Evaluation of SWAT for modelling the water balance of the Woady Yaloak River catchment, Victoria

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Abstract: Future land use change will have a profound effect on the water balance of agricultural and rural catchments in Australia. It is therefore imperative that any such consequences likely to arise from impending land use changes are predicted accurately so that strategies can be implemented to minimise or prevent undesirable impacts to the water balance of catchments. SWAT is a comprehensive hydrologic model developed to predict the impacts of land use change on water balance. SWAT has been applied in Australia but it has not yet been widely adopted. The application of SWAT to the Woady Yaloak River catchment in southwest Victoria is described in this paper. SWAT is being evaluated to determine whether it is suitable for modelling the water balance of catchments in the southwest region of Victoria and to determine if it could be adopted as a planning tool to manage land use change. The results achieved in this initial application of SWAT were very pleasing. However it is shown that the groundwater and tree growth components of the model are not entirely adequate. These shortcomings with SWAT affect its ability to accurately model the water balance of catchments in Australia. It is recommended that both these components be modified to improve model performance.

Keywords: *Hydrologic modelling; SWAT; water balance; physically-based, distributed model*

1. INTRODUCTION

One of the most significant impacts to arise as a direct consequence of the land use change that has occurred over the past 200 years is the alteration to the water balance of catchments. Land use change has been responsible for modifying the hydrologic regime of catchments that were once in equilibrium. Implementation of land use change in the future raises serious issues because it will lead to further alterations in the water balance of catchments. It is imperative that the most likely consequences to arise from impending land use changes are predicted accurately to enable catchment management authorities to implement strategies that will prevent or minimise undesirable impacts to the water balance of catchments. In recent years hydrologic models have become widely utilised for predicting land use change impacts on catchment water balance.

This paper describes the application of the Soil and Water Assessment Tool (SWAT), a comprehensive hydrologic model that has been developed specifically to determine the impacts of land use change on the water balance of large complex catchments. Results for the prediction of streamflow in the Woady Yaloak River catchment are presented and discussed. SWAT is being evaluated to determine its suitability for being adopted as a tool to predict land use change impacts across southwest Victoria.

2. OVERVIEW OF SWAT MODEL

SWAT was developed by the United States Department of Agriculture for use in the United States but has since become prominently used worldwide for studies investigating the impacts of land use and climate change on the water balance and water quality (erosion, nutrients and pesticides) of agricultural catchments. A large body of literature exists detailing the numerous applications of SWAT. A complete description of the model can be found in Neitsch et al. (2001). For the benefit of the readers a brief description of SWAT is presented here.

SWAT is a physically-based, distributed hydrologic model. SWAT operates on a daily time step and has the capabilities to continuously simulate 100 years of streamflows. SWAT is also a non-point source pollution model that simulates the transport of sediment, nutrients and pesticides through catchments. SWAT is a comprehensive tool that enables the impacts of land management practices on water, sediment and agricultural chemical yields to be predicted over long periods of time for large complex watersheds that have varying soils, land use and management practices (Neitsch et al., 2001). Specific information for climate, soils, topography, and land use are required to run the model. The main algorithms used in modelling the processes of the hydrologic cycle are presented in Table 1.

Table 1. Summary of algorithms used by SWAT (Neitsch et al., 2001; Stone et al., 2001).

Hydrologic Process	Algorithms
Surface runoff	SCS Curve Number method; Green & Ampt Infiltration method
Channel routing	Variable storage routing method; Muskingum routing method
Percolation	Storage routing method
Interflow	Kinematic storage model
Groundwater	Base flow recession constant; groundwater storage; re-evaporation
Evapotranspiration	Penman-Monteith; Hargreaves; Priestley-Taylor

SWAT enables a catchment to be discretised into an unlimited number of subbasins. Subbasins are further divided into Hydrologic Response Units (HRUs) which are lumped land areas that are comprised of unique land cover, soil, and management combinations (Neitsch et al., 2001). An ArcView GIS interface has been developed for SWAT and was used in this study. Utilisation of the interface to handle spatial data and create the files needed to run the model saves considerable time for users.

3. CATCHMENT DESCRIPTION

The Woady Yaloak River catchment is located in southwest Victoria (Figure 1).

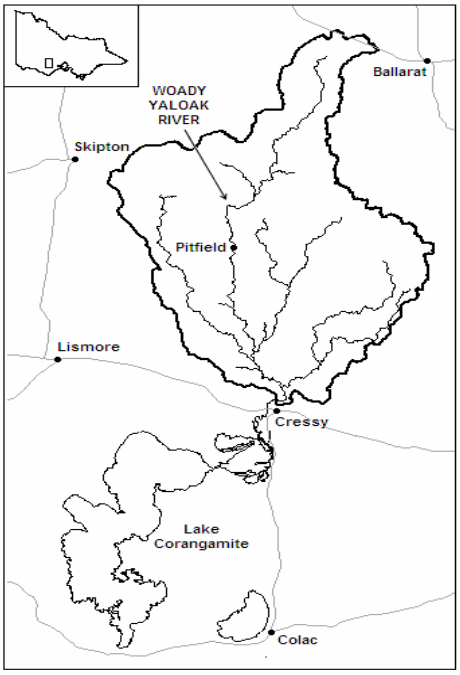

Figure 1. Location of the Woady Yaloak River catchment in southwest Victoria.

Streamflow gauging stations located at Pitfield and Cressy drain areas of 306 km^2 and 1157 km^2 respectively. The topography is generally flat with the elevation varying from 508m at the highest point to 127m at the Cressy gauging station. Annual rainfall varies from 550 mm at Cressy to 700 mm at Ballarat. The majority of land is used for agriculture including livestock grazing (beef cattle and sheep) and cropping (cereals). There are also large eucalyptus forests. Minor land uses include pine and eucalyptus plantations, residential areas and mining.

4. RESULTS AND DISCUSSION

4.1. Calibration and Validation

A traditional split sample test (Klemeš, 1986) was employed to evaluate the performance of SWAT. The calibration period was 1978-1989 and the validation period was 1990-2001. It is recommended that the surface runoff and base flow components are separated from the observed total streamflow and the model calibrated for surface runoff initially and then for base flow. There is some compromise since adjusting parameters to improve the prediction of base flow inevitably affects the surface runoff which is calibrated first. However this methodology produces better results than calibrating against total streamflow alone (SWAT, 2003). Streamflow was separated into surface runoff and base flow using a recursive digital filter (Nathan and McMahon, 1990). The model was calibrated at Pitfield first as it is the furthest upstream. Parameter values for the subbasins upstream of Pitfield were held constant when calibration of the model at Cressy was conducted. There were 92 HRUs in all, each with their own set of parameters. Although SWAT requires hundreds of input variables, only eight were changed in calibrating the model. As recommended by Neitsch et al. (2001) calibration was performed for annual values initially. Once annual conditions were deemed to be acceptable monthly and daily records were used to "fine tune" calibration of the model. Monthly streamflow statistics for the calibration period are shown in Table 2.

Table 2. Monthly streamflow statistics at Pitfield and Cressy for the calibration period

	Pitfield	Cressy
Mean observed (mm)	4.08	3.30
Mean predicted (mm)	4.16	3.81
Coefficient of determination (r^2)	0.62	0.67
Nash and Sutcliffe coefficient (R^2)[a]	0.62	0.65

[a] Nash and Sutcliffe (1970)

A plot of the observed and predicted streamflows (Figure 2) reveals that SWAT has managed to reproduce monthly trends relatively well.

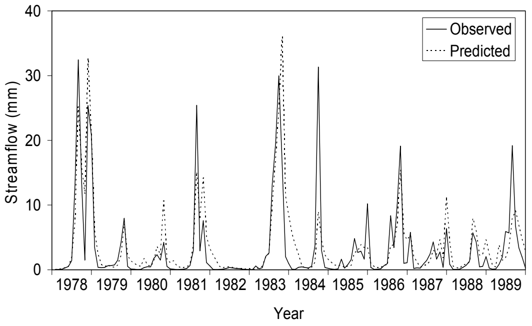

Figure 2. Observed and predicted monthly streamflows at Cressy, 1978-1989.

Monthly streamflow statistics for the validation period are presented in Table 3. Observed and predicted monthly streamflows at Cressy for the validation period are shown in Figure 3.

Table 3. Monthly streamflow statistics at Pitfield and Cressy for the validation period.

	Pitfield	Cressy
Mean observed (mm)	3.32	2.42
Mean predicted (mm)	3.61	2.82
Coefficient of determination (r^2)	0.76	0.77
Nash and Sutcliffe coefficient (R^2)	0.75	0.77

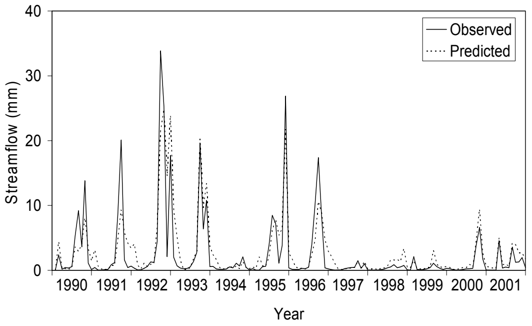

Figure 3. Observed and predicted monthly streamflow at Cressy, 1990-2001.

Overall the results were relatively pleasing at both stations. Annual streamflows were predicted extremely well. R^2 values of 0.75 and 0.92 were achieved at Pitfield for the calibration and validation periods respectively. For the same simulation periods at Cressy, the R^2 values obtained were 0.86 and 0.86 respectively. Interestingly R^2 for monthly flows increased significantly at both gauging stations for the validation period (Tables 2 and 3). The reason for this is difficult to ascertain. The fact that the mean flow for the validation period was lower may have something to do with this. Scatter plots of the observed versus predicted annual streamflows at Cressy for the calibration and validation periods, which are presented in Figures 4 and 5 respectively, show comparatively good agreement with the 1:1 line.

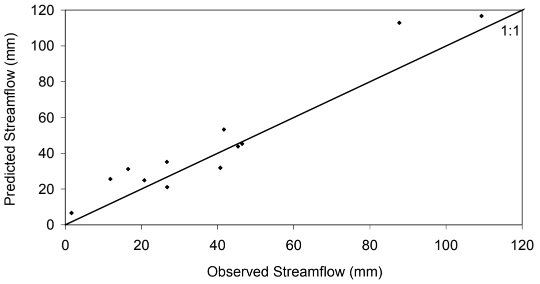

Figure 4. Observed versus predicted annual streamflows at Cressy, 1978-1989.

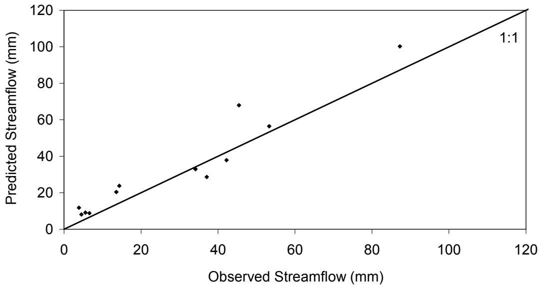

Figure 5. Observed versus predicted annual streamflows at Cressy, 1990-2001.

4.2. Base Flow Recession

Results for daily streamflow predictions compared favorably to some results from overseas studies. However graphical inspection of the daily streamflow hydrographs revealed a problem with base flow recession rates. This problem is clearly evident in Figure 6 where it is very apparent that the recession limb of the predicted hydrograph is much higher than the recession limb of the observed hydrograph.

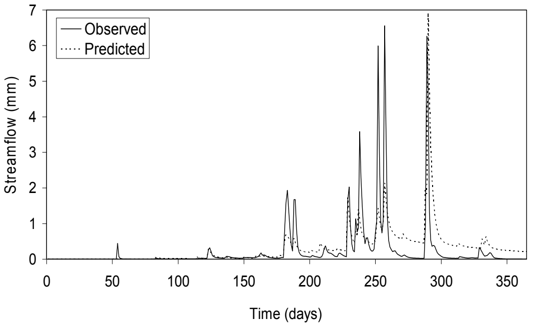

Figure 6. Observed and predicted daily streamflow at Cressy, 1983.

Once recessions “bottom out” the only component contributing to streamflow is base flow. It can be observed in the Figure 6 that after the hydrograph recessions “bottom out” the amount of base flow contributing to the streamflow is simply too great, even after a considerable number of days have passed, and this is the cause of the elevated predicted streamflow during this period. The problem with base flow recession rates can be observed in Figures 2 and 3 to affect the monthly streamflow results as well.

It was discovered this problem occurred for most years of the calibration and validation periods at both gauging stations. Bouraoui et al. (2002) also found that SWAT "tended to over-predict the low-flows during the summer months for the whole catchment."

One possible cause for this occurrence may be due to the routing delay. SWAT routes channel flow but does not route overland flow. Instead a simple surface runoff storage feature is used to lag a portion of the surface runoff released to the main channel. This simple approach may be affecting recession rates. The problem with the recessions might also be caused by the component of SWAT that models the groundwater contribution to streamflow.

Equation (1) is used by SWAT to calculate the daily contribution of groundwater to streamflow.

$$Q_{gw,i} = Q_{gw,i-1} \cdot \exp^{-\alpha\Delta t} + w_{rchrg} \cdot (1 - \exp^{-\alpha\Delta t}) \qquad (1)$$

where $Q_{gw,i}$ is the groundwater flow into the main channel on day i (mm), $Q_{gw,i-1}$ is the groundwater flow into the main channel on day i-1 (mm), α is the base flow recession constant, Δt is the time step (1 day), and w_{rchrg} is the amount of recharge entering the aquifer on day i (mm).

Changing the base flow recession constant (α) in (1) could be seen as a way of correcting the problem. However this did not prove to be the case. Base flow recession constants of 0.078 (Pitfield) and 0.070 (Cressy) were calculated from long term streamflow records using the method described by Laurenson (1961). However from calibration of the model these values were concluded to be inappropriate. It was found that base flow receded too quickly when the above values were used. This was particularly noticeable during periods of low flow. Once groundwater from the shallow aquifer was evacuated at the beginning of summer then for a period of months the shallow aquifer made no contribution at all to streamflow until large rainfall events occurred in winter. Other parameters were changed to rectify this but the problem persisted. The Woady Yaloak River is classified as a perennial stream since it receives a continuous contribution from groundwater sources (Neitsch et al., 2001). The river has only dried up twice in the time that records have been maintained (1955 to present). Therefore the calculated base flow recession constants were considered to be too high.

It was found that a base flow recession constant of 0.01, at both stations, produced better results. A value of 0.01 represents a very slow decline in groundwater evacuation during periods of no recharge. When this value was used in SWAT, base flow contributed to streamflow all year round which is more realistic than what was occurring previously. However it can be observed from Figure 6 that using a value of 0.01 results in too much base flow contributing to streamflow for certain periods of the year.

A possible explanation for this phenomenon is that too much water is infiltrating past the root zone and recharging the shallow aquifer while not enough water is exiting the soil profile as interflow. From (1) it can be seen that the amount of base flow that contributes to streamflow is largely dependent on the amount of recharge entering the shallow aquifer on a daily basis (w_{rchrg}). If more water enters the aquifer than can be evacuated in a single day then the water is stored in the shallow aquifer and released when recharge subsides. The quantity of water that enters and is stored in the shallow aquifer during the winter and spring months appears to affect the simulation of base flow in the summer months. Echkardt et al. (2002) found that when using SWAT the amount of water percolating through soil layers with low permeability was too great. Therefore the base flow contribution to stream flow was too high whereas the interflow was strongly underestimated. By modifying the model to increase the amount interflow they found model results were significantly improved.

The problem with base flow may also be attributed to the underlying simplicity of the groundwater component of SWAT. Heislers and Pillai (2000) state "in reality, hydrogeological systems rarely fall into a simple watertable model, and therefore a fixation on recharge can be a gross simplification." Heislers and Pillai (2000) go on to report:

> In south-west Victoria, the acceptance of physical understanding appears to have been clouded by preconceptions of relatively straightforward groundwater systems (e.g. recharge to regional watertable then discharge model). As a local reaction to this, in some quarters this model has been admonished to such a point that it is perceived as no longer relevant.

Application of SWAT to the Woady Yaloak River catchment has shown that groundwater cannot be predicted accurately in certain catchments using the current groundwater component. As indicated by Bouraoui et al. (2002), in attributing the over prediction of streamflow in summer to (1), the recession constant is independent of the gradient existing between the water table and the water level. Bouraoui et al. (2002) state "using this approach, it will be very difficult to predict accurately long-lasting constant base-flow such as that occurring in summer." The importance of this statement cannot be underestimated for a continent such as Australia where sustained dry periods ensure that low flow hydrology is critical in water balance studies and for maintaining environmental flows.

4.3. Growth and Leaf Area Index of Eucalyptus Trees

Forests are very important to the water balance of catchments. The simulation of the growth of eucalyptus trees by SWAT does not appear to be adequate. All plant and tree growth is simulated by SWAT using a simplified version of the EPIC plant growth component (Neitsch et al., 2001). The two model outputs for plant and tree growth are total biomass (all biomass aboveground and roots) and Leaf Area Index (LAI). The daily total biomass and LAI of the eucalyptus trees growing in subbasin 1 are shown in Figures 7 and 8 respectively for the calibration period.

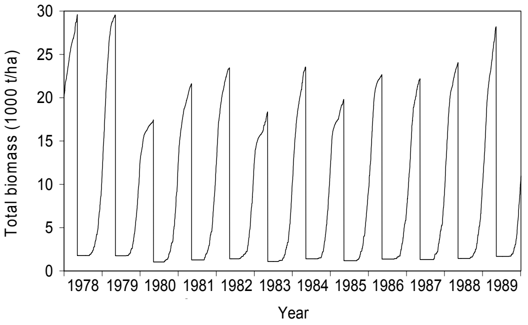

Figure 7. Daily total biomass of eucalyptus trees growing in subbasin 1 for the calibration period.

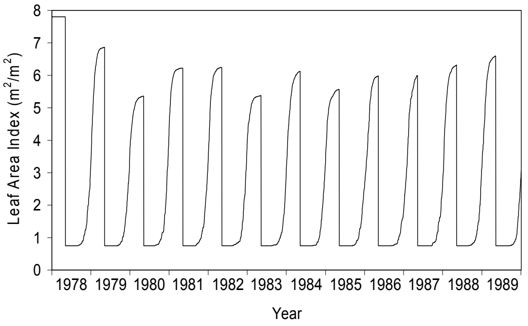

Figure 8. Daily LAI of eucalyptus trees growing in subbasin 1 for the calibration period.

Clearly the large fluctuations exhibited for both the total biomass and LAI warrant investigation. The model theory states that trees go dormant as the day length nears the shortest or minimum day length for the year, during which time no growth takes place. In addition once trees enter dormancy tree leaf biomass is converted to residue and the LAI for the tree species is set to the minimum value allowed (Neitsch et al., 2001). These concepts are responsible for the fluctuations observed in Figures 7 and 8.

It can be observed in Figure 7 that when the trees do lose their leaves the total biomass is reduced to low levels that are implausible. The LAI of eucalypts usually remains more stable over time (Hingston et al., 1998; Battaglia, pers. comm.) unlike the situation occurring in Figure 8. If anything LAI is slightly greater in winter because eucalypts lose their leaves during summer in response to heat and water stress. The large variations in LAI will seriously affect the overall water balance because several algorithms used by SWAT to calculate evapotranspiration require LAI as an input. It is highly possible that the inaccurately simulated LAI contributes to the problem associated with base flow recessions. Evapotranspiration is underestimated in winter and spring due to the low LAI during these periods. Consequently recharge of the shallow aquifer increases. Due to the elevated shallow aquifer level, more water is available to contribute as base flow in the summer when recharge subsides and this leads to the overestimation of streamflow.

5. CONCLUSIONS

SWAT performed extremely well at predicting annual streamflows. Monthly and daily stremflows could be considered adequate although greater accuracy at these time steps is desirable. Problems associated with the groundwater and tree growth components constrain the ability of SWAT to accurately model the water balance. The simple groundwater component makes it very difficult to simulate the base flow contribution to streamflow during summer months. Australia is a very dry continent which makes low flow hydrology critical to water balance studies. Accurate prediction of base flow during dry periods is critical because the quantitative effects of some land use change scenarios may only be very minor but the environmental and economic impacts will be of great significance. Unrealistic simulation of LAI for eucalypts affects important hydrologic processes, i.e. evapotranspiration. A major land use change expected in Australia in the coming decades is a significant increase in the number of eucalyptus trees planted (Zhang et al., 2001). Since SWAT cannot simulate the growth of eucalyptus trees accurately, the validity of predictions for this land use change scenario must surely be highly questionable.

It is recommended that both components of SWAT are modified to enable the water balance in Australian catchments to be modeled with greater accuracy. SWAT is a very comprehensive hydrologic model capable of simulating all the major processes of the hydrologic cycle. It is a very user friendly model with an excellent support network. The proposed modifications are necessary to improve the performance of the model so that it can be utilised as a tool for managing land use change in southwest Victoria.

6. ACKNOWLEDGEMENTS

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