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Assessing the structural adequacy of alternative ecohydrological models using a pattern-oriented approach

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ABSTRACT

The development of environmental system models is challenging because of different disciplinary philosophical approaches to uncertainty in modelling of the terrestrial hydrosphere and ecosphere. We use pattern-oriented modelling to assess model structural adequacy and to select alternative model structures within the hierarchy of a model of flood-groundwater–vegetation interactions. We varied the equation structure of two key model components, flood tolerance and seasonal leaf shedding, and tested how well the model structures reproduced a set of observed patterns: (i) three species coexistence, (ii) species-specific access to groundwater, and (iii) species-specific ability to tolerate flood disturbances. We assessed (a) the role of flood frequency in biomass regulation for modelling of three coexisting species sharing the same water resources, and (b) the effect of alternative process and equation structures on the deviation of hydrological variables (transpiration, groundwater table) from average conditions.

Only model structures that explicitly considered the functional relationship between flood events and biomass regulation were able to reproduce the coexistence pattern and the two secondary patterns (ii and iii). The different coexistence mechanisms had little effect on the average transpiration rates and water table depths. However, shallow and deep average groundwater tables, caused by low and high transpiration rates, were modelled more frequently with model structures that intentionally ignored species-specific phenological cycles rather than models which incorporated them. Our findings indicate that, amongst all tested model structures, the most complex one is most plausible and can explain the observed patterns in an environment controlled by the interplay between periods of water deficit and flood disturbance. It reproduced the three observed ecological patterns and enhanced the general understanding of groundwater-dependent ecosystems along ephemeral rivers.

1. Introduction

Environmental system models are a typical part of any planning scheme for the management of natural systems. However, the model building process is challenging because of different philosophical approaches to address uncertainty in modelling of the terrestrial hydrosphere and ecosphere across different disciplines (Arnold et al., 2012; Gupta et al., 2012). In their conceptual framework of a comprehensive assessment of model structural adequacy, Gupta et al. (2012) identify five formal sources of model inadequacy during the model building process: (i) the conceptual physical structure, (ii) the process structure, (iii) the spatial variability, (iv) the equation structure, and (v) the computational structure of the system.

The critical challenge is to build a minimalistic yet realistic model (Arnold et al., 2012), i.e. to maximise functional adequacy[1] with minimal structural representation (the principle of parsimony) (Gupta et al., 2012). A systematic approach to finding an appropriate model is to formulate alternative model structures within the same model architecture (Clark et al., 2011; Wiegand et al., 2003). Pattern-oriented modelling (POM) is a promising approach to development of realistic and powerful models based

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[1] Functional adequacy describes how well the model simulates spatiotemporal dynamical behaviours of interest (Gupta et al., 2012).

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on the characteristic structures in nature, namely patterns (Grimm et al., 1996; Grimm and Railsback, 2012; Wiegand et al., 2003). In this regard, "a pattern [. . .] goes beyond random variation and thus indicates an underlying process that generates this pattern" (Levin, 1992; Weiner, 1995; Wiegand et al., 2003). Particularly if data are scarce, independent patterns may be invaluable for model building and general system understanding (Wiegand et al., 2003).

In semiarid ecosystems, the patterns of vegetation distribution can be both the cause and the effect of variations in water availability (Rodriguez-Iturbe, 2000). For example, coexistence of tree–grass communities in water-limited ecosystems is governed by the stochastic plant available soil water and plant physiological mechanisms that minimise water stress (Rodriguez-Iturbe et al., 1999a, 1999b). Similarly, riparian vegetation responds to changes in the stochastic flood regime and shallow water table fluctuations (Scott et al., 1997, 1999). On the other hand, woody plant encroachment and invasive plant species can affect stream flow and evaporation along river courses (Huxman et al., 2005; Wilcox and Thurow, 2006). Likewise, riparian vegetation controls diurnal water table fluctuations (Butler et al., 2007), which can be used to estimate evapotranspiration rates of phreatophytes (Fahle and Dietrich, 2014).

These mutual eco-hydrological effects can also govern temporal coexistence patterns of plant communities (Arnold et al., 2009). Modelling of multiple species coexistence is comparatively difficult (Arora and Boer, 2006; Clark et al., 2007). A number of mechanisms can facilitate coexistence in numerical models, for example, temporal and/or spatial ecological niches, or trade-offs between processes influencing the growth and mortality of competing species (Arnold et al., 2009; Chesson, 2000; Clark et al., 2007). Further, temporal environmental variation and disturbance (e.g., flood events) can enhance biodiversity and resilience of ecosystems (Arora and Boer, 2006; D'Odorico et al., 2008; Piou et al., 2008; Roxburgh et al., 2004).

If the ecological consequences (e.g., loss of biodiversity) of water management are part of the management decision, models are required that capture interactions between water availability, flood disturbance, and species coexistence. In this regard, the effect of different coexistence mechanisms on fluctuations of hydrological variables (e.g., transpiration, groundwater table) is poorly understood, though being critical for the management of ecological and water resources (Arnold et al., 2009).

In this study, we apply POM to select between alternative structures of an ecohydrological model of flood-groundwater–vegetation interactions along ephemeral rivers (Arnold et al., 2009). More specifically, we varied the equation structure of two key model components, flood tolerance and seasonal leaf shedding, such that flood tolerance and/or leaf shedding were either the same for all species or species-specific, resulting in four alternative model structures. Additionally, two model structures intentionally ignored the functional link between the flood regime and its destructive effect on plant biomass development. We tested how well these model structures reproduced a set of observed patterns: (i) coexistence of three species, (ii) species-specific access to groundwater, and (iii) species-specific ability to tolerate flood disturbances. The objectives were to assess (a) the role of flood frequency in biomass regulation for modelling of three coexisting species sharing the same water resources, and (b) the effect of alternative process and equation structures on the deviation of hydrological variables (transpiration, groundwater table) from average conditions. Addressing these questions is essential to establishing whether or not the functional linkage between plant development and environmental stressors is critical for numerical modelling of ecosystems controlled by the interplay between periods of water deficit and flood disturbance.

Table 1
Species-specific traits that facilitate the establishment of a stable plant community of three species sharing the same water sources and being disturbed by erratic flood events (Arnold et al., 2009).

Species-specific trait	*T. usneoides*	*F. albida*	*A. erioloba*
Flood tolerant	×	√	√
Water stress tolerant	√	×	×
Evergreen	√	×	×
Deciduous (season)	×	√ (wet)	√ (dry)
Growth rate	Medium	High	Low

2. Methods and materials

We used the Kuiseb River in Namibia as an example of a groundwater-dependent ecosystem, where the species richness is comparatively low and environmental stressors are predominantly related to water deficit. A full description of the Kuiseb River environment and the linked hydrological and plant community model is provided by Arnold et al. (2009). For the purpose of model analysis, we provide here a brief outline of the ecology of three coexisting tree species sharing the same water resources (Section 2.1), the architecture of the linked hydrological and plant community model (Section 2.2), alternative model structures of the plant community model (Section 2.3), and the use of qualitative patterns to assess the alternative model structures, including parameter sampling and ensemble analysis of numerous parameter sets (Section 2.4).

2.1. Ecology of three coexisting plant species

The middle reach of the Kuiseb River is dominated by three tree species – wild tamarix (*Tamarix usneoides*), camel thorn (*Acacia erioloba*), and ana tree (*Faidherbia albida*) – sharing water resources from the shallow unsaturated soil and the groundwater (Schachtschneider and February, 2010). The species have characteristic rooting depths, transpiration rates, and growth rates (Arnold et al., 2009). They also have different phenological patterns and characteristic sensitivities to water availability and flood disturbance (i.e., frequency and magnitude). While the evergreen *T. usneoides* is water stress tolerant, the phreatophytes *A. erioloba* (deciduous during dry season) and *F. albida* (deciduous during wet season) are flood-tolerant (Table 1). As a consequence, a stable plant community has been established based on (i) partitioning of the water resources, (ii) trade-offs between vegetation growth and water stress, and (iii) the vulnerability to flood disturbances (Arnold et al., 2009).

2.2. Architecture of the mathematical model

We used the architecture of a linked hydrological and plant community model (Arnold et al., 2009) to assess the sensitivity of groundwater table and transpiration fluctuations to alternative model structures of the plant community model (Section 2.3). A complete description of the model is provided in the Supplementary information.

The hydrological part of the model is storage based and recharged by periodic flood events (Eq. (3)). The water balance is written as

$$\Delta \mathrm{WS}(t) = \Delta S_u(t) + \Delta S_{\mathrm{gw}}(t) \tag{1}$$

where $\Delta\mathrm{WS}(t)$ is the sum of changes in the unsaturated ($\Delta S_u(t)$) and the groundwater storage ($\Delta S_{\mathrm{gw}}(t)$) over time interval t. The actual transpiration $T_{\mathrm{WS},i}(t)$ [m^3 ha^{-1}] for each species i from the two water storages is a function of the green biomass $G_i(t)$ (Eq.