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River water balance accounts across the Murray-Darling Basin, 1990 – 2006

A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project

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Preface

This is a report to the Australian Government from CSIRO. It is an output of the Murray-Darling Basin Sustainable Yields Project which assessed current and potential future water availability in 18 regions across the Murray-Darling Basin (MDB) considering climate change and other risks to water resources. The project was commissioned following the Murray-Darling Basin Water Summit convened by the then Prime Minister of Australia in November 2006 to report progressively during the latter half of 2007. The reports for each of the 18 regions and for the entire MDB are supported by a series of technical reports detailing the modelling and assessment methods used in the project. This report is one of the supporting technical reports of the project. Project reports can be accessed at http://www.csiro.au/mdbsy.

Project findings are expected to inform the establishment of a new sustainable diversion limit for surface and groundwater in the MDB – one of the responsibilities of a new Murray-Darling Basin Authority in formulating a new Murray-Darling Basin Plan, as required under the Commonwealth Water Act 2007. These reforms are a component of the Australian Government's new national water plan 'Water for our Future'. Amongst other objectives, the national water plan seeks to (i) address over-allocation in the MDB, helping to put it back on a sustainable track, significantly improving the health of rivers and wetlands of the MDB and bringing substantial benefits to irrigators and the community; and (ii) facilitate the modernisation of Australian irrigation, helping to put it on a more sustainable footing against the background of declining water resources.

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1 Introduction

The purpose of this report is to describe in more detail the water balance accounting assessment undertaken in the project. How well do we understand the water balance in the Murray-Darling Basin? How good are the measurements of the water balance? How confident are we of predictions about water availability and use? In this report, we describe river water balance accounts, designed to address these questions as part of the Murray-Darling Basin Sustainable Yields project.

The first part of our purpose is to develop water accounts at the scale of the river reach. Our preference is to use only measurements of water inflows, outflows and diversions to account for all water entering and leaving a reach. Measurements alone often fail to account for much of the water, so we supplement them with other estimates as necessary. From the reach-by-reach water accounts, we build up catchment and basin water accounts.

The water accounts indicate how well we understand the water balance – how much of the total volume of water in a reach, or a catchment, or the basin, is measured. The greater the proportion measured, the better we understand the water balance, and we instinctively feel that river flow models are likely to be more accurate and have greater confidence in predictions of flows and uses. The water accounts also indicate where our understanding is worse, and hence where more measurements (more flow gauges, for example) would increase our understanding and, presumably, our confidence in model predictions.

Water accounting has been used at various scales from national (eg, ABS, 2004; Lenzen, 2004) and basin (eg, Molden, 1997; Molden et al., 2001a; Kirby et al., 2006a, 2006b), where it is used to identify the status of water resources and the consequences of management actions, to river reach (e.g. Gippel, 2006), where it has been used to determine small zones of high seepage loss from a river channel. Although the underlying principles are the same at all these scales – that is, to identify gains and losses from a defined system – the work described here has more in common with Gippel (2006) than the water accounts at national or basin scales, where many small details are glossed over. Water accounts are often presented as annual (eg, ABS, 2004; Lenzen, 2004), or even as long term averages (eg, Molden, 1997; Molden et al., 2001a). The work described here develops monthly water accounts, similar to those described (albeit at a basin scale that glosses over fine spatial detail) by Kirby et al. (2006a and 2006b).

The second part of our purpose is to use the water accounts to assess quantitatively (as opposed to relying only on our instinctive feelings described above) the confidence in predictions of river model predictions of flow and water uses. This assessment is described in a companion report by van Dijk et al. (2008).

2 River water accounting methods

2.1 Overall water balance accounting approach

The basis of our water accounting is the monthly water balance of a river reach. The first, and perhaps rather obvious but nevertheless fundamental point, is that the flow system of the reach must be understood. Main stream and tributary inflows, main stream and tributary outflows and diversion points must all be identified, as must the locations of flow gauges or other measurements within the system. Without this understanding, it can be very difficult to construct a water balance in many of the reaches of the Murray-Darling system: many have distributaries and by-pass flows (a distributary that rejoins the main stem at a later point, sending some of the flow unmeasured past a flow gauge point).

A typical reach water balance is:

$$Q_{in} + Q_{trib} + Q_{runoff} - Q_{out} - Q_{distrib} - Q_{divert} - Q_{evap} - Q_{FP} + \Delta S + e = 0 \quad \text{Equation 1}$$

where Q_{in}, Q_{trib}, and Q_{runoff} are inflows from upstream, a tributary and direct runoff into the reach, and Q_{out}, $Q_{distrib}$, Q_{divert}, Q_{evap}, and Q_{FP} are outflows to the downstream, a distributary, diversions, direct evaporation from the reach, and consumption on the floodplain (as evapotranspiration). ΔS is the change in storage and e is an error term, equal to the difference between the inflows, outflows and change in storage. Additional terms may appear in some reaches, such as flows to or from groundwater, effluent returns from town water use, etcetera.

In a reach in which all the terms are measured, e will be simply the sum of all the measurement errors including calibration errors in rating curves. Nowhere in the Murray-Darling are all the terms measured but in some reaches, especially in reaches near the source regions, there are no major losses, distributaries and diversions, and the reach water balance is dominated by measured Q_{in} and Q_{out}, while other terms and e are small. In other reaches, there may be a large term which is unmeasured but which we can confidently estimate. This is typically the case in reaches with a large direct runoff inflow. In such a reach we will have a measured fraction of the water balance, an unmeasured fraction which we can nevertheless confidently estimate, and a small remainder of other terms and small e. In yet other reaches, there may be many unmeasured terms which dominate the water balance, and which we cannot confidently estimate. This is typical of reaches on the plains where there are large, unmeasured losses to the floodplain, distributaries and groundwater. The residual term e will typically be large, and we cannot distinguish the measurement error from the unknown errors in undetermined terms. Based on the above, we can re-write Equation 1 as:

$$Q_{in,measured} - Q_{out,measured} + Q_{in,estimated} - Q_{out,estimated} + \Delta S + \varepsilon = 0 \quad \text{Equation 2}$$

where $Q_{in,measured}$ and $Q_{out,measured}$ are all inflows and outflows for which we have measurements, $Q_{in,estimated}$ and $Q_{out,estimated}$ are all inflows and outflows for which we have reliable estimates, and ε is the sum of measurement errors and unknown terms. We will refer to the measured inflows and outflows often as gauged, since flow gauges are the main means of measurement. We will refer to the sum of measured and estimated inflows as attributed inflows, and measured and estimated outflows as attributed outflows. ΔS may be measured (e.g. in storages reservoirs), estimated through a model, or become part of ε. Our overall approach in the water accounting is to use as many measurements as possible, and to supplement these with independently verifiable models (such as runoff models) in an attempt to minimize ε. Where model estimates are used these are preferably derived by using additional data sources and methods different from those used in the river model. If the remaining ε is small, knowledge of the reach water balance is considered good.

The monthly water accounts differ from the river modelling in a number of key aspects:

- The accounting was specifically intended to estimate historical water balance patterns, and used observed rather than modelled data wherever possible (including recorded diversions, dam releases and other operations). This reduces the uncertainty associated with error propagation and assumptions in a river model that was not necessarily intended to reproduce historical patterns (e.g. differences in actual historical and assumed degree of entitlement use).

- Each reach is treated independently, and has a separate water balance. In a river model, errors in a reach may propagate downstream.
- The accounting uses independent, additional observations and estimates on water balance components such as actual water use estimates derived from remote sensing observations. This can help to constrain the water balance with greater certainty.

The accounting period chosen was 1990–2006, although in some reaches the availability of data dictated shorter accounting periods. It represents a compromise between being sufficiently long to cover varying climate conditions, and having sufficient data to perform water accounting. The most limiting data in this respect were diversion and streamflow records. We were able to develop water accounts for reaches with both an upstream and a downstream gauge with good quality data. There is a trade-off between number of reaches and quality of information; we could have established water accounts for more reaches by accepting poorer information. The water accounts thus encompass recent water resources development and drought in parts of the Murray-Darling Basin.

In assessing uncertainty and errors in flow estimation, we took no account of the rating curves of gauges (ie the conversion from the water level measured by a gauge to the flow rate calculated at that gauge), nor the likely errors in the rating curves. Thus, where we refer to uncertainty or errors in this report, we refer specifically to those identified with e or ε in equations (1) and (2) – these being the error in the water balance calculated from the measured and / or estimated flows, ignoring any errors in those quantities.

2.2 Attribution of apparent ungauged gains and losses – or choosing when to use independent models

Reach water accounts were calculated in two steps. In the first step, all measurements were collated and a first-pass water account was calculated by assigning $Q_{in,measured}$ and $Q_{out,measured}$ in equation (2), while assuming $Q_{in,estimated}$ and $Q_{out,estimated}$ were zero. This effectively lumped all ungauged terms as well as measurement error into the apparent ungauged gains and losses, ε (which may be smaller than real gains and losses due to compensating errors). In the second step, we assessed for which water balance terms good estimates were available to reduce ε. The monthly patterns of apparent ungauged gains and losses were analysed by:

- analysis of normal (parametric) and ranked (non-parametric) correlation between apparent ungauged gains and losses on one hand, and gauged and estimated water balance components on the other hand. For example, ungauged gains that are highly correlated to rain are reasonably attributed to runoff.
- Visual data exploration: assessment of temporal correlations in ε to assess trends or storage effects, and comparison of patterns in ε with time series of estimated water balance components. For example, temporary storage causes outflows to lag and be smoother than inflows.

Based on this analysis, apparent gains and losses were attributed to the most likely process, and an appropriate method was chosen to estimate the ungauged gain or loss using gauged or estimated data. The water accounting model included the following components:

- a conceptual floodplain and wetland with a running water balance model that estimated net gains and losses based on remote sensing-based estimates of net water use and main stem discharge observations;
- a conceptual irrigation area water balance model that estimated (net) total diversions as a function of any recorded diversions, remote sensing-based estimates of irrigated area and net crop water use;
- a routing model that allowed for the effect of temporary water storage in the river system and connected water bodies and direct rainfall and open water evaporation; and
- a local inflow model that transformed SIMHYD runoff estimates to match ungauged gains.

These model components were only used where the data or ancillary information suggested their relevance. Each component had a small number of unconstrained or partially constrained parameters to be estimated. A combination of direct estimation as well as step-wise or simultaneous automated optimisation was used, with the objective of attributing the largest possible fraction of ε. Large residual losses and gains suggested error in the model or its input data.

Apparent gains and losses, and hence the choice of models for gain and loss processes, vary with time step. The water accounting was done monthly. A flow peak will pass through a small reach in less than a month and therefore storage does not have a very noticeable or predictable influence on the water balance for such reaches. Exceptions were reaches that contained large water bodies.

2.3 Direct runoff estimation

Many river reaches in the basin, particularly those close to the headwaters of rivers, have a measured outflow greater than the measured inflow, and the difference is highly correlated with the rain. Clearly, they receive runoff that enters the reach directly or via small, ungauged tributary streams. To the measured inflows of such reaches was added runoff calculated by SIMHYD, as reported in Chiew et al. (2008). Often the measured inflows plus runoff was greater than the outflows, so the runoff was multiplied by a constant usually less than or equal to one. The constant was chosen such that the long term (1990 – 2006) long term average inflows (measured inflow plus runoff multiplied by the constant) equalled the measured outflow. Occasionally, the measured inflows plus runoff was less than the outflows, and in such cases a constant greater than one was used. On the face of it, this latter condition should not have occurred, since the SIMHYD calculated runoff was calibrated to the known streamflows. However, the periods of the water accounting and the SIMHYD modelling were not the same, so differences arose between the average runoffs for the two periods. Also not all catchments were used for SIMHYD calibration, and in other catchments the SIMHYD runoff differed from the streamflow.

2.4 Wetland and floodplain water use and storage estimation

An important class of independently verifiable modelled estimates of unmeasured water balance terms is the estimates of 1. actual evapotranspiration from floodplains and wetlands based on remote sensing observations, and 2. reach and other open water direct evaporation based on an energy balance method and estimates of open water area.

For the wetland and floodplain estimates, spatial time series of monthly net water use from wetlands and floodplain areas were estimated using interpolated station observations of rainfall and climate combined with remote sensing observations of surface wetness, greenness and temperature. Net water use of surface water resources was calculated as the difference between monthly rainfall and monthly actual evapotranspiration.

The method of estimating actual evapotranspiration from wetlands and floodplains is dealt with in the companion report (McJannet et al. 2008).

The evapotranspiration estimate was used in a floodplain storage and water use model. During floods, water will spill onto floodplains to be consumed as evapotranspiration, with a small proportion draining back to the river. We modelled this as follows:

$$\left.\begin{array}{lll} Q_{FP} = F_{FP}\left(Q_{out} - Q_{threshold}\right) & & Q_{out} > Q_{threshold} \\ Q_{FP} = 0 & & Q_{out} \leq Q_{threshold} \end{array}\right\}$$

Equation 3

where Q_{FP} is the volume of water that spills onto the floodplain in a month, $Q_{threshold}$ is a threshold value of flow below which no water spills onto the floodplain, and F_{FP} is a factor ($0 < F_{FP} < 1$) determining the fraction of the flow that spills onto the floodplain. The volume of water consumed on the floodplain as evapotranspiration, et_{FP}, is:

$$et_{FP} = \left(A_{FP} - A_{OW}\right)\left(F_{ET}\, AET_{FP} - P_{FP}\right)/1000$$

Equation 4

where A_{FP} and A_{OW} are the areas of the floodplain and any open water sitting on the floodplain in that month (which is dealt with by the open water evaporation estimation described in section 2.5 below), F_{ET} is a correction factor (generally set at 1.15) for AET_{FP}, the remote sensed actual evapotranspiration estimation, and P_{FP}, is the precipitation. The factor 1000 converts from km^2.mm, the units on the right hand side of the equation, to GL on the left hand side. Water stored on the floodplain may flow back to the river as a return flow, Q_{return}:

$$Q_{return} = F_{drain}\, S_{FP}^{t-\Delta t}$$

Equation 5

where F_{drain} is a factor (0 < F_{drain} < 1) determining the fraction of the stored floodplain water that returns to the river in a month, and $S_{FP}^{t-\Delta\tau}$ is the volume of water stored on the floodplain in the previous month. The water stored on the floodplain, S_{FP}^{t}, is updated as:

$$S_{FP}^{t} = S_{FP}^{t-\Delta t} + Q_{FP} - et_{FP} - et_{OW} - Q_{return}$$ Equation 6

where et_{OW}, is the open water evaporation, calculated as described in section 2.5 below. The net loss from the reach, Q_{FPnet} is:

$$Q_{FPnet} = Q_{FP} - Q_{return}$$ Equation 7

The factors in the model, especially $Q_{threshold}$ and F_{FP} were generally chosen to minimise the difference between the measured and observed river outflow.

2.5 Open water direct evaporation estimation

Direct evaporation from water bodies across the MDB was estimated using the Penman-Monteith approach (Monteith, 1965) accounting for heat storage within the water body. The method is dealt with in the companion report by McJannet et al. (2008), and yields estimates of evaporation rate for several open water body types associated with each reach. Water body types included reservoirs, ponds, streams, and watercourses that are mapped as polygons (e.g. wetlands) and areas inundated by floods. For each water body type the average evaporation rate (mm d^{-1}) was calculated for each month.

To convert evaporation rate data to water volumes lost, the area of each water body type was estimated. Due to a lack of better datasets, all water body types except streams and flood areas were considered to be constant in time, but we recognise that seasonal changes in water depths and areas may be significant. Values for the area of each of these water body types were extracted from the GEODATA TOPO 250K Series 3 Topographic Data set from Geosciences Australia or from GIS analysis of stream networks.

2.5.1 Stream area calculation

Reach length information is available, but there is no reach width information so areas cannot be calculated directly. In the field of channel metrics, relationships are commonly developed between channel width (*L*), channel depth (*D*) and discharge (*Q*) (e.g. Leopold and Maddock, 1953; Leopold *et al.*, 1964). Such relationships have been developed for two distinct applications; downstream hydraulic geometry, and at-a-station hydraulic geometry. Downstream hydraulic geometry relationships refer to changes in channel geometry at a site at a given flow (i.e. bank full). At-a-station hydraulic geometry takes the same form as downstream hydraulic geometry except this describes the variation in channel geometry at different flows at a location. Channel metrics methods make the assumption that stream channel geomorphology adjusts to flow.

Stewardson *et al.* (2005) analysed stream channel metrics for streams in Victoria for regional scale models. Many of these streams fall within the MDB. They included relationships for downstream hydraulic geometry and at-a-station hydraulic geometry and these relationships were used in this study to estimate stream widths. Such relationships may vary across the MDB, though Tennakoon and Marsh (2007) showed similar downstream hydraulic geometry relationships in Queensland streams.

Determination of channel width is a three step process. The first step is calculating bank full discharge (Q_{bf} (ML d^{-1})) from established relationships (DeRose et al., 2003) with mean annual flow (Q_a (ML)) as follows.

$$Q_{bf} = 0.099 Q_a^{0.993}$$ Equation 8

The second step is to use downstream hydraulic geometry relationships to determine the width of the channel when the channel is at bank full (L_{bf} (m)). Using discharge at bank full and the equations of Stewardson *et al.* (2005) L_{bf} is calculated as follows:

$$L_{bf} = 4.63 Q_{bf}^{0.428}$$ Equation 9

From this we can then work out the width for a given flow using at-a-station hydraulic geometry:

$$\frac{L_{bf}}{L} = \frac{4.63 Q_{bf}^{0.243}}{4.63 Q^{0.243}}$$ Equation 10

Which rearranges to:

$$L = \frac{L_{bf} Q^{0.243}}{Q_{bf}^{0.243}}$$ Equation 11

The channel width was calculated as the average of the width of inlet and outlet stations, and the area as width times length. We took this channel width to be the width of the reach in question.

2.5.2 Flood inundation area estimation

Areas inundated by flooding were determined by the use of MODIS satellite imagery. Algorithms were used to detect the fraction of total catchment area identified as water for each month from February 2000 until December 2006. When flooding occurred the area of stream at bank full was subtracted from the total area to avoid double counting. The following Section describes the algorithm used for mapping open water.

2.5.3 Open water estimation with remote sensing

The open water index developed is based on the combination of the Enhanced Vegetation Index (EVI) (Huete et al. 2002) and the Global Vegetation Moisture Index (GVMI) (Ceccato et al. 2002a; Ceccato et al. 2002b):

$$EVI = G \cdot \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + C_1 \cdot \rho_{red} - C_2 \cdot \rho_{blue} + L}$$ Equation 12

$$GVMI = \frac{(\rho_{NIR} + 0.1) - (\rho_{SWIR2} + 0.02)}{(\rho_{NIR} + 0.1) + (\rho_{SWIR2} + 0.02)}$$ Equation 13

where ρ_{red}, ρ_{nir}, ρ_{blue} and ρ_{swir2} are the reflectances in red, near–infrared, blue and shortwave infrared 2 respectively and correspond to MODIS bands 1, 2, 3 and 6. In the EVI formula, G, C_1, C_2 and L are parameters that account for aerosol scattering and absorption and their values are 2.5, 6, 7.5 and 1 respectively (Huete et al. 2002).

The EVI and GVMI were shown to be useful for distinguishing between vegetated and open water areas. Figure 2-1 shows the distribution of different land cover types in the space defined by the two indices.

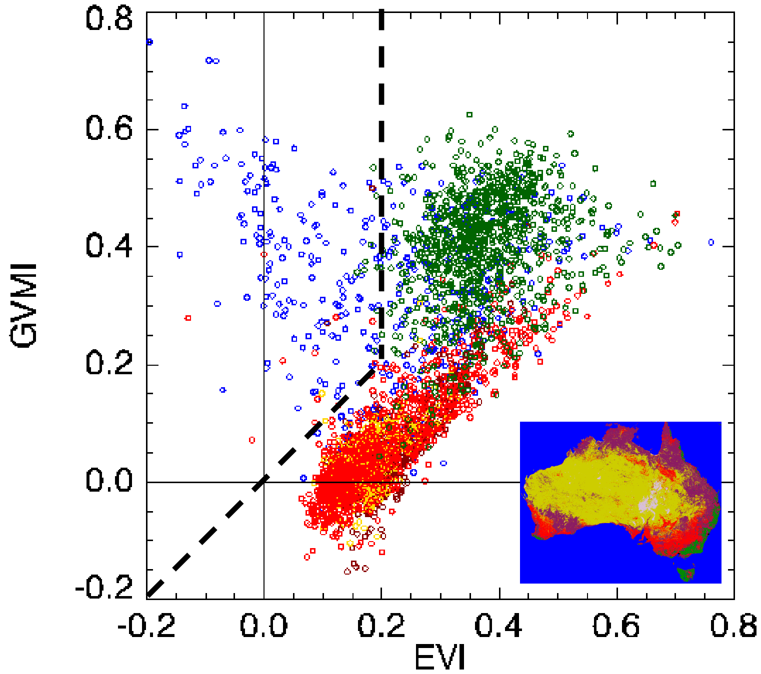


Figure 2-1. Scatterplot of the Global Vegetation Moisture Index (GVMI) and the Enhanced Vegetation Index (EVI) in Australia. Point color indicates vegetation type (inset map) as: blue – water, green – forests, red – grasslands and croplands, yellow – shrublands and brown – woodlands. The dotted line indicates the criteria for separating the open water from the vegetation domain.

An Open Water Index (OWI) was calculated as:

OWI= 0	when EVI ≥ 0.2	Equation 14
OWI= GVMI - EVI	when EVI < 0.2	Equation 15

Then an “Open Water Likelihood” index was calculated as:

$$OWL = \frac{1}{1+\exp(-50\cdot(OWI-0.1))}$$ Equation 16

The expression above gives a sigmoid function which is exemplified in Figure 2-2:

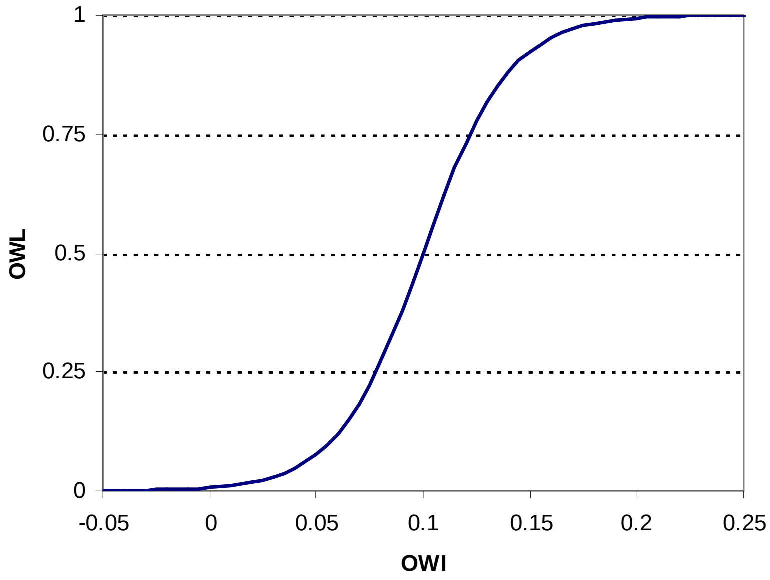


Figure 2-2. Relationship between the open water likelihood and the open water index through the sigmoideal function.

The OWL can be interpreted as the likelihood that a given pixel contains water or, additionally, as the proportion of the pixel occupied by open water. It is important to note that the two indices presented here have not been validated with field measurements.

Both the OWI and the OWL were calculated for the Australian continent using data from the nadir BRDF–adjusted reflectance (NBAR) product (MOD43B4). This product provides a 16–day, 1 km average reflectance corrected for bidirectional reflectance distribution function (BRDF) and atmospheric effects, creating an apparent reflectance that is not affected by the location of the sensor relative to the pixel at the time of acquisition (Schaaf et al. 2002) and is ideally suited for developing a product for monitoring vegetation condition over large areas. We obtained the full series of MOD43B4, collection 4 data for the Australian continent from 2000 to 2006. The image tiles were mosaicked and rectified to a geographical projection using the MODIS reprojection tool. The MODIS–NBAR reflectances were converted into monthly composites using a weighted averaging method:

$$\rho_m = \sum_{1}^{2 or 3} \rho_i \cdot p_{m/i}$$ Equation 17

where ρ_m is the reflectance in the month m, ρ_i is the reflectance in the 16–day composite i and $p_{m/i}$ is the proportion of days of month m included in the 16–day composite i. For example, February 2001, which had 28 days, included 1 day of composite 2–2001 (17 jan to 1 feb), 16 days of composite 3–2001 (2 feb to 17 feb) and 11 days of composite 4–2001 (18 feb to 5 mar). Therefore, the $p_{m/i}$ values for February 2001 were 0.04, 0.57 and 0.39. This method was applied to the seven reflectance bands included in the MODIS NBAR dataset. Using the monthly NBAR data images of the EVI and the GVMI were calculated as described above and the OWI and OWL were calculated. Finally, the proportion of each reach in the MDB occupied with open water was estimated from the OWL for each month from 2000 to 2006.

2.6 Irrigation water use estimation

Where monthly diversion data were available, they were used directly. In the case of New South Wales, annual diversion data only were available, and were disaggregated to monthly using the indirect estimation method similar to the wetland and floodplain estimation method in section 2.3 above.

Diversion data were available from state authorities as annual (New South Wales), monthly (Queensland) or daily (Victoria) estimates. The data were treated differently according to state.

- The Queensland data were used as supplied, though sometimes (as in the Warrego) the diversion data were for the whole catchment, whereas we dealt with four reaches within the catchment. In such cases, the reach from which the diversions were taken had to be decided from other information, often remote sensed, about the location of irrigation areas.
- The Victorian data were supplied by reach, and simply had to be aggregated from daily to monthly values.
- The New South Wales data were supplied by reach, but had to be disaggregated from annual to monthly. This was done by first estimating the actual evapotranspiration in irrigation areas using remote sensing, as described in Section 2.3 and in the companion report (Guerschman et al., 2008). The distribution of monthly diversion through the year was assumed to be proportional to the distribution of monthly differences between the evapotranspiration and the rainfall:

$$\left.\begin{array}{lll} Q_{divert,i} = Q_{divert,Ann} \dfrac{(AET_i - P_i)}{\sum_{j=1}^{12}(AET_j - P_j)} & & (AET_i - P_i) > 0 \\ Q_{divert,i} = 0 & & (AET_i - P_i) \le 0 \end{array}\right\} \quad \text{Equation 18}$$

  where $Q_{divert,i}$ is the diversion in month i, $Q_{divert,Ann}$ is the annual diversion in month, AET_i and P_i are the actual evapotranspiration and precipitation in month i, and the sum $\Sigma(AET_j - P_j)$ is taken over the year but only for the months in which evapotranspiration is greater than precipitation.

2.7 Indicators of understanding of the water accounts

We used two main indicators of quality of understanding of the water accounts. The first is the proportion of the flow that is gauged or attributed. Instinctively we feel that we are better able to understand and predict behaviour of a river reach in which a large proportion of the flow is measured or confidently attributed. The second measure is the proportion of the flow variance that is gauged or attributed. In principle, a large proportion of the flows might be measured, but the actual proportion might vary from one flow event to the next (in other words, the error, ε, varies, perhaps randomly). Thus, while the average flow might be well measured, the variability might be less well measured. Examining the proportion of flow variance gauged or attributed tests this possibility.

2.7.1 Fraction of flows gauged and attributed

With reference to equation (2), we assumed that the total flow, Q_{tot}, is the larger of ($Q_{in,measured}$ + $Q_{in,estimated}$) (which we term the attributed inflows) and ($Q_{out,measured}$ + $Q_{out,estimated}$) (which we termed the attributed outflows). That is, we assumed that the smaller of the flows is missing some unmeasured and unattributable flows, and that the larger of the attributed inflow or outflow is the better estimate of the total flow. Other assumptions may be made. The fractions of flow measured ($F_{in,gauged}$) and confidently attributed ($F_{in,attributed}$) are, for inflow components:

$$\left.\begin{array}{l} F_{in,gauged} = \sum_{i=1}^{n} Q_{i,in,measured} \Big/ \sum_{i=1}^{n}(Q_{i,tot}) \\ F_{in,attributed} = \sum_{i=1}^{n} Q_{i,in,attributed} \Big/ \sum_{i=1}^{n}(Q_{i,tot}) \end{array}\right\} \quad \text{Equation 19}$$

where the sum (1 to n) is taken over all the months in the record. For outflow components, ($F_{out,gauged}$ and $F_{out,attributed}$), the first term on the right hand side is the corresponding Q_{out} term. For the total flow (i.e. inflows plus outflows), the fractions ($F_{tot,gauged}$ and $F_{tot,attributed}$) are:

$$\left.\begin{aligned} F_{tot,gauged} &= \left(\sum_{i=1}^{n} Q_{i,in,measured} + \sum_{i=1}^{n} Q_{i,out,measured}\right) \Big/ 2\sum_{i=1}^{n}\left(Q_{i,tot}\right) \\ F_{tot,attributed} &= \left(\sum_{i=1}^{n} Q_{i,in,attributed} + \sum_{i=1}^{n} Q_{i,out,attributed}\right) \Big/ 2\sum_{i=1}^{n}\left(Q_{i,tot}\right) \end{aligned}\right\}$$

Equation 20

which are also the averages of the corresponding F_{in} and F_{out} terms.

2.7.2 Fraction of variance of flows gauged and attributed

The fractions of variance of the flow measured ($U_{in,gauged}$) and confidently attributed ($U_{in,attributed}$) are, for inflow components:

$$\left.\begin{aligned} U_{in,gauged} &= \sum_{i=1}^{n}\left(Q_{i,in,measured} - \bar{Q}_{in,measured}\right) \Big/ \sum_{i=1}^{n}\left(Q_{i,tot} - \bar{Q}_{tot}\right) \\ U_{in,attributed} &= \sum_{i=1}^{n}\left(Q_{i,in,attributed} - \bar{Q}_{in,attributed}\right) \Big/ \sum_{i=1}^{n}\left(Q_{i,tot} - \bar{Q}_{tot}\right) \end{aligned}\right\}$$

Equation 21

where the sum (1 to n) is taken over all the months in the record. For outflow components, ($U_{,out,gauged}$ and $U_{out,attributed}$), the first term on the right hand side has the corresponding Q_{out} terms, and by analogy with Equation 20, $U_{tot,gauged}$ and $U_{tot,attributed}$ are the averages of the corresponding F_{in} and F_{out} terms.

2.8 Gaining and losing reaches

We defined gaining and losing reaches according to the difference between the main stem inflow and outflow gauges. If the outflow gauge records greater flow than the inflow gauge, the reach has gained water (from a tributary or from direct runoff into the reach), and we termed this a gaining reach. Conversely, a losing reach is one in which the outflow gauge records less than the inflow gauge, and the reach has lost water to diversions, distributaries or floodplain evapotranspiration.

3 Results: Summary of water accounts for the Murray-Darling Basin

The reach-by-reach water accounts are contained within the region reports of the Murray-Darling Basin Sustainable Yield project. Here, we concentrate mainly on the summary water accounts for the whole basin.

3.1 Data availability and accounting framework

The total number of streamflow gauges that has ever been active in the MDB is 1090 with an average of 20 years of data per gauge (as at 2007); 881 gauges have data after 1990. The number of active streamflow gauges in each year is shown in Figure 3-1. The total number of rainfall gauges ever active is 6,232 with an average of 45 years data, but only 52 percent have data after 1990. The distribution of gauges is uneven across the MDB (Figure 3-1) and the network can be more than ten times more dense (e.g. Campaspe region) or less dense (e.g. Paroo region) than the basin average. Rainfall gauging is mostly a function of population density, whereas streamflow gauging appears to vary with the importance of river water resources and the complexity of the surface water system. The number of gauges active during the water accounting period 1990 to 2006 is around 600, but fewer satisfied our criteria for defining accounting reaches: many gauges are on tributaries, not all had sufficient quality data, and sometimes reaches were aggregated to coincide with river model units. We defined 145 accounting reaches, varying from 1 (Paroo) to 32 (Murray) per region (Figure 3-2).

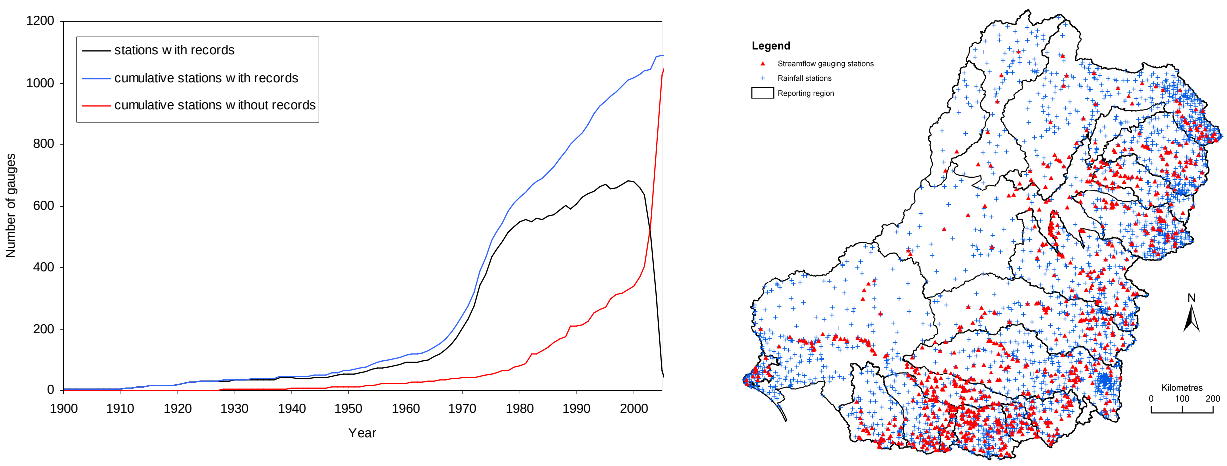


Figure 3-1. Left: The number of new, decommissioned and total active streamflow gauges in the MDB (the steep recent decline is probably mainly due to data latency in available databases). Right: The distribution of rainfall and streamflow gauging stations active after 1990.

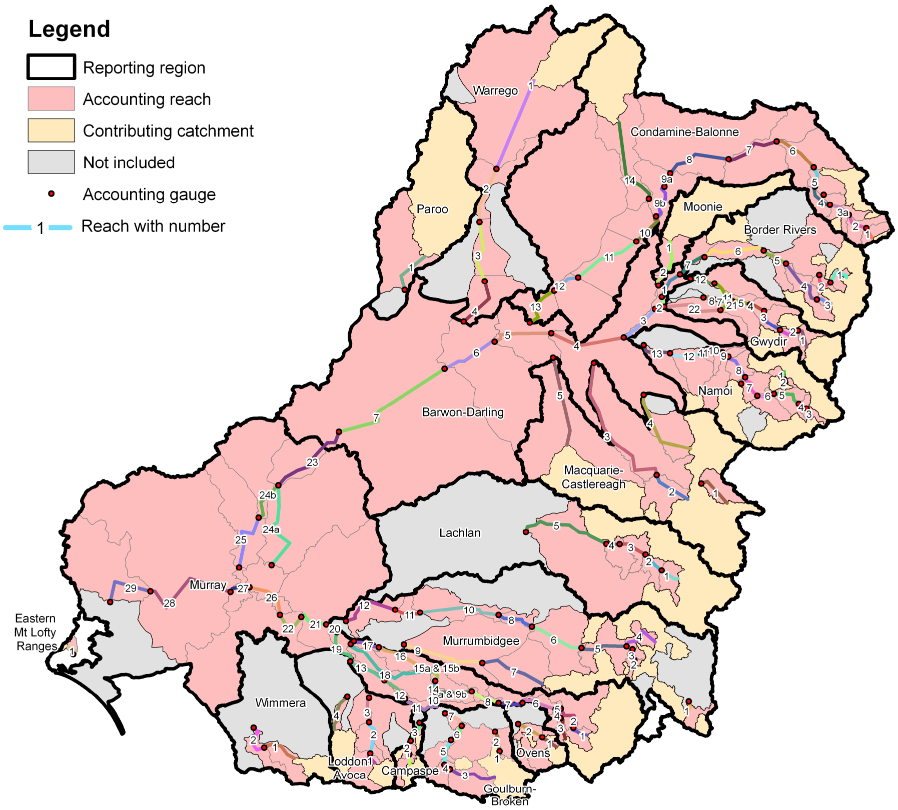


Figure 3-2. Map of river water accounting reaches.

3.2 Gauged and attributed gains and losses

In the next section, we will examine the actual water accounts in the Murray-Darling Basin. First, however, we will in this section examine the quality of the water account information, using the indicators described in section 2.7 – the fractions of gauged and attributed flows, and the fractions of gauged and attributed variance of flows.

3.2.1 Distribution of gauged and attributed gains and losses in a catchment: examples of Lachlan and Condamine-Balonne

In some of the regions the gauged part of the water balance was a large fraction of the total in all reaches. An example is the Lachlan region, where accounts were developed for five reaches from Cowra to Jemalong (Figure 3-3; cf. Figure 3-2).

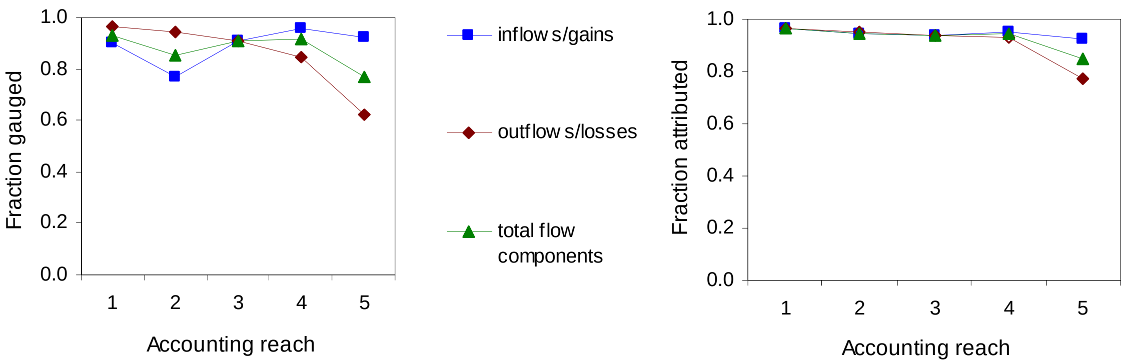


Figure 3-3. Fraction gauged and attributed (gauged plus estimated) in the Lachlan for reaches from Cowra (accounting reach 1) to Jemalong (accounting reach 5). The plot shows the greater certainty in the upstream areas, and greater uncertainty in the downstream.

Whether considering inflows and gains, or outflows and losses, or all components of the water balance combined, the gauged fraction was generally greater than 0.8. The reach outflows were generally the better gauged in the upstream, where ungauged runoff was a large part of the inflows. In the downstream, the inflows were the better gauged, since runoff contributions were generally small, whereas ungauged losses were a significant part of the outflows. Using supplementary models for the ungauged fraction brought the fraction of gauged plus confidently estimated components (the sum of which we refer to as attributed) to greater than 0.9 in most cases. The additional estimates from models were mostly runoff in the upstream reaches and losses to the floodplain and wetlands in the downstream reaches.

The Condamine-Balonne (Figure 3-4) contrasts with the Lachlan where 13 accounting reaches were developed. In many reaches a smaller fraction of the flows was gauged, often lower than 0.5. Again, outflows were generally the better gauged in the upstream, whereas inflows were generally better gauged in the downstream. Many regions in the MDB showed features similar to the Condamine-Balonne.

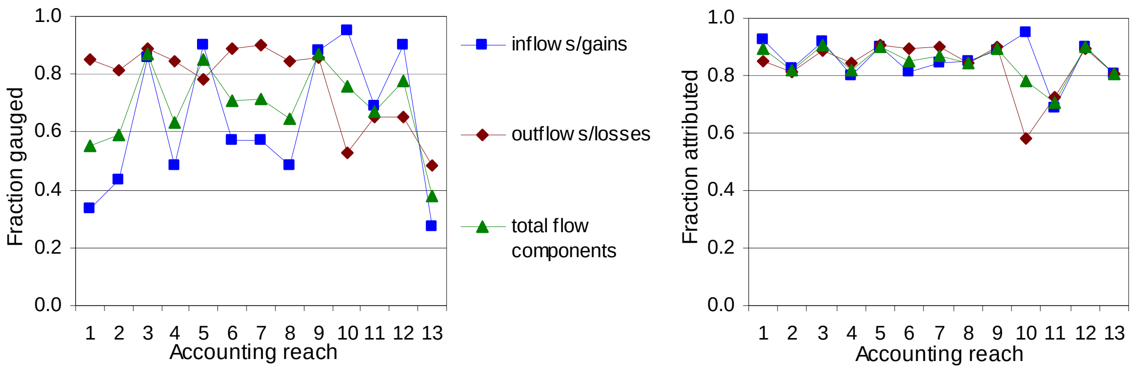


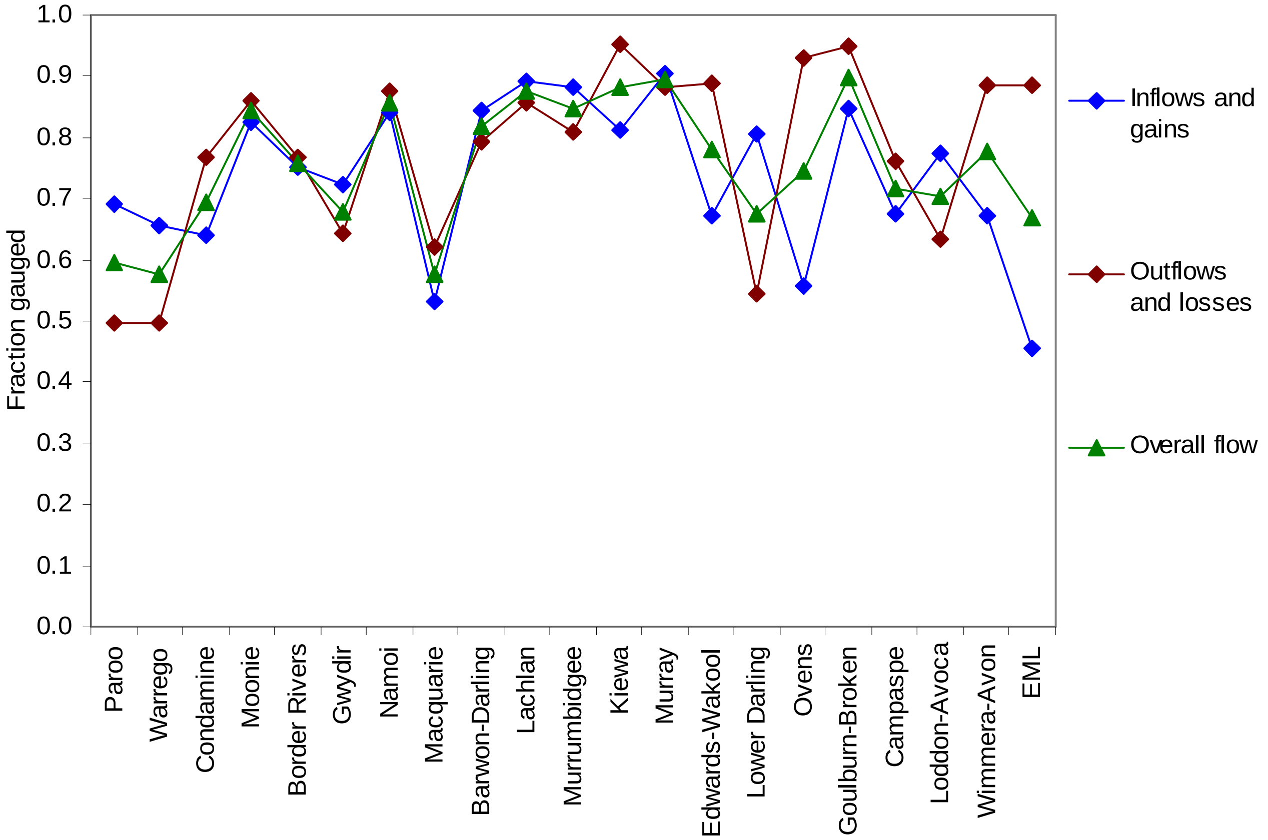
Figure 3-4. Fraction gauged and attributed (gauged plus estimated) in the Condamine-Balonne for the reaches from Warwick (accounting reach 1) to Collerina (accounting reach 13)

3.2.2 Distribution of gauged and attributed gains and losses in the Murray-Darling Basin

The fraction of gauged and attributed gains and losses varied from region to region, as well as within catchments as demonstrated above. Figure 3-5 shows the distribution of region averaged fractions of gauged and attributed flows. These results are the fraction gauged and attributed, averaged across the gauges in a catchment, which is not the same as the overall fraction gauged in a catchment: we will return to this point later. The Murray catchment is divided into several sections in the figure – the Murray main stem, the Kiewa, the Lower Darling and the Edwards-Wakool bypass. These sections behave differently and had different qualities of gauging.

The fraction gauged across the MDB was generally highest in the southeast, with the exception of inflows into the Ovens which included ungauged tributaries. Although the Murray and Kiewa were well gauged, the Lower Darling and the Edwards-Wakool were less well gauged. The fraction attributed across the MDB was generally around 0.85 to 0.9, though again the highest fractions were in the southeast. The lowest fractions were in the Lower Darling, the Campaspe and the Loddon Avoca. The implication is that average flows (time averaged, themselves spatially averaged across catchments) are reasonably well understood across the basin, especially in the southeast, though we are dealing here with spatial catchment averages rather than individual values. Whether 'reasonably well understood' is good enough for a particular application depends on the demands of the application.

The lowest fractions gauged and attributed in any accounting reach in each region are shown in Figure 3-6. As indicated by the examples of the Lachlan and Condamine-Balonne in the previous section, the lowest inflow fractions gained and attributed tended to be in the upper reaches of a region, whereas the lowest outflow fractions gained and attributed tended to be in the lower reaches. Although the minimum faction gauged varied greatly from catchment to catchment, in most cases the fraction attributed was greater than 0.6, again demonstrating that even in the worst case the understanding of average flows is reasonable. Again, whether 'reasonable' is good enough for a particular application depends on the demands of the application.



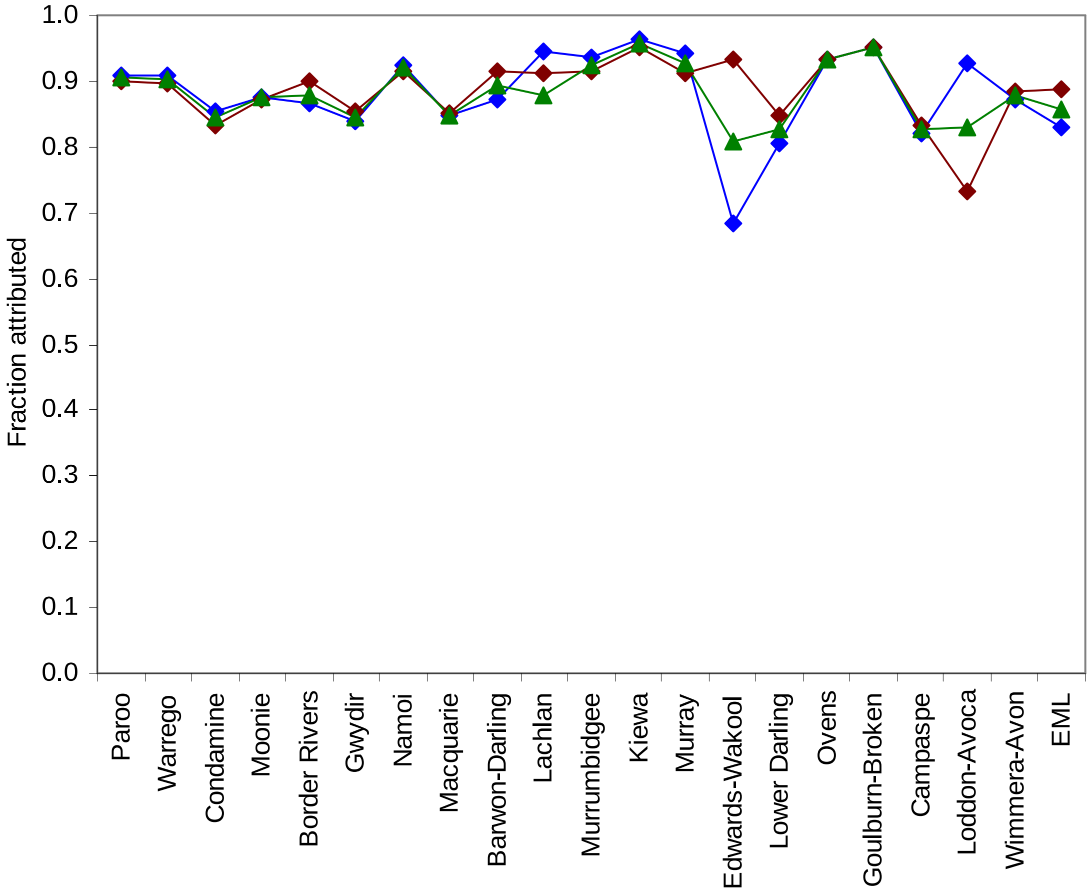


Figure 3-5. Upper: average fraction of flows gauged in the Murray-Darling Basin regions. Lower: average fraction of flows attributed in the Murray-Darling Basin regions.

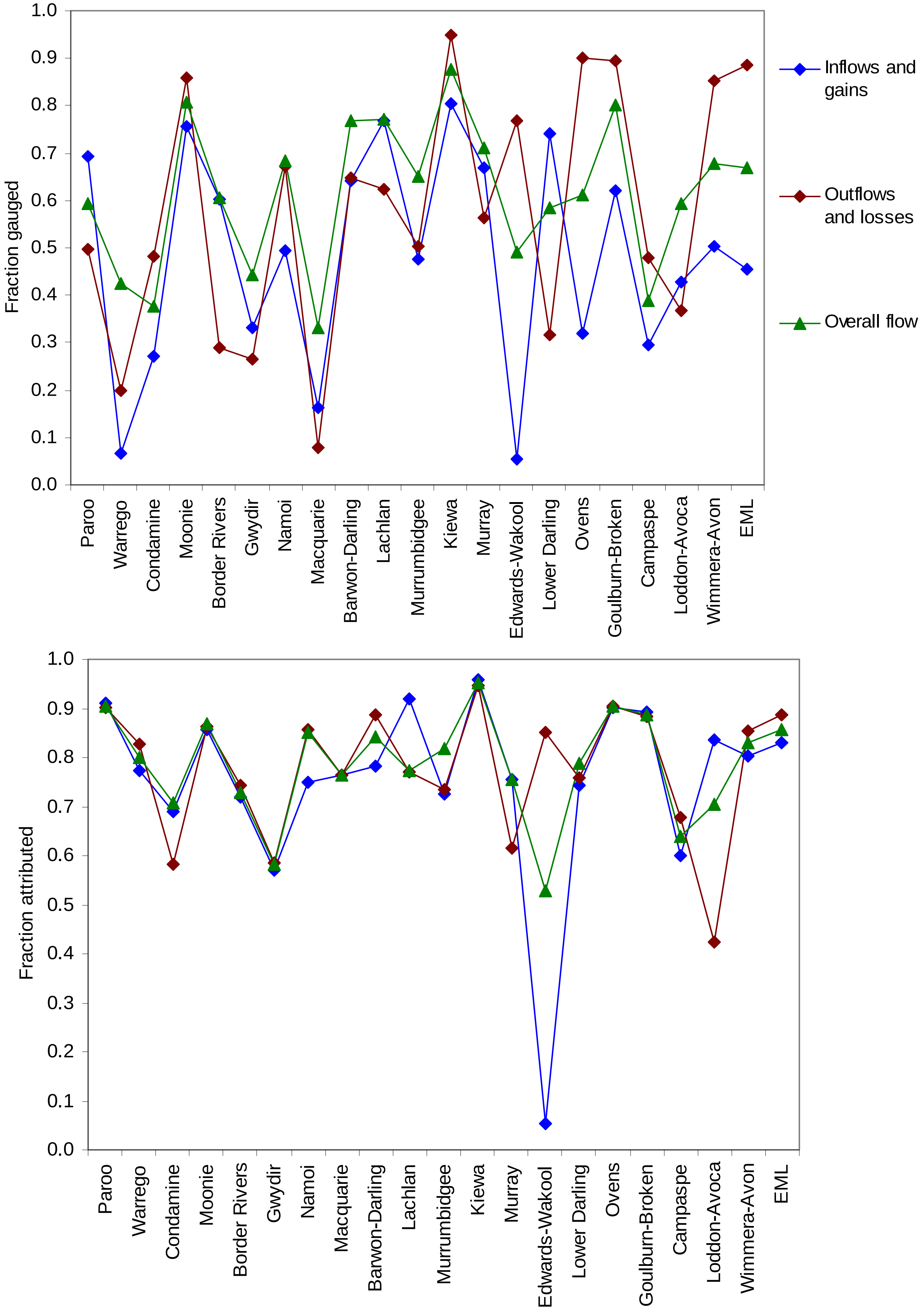
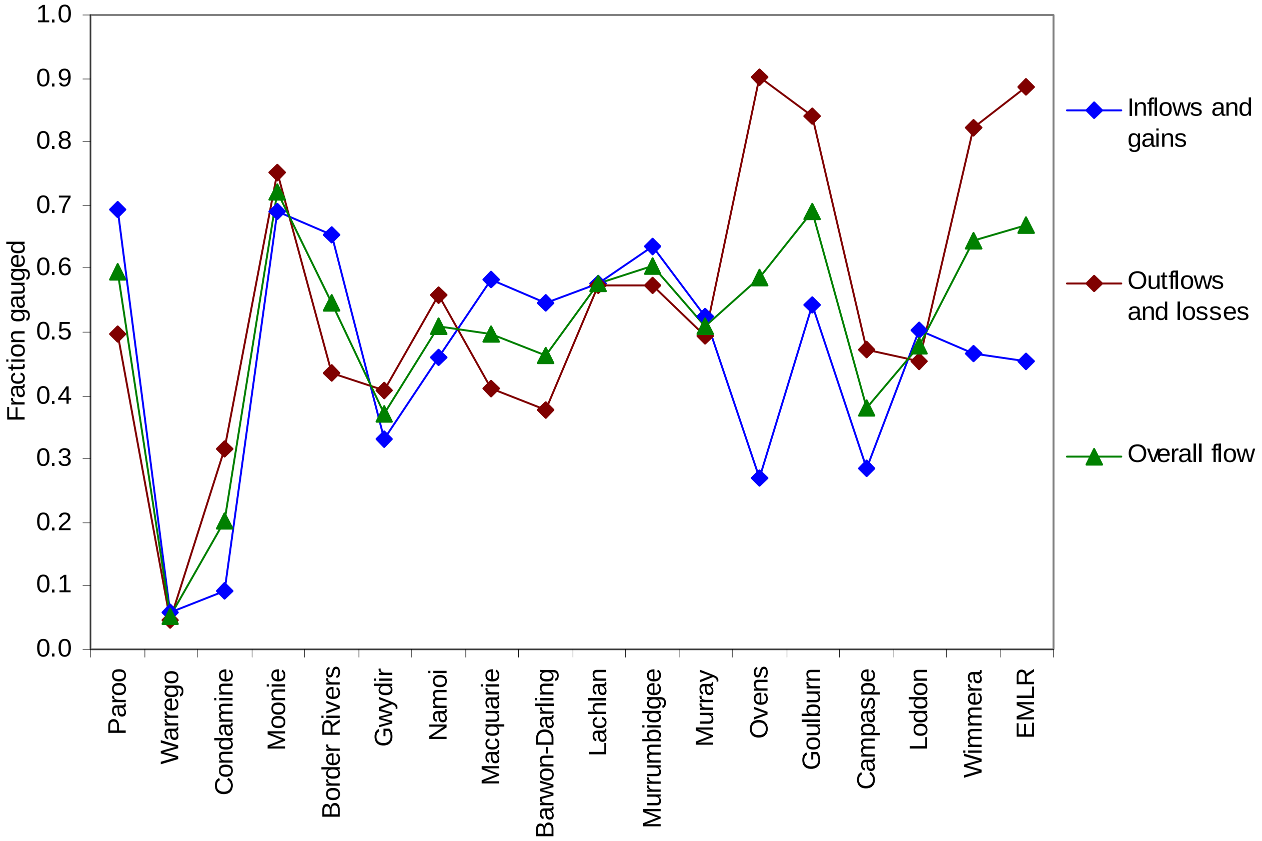


Figure 3-6. Upper: lowest fraction of flows gauged in the Murray-Darling Basin regions. Lower: lowest fraction of flows attributed in the Murray-Darling Basin regions.



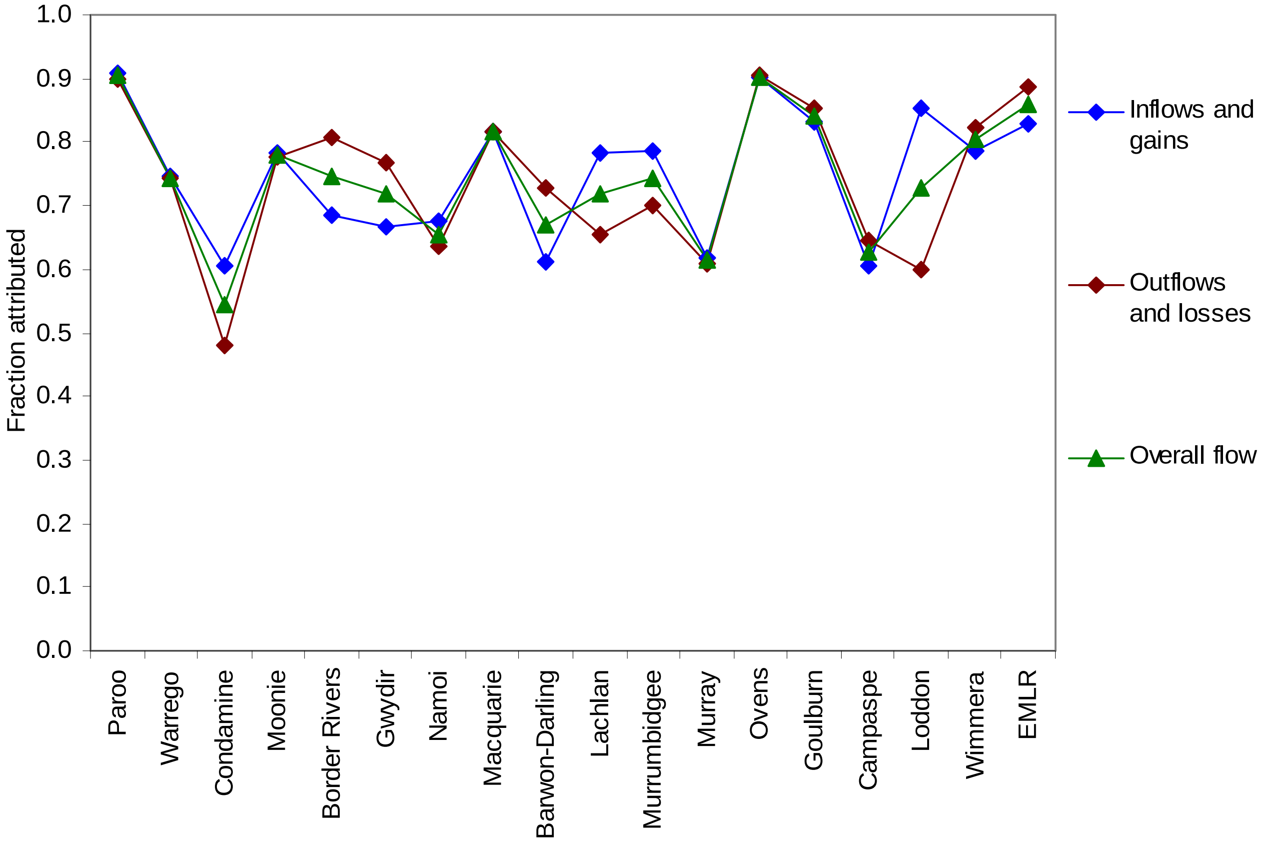


Figure 3-7. Upper: overall fraction of flows gauged in the Murray-Darling Basin regions. Lower: overall fraction of flows attributed in the Murray-Darling Basin regions.

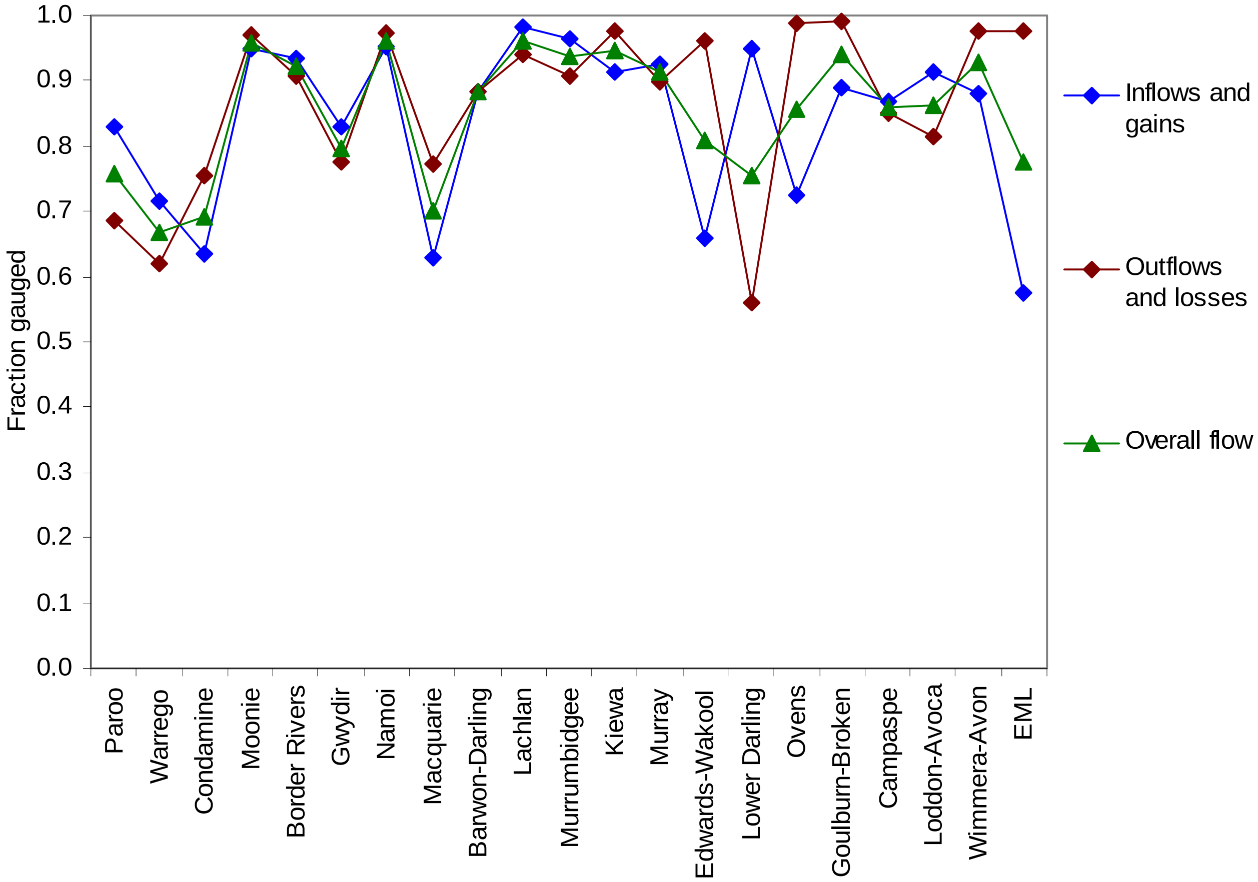
As mentioned above, the discussion has focussed on the fractions gauged and attributed averaged (or a minimum) across a catchment. This is not the same as the overall proportion of flow in a catchment that is gauged and attributed. We calculate this from the sums of gauged inflows and attributed flows as fractions of the total inflows, and likewise for outflows and total flows. Noting that ungauged and unattributed gains and losses sum across a catchment, whereas outflows in one reach are the inflows into the next reach and therefore do not sum across the catchment, the overall catchment fractions gauged and attributed is less than that averaged across the reaches. The catchment fractions gauged and attributed are shown in Figure 3-7.

3.2.3 Distribution of gauged and attributed variance of gains and losses in the Murray-Darling Basin

As noted in Section 2.7, while the average flow might be well measured, the variability might be less well measured. Examining the proportion of flow variance gauged or attributed tests this possibility. Figure 3-8 shows the fraction of variance of gauged and attributed flows, averaged by catchment. The Murray was again split into four sections. The fractions in the figure were generally slightly greater than the analogous values in the fractions of flow shown in Figure 3.5. This arose because the estimated total gauged flows were generally highly correlated with the gauged flows: or, equivalently, the estimated missing flow components were generally highly correlated with the gauged flows.

Thus, the variance accounted for was generally slightly greater than the actual fractions of flow accounted for. The implication is that, while we have a reasonable (subject to the requirements of the application) understanding of average flows (time averaged, themselves spatially averaged across catchments), we also have a reasonable understanding of the variability of flows within the basin. Again, however, the minimum values are worth checking, and they are shown in Figure 3-9. The minimum in each catchment of fractions of flow variance gauged and attributed was sometimes greater, but sometimes less than the analogous values in the fractions of flow shown in Figure 3-6.

In several cases, the least fractions of variance coincided with the least fraction of average flow. The implication is that, while we understand catchment average behaviour reasonably well, where the flows were not well gauged we do not understand flow very well (even though, as shown in the previous section, we understand average flows reasonably well). Thus, for less well gauged reaches, we appear not to understand the overall behaviour particularly well. We might expect in these reaches, models will be less well founded, and predictions less confident. This is particularly the case in many downstream reaches of catchments, often where there are the greatest flood effects and diversions. This expectation is examined in the companion report (van Dijk et al., 2008).



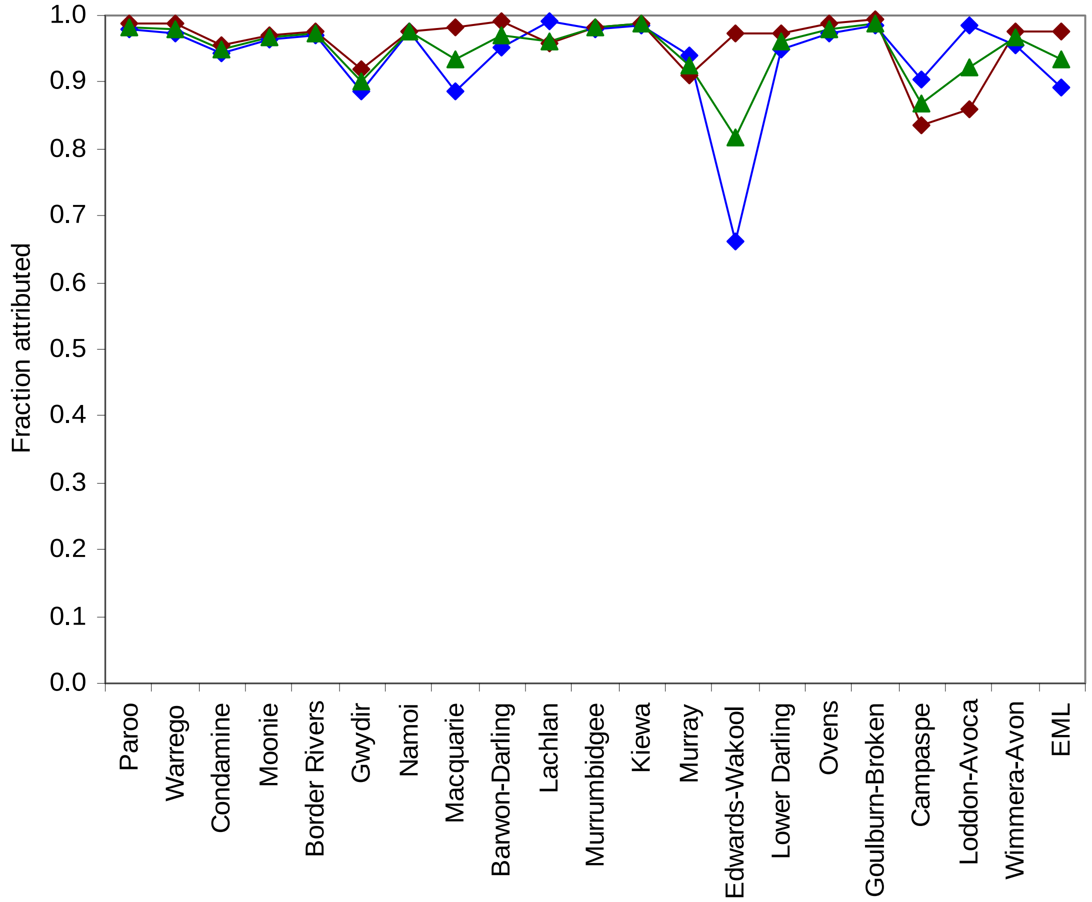


Figure 3-8. Upper: average fraction of variance of flows gauged in the Murray-Darling Basin regions. Lower: average fraction of variance of flows attributed in the Murray-Darling Basin regions.

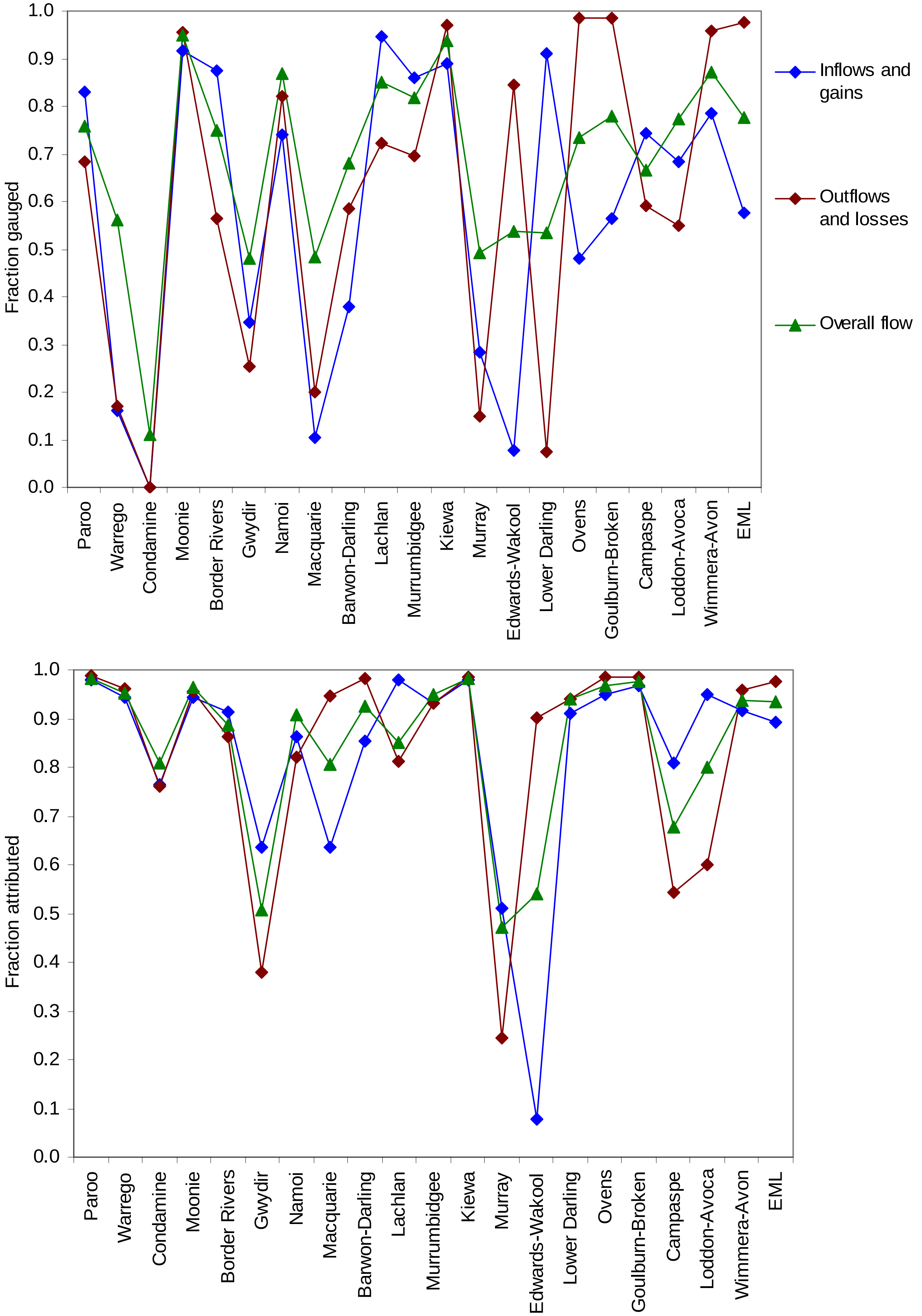


Figure 3-9. Upper: lowest fraction of variance of flows gauged in the Murray-Darling Basin regions. Lower: lowest fraction of variance of flows attributed in the Murray-Darling Basin regions.

3.3 Water use in the Murray-Darling Basin

3.3.1 Broad pattern of water use in the Murray-Darling Basin

The estimated long term average net rainfall (rainfall minus actual evapotranspiration) across the MDB from 2000–2004 is shown in Figure 3-10, where blue colours show a rainfall excess and red colours a rainfall deficit. The dark red colours typically represent open water bodies and irrigation areas, lighter red colours mostly represent ephemeral floodplains and wetlands or vegetation with access to stored surface or groundwater. The importance of water resource generation in the upper Goulburn, Ovens, Murray and Murrumbidgee is emphasised by the dark blue colour.

The broad pattern of flows and the monthly variability of the flows is shown in Figure 3-11. The greater flows and lower flow variability of the Murray than the Darling and its tributaries is readily apparent.

The mapped irrigation areas and wetlands are shown in Figure 3-12. The results usually agreed reasonably well with BRS mapping but notable differences did occur. For example, the methodology used by BRS sometimes led to wetlands being identified as irrigation areas. Merging information from the different data sources removed some of the issues in individual data sets but considerable QA/QC was still required. Over an area the size of the MDB, discrepancies could be efficiently identified and corrected using visual comparison with higher LANDSAT and SPOT resolution imagery.

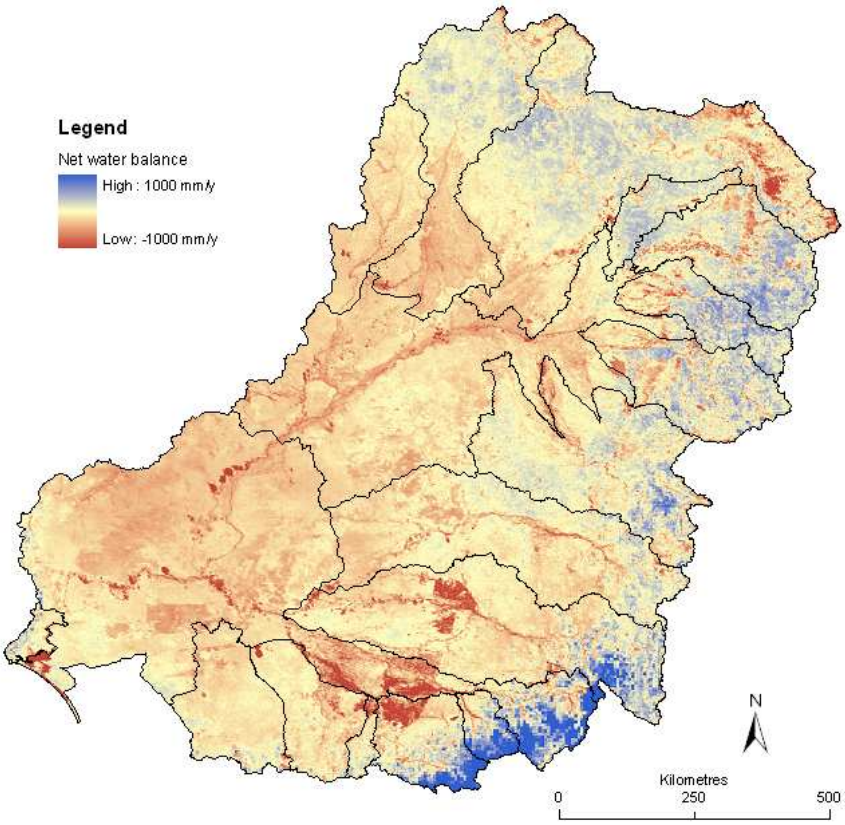


Figure 3-10. Map of estimated net water balance (rainfall minus actual evapotranspiration). Blue areas are runoff generating areas, whereas red colours show irrigation areas, wetlands, water bodies and vegetation with access to stored surface or groundwater.

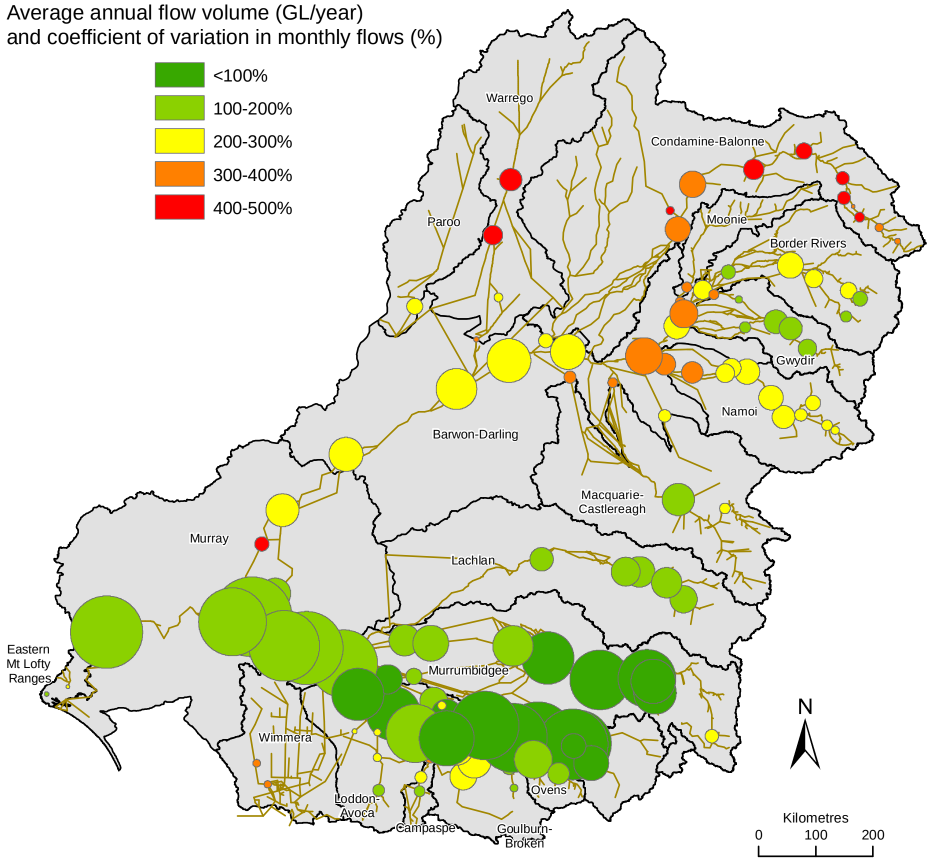


Figure 3-11. Flows and flow variation in the Murray-Darling Basin.

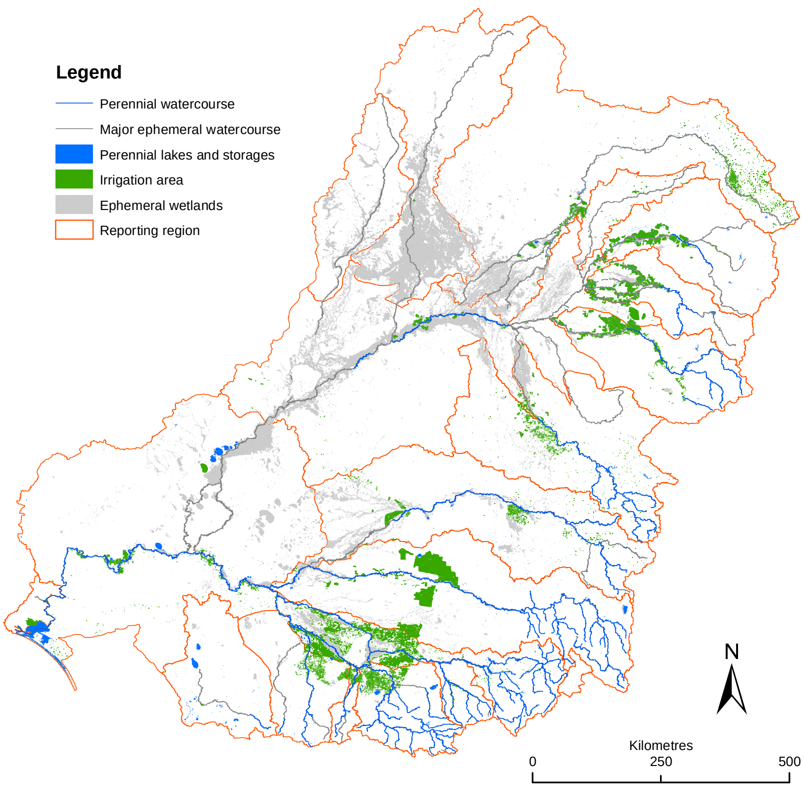


Figure 3-12. Mapped floodplain/wetland and irrigation areas.

3.3.2 Water use distribution in a catchment: examples of Lachlan and Condamine-Balonne

Figure 3-13 shows outflow components of reach-by-reach water accounts for the Lachlan and the Condamine-Balonne. These should be interpreted with caution. Firstly, the Lachlan outflow at Jemalong was much greater than the discharge of the Lachlan into the Murrumbidgee, but this was the last reach for which we could establish a reliable water account for the full period. Secondly, the main stem outflows are water that passes from one reach to the next (ie they are not cumulative), whereas the other outflows and losses accumulate. Thus, while the average fraction of water diverted per reach in the Condamine-Balonne was about 6 percent of the main stem outflow in each reach, the long term average diversion of 248 GL/year from the catchment was about 18 percent of the long term average inflows. In the Lachlan, the total long term average diversion to Jemalong of 164 GL/year was about 16 percent of the long term average inflows, but there were further diversions downstream. The cumulative attributed river and floodplain losses (direct evaporation and floodplain evapotranspiration) were 367 GL/year for the Condamine-Balonne and 106 GL/year for the Lachlan region.

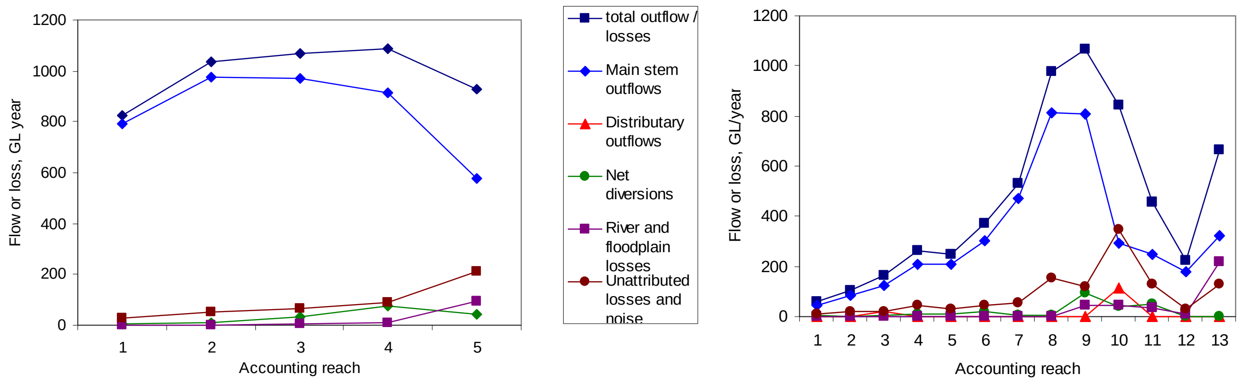


Figure 3-13. Outflow and loss components in, left: the Lachlan for reaches from Cowra (accounting reach 1) to Jemalong (accounting reach 5); and right: the Condamine-Balonne for the reaches from Warwick (accounting reach 1) to Collerina (accounting reach 13).

The unattributed term ε was commonly the next largest loss term after main stem outflows. The exception was reach 13 in the Condamine-Balonne region, where we were able to attribute much of the ungauged loss to consumption of water as evapotranspiration on the floodplain. The term ε can be associated with water that passed from one reach to the next, with accumulated losses and outflows, and with measurement error, but we cannot tell in what proportion. It is tempting to associate them mostly with ungauged losses, but since there were compensating unattributed gains and noise, much of the unattributed loss and noise probably should not simply be assumed to be accumulated losses. The total unattributed losses and noise were 1155 GL/year for the Condamine-Balonne and 447 GL/year for the Lachlan, whereas the unattributed gains and noise were 911 and 282 GL/year respectively.

3.3.3 Water use distribution in the Murray-Darling Basin

The relative magnitudes of the outflows, diversions, estimated losses and unattributed losses varied from region to region (Figure 3-14). The end-of-system outflows are that at the last accounted gauge and may not be the true catchment outflow (particularly in the Paroo, Warrego and Lachlan). In the Murray, the last accounted gauge was at Lock 1, and the long term average measured flow past this gauge was approximately 1,600 GL/year greater than the modelled discharge to the sea (figures taken from the MDBC (2007)): water use between the two points comprised primarily diversions in South Australia and consumption as evaporation from the lower lakes. The figure shows that generally (the Ovens being the greatest exception), the proportion of flow diverted increased towards the wetter southeast, and the floodplain, river and distributary consumption of flows decreases. The proportion of unattributed losses did not seem to follow any particular pattern.

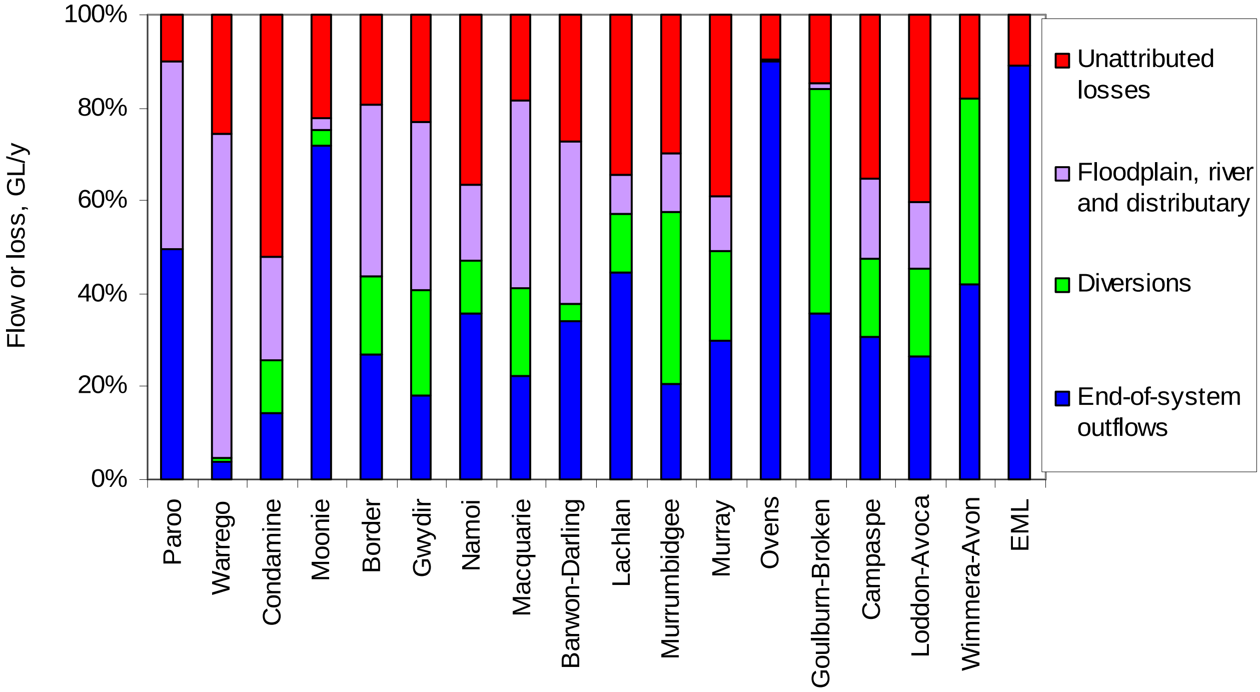
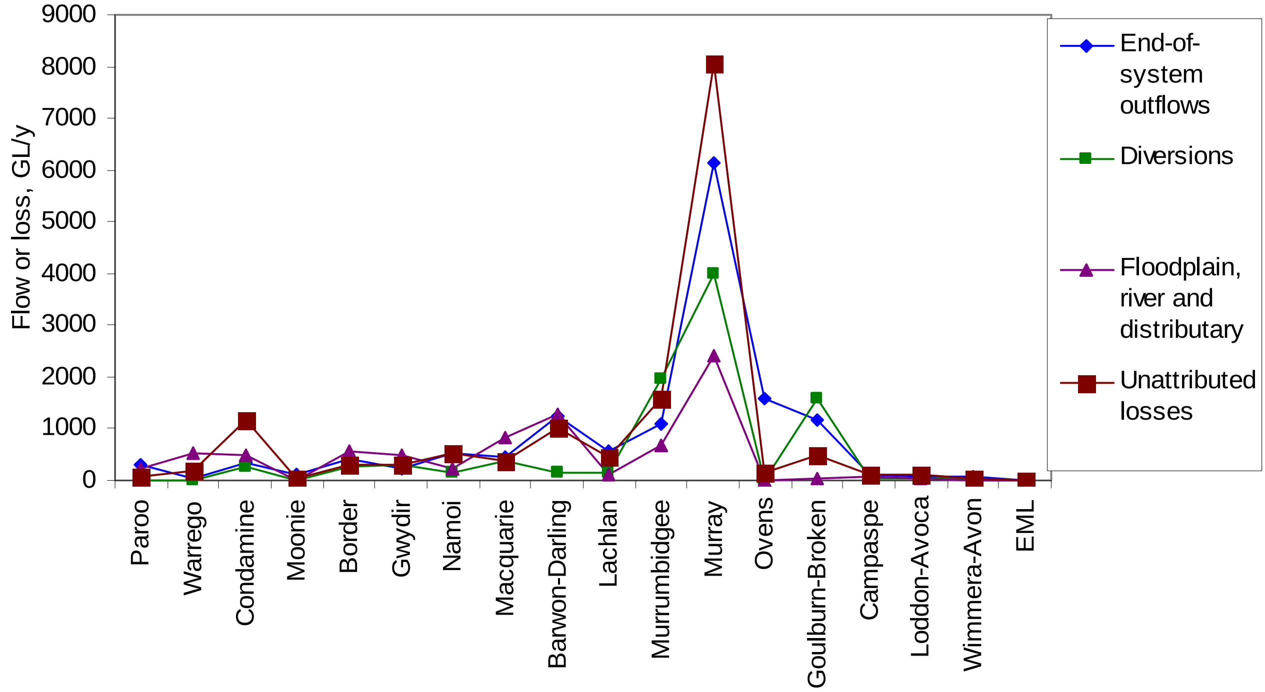


Figure 3-14. Outflow and loss components in the Murray-Darling Basin regions, expressed as a percentage of total outflows. The analyses of the Murray have not been completed at the time of writing. The end-of-system outflows are that at the last accounted gauge and may not be the true catchment outflow (particularly in the Paroo, Warrego and Lachlan).

The end of system outflows (at Lock 1), diversions, floodplain consumption and unattributed losses were much greater in the Murray than any of its tributaries including the Darling (Figure 3-15). The dominance of the Murray, Murrumbidgee and Goulburn-Broken in providing irrigation diversions in the system is clear.



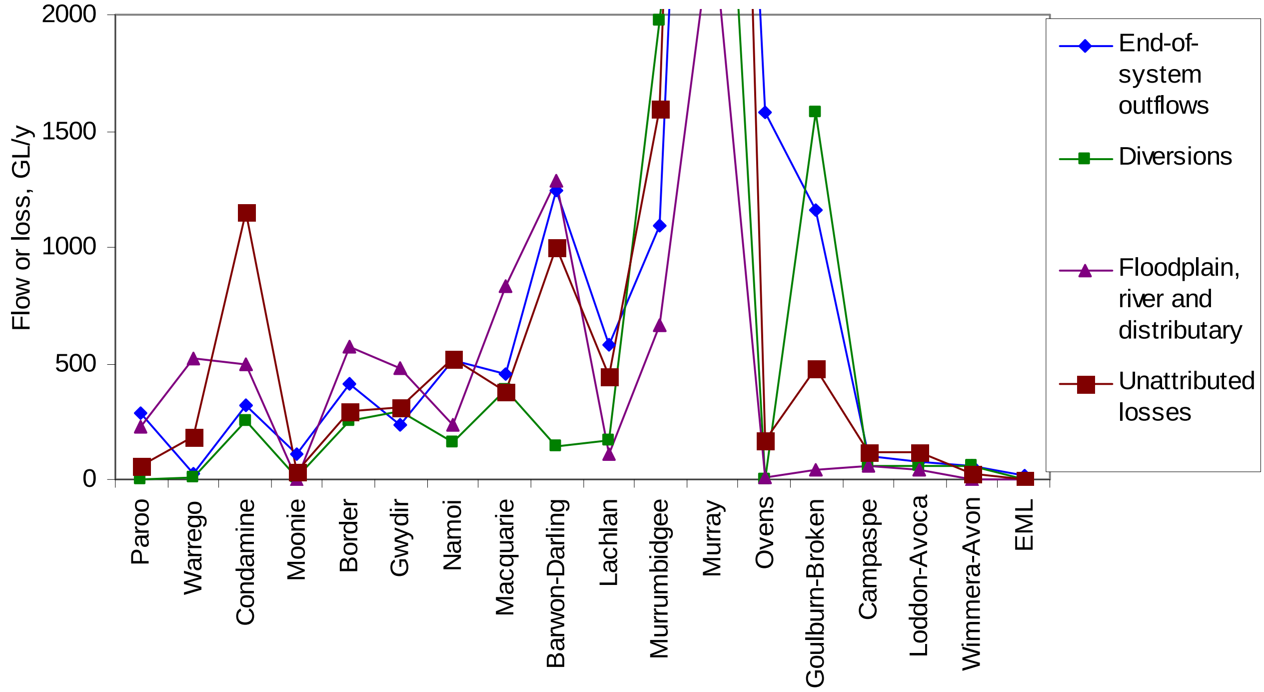


Figure 3-15. Outflow and loss components in the Murray-Darling Basin regions. The lower figure is the same as the upper, plotted at a scale on the Y-axis that shows the detail of the rivers other than the Murray. The analyses of the Murray has not been completed at the time of writing. The end-of-system outflows is that at the last accounted gauge and may not be the true catchment outflow (particularly in the Paroo, Warrego and Lachlan).

3.3.4 Overall water balance / account of the Murray-Darling Basin

We used the region-by-region water accounts to calculate the overall water balance/water account for the MDB. In the calculations, quantities such as local inflows, floodplain losses, diversions and unattributed losses and gains were summed across all regions. Inflows, however, were summed only across headwater catchments: that is, tributary inflows into the Barwon-Darling and the Murray were not summed, as these were already counted in the inflows of catchments upstream. Similarly, the end of system outflow was that of the Murray alone. In the Murray, the last accounted gauge is at Lock 1, and the long term average measured flow past this gauge was approximately 1,600 GL/y greater than the modelled discharge to the sea (figures taken from the MDBC (2007)): water use between the two points comprised primarily diversions in South Australia and consumption as evaporation from the lower lakes.

The resulting water account is shown in Table 3-1. River, lake and wetland evaporation is from open water in the rivers and wetland associated with the accounting reaches. It did not include many reservoirs in the headwaters of the system (Hume, Dartmouth, and Eildon, for example). Nor did it include Lake Victoria, Menindee Lakes or the Lower Lakes.

Table 3-1. Water balance/water account for the Murray-Darling Basin. Figures are long term average quantities for 1990-2006, in GL/year. The end of system outflow is that at Lock 1, which is the outflow from the last gauged reach, whereas the discharge past the barrages is of an order 1600 GL/y less than that.

Gauged inflows	14,836
Local inflows	8,567
Subtotal gains	23,403
Unattributed gains and noise	14,270
End of system outflows	6,156
Net diversions	9,393
River and floodplain losses	3,667
Reach evaporation	3,102
Subtotal losses	22,317
Unattributed losses and noise	15,871

The account is approximate, because:

- individual account could not be established for some river reaches and thus there are gaps in the network – for example, the last accounted reach on the Lachlan ended at Jemalong, and much of the flow past that point was used in diversions and floodplain losses before the Lachlan flows into the Murrumbidgee; these missing diversions and losses were not counted in the total diversion and losses, though the water flowing past Jemalong was of course counted.
- similarly, where there was a gap, the accounted distributary flow into some reaches did not match the outflow at the last accounted gauge above the gap, and the difference in the flows was counted in the unattributed flows; the Lachlan is again an example.
- the unattributed gains or losses in some outflow (end of catchment) may appear as unattributed losses or gains in the next region – that is, there may be compensating errors due to, for example, timing errors in measurements; thus, there may be double counting of unattributed gains and losses.
- the account does not balance fully (the mass balance error is 515 GL / year), with the main error being the mass balance error in the Murray due to the mismatched gauged periods in some sections.

The overall inflow into the system of about 23,000 GL/year was close to the commonly quoted value (eg Kirby et al., 2006c). The diversions were the largest use of the water, consuming 42 percent of the water use accounted for.

River evaporation consumed about 14 percent, floodplain evapotranspiration about 16 percent, and end-of-system flows (i.e. past Lock 1) flows consumed 28 percent of water use accounted for. According to the MDBC (2007), the long term average (1998-2006) evaporation for Lake Victoria was 123 GL/year and that for Menindee was 345 GL/year. The combined evaporation from other lakes excluded from the water accounts was perhaps of order 1,000 GL/year, based on the figures reported in the MDBC (2007). The Lower Lakes contributed around 750 GL/year to evaporation (Close, 2002). Thus the total evaporation from open water in the Murray-Darling Basin was perhaps of order 5,000 GL/year. This is higher than the estimate given by Kirby et al. (2006c) of 3,000 GL/year, with the main difference being the much higher river reach evaporation estimated in this report, using the more robust method described in Section 2.

The figure for floodplain evapotranspiration consumption given here of about 3600 GL/year is a direct estimate, and lower than the 8000 GL/year given by Kirby et al (2006c) based on the balance remaining after other components were estimated.

The overall fractions gauged and attributed for the Murray-Darling Basin are shown in Table 3-2.

Table 3-2. Overall fractions of flow gauged and attributed in the Murray-Darling Basin

	Inflows	Outflows	Total
Fraction gauged	0.39	0.41	0.40
Fraction attributed	0.62	0.58	0.60

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4 Key findings

4.1 Attribution of ungauged gains and losses

Water accounting showed that, on average, about 77 percent of gains and losses in individual reaches were gauged, but with a range from about 0 percent (none of the flow gauged) to close to 100 percent (all the flow gauged). About half the ungauged flows could be attributed to runoff and river and floodplain evapotranspiration using models, bringing the average of the attributed gains and losses to about 89 percent. The remaining unattributed gains and losses were about 11 percent on average, and comprised unknown water balance terms and measurement errors. In general, upstream parts of regions were better gauged than downstream parts. Also, in general, inflows were less well gauged in the upstream parts (where ungauged runoff dominated) than in the downstream parts (where gauged main stem inflows dominated). Outflows, on the other hand, were better gauged in the upstream parts (where gauged main stem outflows dominated) than in the downstream parts (where there were often large ungauged floods and distributary flows).

The average of the fractions gauged and attributed per reach differs from the fraction gauged in the basin overall, because ungauged and unattributed losses sum across the MDB whereas flows do not (since the outflow from one reach is the inflow to the next reach). The overall fractions gauged and attributed across the MDB were about 40 percent and 60 percent.

4.2 Water use in the Murray-Darling Basin

The overall inflows and water use in the MDB can only be approximately determined with the water accounting methods used in this report. We relied on accounting of well gauged river reaches, and could not establish accounts for all reaches of the basin. Some reaches were not included in the accounts, and flows into or out of those reaches into the parts we have dealt with appear as unattributed gains or losses.

The overall gauged and attributed inflows into the basin amounted to some 23,000 GL/year (long term average, 1990-2006) with unattributed gains and noise of about 14,000 GL/year. The overall gauged and attributed outflows, diversions and losses amounted to about 22,000 GL/year, with unattributed losses and noise of about 16,000 GL/year. Discharge past Lock 1 (the last gauged reach in our accounts) was about 6,000 GL/year, net diversions about 9,000 GL/year, river and floodplain losses about 4,000 GL/year, and direct evaporation from rivers, lakes and wetland about 3,000 GL/year. The latter figure included only those rivers, lakes and wetlands directly associated with the accounted reaches, and it is likely that the overall basin figure of direct evaporation was of order 5,000 GL/year.

4.3 Implications for future water accounting

A national system of annual water accounting is expected to be developed over the coming years through the National Water Initiative and the Bureau of Meteorology's new water division. This will include river water resource accounts. Our analyses show that these water accounts are likely to be most uncertain towards the end of inland river systems, particularly where anabranching and wetlands occur alongside irrigated areas. Additional metering and gauging in combination with remote sensing is likely to help to reduce these uncertainties. In addition, more robust estimates of system inflows (achievable through models that can make use of remote sensing estimates of rainfall and AET) and simultaneous calibration of accounting models across all gauges rather than reach by reach is likely to help reduce compensating errors in river water accounting.

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