Comparison of Top-Down and Bottom-Up Models for Simulation of Water Balance as affected by Seasonality, Vegetation Type and Spatial Land Use

E. Wang

L. Zhang

H. Cresswell

K. Hickel

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E. Wang[1,2], L. Zhang[1], H. Cresswell[1,2] and K. Hickel[1]

[1]*CSIRO Land and Water/* [2]*APSRU, GPO Box 1666, Canberra ACT 260, Australia* (*Enli.Wang@csiro.au*)

Abstract: This paper presents a simulation study to compare a top-down and bottom-up approach for water balance modelling as affected by rainfall seasonality, vegetation types and spatially variable land use patterns. It shows that point-based water balance calculations from the two approaches are broadly comparable. When applied at catchment scale water balance predictions were consistent in some years but different in particular years that warrant further investigation. The bottom-up model integrates the impact of different vegetation types, soil types, and management practices, whereas the top-down approach has the advantage of simplicity and associated decrease in error propagation. There is sufficient consistency in the prediction to suggest value in using a detailed bottom-up model to generate data needed for development and parameterisation of top-down catchment water balance models. The bridging of these two approaches may provide a way forward to increase model simplicity without losing the explanatory capacity necessary to analyse the impact of local management changes on catchment water balance.

Keywords: Catchment water balance; Empirical modelling; Biophysically-based modelling; Land use

1. INTRODUCTION

Simulation of biophysical processes from a point to a catchment scale is challenging. A ‘top-down’ approach captures an ‘envelope of the possible’ based on empirical relationships and has advantages including overall simplicity, obtainable input data, and transparent propagation of error. However, catchment scale top-down models may not be able to explain the impact of local scale changes in catchment management. A ‘bottom-up’ approach integrates biophysical process understanding, often at point or paddock level, enabling explicit representation of ‘management levers’ (e.g. management options available to a farmer), and allows prediction of spatial ‘response surfaces’. Disadvantages of the biophysically based approach include extensive input data requirements, risk of missing processes, and increased risk of error propagation. We see merits in both modelling approaches within a philosophy of using the simplest modelling structure that can meet the needs of the issue being addressed whilst ensuring that the model parameters retain biophysical significance.

For catchment water balance modelling, Budyko [1958] derived a simple model to show the relationship between water balance and climate. Others subsequently advanced the understanding of how climatic and catchment characteristics affect long-term average water balance [Milly, 1994; Koster and Suarez, 1999; Choudhury, 1999; Zhang et al., 2001]. The main feature of those studies is use of top-down approach, seeking description of catchment behaviour in response to climate and generalised catchment characteristics. Zhang et al [2005] further developed this approach to simulate monthly water balance by including additional factors such as rainfall seasonality and catchment water storage capacity.

For the assessment of impact of local land use change on catchment water balance, Paydar and Gallant [2003] adopted a bottom-up approach and developed a Framework for Land Use and Spatial Hydrology (FLUSH) to link 1-D farming systems or water balance models such that both vertical and lateral water fluxes are simulated through a catchment comprising multiple land units. FLUSH adopts a simpler ‘lumped’ approach simulating lateral fluxes of water between land units in contrast to a fully distributed grid-based approach. Using FLUSH coupled with the farming systems model APSIM [Keating et al., 2003], Paydar and Gallant [2003] were able to evaluate the impact of increased revegetation in different parts of the catchment on catchment water balance. Other distributed 'bottom-up' approaches have been developed such as TOPOG (Vertessy et al., 1993) and SHE (Abbott et al., 1986).

While APSIM-FLUSH is able to assess the impact of local land management changes on catchment water balance, its extensive data requirements and overall complexity make it more suited to small catchments as compared to a top-down approach. Keating et al. [2002] compared the long term average annual water excess (rainfall minus evapotranspiration) simulated by APSIM and the Zhang et al. [2001] top-down model and found that a modified Zhang model could capture 88% of the variation in the APSIM simulations. Thus they suggested using deterministic simulation modelling to generate data needed for development of static (top-down) models.

This paper further explores the synergy of the top-down and bottom-up approaches for water balance modelling at inter-annual and catchment scales. Firstly, we compare the annual water balance simulated by APSIM and a top-down model using long term historical records. Then we compare the Zhang et al [2005] model and APSIM-FLUSH for simulation of catchment water balance and explore the opportunities of merging these two approaches for parameterisation and further development of empirical catchment water balance models.

2. TOP-DOWN & BOTTOM-UP MODELS FOR CATCHMENT WATER BALANCE

2.1 The Top-Down Model

The top-down catchment water balance model used in this study was based on Fu [1981] and Zhang et al. [2005]. At decadal time scale, changes in catchment water storage can be neglected, thus average annual rainfall (P) equals the sum of evapotranspiration (E) and catchment runoff (Q):

$$E = P\left\{1+\frac{E_0}{P}-\left[1+\left(\frac{E_0}{P}\right)^{\alpha}\right]^{1/\alpha}\right\} = P\cdot f\left(\frac{E_0}{P},\alpha\right) \quad (1)$$

$$Q = \left(P^{\alpha}+E_0^{\alpha}\right)^{1/\alpha} - E_0 \quad (2)$$

Where E_0 is the potential evapotranspiration and α is a model parameter with range $(1,\infty)$. Details of the solutions are given in Zhang et al [2004].

At inter-annual or monthly scales, soil water storage has to be considered. Rainfall available for storage and evapotranspiration ($X(t)$) is given by:

$$X(t) = \begin{cases} P(t)\,f\left(\frac{S_{\max}-S(t-1)+E_0(t)}{P(t)},\alpha_1\right), & P(t)\neq 0 \\ 0, & P(t)=0 \end{cases} \quad (3)$$

Where t denotes time, $S(t\text{-}1)$ and S_{max} are the soil water storage at time t-1 and the maximum soil water storage respectively, $f()$ is as defined in Equation (1), and α_1 is a model parameter.

Evapotranspiration at time t ($E(t)$) is estimated from the total water available ($W(t)$) as:

$$W(t) = X(t) + S(t-1) \quad (4)$$

$$E(t) = \begin{cases} W(t)\,f\left(\frac{E_0(t)}{W(t)},\alpha_2\right), & W(t)\neq 0 \\ 0, & W(t)=0 \end{cases} \quad (5)$$

The sum of evapotranspiration and soil storage at time t ($Y(t)=E(t)+S(t)$) is estimated as:

$$Y(t) = \begin{cases} W(t)\,f\left(\frac{E_0(t)+S_{\max}}{W(t)},\alpha_2\right), & W(t)\neq 0 \\ 0, & W(t)=0 \end{cases} \quad (6)$$

Where α_2 is a model parameter. The direct runoff ($Q(t)$), deep drainage ($D(t)$) and soil water storage ($S(t)$) are:

$$Q(t) = P(t) - X(t) \quad (7)$$

$$D(t) = W(t) - Y(t) \quad (8)$$

$$S(t) = Y(t) - E(t) \quad (9)$$

2.2 The Bottom-up Model

The farming systems model APSIM v3.3 [Keating et al., 2003] was used to simulate water balance of farming systems. APSIM is able to simulate the growth of crops, grasses and trees, plant water uptake, soil water and nutrient balance as well as surface runoff and drainage with a daily time step. In APSIM, 1-D water balance was simulated with a 'cascading bucket' water balance model that uses the lower limit, drained upper limit and saturated water content for soil hydraulic characterisation. Surface runoff is calculated using the curve number technique [USDA Soil Conservation Service, 1972]. The model has been verified using data from locations similar to the study site [Verburg and Bond, 2003].

APSIM-FLUSH was used as the bottom-up model for simulation of catchment water balance. FLUSH predicts lateral fluxes of water between land units delineated by first identifying sub-catchment boundaries and then delineating land units within each sub-catchment using the multi-resolution valley bottom flatness (MRVBF) topographic index [Gallant and Dowling, 2003]. In FLUSH, water running on from an upslope land unit supplements precipitation as the supply of water to the surface. Subsurface lateral flow is enabled when the soil is saturated. The modelling of a catchment involves invoking APSIM on each soil type and land use option for a given up-slope land unit, calculating the area weighted average water balance for that unit, delivering water to the next unit down-slope, and then invoking APSIM on that next land unit. The lateral water flow across land unit boundaries was simulated in APSIM based on Gallant and Paydar [2003]. It is assumed that surface runoff is relatively rapid so all runoff leaves a unit and passes to the next unit in a single time step (1 day). A proportion of the runoff from a unit is discharged as channel flow where channels exist. The size of this proportion is derived as part of the land unit geometry analysis.

3. SIMULATION SCENARIOS AND MODEL PARAMETERISATION

Two sets of simulations were conducted. Firstly, daily water balance of an annual wheat-fallow and a continuous perennial lucerne farming system was simulated with APSIM at 7 selected sites: Emerald (Qld), Dalby (Qld), Dubbo (NSW), Wagga Wagga (NSW), Walbundrie (NSW), Waikerie (SA) and Perth (WA). From 1990 to 2002, these sites received 34% to 90% of their mean annual rainfall between April and October (inclusively), covering a wide range of 'winter rainfall fraction'. One wheat cultivar (Janz) was used for all simulations with a sowing window from 1st May to 30th June each year and assuming no nutrient stress. Maximum rooting depth for wheat and lucerne was assumed to be 1.2 m and 3 m respectively. A single duplex soil (contrasting texture between A and B horizons) was used for all simulations; having a plant available water capacity of 156 mm to 1.2 m depth, and 318 mm to 3 m depth.

Annual water balance was calculated from the APSIM simulation results. Equation (1) was then applied to each site. The value of α parameter was fitted by minimising the differences in results from the two models – a 'best case' comparison. Variation in α could be observed in response to rainfall seasonality and vegetation types.

The whole catchment water balance was simulated using APSIM-FLUSH and the Zhang et al [2005] model for the 178 km^2 Simmons Creek Catchment near Walbundrie in New South Wales, Australia. Three catchment scenarios were simulated assuming 1.6%, 33% and 100% forest cover. In the areas not covered by forest, a mixture of annual pasture and crop (wheat, canola)/pasture rotation system was defined based on local land use observations. In APSIM-FLUSH, a normal planting window and a N application rate of 100 kgN/ha was used for wheat and canola crops.

The Simmons Creek catchment was divided into sub-catchments [Gallant and Paydar, 2003] before three land units were delineated in each sub-catchment corresponding to MRVBF index values less than 0.5 (upper slopes and ridges), between 0.5 and 2.5 (mid slopes) and greater than 2.5 (valley floors). Each land unit may contain multiple soil types and different land uses.

For APSIM-FLUSH, the area and slope of each land unit, the length of the interface with its neighbour and the proportion of the unit's area drained by channels were estimated based on GIS grid analysis together with multi-resolution valley bottom flatness index and DEM [Paydar and Gallant, 2003]. To run APSIM on each land unit, the areal proportion of soil types and soil hydraulic properties (profile depth, bulk density, water contents at saturation, drained upper and lower limits, and saturated hydraulic conductivity) were obtained from field survey, laboratory measurements on selected soil samples in different land units and subsequent extrapolation [McKenzie et al., 2003]. Soil profile depths were specified for the simulations as 1.2-2.0 m for the uphill units, and 3 m for the slope and valley units. The maximum rooting depth for annual crops is assumed to be 1.2 m, annual pasture 0.8 m and perennial lucerne and trees 3 m.

For the monthly scale top-down model (Equation 3-9), the three parameters α_1, α_2 and S_{max} were estimated from catchment characteristics including forest cover proportion, soil water holding capacity, and the difference between maximum and minimum altitude.

The multi-site simulations were run using historical climate records from 1900 to 2002 obtained from the SILO patched database [www.nrm.qld.gov.au /silo/ppd/] The catchment simulations were done from 1957-2002. Evapotranspiration (ET) is the largest term in water balance, so the comparison mainly focuses on ET and water excess (P-ET).

4. RESULTS AND DISCUSSION

4.1 Water balance at long-term mean annual and inter-annual time scale

Figure 1 shows ET simulated by APSIM compared with that estimated from Equation (1) at Walbundrie. The long term mean annual rainfall and ET from APSIM fit Equation (1) with α=3.7 and α=2.4 for perennial lucerne and annual wheat-fallow systems respectively. The fitted top-down model can explain 95% of the inter-annual variations of APSIM simulated ET (Figure 1a) for perennial lucerne, but only 55% of the APSIM simulated ET variation for a wheat-fallow system at a nitrogen application rate of 100 kgN/ha (Figure 1b, 100N). When unlimited N was assumed, 87% of the APSIM simulated ET variation for the wheat-fallow system can be explained by the top-down model (Figure 1b, High N). Nitrogen limitation in wet years significantly restricts ET of wheat, as reflected in lower ET predictions by APSIM, but which can not be represented in Equation (1). For perennial lucerne, the continuous water use around the year reduced the impact of other factors (management) on annual ET, resulting in comparable results between the two models (Figure 1a). This shows the impact of vegetation perenniality and management factors on the performance of top-down models for ET predictions. Soil water storage could also be contributing to some of the unexplained variance.

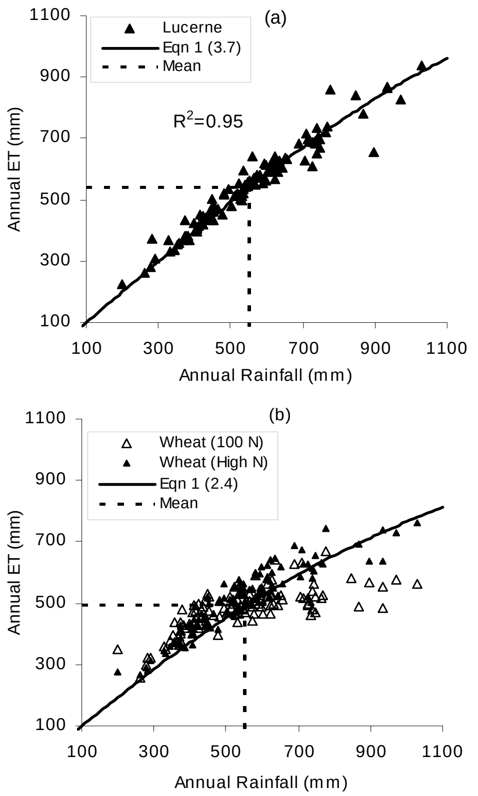

Figure 1. Change of simulated annual evapotranspiration with annual rainfall at Walbundrie (1900-2002). Symbols are values from APSIM, lines are generated using Equation (1) with the value of α in the brackets.

Assuming no nutrient limitation, and using annual rainfall plus APSIM simulated stored soil moisture in the rooting zone at start of the year (P+SW) instead of annual rainfall (P) in Equation (1), the top-down model Equation (1) was fitted to all the APSIM simulations at the 7 sites covering different rainfall seasonality and annual and perennial plants (Figure 2). With all datasets, the top-down model can explain 93% of the inter-annual variations in ET of perennial lucerne simulated by APSIM (Figure 2a). Overall, it can also explain 89% of the variations in ET of annual wheat crop simulated by APSIM (Figure 2b). The lowest R^2 is at Perth (R^2 =0.61 and 0.27 respectively for lucerne and wheat), where rainfall is strongly winter dominant and winter rainfall exceeds potential evapotranspiration (PET), especially for an annual wheat crop, leading to a plateau of ET response at higher annual rainfalls (Figure 2b).

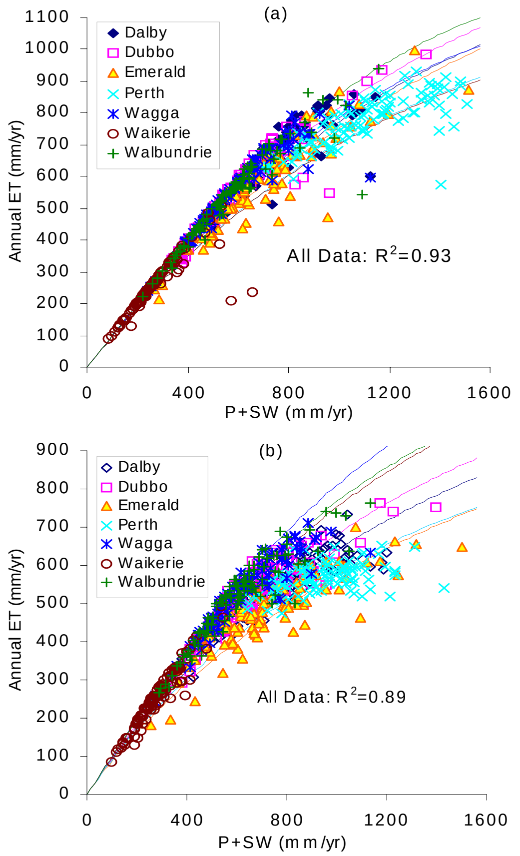

Figure 2. Change of simulated annual ET of lucerne (a) and wheat crop (b) with annual rainfall plus stored soil water (P+SW) at 7 sites (1900-2002) and comparison of ET simulated by APSIM and Equation (1). Symbols are APSIM simulated values, Lines are generated using Equation (1) with α parameter fitted to APSIM results at each site. R^2 was calculated using the data from all sites.

4.2 Changes of Top-down model parameter with seasonality and vegetation types

The value of the α parameter in Equation (1) changes with both vegetation type and rainfall seasonality. For long-term annual average, such changes have been discussed by Zhang et al [2001] and Keating et al [2002]. For the simulation of inter-annual water balance, the fitted values of α are shown in Figure 3. In general, α increases with perenniality. There is a tendency that α increases with winter rainfall fraction (WRF) to around a WRF of 0.65, and then it seems to decrease with further increased winter rainfall fraction (Figure 3). More detailed study is needed to further quantify the dependency of α on rainfall seasonality.

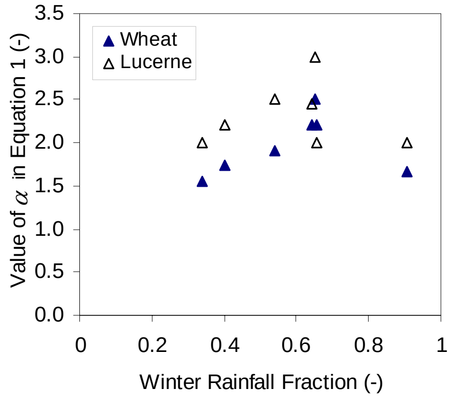

Figure 3. Changes of fitted α values with rainfall seasonality and vegetation types based on APSIM simulations from 1900-2002 for 7 sites.

4.3 Annual catchment water balance with spatially variable soil and vegetation

Figure 4 shows the catchment ET values simulated with Zhang et al [2005]'s top-down monthly water balance model as compared with the area-weighted ET values simulated by the bottom-up APSIM-FLUSH. The comparison is good in some years but not in others. There is a systematic tendency for ET predicted with the top-down model to exceed that from the bottom-up approach in high ET years when forest cover is low (Figure 4a).

For the scenario with 1.6% and 33% of forest cover, a large area of the catchment is assumed to be covered with an annual crop/pasture rotation. In the APSIM-FLUSH simulations, winter active crops (wheat, canola) and pastures were used, and a representative nitrogen application level of 100kgN/ha/yr for crops was assumed. As shown in Figure 1b, nitrogen stress of crops in wet years can limit the crop water use and ET. Each year after crop harvest and before sowing next year, a fallow period was assumed, in which no plant water use occurred. Both factors lead to reduced ET in the bottom-up model, especially in wet years. This can partly explain the difference in modelled ET from the two models at low forest cover (Figure 4a). For 100% forest cover, the results of the two models are more similar (Figure 4b).

The direct runoff simulated by the top-down model tends to be greater than the area-weighted runoff predicted by APSIM-FLUSH in years with lower runoff, but smaller in wetter years (Figure 5). The latter effect is emphasised in scenarios with higher forest cover. These differences likely reflect factors such as the characteristics of individual rainfall events and their interaction with specific attributes such as slope, soils and vegetation characteristics.

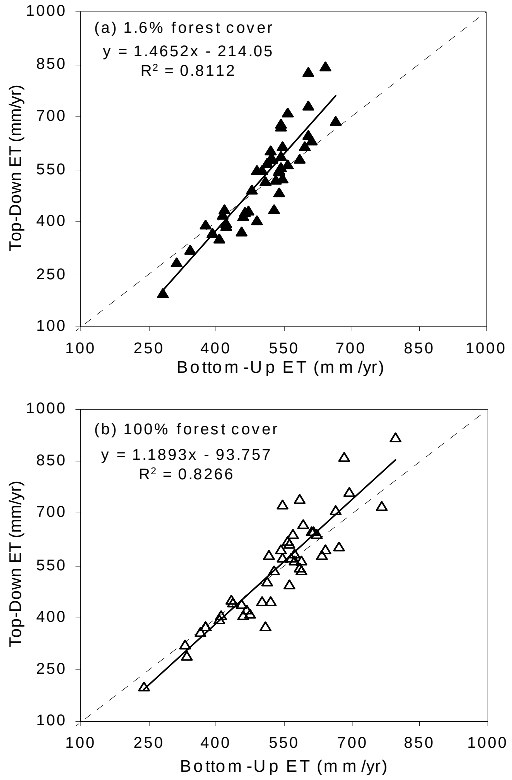

Figure 4. Comparison of annual ET at Simmons Creek catchment for two different forest covers (1957-2002). Bottom-up model is APSIM-FLUSH and the Top-Down model is Zhang et al [2005]

6. CONCLUSION

This paper presents a comparative study of water balance prediction using top-down (mean annual, or monthly) and bottom-up (daily) approaches. It shows that the point-based water balance calculations from the two approaches are broadly comparable. When applied at catchment scale water balance predictions were consistent in some years but different in particular years that warrant further investigation. The bottom-up model integrates the impact of different vegetation types, soil types, and management practices, whereas the top-down approach has the advantage of simplicity and associated decrease in risk of error propagation. There is enough consistency in the prediction to suggest value in using a detailed bottom-up model to generate data needed for development and parameterisation of top-down catchment water balance models that better characterise the impact of seasonality, vegetation types (perenniality) and spatially variable land use types. The bridging of these two approaches may provide a way forward to increase model simplicity without losing the explanatory capacity necessary to analyse the impact of local management changes on catchment water balance.

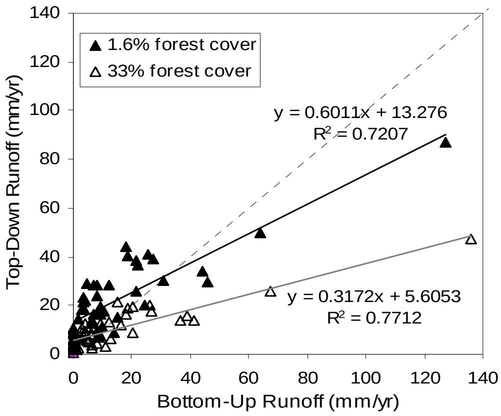

Figure 5. Comparison of catchment runoff at Simmons Creek catchment (1957-2002) simulated by the Bottom-Up APSIM-FLUSH and Top-Down Zhang et al [2005]'s top-down model.

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