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River water balance accounts for the Murray-Darling Basin to support water assessment modelling

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Abstract: Monthly water balance accounts (1990-2006) were developed for 145 river reaches within the Murray-Darling Basin (MDB) as part of the Murray-Darling Basin Sustainable Yields project. They were used to assess how well river hydrology is measured and understood, and to identify the main uncertainties in river modelling. The purpose of accounting was different compared to water accounting systems set up for natural resources management, such as those that will be produced by the Bureau of Meteorology. Many aspects are still relevant however. A brief overview of the methods and data sources is provided, with emphasis on the methods used to combine different data sources in water balance accounts. Some benefits of the approach taken were identified as well as deficiencies requiring improvement.

The aggregate water balance accounts are presented for all reaches that could be assessed, which covered most but not all of the MDB's river sections. The components of the water balance for which on-ground hydrometric data are available were compared to those which could be attributed with less direct observations, and apparent gains and losses that could not be attributed, respectively (noting that these will have included both real water and estimation errors in all terms). Approximately 48% of the overall water balance appeared to be gauged. Another 21% could be attributed, whilst the remaining 31% was unattributed. Comparison of the accounted and simulated water balance was not straightforward but provided useful insights into the assumptions made in modelling, and the uncertainty in these assumptions.

Some implications for 'formal' water accounting are discussed. Unlike perhaps financial accounting, all numbers in a water account will be indirectly derived using estimation methods, because (1) every hydrological observation is indirect and involves a varying degree of estimation; and (2) not including even more indirect estimation methods (e.g. hydrological models) will produce water accounts that are incomplete and probably not useful. The suggested alternative is to use the full range of observations in a modelling framework that considers the uncertainty in the model as well as in all observations, to maximise both accuracy and precision in the accounts. Water accounts were most uncertain towards the end of inland river systems, particularly where anabranching and wetlands occur alongside irrigated areas: through unregulated or distributed diversions and extractions, losses to floodplains and wetlands, and groundwater recharge. These can all occur within the same reach and at the same time. In addition accurate streamflow gauging can also be challenging in this environment. Satellite observations of land use, evapotranspiration and inundation offer the best opportunity for further reducing uncertainty in these areas. Uncertainty is least in the unregulated, wetter headwaters of most of the regions, where gauging is better and processes better known. A degree of model 'over fitting' was identified; for example, increasing the total water balance volume to accommodate what effectively may well be errors in streamflow gauging. Calibration of hydrological models against all gauging and other data simultaneously in a way that considers the error in observations will help reduce such compensating errors, reduce the unattributed component in water accounts, and provide consistent uncertainty estimates for each term.

Keywords: *water accounting, uncertainty estimation, river hydrology*

1. INTRODUCTION

The Murray-Darling Basin Sustainable Yields (MDBSY) project used river hydrology simulation models to assess water availability under future climate and development scenarios. To allow project results to be considered within a risk management framework, the uncertainty in the projections needs to be considered. A distinction was made between *internal* uncertainty inherent to the river models, and *external* uncertainty associated with the climate and development scenarios evaluated.

Several tens of river models were used that were developed by different organisations, and varied in the data used, complexity, assumptions, currency, and other aspects. To assess internal model uncertainty, a 'multiple lines of evidence' approach was taken involving both qualitative and quantitative analysis. River water balance accounts played a prominent role. They made it possible to assess to what extent different components of the hydrological system are metered and gauged; how well the river water balance can be closed by combining data and models; and how well accounts compare with historic fluxes simulated by the river models. It is emphasised however that these water balance accounts are an alternative estimate of the 'true' water balance with uncertainties of their own, and should be interpreted as such.

Full details of the water balance accounting methods and the river model uncertainty assessment can be found in Kirby *et al.* (2008) and Van Dijk *et al.* (2008), respectively. These studies found that external sources of uncertainty (associated with climate and human influences) were greater than the internal river model uncertainties. Despite this, there were still several areas (literally as well as metaphorically) and several catchments where river modelling itself was considered too uncertain to be fit for the project purposes, and where considerable improvements are possible.

This paper provides a brief overview of the methods by which river reach water balance accounts were developed. Emphasis is on the methods used to combine different data sources in the water balance accounts. Some merits and deficiencies in the approach taken are identified.

2. METHODOLOGY

2.1. Conceptual model

A control volume needs to be defined in order to establish any mass balance. We defined it as the water body in the river channel between two gauging stations and any directly connected water bodies. At most, a reach water balance was considered to have the following components:

1. *Streamflow gains from upstream,* gauged at the upper end of the reach (by definition).
2. *Streamflow losses to downstream,* gauged at the lower end of the reach (by definition).
3. *Streamflow gains from tributaries*, which may or may not be gauged at a station. Where they are gauged, this commonly occurs some distance upstream from the actual confluence. In practice, this means that some of these tributary inflows will be effectively included in direct inflows (see below).
4. *Streamflow losses into distributaries*, sometimes gauged (at some distance from the diffluence).
5. *Controlled diversions or releases*, which may be gravity driven (at weirs and releases from reservoirs) or pumped against gravity into water supply storages or distribution networks for human or agricultural use. Typically, smaller weir diversions and pumping volumes are only partially, infrequently or not at all measured for most reaches, and models or statistical methods are used to estimate total diversions for fixed time intervals.
6. *Changes in stored volume*, which are typically only measured in storage reservoirs and weirs.
7. *Direct rainfall on to and evapotranspiration* (ET) *from* the reach and emergent vegetation. These are typically estimated by considering water surface area, rainfall and open water evaporation rates.
8. *Floodplain losses* through evaporation of water on floodplain and wetlands following overbank flows.
9. *Local or 'direct' inflows* from local runoff and groundwater discharging directly into the river. These are normally estimated using rainfall-runoff models or scaling of gauged tributary inflows.
10. *Effluent and irrigation return flows*, which are largely unmetered and therefore need to be estimated. Typically this is done by assuming a small percentage of diversions returns to the river reach.
11. *Leakage* through the river bed to groundwater, which need to be estimated. To date these fluxes have often been assumed negligible, although this situation is changing in the MDB.

It is acknowledged that the definition of control volume and some of the water balance components already introduce a few semantic ambiguities. In particular, water bodies may only occasionally exchange surface flows with the river, and may or may not exchange water with the river through subsurface exchanges during other times, and therefore may be considered to be part of the control volume, or considered outside the control volume and fed by distributaries. This was addressed pragmatically through use of the floodplain mapping and any distributary gauging data (see below).

2.2. Spatial framework

To set up the spatial water balance accounting framework, a data set was compiled with all gauging stations for which data was available during the period 1990–2006. The period chosen reflects a compromise: a shorter period would contain little climate variation and so might produce a biased assessment, whereas a longer period would leave too few gauges with data for the entire period. Even so, including only stations with data for the full period sometimes left large river stretches unaddressed and in a few cases pragmatic decisions were made to produce water balance accounts for somewhat shorter periods (creating some inconsistencies in the aggregated water balance at larger scales). The location of the selected streamflow gauges and terrain analysis were used to define river reaches and the areas contributing 'direct' inflows to each reach. The number of gauges active during 1990–2006 was around 600, but fewer satisfied the 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; the resulting spatial framework is shown in Figure 1.

Considerable areas of the basin were not included in the framework (Figure 1). They included internally draining rivers, distributaries and catchments - at least in our interpretation and during the accounting period (e.g. in lower Lachlan, Wimmera, and Warrego; Lake George in the Murrumbidgee). They also include head water catchments above the first gauge and the Murray River below the last gauge. Reaches above some of the storages could not be included because storage volume time series were not available to us, making it impossible to close the water balance satisfactorily.

2.3. Accounting approach

For each reach considered, prior estimates of some but not all of the eleven water balance terms listed before were available. Using the available estimates, a mass balance can be established that will show a residual gain or loss term for each month. This reflects the combined result of ignoring the other water balance terms, and errors in the available estimates. Using the time series of monthly mass balance residuals, consideration of the sign of the residual and its correlation with the various gauged terms often suggested the nature of some of the residual, and allow a part of it to be attributed to a water balance term. Besides estimates from gauging ancillary estimates for other terms were used (see below). These estimates were considered useful because they represented considerable water volumes, were based on observations of reasonable accuracy, and were (mostly) independent from estimation methods in the river models.

For each reach, a monthly accounting sheet with the listed water balance components was set up in MS Excel™. To allow accounting for river storage changes, a simple running balance equation was included to simulate the effect of water volumes being stored and carried over from one month to the next. To translate floodplain and irrigation evapotranspiration (ET) volumes

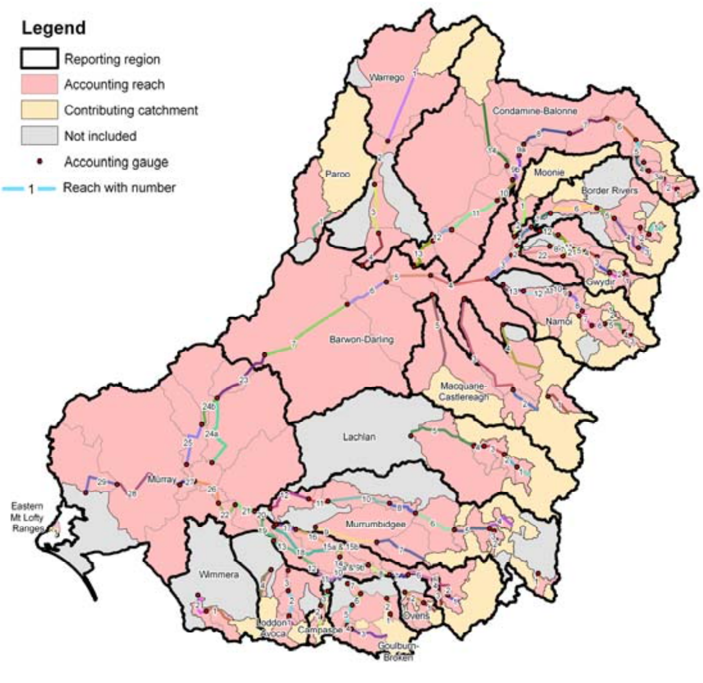

Figure 1. Spatial accounting framework.

into river losses, equally simple running balance models were used that included return flows where these appeared to play an important role. Where diversion estimates were available, these were used instead of ET based estimates (pre-empting the need of a running balance model). Leakage to groundwater was not accounted for; as the only estimates available were those used in the river modelling itself, which would make a comparison trivial. For each reach, simple linear and power regression techniques and visual exploration were used to attribute the ungauged components to gauged or estimated terms. Water balance closure was attempted by adjusting some of the parameters of the water storage models (within bounds considered realistic) to minimise the water balance residuals. In a few cases where there was particularly strong evidence, one of the terms was linearly scaled to improve water balance closure. It is acknowledged that the use of scaling and a running water balance arguably go beyond accounting in a strict sense and shows aspects of a simulation model. This point will be discussed below.

2.4. Estimates of water balance terms

Streamflow and diversion metering data for the selected stations were obtained from the data custodians (generally state agencies) through public data services or by project agreement. Gap filling procedures were already applied in most cases, or else were filled using regression techniques and data for nearby gauges. Estimates of direct streamflow into the river were derived from spatial streamflow generation estimates produced for the entire basin as part of the MDBSY project, derived from interpolated daily station rainfall and meteorology using the SIMHYD rainfall-runoff model, with model parameters estimated from streamflow observations at nearby stations (Chiew *et al.*, 2008). Similar data and techniques are typically used in river modelling, and therefore the two cannot be considered fully independent.

Spatial estimates of monthly ET across the basin were produced by merging estimates derived with two separate algorithms that used satellite observations of water availability at the surface, expressed in vegetation greenness and surface wetness; and expressed in land surface temperature, respectively (Guerschman *et al.*, 2008; Figure 2a). To estimate ET from floodplains, irrigation areas and water bodies of different types (e.g. river, lakes, channels), a multi-objective automated land cover classification was carried out using several sources of satellite observations and pre-existing mapping, followed by extensive visual QA/QC (**Error! Reference source not found.**b). This classification was combined with the spatial rainfall and ET estimates to derive volumetric estimates for wetlands in each accounting reach. For water bodies, evaporation was estimated from the extent of water bodies of different size and depth in each reach using an ET algorithm that accounts for heat storage and advection estimates (McJannet *et al.*, 2008).

2.5. Comparison against river model simulations

The overall approach in assessing river model uncertainty was a combination of quantitative analysis and qualitative interpretation of the model adequacy using multiple lines of evidence. The water accounts played an important role in quantitative analysis. An important assumption was that greater and more complete hydrological measurements in any river would lead to greater system understanding and facilitate

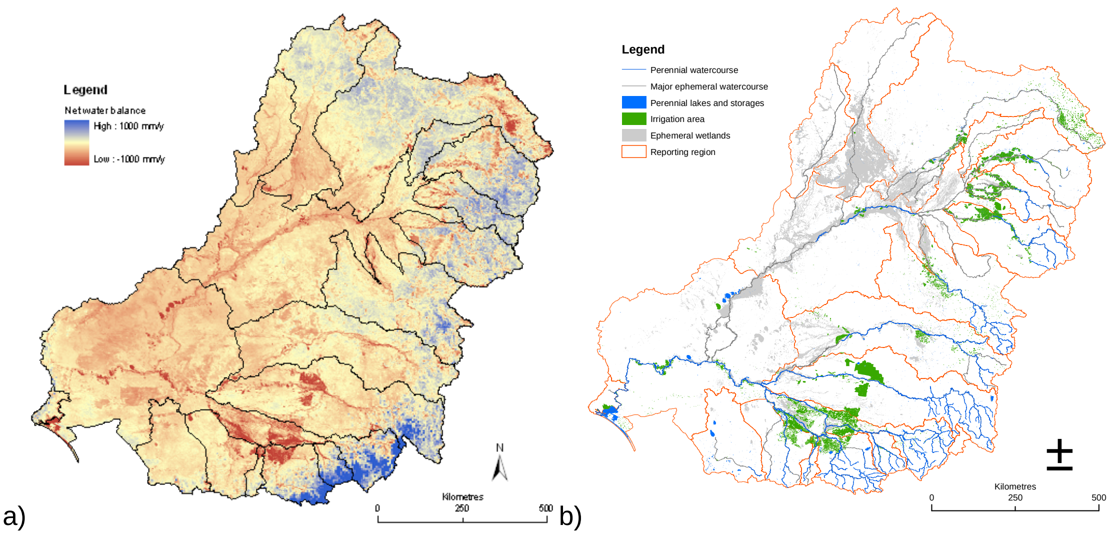

Figure 2 (a) spatial estimates of 1990–2006 average net water use (rainfall minus ET); (b) extent of water bodies, irrigation areas and ephemeral wetlands derived from multi-objective classification.

development of more reliable simulation models. Therefore, two lines of evidence considered were the density and quality of the hydrological observation network, and the fractions of the total water balance volume that was directly gauged or could be attributed in water accounting with little uncertainty. Furthermore, the divergence between the water balance accounts and the water balance simulated by the river model was interpreted as a measure of uncertainty in modelling (but without suggesting that the water accounts were necessarily more accurate than the model results). There are several limitations and caveats associated with each of the individual pieces of evidence, and this was the very reason a 'multiple lines of evidence' approach was used (see Van Dijk *et al.*, 2008; for further details).

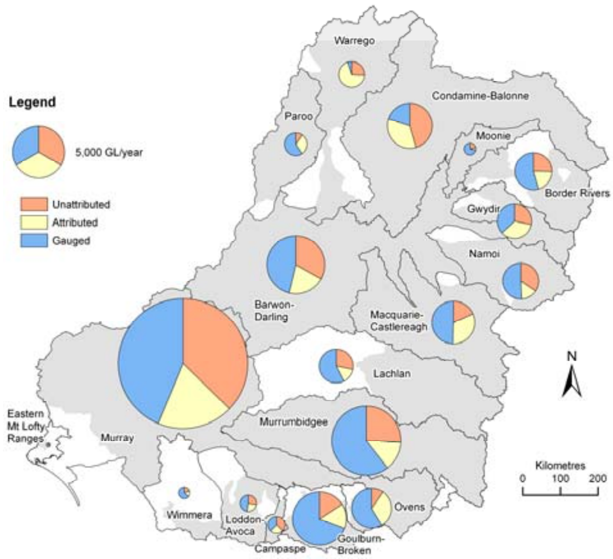

Figure 3. Gauged, attributed and unattributed water balance components for each region and for 1990–2006 (area of circles is proportional to total water balance).

3. RESULTS

3.1. Completeness of gauging

The gauged, attributed and unattributed water balance components for each region in the MDB are shown in **Error! Reference source not found.**. The total water balance volume for each region includes equal parts of gains and losses (apart from the possibility of small storage changes). The Murray and Barwon-Darling regions receive inflows from the other regions and therefore total MDB inflows and losses do not equate to half of the sum of the total of all regional water balances.

Unattributed gains and losses represent about 28,000 GL/year across the Basin. Of these, approximately half (14,000 GL/year) occurred in the Murray region. For the whole basin, approximately 48 percent of the overall water balance appeared to be gauged. Surface water gauging appears reasonably good (>60% gauged) in Moonie, Murrumbidgee, Goulburn-Broken, Wimmera and Eastern-Mount Lofty Ranges, but very poor (<30%) in the Warrego and Condamine-Balonne regions. It is emphasised that the unattributed component is the sum of real unattributed water volumes plus errors in all other estimates. For a region, this error component tends to increase as the number of reaches and water balance terms increases.

For the whole MDB, 69% of the water balance was attributed or gauged. If this is interpreted as an indicator of how well the hydrology of the system is understood then it can be concluded that understanding is least for Condamine-Balonne region (54% gauged or attributed), reasonable for the Murray, Campaspe and Barwon Darling (60–70%), and good for the other regions.

Table 1. River water balance for the accounted section of the Murray-Darling Basin for the period 1990–2006, in GL/year. Due to differences in accounting period the terms do not balance fully.

Gauged inflows (at headwater gauges)	14,836
Local inflows	8,567
Subtotal gains	**23,403**
Unattributed gains and error	**14,270**
End of system outflows (Lock 1)	6,156
Net diversions	9,393
Floodplain losses	3,667
Net direct open water evaporation	3,102
Subtotal losses	**22,317**
Unattributed losses and error	**15,871**

3.2. Basin water balance

The overall basin water balance is listed in Table 1. The overall inflow into the system is close to commonly quoted values. Diversions were the largest use of the water, consuming 42% of the water use accounted for. Evaporation consumed about 14%, floodplain ET about 16% and end-of-system flows (past Lock 1) 28%. Separate modelling suggests that another 1,600 GL/y is lost before reaching the sea, split about equally between urban and agricultural diversions, and ET from the river and Lower Lakes (Close, 2002).

River, lake and wetland evaporation included in the water balance is only from floodplains and wetlands associated with the accounting reaches. For example, combined ET from several large reservoirs outside or above the accounting reaches was not included; these losses were estimated to be around an additional 1,500 GL/year (MDBC, 2007). In the listed water balance these are mostly reflected in lower inflow estimates, and to some extent increased diversion estimates. This example as well as the necessarily partial geographical coverage of these water accounts illustrate some of the definitional challenges in drawing up water accounts.

3.3. Comparison with modelled water balances

Comparison between modelled and accounted water balances was not straightforward, due to the wide variety in river model structures and assumptions. Some river models used gauged inflows making inflow comparison trivial. Some models simulated diversions using assumptions about current rather than historic conditions. Many models simulated ‘unspecified’ losses to achieve agreement with streamflow observations, rather than attempting to estimate responsible losses specifically. River models simulate dam operations, and historic operations can vary considerably (see Van Dijk *et al.*, 2008 for further caveats and full detail on the comparison).

Nevertheless, comparison of accounted and simulated water balance provided many useful insights into the assumptions made in modelling, and the uncertainty in these assumptions for a historic (and arguably therefore future) context. The sum of system inflows from all models combined was 4% greater than the sum of gauged and attributed inflows. This was fortuitous: differences were considerable between regions, and perfect agreement would only exist if all unattributed gains were errors. The modelled inflows are therefore probably an underestimate. Total simulated diversions for all accounted reaches combined were within 1% of accounted diversions, but again for individual regions and reaches differences could be considerable. Model simulated ET losses from water bodies and floodplains (both specified and unspecified) were 6 % greater than account estimates. However if it is assumed that probably more than 3% of the unattributed losses constituted real losses, modelled losses are underestimated.

4. DISCUSSION

4.1. Modelling versus 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 Water Division, and similar developments take place in other countries. The principles of financial accounting have had a role in developing natural resources accounting systems. One of the aspects of such accounting methods is the importance of distinguishing between ‘true’ numbers and estimated numbers. It may be argued that the water balance accounts are closer to a water balance model than a formal account. While it can be argued that at least aspects of financial accounting are exact (as documented transactions are taken to be the point of reference) this would be impossible to maintain in water accounting for at least two reasons. Firstly, the point of truth needs to be the physical world for water accounts to be meaningful, and any observations of it are inexact and always indirect. Streamflow may be estimated from (indirect!) observations of water level at a point, or estimated from rain fallen in a rainfall gauge at some nearby location, the only difference between the two estimates is in the method and the accuracy ascribed to it. Secondly, it will not be possible to produce an insightful full water balance account if only direct estimates are considered; some components will always need to be estimated based on the remaining water balance, e.g. by simple modelling and attribution methods similar to those described here. For example, the reader might have preferred a model estimated water balance for the entire MDB, rather than the water accounts for a somewhat patchy part of it that was provided. This would make further use of models inevitable. In summary, the challenge in water accounting would not seem to be to develop independent estimates of each water balance account, but to use the full range of observations (weather stations, hydrometry, remote sensing, etc.) in a water balance modelling framework that considers the uncertainty in the model as well as in all observations.

4.2. Uncertainty in river modelling

In the light of this artificial difference between water accounting and water balance modelling, it is of interest to consider the greatest uncertainties in river models when compared to historic and partly independent observations. Our analyses suggest that water accounts are likely to be most uncertain towards the end of inland river systems, particularly where anabranching and wetlands occur alongside irrigated areas. Examples include the confluences of the northern rivers into the Barwon River, and the mid-Murray (including Edward-Wakool and Barmah-Millewah floodplains). In these reaches, unregulated or distributed diversions and extractions, losses to floodplains and wetlands, and groundwater recharge can all occur within the same reach and at the same time, while accurate streamflow gauging can also be challenging. Remote sensing arguably offers the best opportunity for further reducing uncertainty in these areas. Uncertainty is least in the unregulated, wetter headwaters of most of the regions.

Any model is only as good as the data used in it, and many measurement problems could be identified. In general, the on-ground climatological and hydrometric station network is insufficient for satisfactory water balance estimation in large parts of Australia. Satellite observations provide the greatest promise to fill the gaps in our observations. In specific, there are many measurement challenges and associated uncertainties. For example, anabranching and instable river channels found in many low-relief areas and connecting many floodplains and wetlands to the main river make effectively gauging of these exchanges very difficult.

Compensating gains and losses going from one reach to the next were identified in some cases, which can often be attributed to model 'over fitting', that is, increasing the total water balance volume to accommodate what might effectively be errors in streamflow gauging. Simultaneous calibration of water balance estimation models against all gauging data (and other observations) rather than reach by reach is likely to help reduce such compensating errors.

5. CONCLUSIONS

Monthly water balance accounts (1990-2006) were developed for 145 river reaches within the Murray-Darling Basin (MDB) as part of the Murray-Darling Basin Sustainable Yields project. Accounts were most uncertain towards the end of inland river systems, particularly where anabranching and wetlands occur alongside irrigated areas. Remote sensing arguably offers the best opportunity for further reducing uncertainty in these areas. Uncertainty is least in the unregulated, wetter headwaters of most of the regions. A degree of river model 'over fitting' was identified; for example, increasing the total water balance volume to accommodate what effectively may well be errors in streamflow gauging. Calibration of hydrological models against all gauging and other data simultaneously in a way that considers the error in observations will help reduce such compensating errors, reduce the unattributed component in water accounts, and provide consistent uncertainty estimates for each term.

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