Testing the VB95 Land Surface Model Against Catchment Runoff

S. L. Zhou[1], A. W. Western[1], F. H. S. Chiew[1]

[1]Cooperative Research Centre for Catchment Hydrology
Department of Civil and Environmental Engineering
The University of Melbourne
E-Mail: s.zhou@civenv.unimelb.edu.au

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EXTENDED ABSTRACT

Numerical weather prediction and climate models require information on the water and energy fluxes from the land surface as a lower boundary condition. Simulations of land surface processes are an important element of these models and provide both the required boundary conditions as well as an estimate of the surface water balance and landscape runoff.

The land surface model developed by Viterbo and Beljaars (VB95) is used in the numerical weather prediction and climate models of the Australian Bureau of Meteorology. At present the operational weather forecasting system routinely simulates runoff for each grid cell. While these simulations potentially have value for various applications, the ability of the land surface model and forecast system to simulate runoff has not been tested. This paper describes offline testing of the hydrological component of VB95.

VB95 is a point model in that each grid is assumed to have one set of parameters and atmospheric forcings. Evapotranspiration in VB95 is simulated using a detailed representation of the surface energy balance and is split into canopy evaporation, bare-soil evaporation and transpiration. Transpiration is drawn from the top three soil layers (top 1 m). The soil hydrological budget is solved by means of a simplified Richards equation applied to a vertical stack of four layers. The generation of runoff is a result of surface and deep runoff (baseflow). Surface runoff is based on a maximum infiltration limit concept, but with no sub-grid scale variability of either the precipitation flux or the near-surface soil water content. Deep runoff is free drainage at the bottom of the 2.89 m deep soil column.

In order to understand the model performance under Australian conditions, the VB95 model was applied to 15 catchments in the upper part of the Murrumbidgee River Basin using 35 years of data (1970-2004). The catchment areas vary from 70 to 3065 km^2.

The modelling results indicate that the VB95 model can simulate the water balance response to the climatic gradient in the Murrumbidgee River Basin. Errors in the modelled mean annual runoff range from -25% to +85%, with the model overestimating runoff in the wetter catchments. However, errors in the mean annual evapotranspiration are generally only about 10%, because runoff compared to evapotranspiration in these catchments is a smaller proportion of total rainfall (10-40%).

The VB95 model considerably overestimates baseflow and underestimates surface runoff because the dominant flow path of the VB95 model is deep runoff (baseflow).

To improve the modelling of the runoff components, several modifications were made to the VB95 model, mainly to increase surface runoff and reduce baseflow. The modifications made to VB95 involved adding an algorithm to represent spatially variable soil saturation (saturation excess runoff) and changing the deep drainage. In this paper VB95 was run with point scale (in space, 30-minute average intensity in time) rainfall intensities so no modification of the infiltration excess runoff algorithms was made. From a process perspective, representation of spatial variability in intensity should also be included when using spatial average intensities (as when implemented in an NWP framework) so that more realistic infiltration excess runoff is simulated.

Comparisons with stream flow timing (base flow vs surface flow) indicate that the modifications to VB95 lead to much more realistic simulations of the runoff components. However, they only improved slightly the estimation of mean annual runoff.

1. INTRODUCTION

The importance of land surface processes in numerical weather prediction (NWP) or general circulation models (GCMs) has led to sustained development of more realistic parameterization schemes in the past decades. The term parameterization refers to functional relationships that describe the processes being modelled. A significant number of studies are dedicated to the evaluation of these schemes using observations at point, regional or global scale. The approach of these studies ranges from fully coupled land surface-atmospheric circulation models to off-line model simulations using driving atmospheric forcings at a reference level close to the surface.

The land surface model developed by Viterbo and Beljaars (1995) (VB95) is used in the NWP models of the Australian Bureau of Meteorology. Models like VB95 have been developed with a focus on land-atmosphere exchanges of water and energy as required in simulations of weather and climate in atmospheric models. While runoff is predicted, it is not generally used operationally and typically receives little emphasis in the modelling effort. However, because such models are routinely run by weather agencies around the world, they provide comprehensive simulations of hydrologic response at spatial scales down to about 100 km^2. These simulations provide a real-time estimate of the hydrologic state of our landscapes along with current and forecast runoff, albeit of questionable accuracy. With appropriate improvements to the modelling, such a product could be provided by the Bureau of Meteorology and would find many beneficial uses.

A first step towards this is to test and improve the VB95 model in an offline context (i.e. using observed meteorological forcing and not coupled to the NWP). This has the advantage of removing the influence of rainfall and other forecast errors on the runoff prediction. This paper discusses results of testing VB95 against streamflow data from 15 unimpaired catchments in the upper Murrumbidgee River Basin. It also explores model modifications to improve these predictions.

2. THE VB95 MODEL

The VB95 land surface scheme processes time series forcing information about environmental surface phenomenon, and produces a comprehensive time series output of the environmental conditions of the surface to be coupled with a large model such as the NWP. In the absence of snow in the ground, the soil heat and water budget are represented by two partial differential equations. The top boundary conditions are the net heat flux and infiltration minus evaporation for the heat and water budget, respectively. Bottom boundary conditions are zero heat flux and free drainage. The following sections only describe the flow algorithms in VB95.

2.1. The Structure of VB95

The water balance in VB95 is based on a vertical stack of four-layers (Table 1) and solution of the moisture-based form of Richards Equation. For each layer, the soil moisture content θ is calculated using

$$\frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial z}\left(\lambda \frac{\partial \theta}{\partial z} - \gamma\right) - S_\theta \quad (1)$$

where z is depth, λ is hydraulic diffusivity, γ is hydraulic conductivity, and S_θ is the root extraction sink term. λ and γ are based on the widely used parametric relations of Clapp and Hornberger (1978):

$$\gamma = \gamma_{sat}\left(\frac{\theta}{\theta_{sat}}\right)^{2b_c+3} \quad (2)$$

$$\lambda = \frac{b_c\,\gamma_{sat}(-\psi_{sat})}{\theta_{sat}}\left(\frac{\theta}{\theta_{sat}}\right)^{b_c+2} \quad (3)$$

where b_c is a nondimensional exponent and ψ_{sat} is the air-entry matric potential. γ_{sat} and θ_{sat} are the hydraulic conductivity and the soil moisture content at saturation, respectively.

Throughfall from the canopy infiltrates and is subject to bare soil evaporation and transpiration before draining from the 2.89 m deep soil profile under a unit hydraulic gradient. The generation of runoff is a result of either of the following two processes.

Surface runoff is produced when the throughfall rate exceeds the maximum infiltration capacity, which is given by

$$I_{\max} = \rho_w\left(\frac{b_c\,\gamma_{sat}(-\psi_{sat})}{\theta_{sat}}\frac{\theta_{sat}-\theta_1}{0.5z_1} + \gamma_{sat}\right) \quad (4)$$

where θ_1 and z_1 are the water content and depth of the upper layer, respectively. In practice the maximum infiltration rate is generally quite large and it is rarely reached.

Deep runoff is given by the free drainage rate from the lowest soil layer, Eq. (2). This drainage forms the bulk of the simulated runoff and represents a slow response runoff pathway.

Evapotranspiration in VB95 is simulated using a detailed representation of the surface energy balance and is split into canopy evaporation, bare-soil evaporation and transpiration. Transpiration is drawn from the top three soil layers (top 1 m) directly. Since the majority of simulated runoff is from drainage out the bottom of the soil, rather than from surface runoff processes (that provide no opportunity for transpiration), the evapotranspiration in combination with the rainfall is the key control on water balance.

In this study the parameters of VB95 have been set to the a priori values used in the Bureau of Meteorology's operational forecasting models. In other words no calibration has been performed. The model uses a single soil type, which is represented as a typical medium textured soil with a nominal plant available water holding capacity of 250 mm and saturated hydraulic conductivity of 16 mm/h. Table 1 lists the soil physical coefficients in the VB95 land surface scheme. The vegetation fraction of cover in the model is determined from a coarse temporally averaged data set and is about 0.85 for these catchments.

Table 1. Soil physical coefficients in the VB95 land surface scheme

Symbol	Description	Value
z_1	Depth of soil layer 1	0.07m
z_2	Depth of soil layer 2	0.21m
z_3	Depth of soil layer 3	0.72m
z_4	Depth of soil layer 4	1.89m
θ_{sat}	Soil moisture at saturation	$0.472 m^3 m^{-3}$
θ_{cap}	Soil moisture at field capacity	$0.323 m^3 m^{-3}$
θ_{pwp}	Soil moisture at permanent wilting point	$0.171 m^3 m^{-3}$
ψ_{sat}	Matric potential at saturation	-0.338m
γ_{sat}	Hydraulic conductivity at saturation	$4.57 \times 10^{-4} m\ s^{-1}$
b_c	Clapp and Hormber soil parameter	6.04

2.2. Model Improvements

There are two challenges to improving the performance of VB95 (and other similarly structured models) from a hydrological perspective. The first area critical to model performance is the setting of parameter values to better represent landscape variability at scales resolved by the model grid. Previous work has focused on this with respect to soil moisture prediction and the impact of soil property and vegetation assumptions (Richter et al., 2004). A significant challenge in this area remains the derivation of accurate hydrologic parameters from maps of soil type, vegetation type and vegetation quantity (i.e. biomass, fraction cover, leaf area, etc).

The second relates to model structure and the importance of different flow pathways (residence times) to the simulated runoff. VB95 needs to simulate more surface runoff and rapid subsurface runoff if it is to realistically represent landscape hydrology. This requires recognition of spatial variability, its impact on soil water storage and runoff production at the sub-grid scale (noting that these models typically run on a grid scale of the order of 100 km^2 or larger). The free-draining lower boundary condition assumption (with rate parameters typical of surface soils) also needs modification.

2.2.1 Infiltration excess runoff

The excess of rainfall intensity over soil infiltrability and the occurrence of rainfall over saturated and impermeable surfaces have been identified as two major mechanisms of inducing surface runoff. For a physically realistic simulation of surface runoff, both fractions due to saturation excess and infiltration excess must be modelled. At present there are several approaches available that can take into account the areal or sub-grid-scale variability of soil moisture and rainfall intensity. These approaches range from the conceptual and statistical-dynamical representation of soil moisture to rainfall intensity to the more physically based formulations. In order to realistically simulate the surface runoff, we made modifications to the upper boundary conditions of the VB95 scheme, based on the approach of Arora et al. (2001). According to the work of Entekhabi and Eagleson (1989), the surface runoff ratio, *R*, that is the ratio of surface runoff against throughfall *T*, can be expressed as:

$$R = A_s + (1 - A_s)e^{-\kappa I} \tag{5}$$

where I is a dimensionless saturated hydraulic conductivity ratio and A_s is the fraction of saturated area. The parameter κ represents the fraction of the grid cell wetted by rainfall, and ranges between zero and one. In this study we define $I = I_{\max}/T$, where I_{max} is the maximum infiltration calculated by VB95, and set $\kappa = 1$. In Eq. (5) the saturated fraction is assumed to have a runoff ratio of unity, hence all the throughfall is runoff over this fraction. The remaining or unsaturated fraction has a runoff ratio of $e^{-\kappa I}$.

2.2.2 Saturation excess runoff

There are several approaches available for modelling the fraction of surface runoff due to saturation excess. The commonly used approach based on the concept of Xinanjiang model (Zhao et al., 1980) is used here. The method defines A_s as:

$$A_s = 1 - \left(1 - \frac{W}{W_{\max}}\right)^{\frac{b}{1+b}} \tag{6}$$

where b is a parameter. The soil moisture storage, is defined as $W = \sum_{i=1}^{n} \left(\theta_i - \theta_{pwp}\right) z_i$, and the maximum soil moisture storage is defined as $W_{\max} = z\left(\theta_{sat} - \theta_{pwp}\right)$, where $z = \sum_{i=1}^{n} z_i$. We considered storage in the upper two layers ($n = 2$). Thus $z = 0.28$ m and $W_{\max} = 84$ mm. Initial trials suggested the model performed slightly better when using $n = 2$ rather than $n = 3$. The surface runoff ratio is therefore estimated as

$$R = A_s + \left(1 - A_s\right) e^{-\kappa \frac{I_{\max}}{T}} \tag{7}$$

2.2.3 Deep water drainage (baseflow)

The bottom boundary conditions of the VB95 was also modified to realistically simulate the deep-drainage of water. Deep runoff generated from the lowest soil layer is modelled by Eq. (2) times a coefficient, k_b.

3. DATA AND MODELLING

VB95 was applied to 15 catchments (Figure 1) in the mid-upper Murrumbidgee for the period 1970 to 2004. A thirty-minute time step was used in the simulations. Most atmospheric forcing data (air temperature, humidity, shortwave radiation, longwave radiation and wind speed) are derived from Bureau of Meteorology data sets (Siriwardena et al., 2003), while catchment average precipitation is estimated from the SILO daily rainfall grids and disaggregated to a 30-minute time step using temporal patterns from nearby pluviographs. Thus rainfall accumulations represent areal averages but the intensity is more typical of the point scale intensity.

3.1. Long-term water balance

The fifteen catchments modelled in the Murrumbidgee River Basin are spread along a climatic gradient defined mainly by the mean annual catchment precipitation, which ranges from 650 mm to nearly 1200 mm (Figure 1, Table 2). The runoff coefficient is strongly determined by this gradient (Figure 2) and varies by a factor of six across the catchments. Annual runoff depth varies by a factor of ten and is strongly related to the annual rainfall pattern.

Table 2. Catchment characteristics and model performance. Rf – mean annual rainfall. Ro – mean annual runoff. BFI – baseflow index (baseflow/total flow). E_{orig} – coefficient of efficiency of monthly discharges for original VB95. E_{mod} – coefficient of efficiency for modified VB95

Catch ID	Rf mm	Ro mm	BFI	E_{orig}	E_{mod}
410038	1061	200	0.45	-0.45	0.11
410044	655	43	0.25	-0.08	0.42
410047	798	106	0.41	0.37	0.35
410057	1176	418	0.60	0.61	0.46
410061	1086	246	0.51	-0.20	0.12
410091	678	49	0.34	0.30	0.46
410097	693	60	0.33	0.29	0.22
410141	735	42	0.26	-0.22	0.30
410156	688	77	0.26	0.17	0.11
410705	727	94	0.21	0.01	0.22
410730	1105	333	0.57	0.41	0.52
410731	905	117	0.42	-0.41	0.01
410733	1002	233	0.46	0.50	0.60
410734	843	152	0.38	0.43	0.41
410736	990	152	0.49	-1.10	-0.30

VB95 simulates the long-term water balance response to this climatic gradient reasonably well, with a slight tendency to overestimate runoff. This is more noticeable in the wetter catchments, where runoff is overestimated in six of the seven wettest catchments.

However, the percentage errors in the runoff coefficient are often quite large, varying between -25% and +85% of the observed runoff. The errors in long-term evapotranspiration estimates are generally only about 10%, because runoff is a smaller proportion of rainfall here compared to evapotranspiration (runoff coefficient of 10-40%). This partly explains why atmospheric models can continue to model the water budgets realistically despite large errors in runoff simulations.

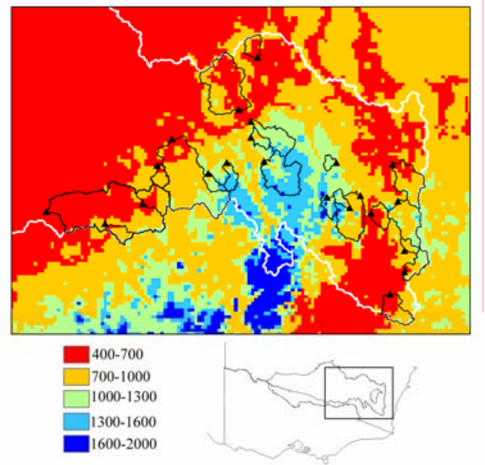

Figure 1. Gauged unregulated catchments in the mid- and upper-Murrumbidgee catchment. The mean annual rainfall (mm) is shown.

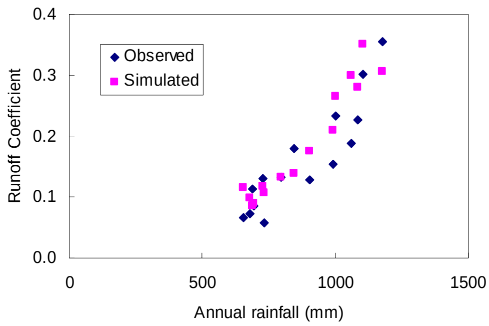

Figure 2. Simulated and observed runoff coefficients for 15 catchments in the mid to upper Murrumbidgee River Basin

Figure 3 shows the ratio of baseflow against annual rainfall. For the simulations, baseflow was taken as the deep drainage component of the modelled runoff, while a digital filter (Lyne and Hollick, 1979) was used to estimate baseflow from the observed runoff. The filter parameter was set to 0.925 and daily flows were used. Realistic partitioning of runoff to surface and sub-surface (baseflow) components is important for correctly simulating the timing of runoff and for managing water resources, water quality and ecosystems. Figure 3 shows that the present VB95 considerably overestimates baseflow for the reasons described earlier.

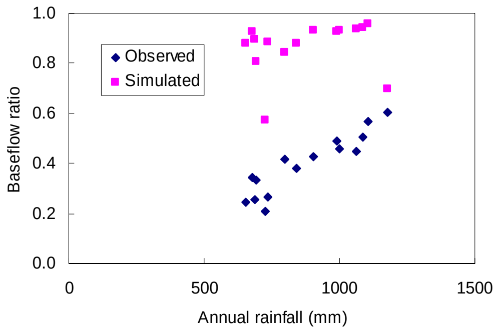

Figure 3. Simulated and observed baseflow index for 15 catchments in the mid to upper Murrumbidgee River Basin

3.2. Seasonal and monthly simulations

Figures 4 and 5 show the seasonal and monthly water balance for the Cotter River catchment and the Tarcutta Creek catchment. The Cotter River is one of the best modelled catchments, while Tarrcutta Creek is more typical. Tarrcutta Creek shows a reasonable simulation of the monthly runoff, but with a delay of typically about one month in the timing of the main runoff response. There is a slight delay evident in the simulated runoff early in the main runoff season for the Cotter River as well. This delay varies between catchments and tends to become more pronounced in the drier catchments.

The delay relates to the runoff processes embodied in the model. Very little runoff is produced by surface runoff pathways, thus the infiltration must percolate through about 3 m of soil profile before becoming runoff. In reality, a much greater proportion of runoff is produced by processes characterised by fast flow paths, including subsurface stormflow, saturation excess and infiltration excess surface runoff. The unrealistic delay introduced by the dominant flow pathway assumed in the model is even more obvious at the daily timescale (not shown).

4. RESULTS FROM SIMULATIONS USING MODIFIED VB95

VB95 was modified primarily to increase surface runoff and reduce baseflow (deep water drainage). The plots in Figures 6 and 7 compare the observed and simulated runoff coefficients and runoff components for the 15 catchments. It should be noted that some trial and error tuning of b and k_b was undertaken to improve simulated average runoff and baseflow index using only two of the fifteen catchments (Muttama Creek and Adelong Creek). The remaining 13 catchments were simulated with no tuning. The simulations presented here use b=0.1 and k_b=0.05.

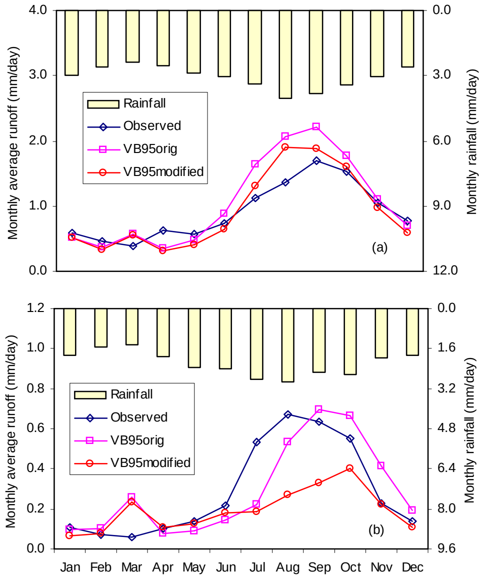

Figure 4. Simulated (using both the original VB95 and the modified model) and observed seasonality in runoff for (a) the Cotter River (410730) and (b) Tarcutta Creek (410047). The seasonal rainfall distribution is also shown.

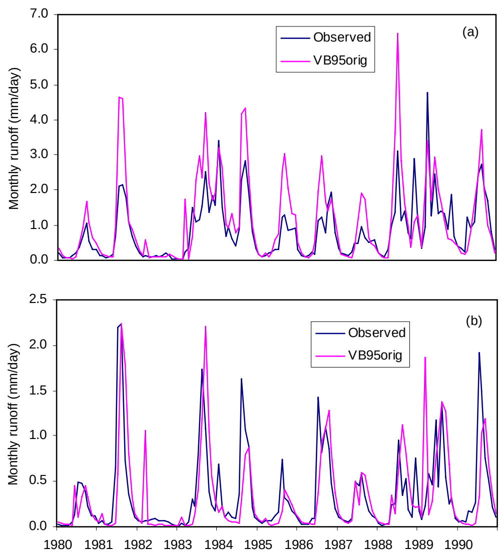

Figure 5. Simulated (original VB95) and observed monthly runoffs for (a) the Cotter River (410730) and (b) Tarcutta Creek (410047)

The modifications slightly improved the estimation of annual runoff (compare Figures 6 and 2). As noted above there are significant catchment-to-catchment errors in runoff but the proportional errors in evapotranspiration are much smaller. Comparing Figures 7 and 3 indicates that the flow distribution between slow and fast flow pathways is much more realistically simulated.

Table 2 shows Nash and Sutcliffe (1970) coefficient of efficiency for the simulated monthly runoff. In most cases the efficiency has improved and there is only one negative value for the modified model. In many cases this improvement in efficiency is related to an improvement in the timing of simulated runoff (see Figure 4a and compare Figures 8 and 5).

Figure 4a shows an improvement in the timing of runoff for the Cotter River and this improvement is typical of most of the wetter catchments. Figure 4b shows quite different behaviour, with runoff being delayed by about a month in the original model but only slowly building up over the winter spring period in the modified model. This is more typical of the dry catchments. It is not clear why this is occurring in the modified model; however, it may be related to excessive drainage to depths below the top 1m in the model and thus little build up of soil moisture and saturated area in the simulations earlier in the winter/spring period. The modified drainage from the model base limits runoff to be less than the original simulation. Hence the total runoff is reduced. This probably occurs in the drier catchments rather than the wetter ones due to the low rainfall accumulations. One of the features of this model that would promote such behaviour is the use of a vertically homogenous soil with properties more typical of surface soils than subsoils.

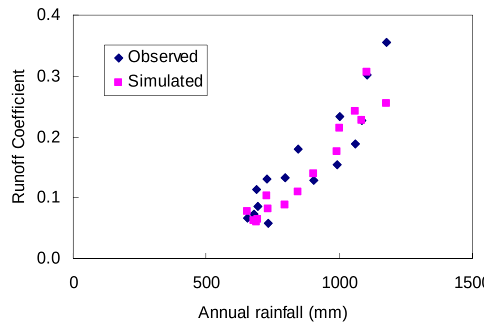

Figure 6. Simulated (modified VB95) and observed runoff coefficients for 15 catchments in the mid to upper Murrumbidgee River Basin

5. CONCLUSIONS

With a priori parameters, the present VB95 model can simulate the average water balance response to the climatic gradient in the Murrumbidgee River Basin. This reflects the modeling successfully capturing the first order water balance and energy balance constraints. Errors in the modelled mean annual runoff range from -25% to +85%, with the model overestimating runoff in the wetter catchments. This illustrates the challenge of making accurate predictions for ungauged basins in water limited environments. However, errors in the mean annual evapotranspiration are generally only about 10%, because runoff here, compared to evapotranspiration, is a smaller proportion of rainfall (10-40%).

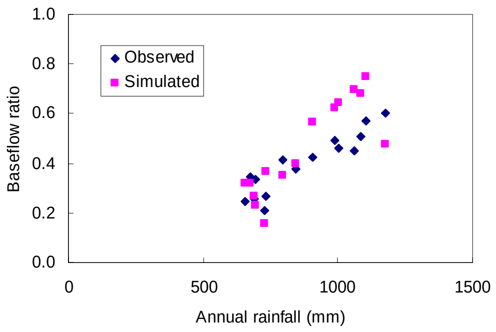

Figure 7. Simulated (modified VB95) and observed baseflow index for 15 catchments in the mid to upper Murrumbidgee River Basin

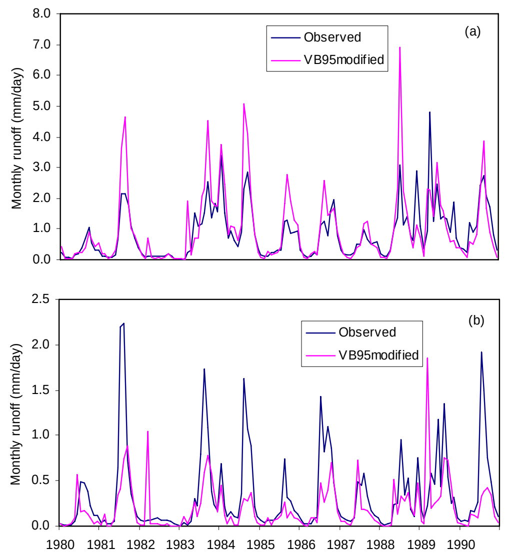

Figure 8. Simulated (modified VB95) and observed monthly runoffs for (a) the Cotter River (410730) and (b) Tarcutta Creek (410047)

The VB95 model considerably overestimates baseflow and underestimates surface runoff because the dominant flow path of the VB95 model is deep drainage (baseflow). The modification to VB95 in this paper to increase surface runoff and reduce baseflow significantly improved the simulation of flow components, but only slightly improved the estimation of mean annual runoff.

The modifications to the VB95 model did lead to improvements in the timing of runoff in the wetter catchments studied but not in the dry catchments. The causes of this are the subject of further exploration.

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