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A multi-objective assessment of alternate conceptual ecohydrological models

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SUMMARY

A merging of a conceptual hydrological model with two vegetation models is performed to improve the ability to simultaneously predict catchment scale streamflow and vegetation dynamics (represented by the Leaf Area Index, LAI). A modeling study is performed across 27 catchments of 90–1600 km^2 in the Murray–Darling Basin in Australia. Validation results from the modeling exercise show that the merged ecohydrological models were capable of improving streamflow prediction compared to hydrological models alone, while also providing as good estimates of LAI as dynamic vegetation models alone. It was shown that a single-objective optimization could independently produce good estimates of streamflow and LAI, but the other un-calibrated predicted outcome (LAI if streamflow was the focus of the optimization and vice versa) was consistently compromised. In essence, single-objective optimization has limited capacity to represent the multi-response dynamics in conceptual ecohydrological models. However, using multi-objective optimization, good predictions for both streamflow and LAI are obtained. Our results illustrate that the multi-objective optimization provides a balanced solution for multivariate responses and gives better representation of streamflow and LAI dynamics. It is suggested that further development of this approach in terms of conceptual model design and optimization techniques could lead to greatly improved ecohydrological modeling and applications.

1. Introduction

Hydrological behavior of any catchment can be conceptualized as a number of interconnected ecological, hydrological (Fenicia et al., 2008; Kirchner, 2006; Savenije, 2009) and energy transfer processes (Montaldo et al., 2005; Rodriguez-Iturbe et al., 2001). The intertwined interactions of hydrological and ecological processes characterize the vegetation dynamics in a region (Laio et al., 2001) and it has been shown that vegetation density regulates hydrological processes such as interception, infiltration and evapotranspiration (Arora, 2002; Li and Ishidaira, 2012; Montaldo et al., 2005; Porporato et al., 2002; Rodriguez-Iturbe, 2000; Rodriguez-Iturbe et al., 2001; Dekker et al., 2012; Wegehenkel, 2009). Although the role of vegetation is embedded in the structure of some conceptual hydrological models, e.g. HBV (Lindström et al., 1997) and THESEUS (Lindström et al., 1997; Wegehenkel, 2002), the effect of vegetation dynamics on hydrological processes is often ignored in conceptual hydrologic models (Tuteja et al., 2007). Despite their simple structure and having only a few calibrating parameters, conceptual lumped hydrologic models can successfully reproduce observed streamflow (Sorooshian et al., 1993) while ignoring other components of the hydrological cycle such as interception. As a result, other fluxes including soil evaporation and soil moisture dynamics vary significantly from the real values in these models (Krysanova et al., 1999; Li and Ishidaira, 2012). Li and Ishidaira (2012) showed that changes in precipitation and temperature impact runoff through changes in soil moisture and vegetation cover. Similarly, conceptual dynamic vegetation models consider streamflow as a side product (Istanbulluoglu et al., 2011; Montaldo et al., 2005; Pumo et al., 2008; Quevedo and Francés, 2008; Viola et al., 2013), produce biased streamflow predictions. On the other hand, physically-based distributed ecohydrologic models such as tRIBS + Veggie (Ivanov, 2006; Ivanov et al., 2008) and Regional Hydro-Ecological Simulation System (RHESSys) (Tague and Band, 2004) simultaneously simulate water and vegetation growth dynamics, but they require lots of parameters that are often difficult to obtain. This leads to the question does a merged ecohydrological model offer an improved representation of both streamflow and LAI dynamics at the catchment scale.

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To model ecohydrological processes successfully, model structure and parameterization are highly important. However, most of the parameters describing the soil–vegetation system are not easily measured particularly at large scales and long term observations of different fluxes are not available (Wöhling et al., 2013). Therefore in practice, automatic calibration procedures that are mainly focussed on single-objective optimization are implemented (Vrugt et al., 2003). To simulate multiple fluxes, multi-objective optimization approaches have gained popularity due to their capabilities to measure different aspects of system behavior and find a set of trade-off solutions in a single simulation run (Gupta et al., 1998; Vrugt et al., 2003). Recently, Wöhling et al. (2013) assessed performance of five coupled soil–plant models and a land surface model, Community Land Model CLM 3.5 in a multi-objective framework using AMALGAM (Vrugt and Robinson, 2007). AMALGAM is an evolutionary search algorithm and it is used for simultaneous estimation of soil and plant parameters to improve land surface models predictions. In this study, soil volumetric water content, LAI and weekly averages of daily evapotranspiration measurements were used for model comparisons. Despite this progress, previous studies were not aimed at identifying the impact of ecology (represented by LAI in our study) on streamflow in conceptual lumped hydrological models. Our objective is to assess the ability of two conceptual ecohydrological models to predict streamflow while taking into account LAI dynamics. Specifically we (1) assess how the complexity of two conceptual ecohydrological models will affect streamflow predictions; and (2) compare performances of single-objective optimization of ecohydrological models using streamflow or LAI versus the multi-objective optimization of the models using both observations.

To accomplish these objectives, the vegetation processes such as interception and growth of two conceptual dynamic vegetation models are merged with a conceptual hydrological model. The detailed description of the methodology is discussed in Section 3 followed by the results and analysis in Section 4.

2. Data and catchment details

On the basis of dominant vegetation types (www.ga.gov.au) and availability of long term time series of daily rainfall, potential evapotranspiration (PET) and gauged streamflow data, 27 catchments are selected (Table 1 and Fig. 1) out of 240 catchments across the Murray Darling Basin (MDB) (Pathiraja et al., 2012; Vaze et al., 2010). The catchment sizes range from 90 to 1620 km^2 and Eucalypts are the dominant vegetation type in the selected catchments. There is low variation in mean annual rainfall among the selected catchments but the mean annual runoff varies considerably (Table 1).

The catchment averaged daily rainfall is from the 5 km $\times$ 5 km gridded daily rainfall of the SILO database (Jeffrey et al., 2001). The daily PET data is based on the potential evapotranspiration maps published by the Bureau of Meteorology (http://www.bom.gov.au/climate/how/newproducts/IDCetatlas.shtml). The record length for rainfall, runoff and PET data is 32 years from 1974 to 2005 and the selected catchments have no missing records for rainfall and PET. The level-4 MODIS global Leaf Area Index (LAI) product (MODIS15A2) were acquired from the Land Processes Distributed Active Archive Centre (LP DAAC, http://lpdaa.usgs.gov) for the period of February 2000–2005 corresponding to the observed streamflow record. The LAI data is composited every 8 days and has a spatial resolution of one kilometer. The LAI observations are used for model calibration and validation. The soil type data is from the Digital Atlas of Australian Soils, Department of Agriculture, Australian Bureau of Agricultural and Resource Economics and Science (http://data.daff.gov.au/anrdl/metadata_files/) and is used for parametrization of soil in the models.

Table 1
Catchment characteristics including area, mean annual precipitation, runoff, vegetation and soil types.

	Station	Location	Area (km^2)	Mean annual rainfall (mm)	Mean annual runoff (mm)	Vegetation type	Soil type
1	210040	Wybong [a]Ck at Wybong	676	703	36	Grasses	Clay
2	401210	Snowy Ck below Granite Flat, [b]VIC	407	1212	464	Eucalypts	Loamy sand
3	402204	Yackandandh Ck at Obsomes Flat, VIC	255	1099	185	Eucalypts	Clay
4	402206	Running Ckat Running Creek, VIC	126	1261	260	Eucalypts	Clay
5	403213	Fifteen Mile Ck at Greta South, VIC	229	1139	254	Eucalypts	Loamy sand
6	403214	Happy Valley Ck at Rosewhite, VIC	135	1201	184	Eucalyptus	Clay
7	403217	Rose [c]R at Matong North, VIC	154	1289	358	Eucalypts	Loamy sand
8	403224	Hurdle Ck at Bobinawarrah, VIC	155	983	178	Eucalypts	Clay
9	404208	Moonee Ck at Lima, VIC	90.9	963	201	Eucalypts	Clay
10	405205	Murrindindi R above "Colwells", VIC	108	1358	475	Eucalypts	Clay
11	405209	Acheron R at Taggerty, VIC	619	1343	450	Eucalypts	Loamy sand
12	405214	Delatite R at Tonga Bridge, VIC	368	1143	291	Eucalypts	Clay
13	405219	Goulburn R at Dohertys, VIC	694	1276	440	Eucalypts	Clay
14	405226	Pranjip Ck at Moorilim, VIC	787	654	69	Eucalypts and others	Clay
15	405228	Hughes Ck at Tarcombe Road, VIC	471	773	157	Eucalypts	Clay
16	405229	Wanatla Ck at Wanatla, VIC	108	513	32	Eucalypts and others	Clay
17	406213	Campaspe R at Redesdale, VIC	629	757	118	Eucalypts	Clay
18	406214	Axe Ck at Longlea, VIC	234	584	56	Eucalypts	Clay
19	407236	Mount Hope Ck at Mitiamo, VIC	1629	448	14	Eucalypts and others	Clay
20	410044	Muttama Ck at Coolac, [d]NSW	1025	659	42	Eucalypts and others	Clay
21	410057	Goobarragandra R at Lacmalac, NSW	673	1173	414	Eucalypts	Clay
22	410061	Adelong Ck at Batlow Road, NSW	155	1031	252	Eucalypts	Clay
23	410731	Gudgenby at Tennent, [e]ACT	670	942	94	Eucalypts	Clay
24	418027	Horton R at Horton Dam Site, NSW	220	904	177	Eucalypts	Clay
25	421018	Bell R at Newrea, NSW	1620	718	61	Eucalypts and others	Clay
26	421026	Turon R at Sofala, NSW	883	772	88	Eucalypts and others	Clay
27	426504	Finniss R at 4 km east of Yundi, [f]SA	191	834	128	Eucalypts	Clay

[a] Creek.
[b] Victoria.
[c] River.
[d] New South Wales.
[e] Australian Capital Territory.
[f] South Australia.