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Water Balance Modelling – Impact of land use, soil properties and rainfall seasonality

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Abstract: The daily water balance model PERFECT is currently being applied to investigate the impacts of land use changes, soil properties and rainfall seasonality on mean annual water balance across New South Wales.

Four different land use types (pasture, crop, trees and bare soil) along with 355 soil types are modelled. Estimates of mean annual evapotranspiration (ET) and water excess (runoff and drainage) for each of the combinations are analysed. The purpose of this study is to develop more variability and landuse options around the Zhang's curves which currently only provide relationships between long-term average annual evapotranspiration (ET) and rainfall for two vegetation classes (forest and herbaceous plants). The Zhang curves are often used as a simple extrapolation tool when modelling landuse change.

The results from this study clearly show that ET for trees is the highest followed by pasture, then crop with bare soil giving the least ET. As expected, water excess is highest for bare soil followed by crop, then pasture and the least for trees. The ET/water excess differences among 355 soil types increase with increase in average annual rainfall for each land use type. The correlations between ET/water excess of different land use types are generally good, with the best between trees and pasture. The correlation can be used to estimate ET/ water excess for other land use types if estimates for one of the land use types are already known (also need an estimate of either ET or water excess for all other land uses).

The results also show that soil properties and rainfall seasonality play a critical role in determining the overall water balance. The effects of plant available water capacity (PAWC) are particularly important in determining the water balance. Higher PAWC leads to higher ET and lower water excess for each land use type. The correlations between ET/water excess and rainfall for each PAWC category in four land use types are strong enough that it is proposed that this can be used to directly estimate ET and water excess from rainfall. The correlations between water excess of different land use types and the correlations between ET/water excess and rainfall for each land use type are higher in more winter dominant rainfall areas than those in less winter dominant rainfall areas.

Keywords: *Zhang's Curves, water balance, Evapotranspiration, water excess, plant available water capacity (PAWC)*

1. INTRODUCTION

Daily water balance model PERFECT (Littleboy *et al*. 1989) has been widely used in Australia to estimate soil water balance. The model was developed as a cropping system model that predicts the water balance (runoff, infiltration, soil evaporation, transpiration and recharge) for crop/fallow sequences. It has been applied to estimate water balance for a range of perennial pasture systems and tree water use in eastern Australia (e.g. Abbs and Littleboy, 1998). The model has been validated against measured runoff, soil water yield and cover data in grazing and cropping systems (Littleboy *et al.* 1989, 1992, Silburn and Freebairn 1992, Day *et al*. 1997, Owens *et al*. 2003, 2004).

The aims of this study are

- to use the water balance model PERFECT to investigate the impact of land use changes on mean annual water balance across New South Wales,
- to investigate the role of soil properties and rainfall seasonality in determining the water balance,
- to develop simple relationships between rainfall and components of the soil water balance,
- to provide an approach for direct or indirect estimation of water balance from rainfall instead of water balance modelling.

2. MODEL DESCRIPTION AND DATA

The daily one-dimensional water balance model PERFECT is used in this study. Within PERFECT, simulation is performed on a daily time step based on daily weather data. Runoff is calculated as a function of rainfall, soil water deficit, surface roughness, surface residue and land cover. Soil water is updated on a daily basis by any rainfall exceeding the daily runoff volume. For dry profiles this infiltration may flow directly into the lower profile layer/s using an optional soil cracking algorithm. Infiltration is redistributed through the profile using a linear routing method. Redistribution from the lowest profile layer is assumed lost from the system as drainage. Transpiration is represented as a function of potential evaporation, leaf area and soil moisture. Water is removed from the profile according to the current depth and distribution of roots. Soil evaporation is based on Ritchie's two stage evaporation algorithm (Ritchie 1972).

Modelling is carried out for entire NSW and ACT which covers an area of 803,922 square kilometres. Mean annual rainfall across NSW and ACT (1975-2006) ranges from a minimum of 239mm/yr to a maximum rainfall of 2152mm/yr. There is a clear east-west rainfall gradient across the region, where rainfall is highest in the east and lowest in the west.

The model requires daily climate data (rainfall, maximum temperature, minimum temperature, potential evapotranspiration, and radiation), soil profile hydraulic properties and land use types as its inputs. The source of the climate data is the 'SILO Data drill' of the Queensland Department of Natural Resources and Water (www.longpaddock.qld.gov.au/silo/, Jeffrey *et al*. 2001). The SILO Data Drill provides daily rainfall and other climate variables for 0.05°x0.05° grids across Australia, interpolated from point measurements made by the Australian Bureau of Meteorology. These surfaces were grouped into climatic zones on the basis of average annual rainfall and rainfall seasonality. For each of the defined 628 climate zones, the SILO data closest to the centroid of each zone were used. Four land use types (pasture, crop, trees and bare soil) were used in this modelling. The soil types used in this study is a dataset with 355 soil types as described in McKenzie *et al.* (2000).

The Zhang's curves (Zhang *et al*. 2001) were used to validate the results obtained from this study. Zhang *et al*. collated results from 250 catchments worldwide, and derived relationships between long-term average annual evapotranspiration (ET) and rainfall for two vegetation classes (forest and herbaceous plants).

3. MODELLING METHODOLOGY

Four different land use types along with 355 soil types and 628 climate zones are modelled. The results from this simulation analysis are used to explore the influence of land use type, soil hydraulic properties and rainfall seasonality on average annual ET and water excess.

Impacts of land use on ET and water excess. The modelling results for pasture, crop, trees and bare soil are used to analyse correlations between ET/water excess of the four land use types. Each of the four modelling results is then used to analyse impacts on ET and water excess of soil capacities and rainfall seasonality.

Influence of soil hydraulic properties on ET and water excess. The approach used to analyse the impacts on ET and water excess of three soil properties (plant available water capacity - PAWC, soil depth, and saturated hydraulic conductivity - Ksat) is to: classify PAWC, soil depth and Ksat for all 355 soil types using the following thresholds.

- PAWC <100 mm, 100 -200 mm and >200;
- Soil depth <1 m, 1 - 2 m and > 2 m.
- Ksat <1 cm/hr, 1 - 10 cm/hr and >10 cm/hr.

Average annual ET and water excess are analysed to explore the differences between soil hydraulic properties.

Influence of rainfall seasonality on ET and water excess. Rainfall seasonality is defined as average winter rain divided by average annual rain for 628 locations. This is then indexed into 5 classes (1-5). Class 1 is the least winter dominant rainfall pattern to class 5 being the most winter dominant rainfall pattern. The impacts of rainfall seasonality on ET and water excess are investigated by grouping the PERFECT modelling results by rainfall seasonality class and analysing the relations between ET/water excess and rainfall within each rainfall pattern.

4. RESULTS AND DISCUSSION

Estimated average annual ET vs. rainfall for trees, pasture, crop, bare soil and Zhang's Curves for trees and herbaceous plants are presented in Figure 1. Patterns of ET variation with rainfall for the four land use types are similar; for each land use type, average annual ET increases when average annual rainfall increases. In general, annual average ET is highest for trees followed by pasture, then crop with bare soil giving the least ET. Annual average ET for trees and that for crop are generally in agreement with Zhang's Curves for forest and for herbaceous plants. The trend lines of ET for trees and crop are almost identical to Zhang's curves for average annual rainfall <1000mm. For average annual rainfall >1000mm, the differences between the trend lines for trees, crop and Zhang's curves increase when average annual rainfall increases, which indicates that average ET for trees and cropping are less than Zhang's results for forest and for herbaceous plants (Figure 1).

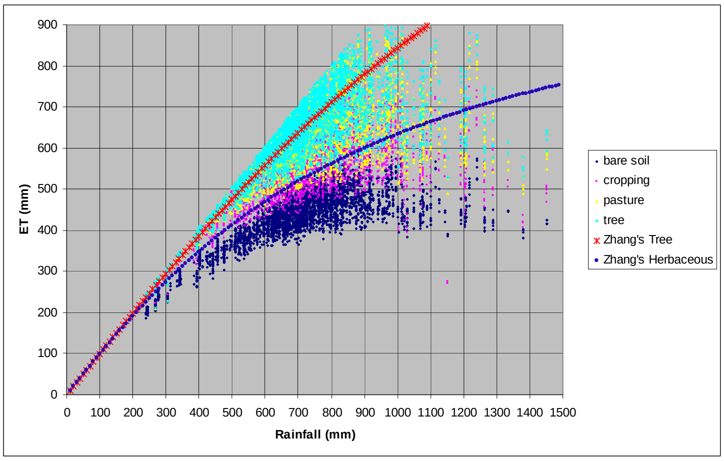


Figure 1. Annual mean evapotranspiration variation with rainfall for four different land use types compared with Zhang's Curves

Average annual water excess for trees, pasture, crop and bare soils vs. average annual rainfall is presented in Figure 2. The water excess distribution patterns for four land use types are similar. For each land use type, water excess increases with the increase in average annual rainfall. Generally, water excess is highest for bare soil followed by crop, then pasture and the least for trees.

Correlations between rainfall and either ET or water excess for the different land use types are generally good, with the best between trees and pasture (Figure 3). The ET relationships generally follow a power function distribution and water excess relationships follow a polynomial function distribution. The strength of the correlations found implies that they can be used to estimate average annual ET and water excess for other land use types if those of one land use type are already known.

The effects of soil properties (PAWC, soil depth and Ksat) on average annual ET and water excess are also investigated. On average, higher PAWC leads to higher ET and lower water excess for each land use type

(Figure 4). The impact of soil depth is less critical in determining water balance when compared to PAWC, but more important when compared to Ksat.

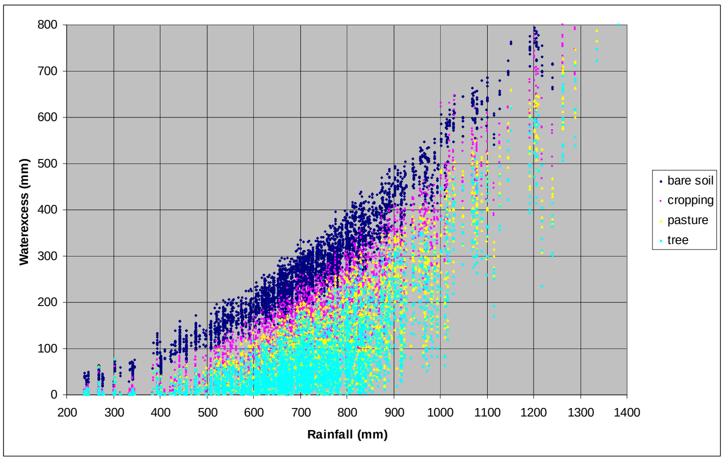


Figure 2. Annual water excess for different land use types

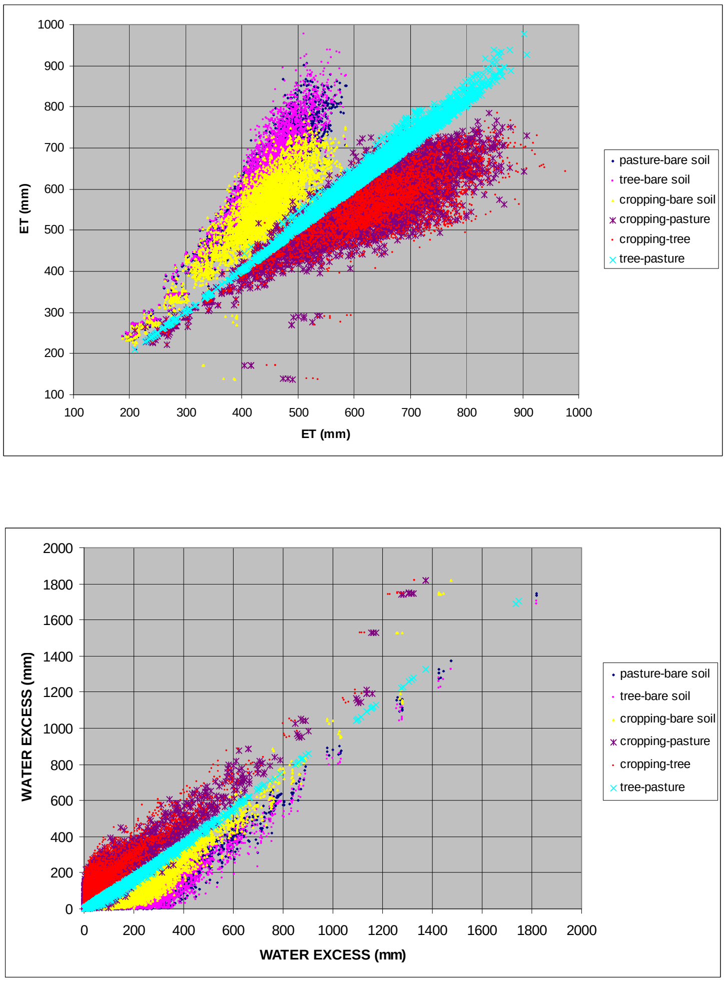
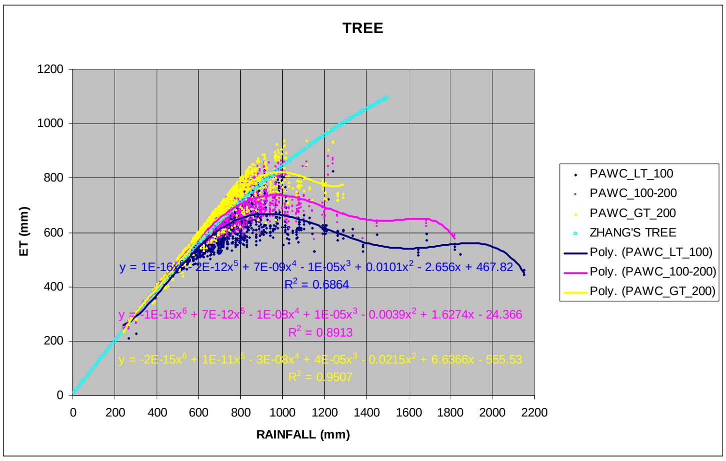


Figure 3. Evapotranspiration and water excess correlations between different land use types

The correlations between rainfall and either ET or water excess are generally good, particularly when PAWC is >100 mm for ET and <200mm for water excess. This provides an approach to directly estimate ET and water excess for each land use type when rainfall and PAWC are available, even if there is still variation among soil types within each PAWC category.



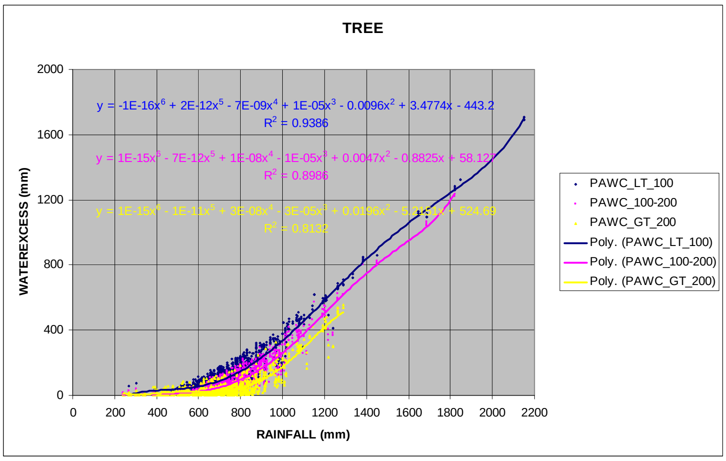


Figure 4. Evapotranspiration and water excess varying with rainfall for different PAWC categories for trees and their trend lines

The correlations between water excess and average annual rainfall for each rainfall seasonality class are presented in Figure 5. The results show that the correlation is best for class 5 followed by class 4, with least for class 3 (Figure 5). Higher confidence in the water excess estimation can be achieved in more winter dominant rainfall areas giving estimates in ET and water excess that are more accurately represented if water balance information about one landuse type is already known.

The correlations between water excess of four land use types variation with rainfall seasonality are also been analysed. The correlations are higher in more winter dominated rainfall areas. This shows that water excess can be more accurately estimated in more winter dominant rainfall areas for other land use types if an estimate of water excess for one land use type are already known.

There were only 22 rainfall stations within class 2 rainfall seasonality; this is considered insufficient for analysing the effects of PAWC. Therefore, only three classes (class 5 to class 3) are analysed to investigate the effect of PAWC.

Within each rainfall class, the effects of PAWC were analysed for trees, pasture, crop and bare soil. The effect of PAWC for class 4 is greater than that for class 3 but less than that for class 5 in determining the water balance. Class 5 shows an extremely good relationship between ET/water excess and PAWC; higher PAWC leads to higher ET and lower water excess (Figure 6).

The correlations between ET/water excess and rainfall for each PAWC category in more winter dominant rainfall areas are much higher than those in less winter dominant rainfall areas. This shows that ET/water excess can be more accurately estimated from rainfall and PAWC categories in more winter dominated rainfall areas.

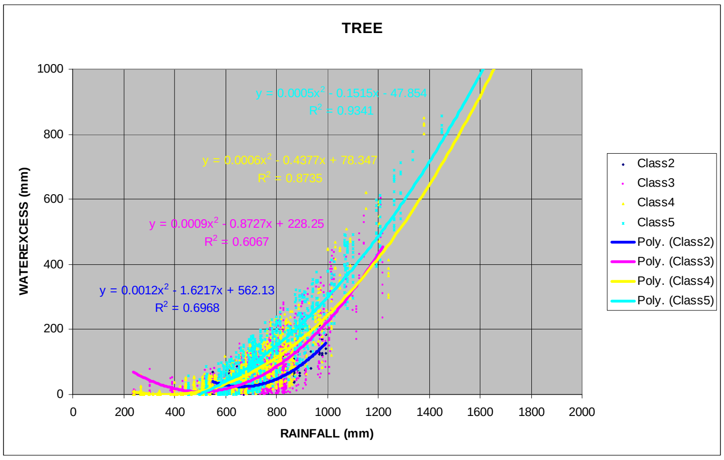


Figure 5. Correlations between water excess and rainfall within rainfall classes for trees

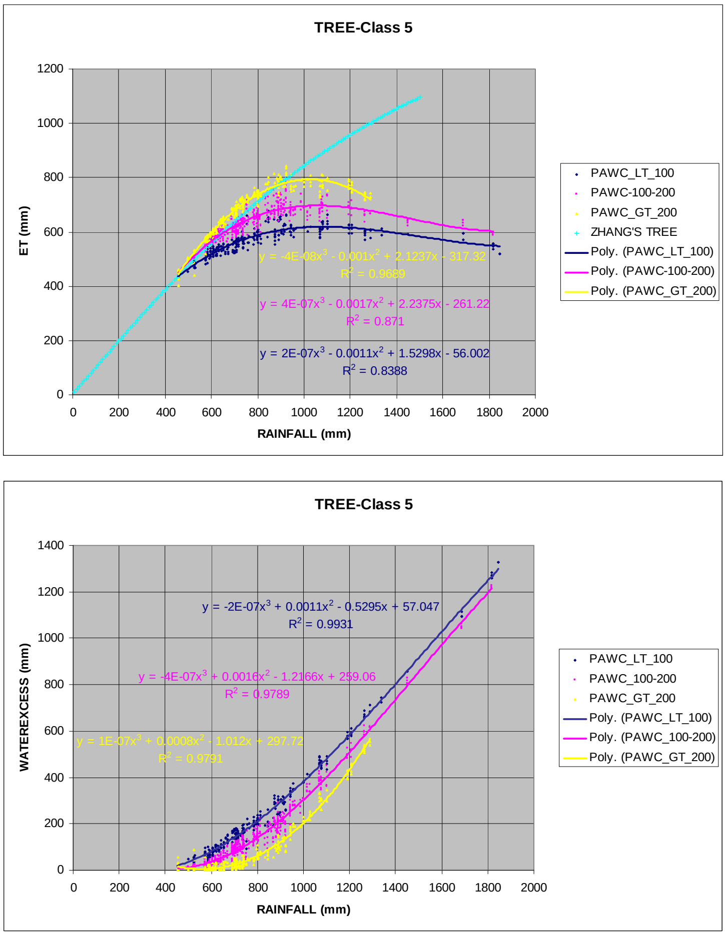


Figure 6. Evapotranspiration and water excess varying with rainfall in most winter dominant rainfall pattern for different PAWC categories for trees.

5. CONCLUSIONS

The impacts of land use changes on water balance are investigated by applying daily water balance model PERFECT to model four different land use types (pasture, crop, trees and bare soil) along with 355 soil types. The results show that:

- In agreement with previous knowledge ET for bare soil is the least followed by crop, then pasture with trees giving the most ET. Conversely water excess is highest for bare soil followed by crop, then pasture and the least for trees.
- Correlations between ET/water excess of different landuse types are good. These correlations can be used to estimate ET or water excess for other landuse types if an estimate of both quantities for one landuse type are already known (also need an estimate for one of the quantities for all other land use types).
- PAWC plays a critical role in determining the overall water balance. Higher PAWC leads to higher ET and lower water excess for each landuse type. The correlations between rainfall and either ET or water excess within each PAWC category are strong enough that it is proposed that ET and water excess can be directly estimated from rainfall even if there is still variation among soil types within each PAWC category.
- Rainfall seasonality is also very important in determining the overall water balance. Correlations between water excess of different landuse types and correlations between rainfall and either ET or water excess within each landuse type are much higher in more winter dominant rainfall areas. ET and water excess can be more accurately estimated in more winter dominant rainfall areas from rainfall and PAWC category and for other landuse types if estimates ET and water excess for one landuse types are already known.
- ET and water excess can be directly or indirectly estimated from rainfall instead of water balance modelling.

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