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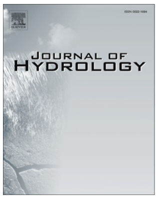

# A test of how coupling of vegetation to the atmosphere and climate spatial variation affects water yield modelling in mountainous catchments

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## SUMMARY

Evapotranspiration (ET) is a major component of the water balance in water-limited ecosystems in south-east Australia. ET is spatially variable, especially in steeper catchments, due to variations in land cover and topography. In hydrological models, ET is most often simulated as supply-limited, i.e. depending on the soil moisture availability. In reality, transpiration is also strongly controlled by atmospheric demand, particularly during demand-limited periods. In this study we used a simple conceptual rainfall-runoff model (HBV) to test the hypothesis that atmospheric constraints to transpiration, especially during conditions when soil moisture is not limiting, determine the variations in catchment water yield in the Australian Alps. This is tested by including demand limitations of transpiration in the macroscopic ET function.

A second hypothesis was that model performance can be improved by using spatial climate surfaces, derived using physiographic co-variables, rather than point (gauge) measurements. Both hypotheses were tested on a medium-sized catchment (148 km$^2$) in south-east Australia, under a forest cover composed of mostly native eucalypts.

Spatial surfaces of the model inputs (air temperature, rainfall, vapour pressure deficit and potential ET) were generated, taking into account the topographic influence of the forcing meteorological variables. Spatial variability in meteorological variables and potential ET was greatest during winter.

Inclusion of atmospheric-induced limitations to transpiration into the ET sub model improved streamflow simulation, especially during demand-limited periods. This was expected given that canopies of eucalypt forests are well-coupled to the atmosphere – changes in atmospheric demand have a large influence on transpiration. In addition, high resolution (30 m) surfaces of potential ET, temperature, and vapour pressure deficit, developed by including the influence of topography on forcing variables, improved model performance compared to point-based inputs.

## 1. Introduction

Evapotranspiration (ET) is a major flux of water and energy, and is closely linked to vegetation characteristics in forested catchments (Eagleson, 1982; Rodriguez-Iturbe and Porporato, 2004). In Australia, ET sometimes approaches 100% of incoming rainfall (Bren and Hopmans, 2007; Eamus et al., 2006). Among different processes included in evapotranspiration (e.g. transpiration, soil and leaf evaporation, canopy interception) transpiration is the most important component, especially in forested catchments of south-east Australia (e.g. Mitchell et al., 2012). Understanding how transpiration is regulated is therefore crucial for water yield management in water supply catchments in this area.

Vegetation water use fundamentally depends on the amount of water stored in the soil that is available to plants (Fisher et al., 2008). This dependency is partly governed by plant responses to climatic conditions and water stress (Emanuel et al., 2010). As a result actual rates of ET (ET$_a$) are less than potential rates (ET$_p$) due to the variable resistance of leaves to molecular diffusion of water to the atmosphere, imposed by stomata and other features of plant leaves (Dickinson et al., 1991).

The amount of water transpired can be divided into water transpired under stressed and water transpired under non-stressed conditions. While prescribed values of soil moisture are commonly

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used to define the transition between water-stressed and unstressed conditions, several other variables (e.g. atmospheric humidity, radiation, nutrient availability) can at different times limit vegetation water use, either individually or in combination. For example, based on physiological models described by Leuning (1995), Gao et al. (2002), and Emanuel et al. (2007) provide an ecophysiological explanation for the effects of atmospheric humidity and other environmental variables on transpiration in the absence of soil moisture stress.

In Australia, eucalypt forests cover the high country catchments of the south-east and have sparse and relatively well-ventilated canopies (Hutley et al., 2000), that are well coupled with the atmosphere (Jarvis and McNaughton, 1986). During periods when soil moisture is abundant (no water stress), transpiration is limited by the plant demand for water, and regulation of water loss at the leaf level is strongly coupled to atmospheric demand. Once atmospheric demand reaches a certain level, stomata begin to close and this limits transpiration to a constant level (e.g. Gharun et al., 2013a,b). In other words, constraints on transpiration are not limited to dry seasons. In terms of hydrology, attention is generally focused on how transpiration mediates streamflow during dry seasons (Barnard et al., 2010; Graham et al., 2012; Moore et al., 2011). However during wet periods, transpiration is more likely to involve gravitational water, with consequent effects on streamflow (Brooks et al., 2010).

Assessment of physiological responses to water stress can be included in hydrological modelling based on a mechanistic framework (Porporato et al., 2001). A suite of physical models have been used to predict stomatal conductance as a function of water availability in the soil and atmosphere (Damour et al., 2010; Gerosa et al., 2012), and can be included in models of $ET_a$, such as in the Penman–Monteith equation (Monteith, 1981), depending on the complexity of the hydrological model.

Estimation of $ET_a$ via such models requires extensive data inputs – data that are not readily available in many instances. As an alternative, $ET_a$ is commonly represented, more conceptually, as a macroscopic function where available soil moisture determines the proportion of $ET_p$ (Budyko, 1958, 1974), based on a soil moisture extraction function. Such a supply limiting function is based on long term patterns between climate, evapotranspiration and runoff, but does not include the demand-limiting impacts effects of vegetation on $ET_a$. Macroscopic functions are common in many conceptual hydrological models, for example SIMHYD (Chiew et al., 2002), GR4J (Perrin et al., 2003), HBV (Seibert, 1997), and IHACRES (Croke et al., 2006), that employ a range of soil moisture extraction functions (Zhao et al., 2013), none of which incorporate a demand-limitation.

Considering the key role of atmospheric demand in determining transpiration and the complexity of calculating $ET_a$, we hypothesize that including a simple description of atmospheric vapour pressure deficit (VPD) in a standard supply-limited representation of $ET_a$ in hydrological models can improve streamflow simulation, and improve the understanding of how transpiration signals are transferred to the stream in forested catchments.

An additional issue is that lumped hydrological models require input data that can be collected from a single weather station, or from the average of several stations. Since climate variables can be influenced by terrain (Moore et al., 1993; Raupach and Finnigan, 1997), we hypothesized that when climate variables are interpolated in space, a better representation of the actual distribution of the climate across terrain is provided, because sparse weather stations, even if numerous and spread across terrain, are unlikely to represent actual distributions of climate variables. Even if extrapolated variables are later lumped, this approach should still yield a better representation of "average" climate conditions within a given catchment. A lumped model (discussed later) is used to test this effect on streamflow simulation.

Numerous methods exist to interpolate and aggregate forcing variables across landscapes (e.g. deterministic, geostatistical). Geostatistical methods can incorporate secondary information such as elevation and distance to the regional maximum, but a relatively large number (generally more than 30) of measurement stations is required (Mair and Fares, 2011). Alternatively, meteorological variables can be physically modelled across terrain using empirical relationships that incorporate factors such as topography, elevation, and land cover (Granger, 2000; Wilson and Gallant, 2000).

Currently, interpolated rainfall and climate 'surfaces' are available for much of Australia (e.g. Jeffrey et al., 2001); however their coarse spatial resolution (e.g. 0.05° grid, about 5 km) is a major shortcoming for quantitative hydrological analysis in mountainous terrain. Temperature and vapour pressure deficit change strongly with topography in the high country of south-east Australia (as they do elsewhere) and it is important to investigate how this affects hydrological model inputs.

Other studies have mostly followed a 'calculate-then-interpolate' approach, where ET is first calculated and then interpolated across terrain (Xu et al., 2006). However even studies that first interpolate input variables and then calculate ET, have focused on conventional interpolation methods (e.g. inverse distance weighting, various forms of kriging), rather than physically calculating these variables for each pixel (e.g. McVicar et al., 2007).

The aims of this paper are twofold: (1) to test how the coupling of vegetation to atmospheric and soil water availability affects catchment water yield, and (2) whether spatial aggregation of climate factors that largely influence ET improves model accuracy.

## 2. Methods

### 2.1. Site description

The Corin Catchment is located in the Namadgi National Park and is part of the Cotter river catchment in the Australian Capital Territory (ACT), 50 km west of Canberra and lies at the end of the Australian Alps (lat 35.6 °S, long 148.8 °E) encompassing an area of 148 $km^2$ (Fig. 1). Vegetation cover is native eucalypt forests and soils are derived from highly weathered Ordovician sediments. The soils are acidic and duplex in structure (Talsma, 1983). The underlying bedrock of the area is granite, limestone and shale, and topography is mountainous. The catchment is exposed to fogs, frosts and snowfall in winter, while summers are characterized as warm and often have hot and dry periods of between 6 and 8 weeks (Moore et al., 1993). Maximum and minimum temperatures are 4 °C and −1 °C in July (winter), and 24 °C and 10 °C in January (summer). Mean annual rainfall across the catchment is approximately 1150 mm. Snowfalls are common in winter (on the higher elevations only, hence not modelled here) but the soil never freezes (Woods and Raison, 1983). Average annual evaporation and seepage losses from the catchment are estimated at 630 mm (White et al., 2006). Stream discharge typically peaks between August and September and reaches a minimum during late March to May.

### 2.2. Hydrologic model

We use a conceptual rainfall-runoff model, HBV (Seibert, 1997) that operates on a daily time step to test our hypotheses. Our reason for using a low parameter model is that this will allow tracking of the different processes more directly. The HBV (Hydrologiska Byråns Vattenbalansavdelning) model simulates discharge using rainfall, temperature and estimates of potential evapotranspiration. The model has previously been used to calculate the water balance in Norway (Beldring et al., 2002), to assess climate change