Development of a national, landuse-based water balance model for Australia

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Abstract: Australia currently has no nation-wide comprehensive and consistent information on the spatial and temporal relationships between rainfall, evapotranspiration, drainage to groundwater and runoff to rivers. To estimate this information a simple modelling approach utilising existing data was sought. A review of existing models and their data requirements led to the development of a steady state Geographic Information System (GIS) based method driven by long-term average climate data and high resolution land cover and land use data. Mean annual and mean monthly runoff, evapotranspiration and drainage were modelled. Runoff results were evaluated against other published values where available and found to generally compare favourably, except in arid river basins. The model parameterisation was refined by calibrating against 330 and 211 sub-basins for the annual and monthly models respectively.

Keywords: Water balance; Modelling; Continent scale; Ungauged catchments

1. INTRODUCTION

A better understanding of water availability is needed across Australia to assist with the implementation of key government policies such as the National Water Initiative (NWI). At present, Australia has no comprehensive and consistent source of information on the dynamic water balance, that is, on the spatial and temporal relationships between rainfall, evaporation, transpiration, drainage to ground and surface water, and runoff to rivers and storages. Addressing this fundamental knowledge gap is the primary focus of a collaborative Bureau of Rural Sciences (BRS) project known as Water 2010.

An overview of existing water balance models and their data requirements was carried out with an emphasis on matching existing data availability with input data requirements [Ranatunga et al., in prep].

A simple, steady-state water balance modelling approach was adopted, driven by long-term average climate data and high resolution land cover and land use data. The adopted model is described in this paper, and the calibration and validation of the results are discussed.

2. REVIEW OF AUSTRALIAN WATER BALANCE MODELS

A review of more than 20 widely-used mathematical models developed in Australia over the last three to four decades, for simulating and predicting soil water and catchment water balances, was carried out by Ranatunga et al. [in prep]. It considered the data currently available for national scale water balance modelling and described existing water balance models in terms of their complexity, their performance under various conditions and their limitations. In particular, models were examined for their ability to use and output spatial data, as well as their currency, data requirements and national applicability.

Six catchment-scale modelling approaches were identified for further consideration and possible use in the Water 2010 project. Most simulate evapotranspiration, runoff and deep drainage, and are distributed, so their outputs can be aggregated to different hydrological and management boundaries. However, two are complex, have considerable data requirements and are very computationally demanding at a national scale. Four models require daily stream flow for calibration, but these data are not available for all catchments in Australia. Only two of the models investigated had been applied at the national scale.

The modelling approach described by Raupach et al. [2001a, 2001b], known as BiosEquil, was deemed the most suitable paradigm for Water 2010. BiosEquil is a steady-state model that produces long-term mean annual outputs suitable for strategic planning. It can also be used to model the effect of land use change by modifying this input.

A model similar to BiosEquil was developed [Welsh et al., in prep] based on landuse and incorporating the work of Zhang et al. [2004, 2005]. Runoff, evapotranspiration, deep drainage recharge and irrigation deficit are calculated for each 1 kilometre (km) pixel over the Australian continent and its near islands. The model relies primarily on existing datasets and outputs can be aggregated to different management boundaries, although outputs are routinely aggregated to river basin level using the 245 basins defined by the Australian Water Resources Council (AWRC) in 1985 [AWRC, 1987].

3. AVERAGE ANNUAL STEADY-STATE WATER BALANCE MODEL

3. 1 Data

The annual steady-state water balance model requires grided inputs of land cover, precipitation, potential evapotranspiration and soils. To facilitate this, a new Australian land cover map was generated from a number of sources including the most recent versions of:

- catchment-scale land use at a cell size of about 50m collected by State agencies according to the Australian Land Use Mapping program,
- regional-scale land use data at a cell size of about 1km modelled using the SPREAD II method, which constrains the classification of AVHRR NDVI data for 1996-97 and 2000-01 over the Murray-Darling Basin (Figure 1) to the Australian Bureau of Statistics agricultural census data,
- National Forest Inventory forest and plantation types at a cell size of about 250m,
- topographic data from Geoscience Australia at cell size of about 250m,
- MODIS NDVI data at a cell size of about 250m.

These data were prioritised by their scale and age, and combined to attribute each cell with the best available data. The data were then converted into Albers projection and re-sampled to 1 km resolution. A separate irrigation map was produced from catchment-scale and national-scale land use data sources.

The most recent mean monthly rainfall data, with a cell size of about 2.5 km, was obtained from the Bureau of Meteorology.

Potential evaporation data at a cell size of about 5 km were sourced from the Commonwealth Scientific and Industrial Research Organisation (CSIRO). The data were calculated by the Priestley-Taylor method and were originally developed for use in the BiosEquil model [Raupach et al 2001a, 2001b].

Soils data at a cell size of about 1 km were sourced from the National Land and Water Resources Audit (NLWRA) [NLWRA, 2001].

3. 2 Modelling approach

The annual water balance modelling approach is based on the work of Zhang et al. [2004] who built on the work of Fu [1981]. Precipitation is equal to total evaporation (soil evaporation and transpiration) plus surface/sub-surface runoff and drainage to below the root zone:

$$P = E + R + D \qquad (1)$$

where P is effective precipitation, E is actual evapotranspiration, R is surface and sub-surface runoff and D is deep drainage.

3.2.1 Evapotranspiration

Actual evapotranspiration is calculated in the model using the following equation from Zhang et al [2004]:

$$\frac{E}{P} = 1 + \frac{E_0}{P} - \left[1 + \left(\frac{E_0}{P}\right)^{\alpha}\right]^{1/\alpha} \qquad (2)$$

where E is evapotranspiration, P is rainfall, E_0 is potential evapotranspiration and α is the empirical plant available water coefficient.

Gridded national land use data were categorised into 15 classes for utilisation in the model (Table 1). Annual α values were estimated for each class based on the values obtained by Zhang et al [2004] and by their relative rooting depths.

Table 1. Land use classes utilised in the catchment water balance model.

Closed Forest	Winter crop
Open Forest	Perennial horticulture
Plantation Forest	Cotton
Woodland	Sugarcane
Woody pasture	Bare Ground
Shrubby pasture	Water
Native & modified pasture	Urban
Summer crop	

3.2.2 Irrigation deficit

Potential irrigation demand I is estimated as 70% of the evapotranspiration deficit over grid cells classified as being under irrigation:

$$I = 0.7(E_0 - E) \quad (3)$$

A weighting of 0.7 recognises that not all potentially irrigated land is irrigated all the time. The equation assumes that under irrigation there is no surface runoff beyond that generated from precipitation, and vegetation growth is limited only by energy.

3.2.3 Deep drainage

Deep drainage is calculated using a rule-based algorithm from Raupach et al [2001b]:

$$D = (M_{nc}(1-F_c) + M_c F_c)(M_{sa}F_{sa} + M_{si}F_{si} + M_{cl}F_{cl}) P_{all} \quad (4)$$

where D is the drainage flux, M_c and M_{nc} are cropping and non-cropping multipliers that take the values of 3 and 1 respectively, F_c is a cultivation fraction that is 1 when the landuse is cropping, cotton or sugarcane but zero otherwise, M_{sa}, M_{si} and M_{cl} are sand, silt and clay multipliers that take the values of 0.02, 0.015 and 0.01 respectively, F_{sa}, F_{si} and F_{cl} are sand, silt and clay fractions that sum to unity in each grid cell, and P_{all} is precipitation plus irrigation.

3.2.4 Runoff

Runoff is calculated as the balance after rain-based deep drainage and evapotranspiration are subtracted from precipitation:

$$R = P - E - D \quad (5)$$

where R is surface and sub-surface runoff, E is evapotranspiration and D is deep drainage.

4. LONG-TERM AVERAGE MONTHLY WATER BALANCE MODEL

4. 1 Data

The monthly water balance model requires the same data as the annual model with the addition of soil water storage. At annual time scales the change in water storage can be neglected, but is significant at monthly time scales.

Long-term monthly soil moisture indices were created at a cell size of about 25 km from long-term monthly averages of evaporation and rainfall, plus soil texture and water holding capacity. Monthly change in water storage was calculated as the difference between the mean of all months and the long-term monthly average for each month.

4. 2 Modelling approach

The monthly water balance modelling approach is based on the work of Zhang et al. [2005]. All equations except (2) are unchanged from the annual model.

4.2.1 Evapotranspiration

Actual evapotranspiration is a variation of (2) and is calculated using the following equation from Zhang et al [2005]:

$$\frac{E}{P} = 1 + \frac{E_0 + \Delta S}{P} - \left[1 + \left(\frac{E_0 + \Delta S}{P}\right)^{\alpha}\right]^{1/\alpha} \quad (6)$$

where E is evapotranspiration, P is rainfall, E_0 is potential evapotranspiration, α is the same empirical plant available water coefficient as in (2) and ΔS is the change is water storage.

5. MODEL CALIBRATION

Runoff coefficients C_r, defined as:

$$C_r = S/P \quad (7)$$

where S is mean stream flow and P is mean rainfall over the catchment, were used to calibrate the annual model. To account for the baseflow component of observed stream flow, modelled deep drainage was added to modelled runoff. Observed measurements were provided by the Peel et al. [2000] runoff dataset. The locations of these sub-basins are shown in Figure 1.

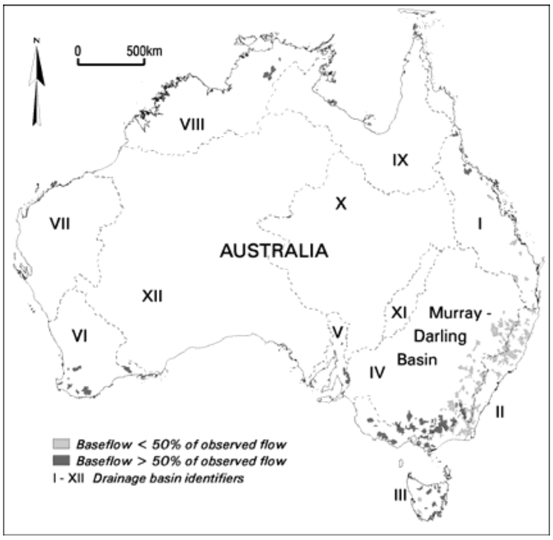

Figure 1. Location of Peel et al. [2000] sub-basins and the major drainage basins.

The calibration routine adjusted α, calculated the water balance components and compared modelled with observed runoff coefficients. Fixed amounts (eg. -0.1, 0.1) were added to an initial grid of α values and the RMS error was calculated from the two sets of runoff coefficients.

The lowest RMS error for mean annual runoff has α ranging from 2.4 for bare ground to 3.4 for closed forest (RMS = 0.08197 from 330 sub-basins). However, Zhang et al. [2004] found the best fit value of α was 2.84 for predominantly forested catchments and 2.55 for predominantly grassed catchments, with α varying between 1.7 and 5.0.

The monthly model was assessed using daily stream flow and rainfall data from Peel et al. [2000] aggregated to monthly time steps. Gauging stations in this dataset with more than 50% baseflow, determined as the fraction of slow flow over observed flow, were discarded to reduce the effect of soil water storage on stream flow. The RMS errors for monthly runoff vary between 0.15 and 0.34 over 211 sub-basins, with the largest discrepancies in winter and the smallest in summer.

The preliminary results suggest that the α values need to be reduced over the winter months. This will require an iterative process of adjusting the sets of α values for each landuse type to minimise the calibration error, while ensuring the consistency of α values between landuse types.

It is anticipated that stream flow data from more gauging stations will be used to improve the calibration. However, the coverage of suitable stations is expected to be poor over most of the country, reflecting the uneven spread of arable mountainous areas and of the population.

6. MODEL VALIDATION

6.1 Annual model validation

Australia-wide datasets available for runoff validation are limited. CSIRO Land and Water [2003] report modelled data, while NLWRA [2000] and AWRC [1987] both report a combination of observed, modelled and estimated runoff. Comparisons of mean annual model outputs, summarised by AWRC river basin, were carried out to assess the level of agreement with the published data.

6.1.1 Runoff

Table 2 lists average runoff coefficients for the AWRC basins aggregated into the 12 major drainage basins shown in Figure 1. Reasonable to good agreement was found between modelled average annual runoff estimates and data collated by the NLWRA and the AWRC for the southern higher rainfall catchments (drainage basins II, III, IV, V and VI). However, average annual runoff predictions for the relatively arid river basins tend to be significantly lower than estimates provided by the NLWRA and the AWRC (drainage basins VII, X, XI). Drainage basin XII, which is also arid, has the least complete data for comparison with only 4 of the 9 AWRC river basins included in the NLWRA and AWRC data.

There are some apparent internal inconsistencies in the NLWRA runoff data. When expressed as a proportion of rainfall, the NLWRA average annual runoff rates in the arid inland basins are greater than in some higher-rainfall river basins with lower evapotranspiration rates. For example, west of the Murray-Darling Basin, the Lake Frome Basin has a mean annual precipitation of 196 mm and a runoff coefficient of 1.04%, while the Broughton River Basin to the south and on the coast, with a mean annual precipitation of 427 mm, has a runoff coefficient of 0.93%. Unusual basin runoff coefficient comparisons are also evident among the AWRC data.

Table 2. Average runoff coefficients for the AWRC river basins aggregated into the major drainage basins.

Drainage basin	This study (%)	NLWRA [2000] (%)	AWRC [1987] (%)	No. of AWRC river basins
I	20	30	32	44
II	23	20	19	39
III	43	44	46	19
IV	9.5	7.5	7.2	23
V	6.6	7.3	6.7	12
VI	11	9.7	9.8	17
VII	0.17	3.4	2.7	9
VIII	11	17	16	25
IX	9.5	20	22	29
X	0.19	2.2	1.6	7
XI	0.22	2.4	4.7	1
XII	0.39	0.53	0.56	4

A possible explanation for the high reported runoff rates in the central arid basins could be that the AWRC and NLWRA estimates reflect average flows from years when these rivers were flowing, rather than average flows from all years including those years with no flow.

6.1.2 Irrigation

Modelled mean annual irrigation estimates are generally higher than the observed and estimated data reported by the NLWRA [2000], and slightly higher than the modelled results reported by CSIRO [Bryan and Marvanek, 2004] for the Murray-Darling Basin (Table 3). However, NLWRA figures may underestimate total irrigation if they do not include opportunistic irrigation outside the regularly irrigated areas. If so, the Water 2010 model estimates may better represent the combined regulated and opportunistic water use.

6.2 Monthly model validation

Previous studies [e.g. Abulohom et al., 2001; Donigian, 2002; Gordon et al., 2004] have validated water balance models at the catchment level using monthly runoff data. A monthly validation methodology to investigate the influence on model performance of catchment characteristics is currently under development.

Table 3. Total irrigation rates for the AWRC river basins aggregated into the major drainage basins: (a) Bryan and Marvanek [2004].

Drainage basin	This study (GL/yr)	NLWRA [2000] (GL/yr)	(a) (GL/yr)	No. of AWRC river basins
I	3,917	1,994		44
II	1,095	934		39
III	298	285		19
IV	13,920	11,321	12,050	26
V	483	50		12
VI	222	325		17
VII	40	117		9
VIII	213	308		25
IX	135	192		29
X	9	79		7
XI	0	6		1
XII	37	13		4

7. CONCLUSIONS

The water balance modelling method presented here is parsimonious, requiring only grids of landuse (with surrogates for cultivation and cropping), rainfall, potential evapotranspiration, soil water storage and plant-available water coefficients. It uses simple mathematical relations.

The flexibility to aggregate results to different catchment boundaries allows comparison with other estimates and measurements.

The annual method presented may provide improved runoff predictions in ungauged basins. The mean annual runoff outputs for river basins generally compare favourably with estimates from the AWRC and the NLWRA, except in arid river basins where the internal inconsistencies in those data are not replicated with this method.

This work is on-going and it is anticipated that the calibration of the monthly results will feed back into the steady state mean annual model. The use of additional stream gauging stations in the calibration will improve confidence in the model results.

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