height
          60 E          Estimate
          69 *          CITEC - Derived Discharge
          79 $          CITEC - Backwater Record
          80            BOM data - Accumulated
          81            BOM data - Wet day within accumulated rainfall period
         119 X          old - Gauge Ht > instrument threshold
         125 ~          Historic Water Quality Data, Quality fair.
         130 *          Not coded value
         131 *          NRSc unvalidated water quality data
         135 ~          Historic Water Quality Data, Quality poor.
         140 I          Interim value
         150 U          Unknown
         151 N          Data not yet available
         160 S          Suspect
         170 A          Water level above threshold
         180 !          old - Gauge Height < Instrument Threshold
         200 B          Water level below threshold
```

A.5 DLWBC – South Australia

DWLBC Hydstra Quality Codes (06/07/2009)

Quality	Print Quality	Text	TS	Gaugings	Ratings	Description
		Good Range (1-29)				
1		Good	Y	Y	Y	The data is the best available given the technologies, techniques and monitoring objectives at the time of classification. The data has been validated and may have been adjusted to calibration readings but no modifications have been made to the data.
25		Operational Data	Y	N	N	The data has intermittent timing and should not be analysed at a timing resolution less than that supplied. Includes daily read data.
		Fair Range (30-89)				
30	F	Fair	Y	Y	Y	The data is compromised in its ability to represent the monitored parameter. Data is a fair representation of actual events. The data has not been modified.
34	F	Fair – Estimated	Y	N	N	Data has been estimated with resulting record believed to be a fair representation of actual events.
36	F	Fair – Extrapolated Rating	*D*	N	Y	Used for Ratings only to designate an extrapolated segment of fair reliability. Data derived through a rating relationship such as a stage - discharge table where the rating has been extrapolated and is designated as fair quality.
37	F	Fair - Theoretical Rating	*D*	N	Y	Used for Ratings only to designate a segment based on a fair theoretical derivation without in-field calibration. Data derived through a rating relationship such as a stage - discharge table where the rating is based on a theoretical method and has been designated as poor quality.
80	A	Fair - Accumulated Data	Y	N	N	Missing manual reading data values that have been accumulated (totalled) over a period of time with resulting record believed to be a fair representation of actual events.
81	A	Fair – Accumulated Total	Y	N	N	Indicates a day within an accumulated period when the total value for the period is entered.
		Poor Range (90-129)				
90	P	Poor	Y	Y	Y	The data is an unreliable, poor representation of actual events and is compromised in its ability to represent the monitored parameter.
91	P	Poor - Estimated	Y	N	N	Data has been modified or estimated with resulting record believed to be an unreliable, poor representation of actual events.
102	P	Poor - Extrapolated Rating	*D*	N	Y	Used for Ratings only to designate an extrapolated segment of poor reliability. Data derived through a rating relationship such as a stage - discharge table where the rating has been extrapolated and is designated as poor quality.
108	P	Poor - Theoretical Rating	*D*	N	Y	Used for Ratings only to designate a segment based on a poor theoretical derivation without in-field calibration. Data derived through a rating relationship such as a stage - discharge table where the rating is based on a theoretical method and has been designated as poor quality.
129	P	Poor – Distributed Total	Y	N	N	Event recorded data, in particular rainfall, where an accumulated total value has been distributed proportionally over a missing period.

Quality	Print Quality	Text	TS	Gaugings	Ratings	Description
		Unknown/Unvalidated Range (130-150)				
130	?	Unverified – Water level below recordable range	Y	N	N	Water level data recorded below cease to flow and below the range of the monitoring device.
132	?	Quality unknown	Y	Y	Y	The data has not been validated / verified or is of unknown data collection standards and it's ability to represent the monitored parameter is not known.
150	T	Unverified telemetry data	Y	N	N	Telemetered data that has not been verified, validated or adjusted with in-field calibration readings.
		Not Recorded Range (151-199)				
153	$	Not Recorded - Outside recordable range	Y	N	N	The data is known to be incorrect as the parameter is outside of the specified recordable range. Actual events were above or below the range of the recording equipment and recorded data does not representative actual values.
154	X	Not Operating	Y	N	N	Instrument not operating or parameter not being recorded. No recording attempted.
		Missing Range (200-254)				
201	M	Missing	Y	N	N	Data recording was attempted however the data is missing, void or known to be incorrect.
202	#	Missing - Outside Rating Range	*D*	N	Y	Used for Ratings only to designate a segment that is not covered by the range of the rating. Data derived through a rating relationship such as a stage - discharge table where the rating does not cover the recorded range.
255		*Reserved code used by Hydstra system - DO NOT USE*	N	N	N	*Reserved code used by Hydstra system.*

A.6 HydroTasmania – Tasmania

Numeric quality code	Code symbol	Description
1		Excellent Data
3		Excellent Rating
4		Certified data. From an external source - as in WQ sample data from a NATA certified laboratory
5	A	NEM Energy Metering, Actual Meter
7		Good data. Confirmed by site visit. (Dam Safety data only)
11		Good Data
13		Good Rating
21		Fair Data
22	G	Good Estimated Data.
23		Fair Rating
24		Good Extrapolated Rating
25	M	Modelled or Derived data. Includes forecast data or data derived from ratings etc.
26		
27	I	Interim code for telemetered data visually checked on graphical editor against appropriate comparison plots. No fault found but a more definitive final code cannot be assigned until after a field visit.
29	U	Data from source external to Resource Monitoring & Information Group. Minor checking & editing may have been done.
30	V	No requirement for Quality Coding and/or checking or editing. Data is often from source external to Resource Monitoring & Information Group.
31	D	Poor Data
32	E	Fair Estimated Data
33	R	Poor Rating
34	X	Fair Extrapolated Rating
40		Excluded Gauging. A gauging that has been formally identified and excluded as part of a rating review.. The gauging comment will say why it was excluded. No code necessary. WRSoutter 03/03/2004
41	C	Important Comment ......
42	Y	Poor Estimated Data
43		
44	Z	Poor Extrapolated Rating
101	#	Data that has been checked and found to be unreliable. DON"T USE on Wind Data. No longer appropriate for wind. Use QC147 (LOW IMPACT) or QC170 (HIGH IMPACT) W R Soutter 05/03/2003
138	E	NEM Energy Metering, Estimated Energy Data
139	F	NEM Energy Metering, Final estimation or substitution
140	?	Manually unloaded and archived. Unverified data. May have been visually inspected. Final quality code not yet assigned.
141	S	SCADA data. Not verified. Final quality code not yet assigned.
142	T	Telemetry data. Not verified. Final quality code not yet assigned. [Same code marker (T) as Q149]
143	!	SCADA data. Not verified and it has been flagged by the SCADA system as SUSPECT. The associated SCADA code is 128. Final quality code yet to be assigned.
144	S	NEM Energy Metering, Substitution
145	<	Minimum range check threshold exceeded. Final quality code not yet assigned.Don`t tinker with it. It is also assigned in the system setup table

146	>	Maximum range check threshold exceeded. Final quality code not yet assignedDon`t tinker with it. It is also assigned in the system setup table
147	N	Non conforming data. Known errors. LOW IMPACT. Final quality code not yet assigned.
148		Temporary Qcode for ERRTS rainfall data where >1 tip recorded by sensor. WRSoutter 18/03/2008
149	t	Telemetry data from an EXTERNAL source. No visual verification. Final quality code not yet assigned. [Same code marker (T) as Q142]
150	P	Partial Statistic - some data missing in period. A SYSTEM quality code applied to data when processing/outputting. Not to be applied by individuals as a quality code when editing data.
160	NULL VAL	Covers the case where a parameter value does not exist at that time. Examples (a) Null turbidity when 0 flow in a stream. (b) Data values exceed range values of deliberately limited range sensor. (c) Target level not declared for some time periods
170	BAD	Non conforming data. Known errors. HIGH IMPACT. Final quality code not yet assigned.
180	[ ]	Unprocessed Record, data exists (e.g. charts) but not yet imported.
190	MISSING	Lost record or insufficient data for reasonable archive. DATA lost from an OPEN site. Compare with QC200 that deals with the case of no data because the site was CLOSED for a period of its history.
191	CLIPPED	Lost data where out of range data deemed spurious has been amended as it was archived. The data value is what the spurious value was clipped to. Pre-existing clips have not been converted to output to this quality. They output to QC190. WRS 16/06/2008
200	NO DATA	No data available at this site for the current period. Generally because of an executive decision to CLOSE the site. Associated with sites that are CLOSED and later RE-OPENED. Do not confuse with QC190 that covers data that was lost from an OPEN site.
201	RAT ERR	Error occurred in applying rating equation to data QUALITY CODES GREATER THAN 201 ARE RESERVED BY TSM, THEY MUST NOT BE ALTERED UNDER ANY CIRCUMSTANCES !!!
202	RAT LOW	Data point below lower limit of rating
203	RAT UPP	Data point above upper limit of rating
204	NO RAT	Period found but specified rating does not exist
205	RAT PER	No application period found for data point. Rating period error.
206	NO CONV	No conversion available
207	INTP ERR	Interpolation error. This may be caused by a timing error or by incompatible data types.
208	NOINVERT	Rating/conversion is non invertible.
209	DATUM	Chain conversion uses datum which is outside range of rating
210	UNDF VEC	Undefined vector. Resultant vector has zero length.
211	NO INTEG	Integration inappropriate for this data type - data types 3,4,7
212	NO DIFFN	Differentiation inappropriate for this data type - data types 2,3,4,7,8,9
213	NO AGGRG	Data Type change or other problem encountered - no Aggregation allowed.
214	NO INTRP	Data Type change or other problem encountered - no Interpolation allowed.
220	UNKNOWN	No value or quality associated with current point.
225	<-GAP->	Gap between time series records. Code assigned when gap is filled automatically by archiving operations. Check reason and then assign appropriate quality code
230	QEXCLUDE	Original quality in user specified exclusion range. Generated by QMax and QExclude transformations.
255	NULL	Used for initialisation purposes

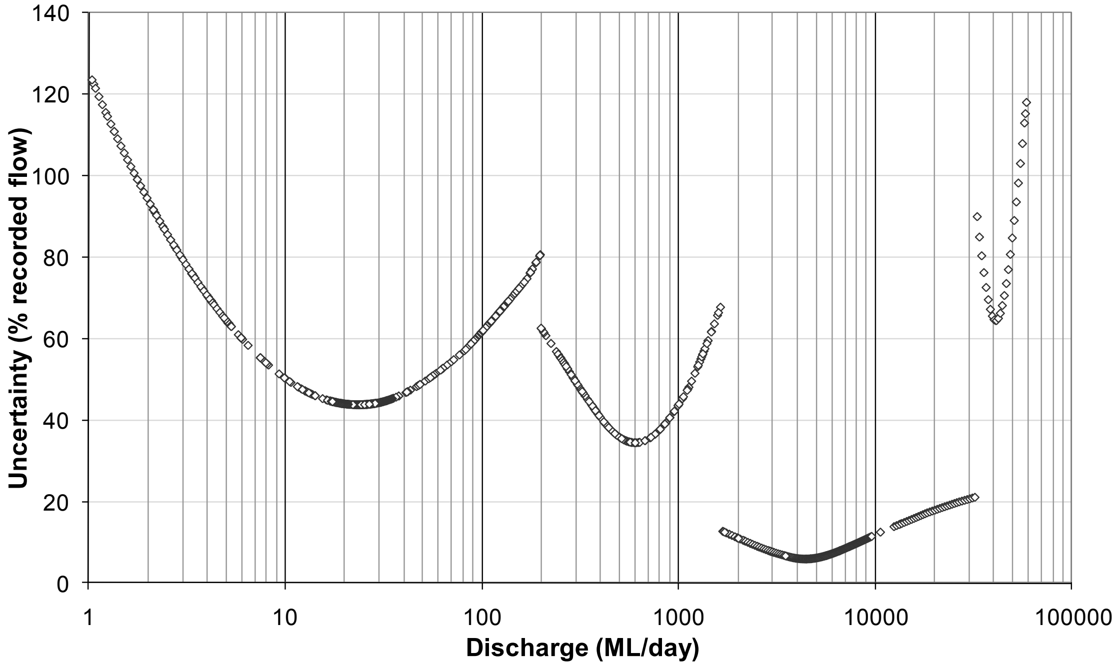
A.7 Department of Water – Western Australia

Quality Code	Report Symbol	Description
1		Very Good Record
2	'	Very Good Record - Corrections applied
3	"	Good Record - Corrections or Estimations applied
4	*	Estimated Record - Good
5	*	Estimated Record - Fair
6	*	Estimated Record - Poor
10	*	Estimated Record - Not reviewed / Quality not known
11	@	Theoretical Rating
12	&	Estimated Rating
21	$	Daily Read - Good Record
22	*	Daily Read - Estimated
23	#	Daily Read - Derived from incomplete record
24	R	Daily Read - Rainday within period of accumulated record
25	A	Daily Read - Accumulated Rainfall
30	"	Station data, as supplied by BoM
31	"	Deaccumulated using nearby station
32	"	Deaccumulated using interpolated data
33	"	Nearby station, data from BoM
34	"	Interpolated daily observations
35	"	Interpolated long term average
100	=	Sample Group Code - WIN SAMP CUSTODIANS
101	<	Sample Group Code - WIN SAMP CUSTODIANS
102	>	Sample Group Code - WIN SAMP CUSTODIANS
103	~	Sample Group Code - WIN SAMP CUSTODIANS
104	=	Sample Group Code - WIN SITE SAMPLE CUST
105	<	Sample Group Code - WIN SITE SAMPLE CUST
106	>	Sample Group Code - WIN SITE SAMPLE CUST
107	~	Sample Group Code - WIN SITE SAMPLE CUST
108	=	Sample Group Code - WIN INV CUSTODIANS
109	<	Sample Group Code - WIN INV CUSTODIANS
110	>	Sample Group Code - WIN INV CUSTODIANS
111	~	Sample Group Code - WIN INV CUSTODIANS
151	B	Below inlet
152	[	Not available
161	U	Unrated
255	[	No record

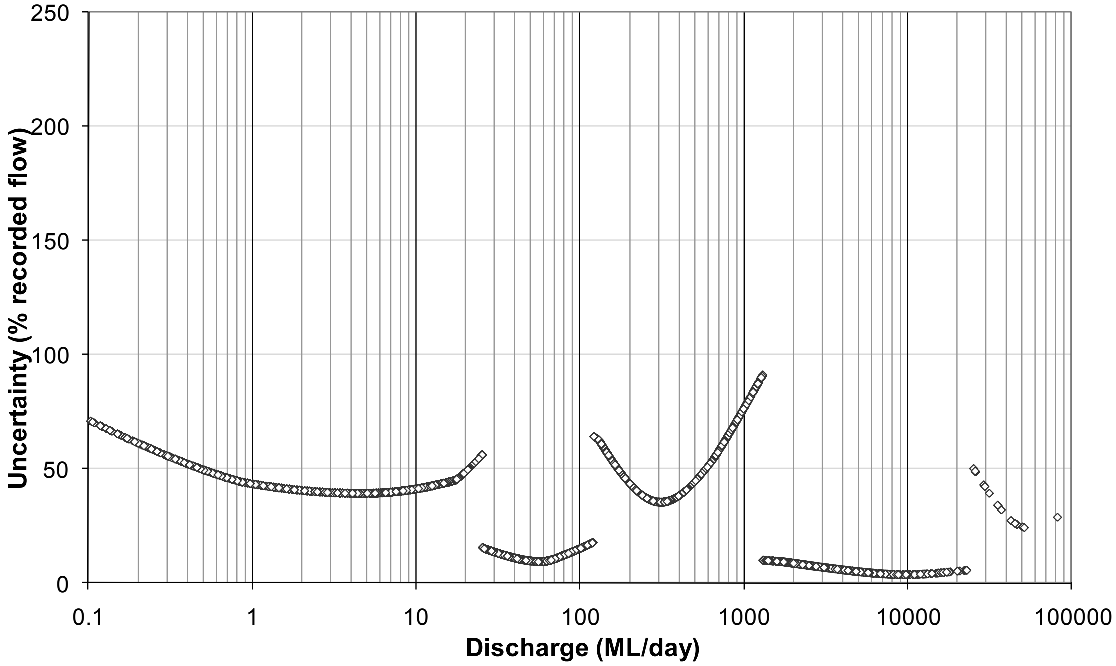
Appendix B Uncertainty plots for Adelaide River at Railway Bridge

The method for deriving these uncertainty plots was outlined in Section 3.5. The three plots below illustrate the uncertainty for each rating table period over different segments of the rating table. For example, the uncertainty plot for the rating table covering the period 1952-58 shows that uncertainty in the first segment is high in percentage terms at low flows and reduces to a minimum of around 42% at a flow of approximately 25 ML/d. The method appears to be affected by end effects in estimating uncertainty, because uncertainty always rises at the ends of the segments. Uncertainty for this rating table is lowest in the third segment covering the flow range from approximately 1500 ML/d to 32,000 ML/d. Uncertainty rises again in the fourth segment in the high flow range.

B.1 Uncertainty plot for 1952-1958



B.2 Uncertainty plot for 1958-1979



B.3 Uncertainty plot for 1979-current