18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009
http://mssanz.org.au/modsim09

Addressing uncertainties in water accounting

Lowe, L[1], **T. Etchells**[1], **H. Malano**[1], **R. Nathan**[2] **and B. Potter**[3]

[1] *Department of Civil and Environmental Engineering, University of Melbourne, Victoria*
Email: llowe@civenv.unimelb.edu.au
[2] *Sinclair Knight Merz, Victoria*
[3] *Department of Accounting and Business Information Systems, University of Melbourne, Victoria*

Abstract: A precursor to effective water management is the availability of useful information. Water accounts are being developed to meet these needs. However, there are considerable problems in quantifying all of the reported elements. Even where direct measurements are available, they are often prone to measurement uncertainties. The volumes of other elements are difficult to measure and often can only be quantified based on a series of assumptions. The presence of uncertainties in water accounts poses two problems. Firstly, the decisions made based on information presented in the accounts may change if the associated uncertainties were disclosed to those making decisions. Secondly, due to the uncertainties associated with each element, the accounts rarely balance.

There has been surprisingly little research into understanding and reducing the uncertainty in water accounts, and at present, it is not systematically captured and reported in accounts. This paper addresses the uncertainties associated with water accounts by:

- identifying and quantifying the major sources of uncertainty associated with each element in the water accounts; and,
- presenting a method to constrain the uncertainty associated with each component of the water accounts by only including those values that can create a balanced set of accounts.

The Werribee River catchment (Victoria, Australia) is used as a case study and accounts are prepared for 2005/06. The largest inflows to the catchment are from catchment runoff. Other sources of inflows include groundwater, recycled water, return flows and water supplied from an adjoining catchment. During 2005/06 the total inflows are estimated to be 28,002 ML. The uncertainty associated with these inflows is equivalent to ±21% of the best estimate, mainly due to the uncertainties associated with estimating ungauged catchment runoff. The outflows from the catchment consist of water use, net evaporation from reservoirs, surface and groundwater interactions and runoff into the bay. In 2005/06 the combined outflows were 40,552 ML. The associated uncertainty is equivalent to ±6% of the estimated outflows, and is predominantly due to the uncertainty in surface and groundwater interactions. Finally, during 2005/06 the drawdown from storage volumes across the catchment was 12,765 ML, with an uncertainty equivalent to ±13%.

The initial water accounts (i.e. without consideration of uncertainty) for the Werribee River catchment did not balance. The combined inflows and drawdown in storage volume exceed the estimated outflows by 245 ML. This study identifies combinations of inflows and outflows, each selected from within their uncertainty range, that provide a balanced set of accounts. New estimates are adopted from the combination which has the highest likelihood of occurring. The combination with the maximum likelihood is selected and replaces the initial values used in the accounts. Finally, the uncertainty associated with each element of the accounts is reduced by excluding values that are unlikely to combine with other elements to produce a balanced set of accounts.

Disclosure of the uncertainty associated with the information presented in the water accounts will improve water management decisions. Furthermore, the results highlight those elements in the water accounts that have the greatest influence on the overall uncertainty and should be the focus of further research.

Keywords: *Water Accounting, Uncertainty*

1. INTRODUCTION

Measurement is a major task in a water accounting system. Water accounts established for the purpose of assessing compliance or tracking the movement of water tend to be based on data collected to meet this specific need (e.g. Owen-Joyce and Raymond 1996). Other water accounting systems rely heavily on data collected for other purposes (e.g. DSE 2007). The information presented in these accounts is limited by data availability and there is a significant reliance on models and relationships to transform data into useful information. Overall, significant sources of uncertainty are introduced into the water accounts via measurement uncertainty, model uncertainty and by the various assumptions made during the preparation of the accounts.

Existing water accounting systems recognise the presence of uncertainties in the water accounts, but many conclude that the accounts are useful despite the uncertainties (e.g. DSE 2007; Lange 1997). Only a few accounts attempted to quantify the uncertainties, and these were largely based on subjective judgment (e.g. NWC 2007). No guidelines or accepted approach exists for quantifying or reporting uncertainties within water accounts.

The presence of uncertainties in water accounts poses two problems. Firstly, the water management decisions made based on information presented in the accounts may change if the associated uncertainties were disclosed to those making the decisions. Secondly, due to the uncertainties associated with each component of the water accounts, the accounts rarely balance. This paper addresses the uncertainties associated with water accounts. A method for quantifying the uncertainties associated with water accounts is presented in Section 2. In Section 3 the paper presents a method to constrain the uncertainty associated with each component of the water accounts. The Werribee River catchment, located in south-eastern Australia, is selected as a case study. A simple set of water accounts is prepared for the Werribee river catchment and used to demonstrate the methods developed within each section. The case study is limited to an annual time step and the 2005/06 water year was selected to coincide with available information. A final synthesis is given in Section 4.

2. QUANTIFYING UNCERTAINTIES IN WATER ACCOUNTS

2.1. Overall Approach

Before the uncertainties associated with water accounts can be quantified, the process used to quantify each element and the potential sources of uncertainty must be understood. The quantification of each element in the water accounts follows a general process. The availability of *raw data*, such as the water level in a river, underpins the quantification process. In many cases it is not possible to measure the parameter of interest directly and a *model* is required to convert the raw data to estimate the parameter. For example, the water level in a river is converted to a rate of flow using a rating curve. The raw data or modelled estimate may not be at the location or spatial scale required and a *spatial adjustment* may be required. In a few cases, *temporal adjustments* may also be required to present the information at the temporal scale required. The exact quantification process will vary between accounting elements. For some elements several quantification methods are available and preference is given to simple methods that enable water accounts to be compiled over large regions in a timely manner.

Uncertainties are introduced in each step of quantifying an accounting element. There is *measurement uncertainty* associated with the raw data because equipment does not measure quantities perfectly. The use of a model introduces a range of potential errors due to uncertainty in the model structure, the model parameters, model inputs and technical errors (Walker et al. 2003). As a whole, these are referred to as *model uncertainty*. There can be considerable spatial and temporal variability in hydrological parameters and as such, *spatial uncertainty* and *temporal uncertainty* is introduced by any spatial and temporal adjustments respectively. The specific sources of uncertainty associated with each accounting element are identified through a review of the literature, discussion with data providers and based on a thorough understanding of the quantification method.

Quantifying uncertainty is inherently difficult and the approach used depends on the type of information available. There are three possible approaches. Firstly, if there is plenty of information available to quantify the uncertainty, the probability distribution to characterise the uncertainty can be determined using *standard statistical techniques* (e.g placing a confidence interval around mean). Secondly, if only a few measurements are available, possibly from a suite of previous experiments, *Bayesian statistics* can be used to generate a probability distribution as it allows a few measurements to be combined with a prior understanding of the distribution. Thirdly, if no quantitative information is available, *subjective judgment* must be used to select the parameters of a suitable probability distribution. In these cases, the probability distribution may be based on information available from a review of the literature, a cross validation exercise for a similar problem, or consultation with data providers and experts in the field. As there are multiple sources of uncertainty in estimating most accounting elements, it is necessary for these to be combined to estimate the overall uncertainty. Monte Carlo simulations provide the flexibility needed for wide applicability.

The remainder of this section summarises the key methods available to quantify elements in the water accounts and identifies the dominant sources of uncertainty. Existing and accepted methods are used to quantify uncertainties in the few cases where they are available. However, substantial effort is required to quantify uncertainties for other elements and a brief summary of the methods developed is provided. The magnitude of uncertainties is represented using a 95% confidence interval and presented as a percentage of the best estimate of the element. The Werribee River water accounts and associated uncertainties are presented in Table 1.

2.2. Streamflows

Streamflow measurements are used in water accounts to quantify the outflow from the catchment and in some cases, may also be used to measure runoff from sub-catchments in which there are no upstream diversions. Streamflow measurements are based on water level measurements which are converted to a flow rate using a rating curve. Unlike many of the accounting elements, an Australian Standard exists which specifies a method to quantify the uncertainty associated with streamflow measurements (Standards Australia 1990). The method considers the uncertainty due to measurement error associated with the water level and uncertainty in the rating curve. The method was used to assess 14 streamflow gauges within the Werribee River catchment. The uncertainty in the annual streamflows during 2005/06 ranged from ±4% to ±41% of the reported flow.

2.3. Catchment Runoff

Catchment runoff refers to the total volume of rainfall that is converted to flow in a waterway may constitute a large proportion of the total inflows reported in the water accounts. Streamflow transposition is adopted to estimate catchment runoff where streamflow measurements are either not available or are influenced by upstream diversions. In applying this approach two steps are taken. The most appropriate gauged catchment is selected and the recorded flows adjusted to reflect the ungauged catchment using a transposition factor (Lowe and Nathan 2006). The overall model uncertainty associated with streamflow transposition was estimated using a cross-validation approach. Information available for the 165 gauged Victorian catchments used in Lowe and Nathan (2006). Each of the 165 gauged catchments was, in turn, assumed to be ungauged. The annual streamflows estimated using transposition were compared to the annual recorded streamflows. The observed differences ranged between -60% and +160% of the transposed streamflow.

2.4. Metered Flows

A large number of accounting elements are quantified using water meters. These elements include metered water use and the volume of recycled water. Manufactures test the accuracy of water meters by comparing the meter's measurements with more reliable techniques in the laboratory. The accuracy varies between the types of meters and can typically range from ±0.5% for an electromagnetic flow meter to ±5% for a flume or measuring weir (ANCID 2002). In practice a flow meter will not operate under ideal conditions due to factors including incorrect installation and obstruction by debris, silt or vegetation. Hydro Environmental (2007) compared the in-situ flow measured by several types of meters with that of a more accurate remote electronic verification system. They found that for the Dethridge wheel, the errors ranged from -1% to 25% for the 12 meters they tested and between -2.3% and 3.3% for the seven electromagnetic meters tested. The results from Hydro Environmental (2007) and other similar studies were used to estimate the potential uncertainties associated with metered flows in the Werribee River catchment.

2.5. Reservoirs

The water level of a reservoir is measured on a regular basis and used to estimate the current reservoir volume. A bathymetric survey is conducted before the reservoir is constructed and used to generate a stage-volume relationship. Over time the capacity of the reservoir may decrease due to sedimentation, altering the stage-volume relationship. The range-line method can be used to monitor sedimentation along pre-defined transects and estimate changes in reservoir volumes (Davis 1996). Using this method there are uncertainties associated with the measured reservoir depths along each transect and the extrapolation of these sediment depths to the entire reservoir. The uncertainty associated with the capacity and current volumes of large reservoirs in the Werribee River catchment were estimated. It was assumed that the uncertainty associated with measured reservoir depths was ±15 cm (Furnans and Austin 2008). The sample depths were treated as a stratified sample and used to calculate the uncertainty associated with the mean sediment depth. The uncertainties associated with the reservoir capacity were in the order of ±5%. The uncertainty associated with the average depth of sedimentation at various reservoir depths was assessed and incorporated into the stage-volume relationship. Larger uncertainties were observed in the deepest parts of the reservoir where there was more sedimentation and less sampling.

2.6. Farm Dams

The TEDI simulation model developed by Nathan et al. (2000) is used to estimate the volume of farm dams (also known as catchment dams or farm ponds) in the catchment and the annual magnitude of net evaporation and extractions. It requires information on the number and volume of farm dams, climate data, catchment inflows and various farm dam characteristics. Techniques are available to obtain farm dam numbers and volumes from topographic maps and regional estimates of farm dam characteristics are also available (Lowe et al. 2005), however, these introduce considerable uncertainty. Lowe and Nathan (2008) developed a framework to incorporate these uncertainties into the TEDI simulation modelling. In 2005/06 the decrease in the volume of water stored in farm dams in the Werribee River Catchment varied by ±180% and the uncertainty in the volume of net evaporation and extractions was in the order of ±55% and ±65% respectively.

2.7. Self – Extracted Water Use

Self-extracted water is diverted from waterways, extracted from groundwater or collected in farm dams by private landholders. Some of the waterway and groundwater extractions are metered and the volume of water extracted from farm dams is modelled. However, in some regions a large portion of self-extracted water use may need to be estimated. Lowe et al. (2009) identify two approaches to estimate unmetered water use. In the first approach, the estimate can be based on the demand for water. For example, the area of irrigated crops in the river catchment may be known and combined with water use coefficients to estimate irrigation water use. The second approach bases the water use estimate on the volume of issued water entitlements. In this paper the second approach is adopted. In the Werribee River Catchment there are 1,040 ML of licences that are not metered and it was assumed that the water use in 2005/06 fell within the range bounded by zero and the maximum volume allowed under the conditions of the license.

2.8. Net Evaporation

Net evaporation takes into account the rainfall onto and evaporation from the surface of the reservoir. The pan coefficient method was adopted to estimate the volume of evaporation from reservoirs in the Werribee River catchment. An assessment of the uncertainties associated with evaporation from three reservoirs in the Werribee River catchment calculated using this method is presented in Lowe et al. (submitted). There are also uncertainties associated with estimates of rainfall due to measurement uncertainty and spatial transposition from the climate station to the location of the reservoir. The estimated surface area of the reservoir was found to have little influence on the overall uncertainty. For reservoirs in the Werribee River catchment the uncertainty associated with estimates of net evaporation from each reservoir ranged from ±16% to ±26%.

2.9. Surface – Groundwater Flow

Interactions between surface water and groundwater are complex. In this study the quantification of these interactions is limited to the lower reaches of the Werribee River and supply channels within irrigation districts. The net transfer of water is determined by undertaking a reach balance in which all other inflows and outflows are either measured directly or estimated. The uncertainty associated with the transfer is therefore dependent upon the uncertainty associated with each of the other inflows and outflows and can be quantified using Monte Carlo simulations.

2.10. Summary of Uncertainties Associated with the Werribee River Water Accounts

A simple set of water accounts for the Werribee River catchment is provided in Table 1. The uncertainty associated with element is included in Table 1 and is represented by the 95% confidence interval expressed as a percentage of the best estimate. The most certain elements are those which are quantified using water meters. The largest uncertainties (as a percentage of the reported value) are associated with the decrease in farm dam volume, net evaporation from farm dams and catchment runoff. A visual comparison of the magnitude of inflows and outflows and their associated uncertainty is provided using box plots in Figure 2. Of note, due to the bias in some water meters the reported volume of some elements does not fall within the 95% confidence interval. Although the closure term of the water accounts is relatively small, the uncertainty surrounding the total inflows and outflows is substantial (Figure 1).

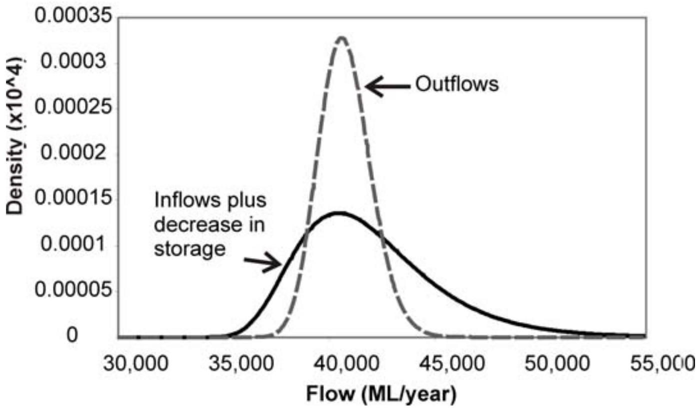

Figure 1. Distribution of the total inflows plus decrease in storage and the total outflows for the Werribee River catchment

Table 1. Werribee Water Accounts and Associated Uncertainties

Water Accounting Element		**Section**	**Initial Value (ML/year)**	**Uncertainty (%)**
IN				
Inflows	Catchment runoff	2.2 & 2.3	13,323	-27%,+66%
	Recycled water	2.4	5,543	±3%
	Returns of unconsumed water	2.4	605	-6%,+9%
	Inter-basin transfers	2.4	5,607	±1%
	Groundwater extractions	2.4 & 2.7	2,924	-4%,+28%
Change in storage	Water supply reservoirs	2.5	11,754	±3%
	Farm dams	2.6	1,011	-150%,+170%
OUT				
Water use	Water use – from a water supply system	2.4	20,062	±1%
	Water use – self extracted	2.4,2.6 & 2.7	5,555	-21%,+29%
Atmospheric interchanges	Net evaporation from reservoirs	2.8	2,903	±1%
	Net evaporation from farm dams	2.6	1,481	-48%,+82%
Surface-groundwater flow	Unaccounted for water in water supply systems	2.9	5,946	-17%,+19%
	Aquifer recharge from rivers	2.9	3,036	-46%,+35%
Outflows	Streamflows out of the catchment	2.2	1,298	-39%,+45%
	Other discharge from the catchment	2.4	241	±5%
Closure term			245	-459%,+715%

3. DATA RECONCILIATION

Traditionally, two approaches have been used to close a water balance where elements are presented in a deterministic manner. Firstly, a closure term can be included in the accounts and this can be simply referred to as an ‘error’ (e.g. NWC 2007). Secondly, one component of the water balance can be estimated as the residual of all the other elements in the water balance (e.g. DSE 2007). If the water balance is probabilistic, that is, the uncertainties surrounding all of the other components in the water balance are known, the uncertainty of the closing term can be calculated (e.g. Sattary et al. 2002). However, if a closure term is not included in the accounts, and the uncertainty surrounding each element is known, it is possible to improve the estimates and reduce the uncertainties by removing combinations of inflows and outflows that do not create a balanced set of accounts. This is called data reconciliation.

Data reconciliation adjusts each element so that the closure term in the water accounts is zero. Minimal adjustments are made and in such a way that the adjustments are proportional to the uncertainty surrounding the element, that is, elements that are highly uncertain will be adjusted more than elements for which very precise measurements are available. The uncertainties associated with each accounting element are also reduced by considering the likelihood of various combinations of accounting elements that produce a balanced set of accounts. Data reconciliation methods have been used in other applications (Stone et al. 1942; Veverka and Madron 1997), however, the analytical approach they adopt assumes that the uncertainties surrounding each element can be described with a Gaussian distribution. This assumption does not always hold in water accounting.

A numerical approach to data reconciliation is developed to accommodate non-Gaussian distributions that represent uncertainties associated with water accounting elements. Each of the *Nin* inflows and *Nout* outflows are adjusted (or reconciled) in such a way that the probability of observing the initial values ($E(I_j)$ and $E(O_j)$) is maximised. The likelihood function (*LF*) is given by:

$$LF_k = \prod_{j=1}^{Nin} \Pr(E(I_j) \mid E(I^{/}_{j,k})) . \prod_{i=1}^{Nout} \Pr(E(O_i) \mid E(O^{/}_{i,k})) \qquad \text{Equation (1)}$$

The largest likelihood function is found by calculating the likelihood of many different combinations of inflows and outflows. A large number of iterations are performed in which the following steps are taken. First, individual inflows ($E(I^{'}_{j,k})$) and outflows ($E(O^{'}_{j,k})$), except one element, are randomly selected from their defined distributions. These are considered to be the reconciled flows for iteration *k*. Second, the last reconciled inflow ($E(I^{'}_{Nin,k})$) is calculated as the difference between all other outflows and inflows. Third, for each inflow, the probability of observing the initial value given the selected reconciled value for iteration *k* ($\Pr(E(I_j) \mid E(I^{'}_{j,k}))$) is calculated. Similarly, $\Pr(E(O_j) \mid E(O^{'}_{j,k}))$ is calculated for each outflow. Finally, the *LF* for iteration *k* is calculated. The iteration (*kmax*) that produced the largest *LF* is selected and the reconciled values from this iteration ($E(I^{'}_{j,kmax})$ and $E(O^{'}_{j,kmax})$) are adopted.

The *LF* is also used to reduce the uncertainties associated with each element. Each inflow and outflow is considered in turn. The range of potential values is divided into *Nint* intervals. For each interval (*int*), the value of the element under consideration is kept constant and the steps described in the previous paragraph are undertaken to find the combination of all other inflows and outflows that produce the largest *LF* ($LF_{j,kmax,int}$). The reconciled probability distribution is based on the $LF_{j,kma}$ found for each interval. The values of $LF_{j,kmax,int}$ are multiplied by a constant selected so that the total cumulative probability equals one.

Numerical data reconciliation is used to reduce the uncertainty associated with elements in the Werribee water accounts. In Figure 2 the reconciled values and variation in each element is presented. As the total inflows exceeded the total outflows, all of the inflows are decreased by an amount proportional to the initial uncertainty. Similarly, all outflows are increased. The decrease in uncertainty is also proportional to the initial uncertainty surrounding the element type. The greatest reduction in uncertainty is observed for rainfall runoff over 2005/06.

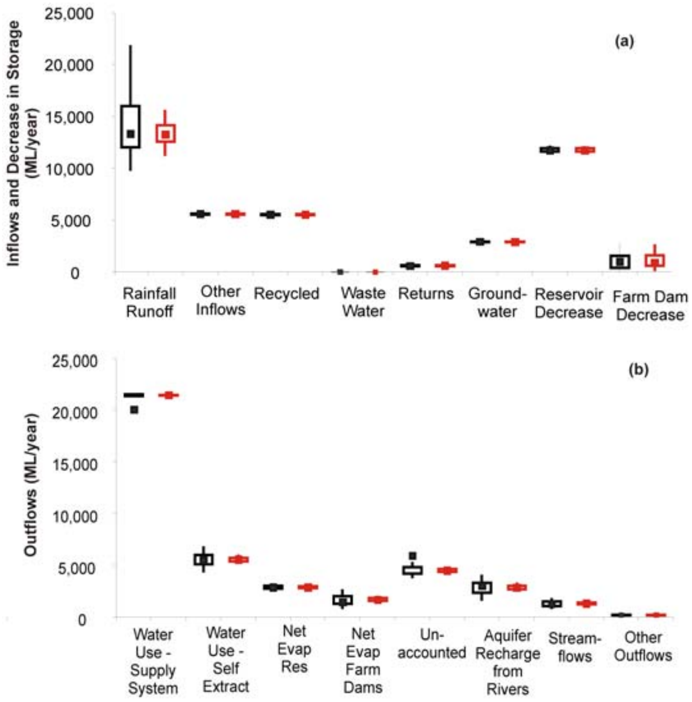

Figure 2. Uncertainties associated with (a) inflows and (b) outflows before (denoted in black) and after (denoted in red) data reconciliation. Box plots show the reported volume (square), interquartile range (hollow rectangle) and the 95% confidence interval (top and bottom of the vertical line).

4. DISCUSSION AND CONCLUSIONS

If each of the elements in the water accounts are measured or estimated independently, the water accounts may not balance due to the uncertainties surrounding the values and this was shown in reference to the Werribee River catchment in Section 2. The use of data reconciliation adjusts the quantities of each element to ensure that the accounts balance, thereby reducing the uncertainty associated with each element.

If the water accounts contain one large and also very uncertain element the data reconciliation approach will provide similar results as estimating this term as the residual of all other terms. However, the advantage of using data reconciliation is that the uncertainties associated with this term are quantified and minimised.

Despite the improvements possible using data reconciliation, there are still substantial uncertainties surrounding some elements in the water accounts. These uncertainties may influence the decisions made by water accounting users. However, not all users are aware of these uncertainties and often lack the time, money or expertise to estimate the magnitude of these uncertainties. Therefore it is important that water accounts also provide useful information regarding the uncertainties associated with each element.

ACKNOWLEDGMENTS

Funding for the research was provided by the Victorian Department of Sustainability and Environment. The authors would like to thank Southern Rural Water and Western Water for their support and provision of the data necessary to undertake this research. The authors would also like to thank all of the individuals who gave their time to share their knowledge about water accounting and uncertainties.

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