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Eco-hydrology of Semiarid
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Introduction to a special section on ecohydrology of semiarid environments: Confronting mathematical models with ecosystem complexity

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Abstract Current literature provides large number of publications about ecohydrological processes and their effect on the biota in drylands. Given the limited laboratory and field experiments in such systems, many of these publications are based on mathematical models of varying complexity. The underlying implicit assumption is that the data set used to evaluate these models covers the parameter space of conditions that characterize drylands and that the models represent the actual processes with acceptable certainty. However, a question raised is to what extent these mathematical models are valid when confronted with observed ecosystem complexity? This Introduction reviews the 16 papers that comprise the Special Section on *Eco-hydrology of Semiarid Environments: Confronting Mathematical Models with Ecosystem Complexity*. The subjects studied in these papers include rainfall regime, infiltration and preferential flow, evaporation and evapotranspiration, annual net primary production, dispersal and invasion, and vegetation greening. The findings in the papers published in this Special Section show that innovative mathematical modeling approaches can represent actual field measurements. Hence, there are strong grounds for suggesting that mathematical models can contribute to greater understanding of ecosystem complexity through characterization of space-time dynamics of biomass and water storage as well as their multiscale interactions. However, the generality of the models and their low-dimensional representation of many processes may also be a “curse” that results in failures when particulars of an ecosystem are required. It is envisaged that the search for a unifying “general” model, while seductive, may remain elusive in the foreseeable future. It is for this reason that improving the merger between experiments and models of various degrees of complexity continues to shape the future research agenda.

1. Introduction

Drylands cover arid and semiarid areas as well as some of the dry subtropical regions now spanning approximately one third of the global land. These areas currently support in excess of 2 billion people, and all indications show that the number of people supported by these ecosystems will continue to grow. It is now becoming evident that drylands are vulnerable biomes, with some estimates placing about 10–20% of these dryland areas to have already undergone degradation or irreversible desertification. Virtually, every scientific report, including the recent millennium Ecosystem Assessment, repeatedly stated that biophysical and socio-economic monitoring and assessment of desertification and land degradation are first priority for desertification science.

While all aspects of this problem are well beyond the scope of a single Special Section, a common theme to all scientific investigations of dryland regions is water movement and its links to the state and rate of change of vegetation biomass. One aspect of the water-vegetation interactions is the self-organization of vegetation into regular spatial patterns interspersed by sparsely vegetated or bare soils. These patterns have been observed in dry ecosystems worldwide, and many of their features can be reproduced using mathematical models with different assumptions and approximations about biota-water interactions. However, numerous knowledge gaps still exist between model predictions and observations or field measurements. The aim of this Special Section is to assemble papers written by hydrologists, ecologists, Earth scientists, and physicists to explore the main factors affecting the water-vegetation interactions at multiple

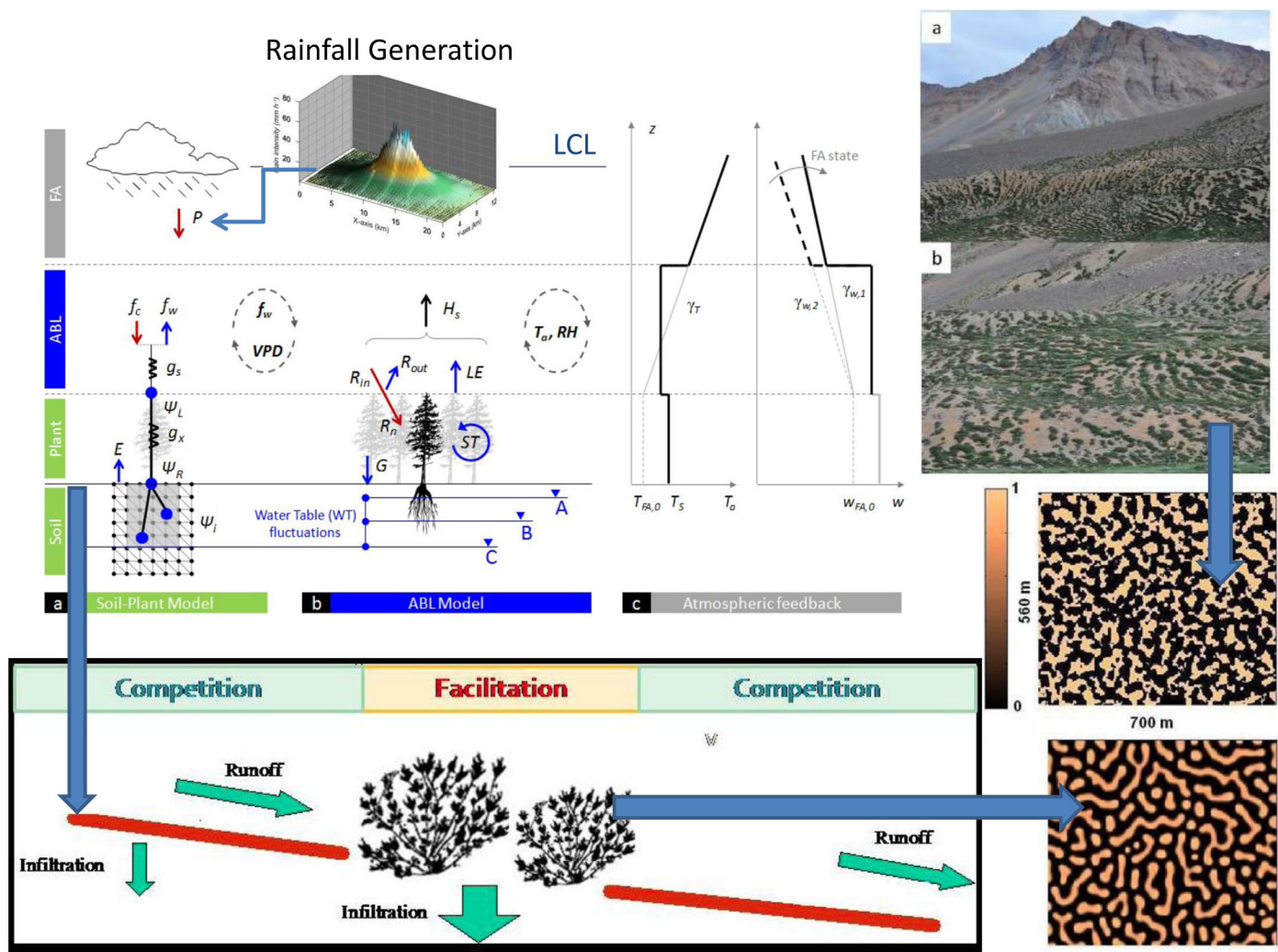


Figure 1. (top left) The soil-plant system (a) is modeled in terms of water potential in the soil (ψ_i), plant trunk (ψ_R), and plant leaf (ψ_L) through a series of conductance (e.g., trunk xylem, g_x , and stomata, g_s). The soil-plant model is linked to the atmosphere by leaf transpiration flux f_w , carbon dioxide assimilation f_c , and vapor pressure deficit (VPD). The atmospheric boundary layer (ABL) model is based on a 1-D energy balance (b) and the atmospheric feedback (c) is included by considering the evolution of ABL temperature (T_a) and humidity (w). The lifting condensation level (LCL) and ABL height are both needed to model rainfall initiation and subsequent amounts (revised from Bonetti et al. [2015]). (bottom right) Vegetation pattern formation (top) measured and (bottom) modeled using coupled carbon-water budgets with dispersive or diffusive movement of biomass in space. (bottom left) The role of vegetation and soil crusting in runoff/infiltration and their links to facilitation-competition responsible for vegetation pattern formation in space. (top right) The role of hydrologic pathways, above and below ground on various pattern-formation morphology. Rainfall generation graph is revised from Peleg and Morin [2014] and vegetation patches pictures are extracted from Yizhaq et al. [2014].

spatial and temporal scales, and to determine the steps required (on a theoretical and experimental level) to improve the predictive skills of mathematical models in ecohydrology.

It has not been an easy journey for mathematical models in ecohydrology to reach a predictive phase. The complex structure of soils, dynamics of soil moisture, vegetation productivity, and ecosystem functioning in drylands, and their interactions, involve processes operating at different spatial and temporal scales. The irregular effect of rainfall pulses, soil surface sealing, high evaporation rates, runoff mechanism that are not fully understood, seed transportation by wind and water, and importance of water subsidy creates an environment which challenges every modeler, yielding various research approaches to tackle the notorious task of predicting productivity and available soil moisture to the plants.

The papers in this Special Section are based on contributions to the International Workshop on *Eco-Hydrology of Semiarid Environments: Confronting Mathematical Models with Ecosystem Complexity* that took place in May 2013 at the Ben-Gurion University of the Negev in Israel. This meeting brought together scientists from different disciplines that share the goal of advancing mathematical models representing ecohydrological

processes featured in such systems. The workshop hosted 75 scientists with 30 oral presentations, 3 round table discussions, and 15 poster presentations, all discussing most recent research in the field. The aim of this workshop was to bring together scientists from the aforementioned disciplines to explore the main factors affecting water-vegetation interactions at multiple spatial and temporal scales in drylands and to determine the steps required to improve the predictive skills of mathematical models in ecohydrology. Overall, the Special Section was open to submission of manuscripts that were not necessarily presented at the workshop and the following 16 papers represent the outcome of this attempt.

The papers apply a variety of mathematical models and conceptual techniques to explore the manifold of ecohydrological processes and the dependency of vegetation productivity on water availability in dry environments. Several studies combine vegetation and water balance models to represent watershed dynamics for past and projected climates. Other studies examine rainfall, runoff, and water flow processes and their effect on natural and agricultural vegetation plants. The largest cluster of studies considers water dynamics (soil moisture and evaporation) in different parts of the world that experience water shortage with periods of severe drought. Such studies certainly assist the explanation of the mechanisms and interactions between water and biota in the dry areas of the Earth. Among the most important contributions of using mathematical models in ecohydrology of drylands is the ability to test the contribution of processes to evolved patterns in spatial and temporal scales that can hardly be measured in the field (Figure 1).

2. Summary of Papers

Simulation of rainfall patterns and rainfall characteristics are highly sought in studies of dry environments as rainfall is the main supply for water in these ecosystems. *Peleg and Morin* [2014] presented a new stochastic high-resolution synoptically conditioned weather generator appropriate for the production of rain fields at the resolution required for hydrological modeling of small to medium-size catchments. The weather generator well-quantified rainfall properties compared with radar and rain gauge observations with one limitation—an inability to reproduce the most extreme cases. Such a weather generator can make a valuable contribution to study the ecohydrology of dry environments as it can be used as an input for vegetation productivity models to study the effect of expected drought events and climate change on vegetation patterns (Figure 1). Such application can substantially outperform previous predictions of future rainfall characteristics that were based on statistical analysis of measured rainfall events to interpolate the expected climatic change [*Shafan-Nathan et al.*, 2013].

Another work focused on rainfall predisposition is the study of *Bonetti et al.* [2015]. The authors have coupled a mechanistic model for the soil-plant system with a conventional slab representation of the atmospheric boundary layer to explore the role of groundwater table variations and free atmospheric states on convective rainfall predisposition at a Loblolly pine plantation with a focus on the role of drought. The authors have shown that in an intermediate regime of free atmospheric moisture supply, the surface latent heat flux controlled by soil water availability can supplement or suppress the necessary water vapor leading to reduced lifting condensation level (LCL) and subsequent atmospheric boundary layer (ABL)—lifting condensation level crossing (Figure 1). This intermediate state also corresponded to free atmospheric (FA) values around the mode in observed humidity lapse rates and the authors suggest that vegetation water uptake may be controlling convective rainfall predisposition, a conclusion that may be applicable to a wide range of ecosystems.

Rainfall characteristics affect substantially water infiltration into the soil and water flow along the soil profile [*Assouline*, 2013]. *Bargues Tobella et al.* [2014] have studied the effect of trees on preferential flow and soil infiltrability in an agroforestry parkland in a semiarid site in Burkina Faso. The methods the authors used include rainfall simulations and blue dye tracing experiments as well as image processing and analysis to extract preferential flow indices. The results showed that trees in dry landscapes increase soil infiltrability and preferential flow (e.g., Figure 1). Termite mounds located in association with trees even further enhanced preferential flow. This suggests that scattered trees in dryland landscapes can improve soil infiltration and preferential flow. Therefore, trees may function as water harvesters contributing to deeper drainage and recharge.

The plants also play a major role in water conductance within the dry ecosystem. *Manzoni et al.* [2014] have used a dynamical model of water flow in plants to describe the soil-plant-atmosphere system as a discrete

sequence of resistances linking the soil at water potential to the roots (Figure 1), the stem and branches, and the leaves. The model was specifically applied to study a dynamical system perspective on plant hydraulic failure, which was interpreted as a dynamic catastrophe. The results have shown that depending on environmental conditions, the plant water status may reach one or two stable equilibrium points. Such results may have further implications in representing macroscopically the effects of embolism and runaway cavitation in hydrological models. Linking such a model to a plant carbon balance and describing the dynamics of recovery from xylem damage might provide further insights in the mechanisms leading to plant mortality.

Water flow in the lateral dimension can also have important impact on water available to plants and vice versa. *Pierini et al.* [2014] have used observations from two small semiarid watersheds in Arizona that have been encroached by the velvet mesquite tree and apply a distributed hydrologic model to explore runoff threshold processes experienced during the North American monsoon. Paired watersheds, which have a long history as a research tool in forestry studies, show long-term runoff changes due to mesquite removal. Model predictions agreed with sensor network over a range of scales and variables. The model was capable to explain how woody plants can control runoff depending on storm size. Long-term observations revealed a shift in the relative runoff generation from the paired watersheds resulting from mesquite removal, grass reestablishment, and continued woody plant encroachment. Model-derived spatiotemporal fields from a set of alternative vegetation scenarios revealed how soil moisture differences scaled up to runoff generation in the paired watersheds.

In another work on lateral flow, *Zhou et al.* [2015] investigated the long-term effects of dams on fluvial regimes of P and P-enriched sediment using simultaneously measured P distributions and sediment size. Their computations revealed that a reservoir would significantly lower the downstream availability of P in the dry season and promote high pulses of P in summer when the reservoir is flushed as sedimentation accumulates. As a result, the P buffering and replenishing mechanism in the pristine ecosystem from upstream supplies and local resuspension are permanently eliminated when a regulating reservoir is built upstream. Changes could potentially aggravate the existing P-limitation, decrease the water's ability to adjust nutrient/pollutant fluctuations, accumulate a greater surplus of carbon and nitrogen, and even exacerbate blooms in favorable conditions.

Evapotranspiration is among the most frequently studied process in ecohydrology and this is well reflected in the current special issue. *Fatichi and Ivanov* [2014] have merged a stochastic weather generator in a mechanistic ecohydrological model to describe the interannual variability of evapotranspiration and vegetation productivity in Michigan, California, south Arizona, and Zurich (e.g., Figure 1). The results show that sensitivities are larger for changes in precipitation mean than in variance. In addition, the authors have found that sensitivities to changes in precipitation are larger regionally than locally and that short temporal scales are controlling interannual variability of evapotranspiration and productivity. The results indicate that local sensitivities in a single site are smaller than those observed across climatic and vegetation gradients in space and thus an important role of ecosystem reorganization in modifying productivity and evapotranspiration sensitivity in a changing climate is recognized.

Mendez-Barroso et al. [2014] have used field observations, remote sensing estimates, and hydrological modeling to apply a comparative analysis and reveal differences in evapotranspiration (Figure 1) and its partitioning in two semiarid ecosystems in northwest Mexico. The authors have found agreement between field observations of evapotranspiration and soil moisture and simulations from dynamic scenarios, indicating that the hydrologic model can represent interannual differences in the water and energy fluxes in the two ecosystems. The variations in seasonal and interannual dynamics of evapotranspiration in the two ecosystems have the following implications on the ecological and hydrologic properties of semiarid mountain fronts: (1) the switch from soil to vegetation-mediated losses affects soil moisture storage since evaporation is primarily sourced from shallower layers; (2) the rapid transition toward transpiration in subtropical scrublands implies these sites are more likely to be responsible for the precipitation-soil moisture-vegetation feedback mechanism; (3) spatially variable consumption of precipitation in the different ecosystems through evapotranspiration may have implications on runoff regime.

Evaporation can vary substantially in space. *Kool et al.* [2014] have quantified successfully evaporation from the soil surface and simulated below canopy evaporation using HYDRUS (2-D/3-D) while considering

variability in both time and space. Considering a drip-irrigated vineyard, they have found that below canopy evaporation is highly variable both during the day and with distance from the vine row. While the magnitude of evaporation was mostly determined by water content, diurnal patterns depended strongly on canopy shading. HYDRUS (2-D/3-D) successfully simulated the magnitude and diurnal patterns of evaporation including spatial variability due to uneven water content and soil saturated hydraulic conductivity and therefore should prove useful in simulating evaporation under different conditions or management scenarios.

In a study relating directly soil moisture and plant production, *Yizhaq et al.* [2014] have investigated the effects of heterogeneous soil-water diffusivity on vegetation pattern formation (Figure 1). The mathematical models the authors used were parameterized to simulate the conditions of a semiarid area in the center of Israel. The authors have modeled the effects of heterogeneous soil-water diffusivity and found that heterogeneity increases vegetation durability. An additional effect is that the heterogeneity makes the desertification process, namely, the transition from a spotted vegetation pattern to a bare-soil state, more gradual than in the homogeneous system. The modeling effort captured the infiltration contrast between vegetated and bare-soil domains and the increased growth rate of denser vegetation due to an enhanced ability to extract water from the soil.

Sela et al. [2015] has explored the effect of soil surface sealing on vegetation water uptake at the scale of a single plant (Figure 1). The authors used experimental data of plant water uptake, a physically based model using HYDRUS 2-D platform to solve the flow equation, and a long-term climatic data set from three dry sites presenting a climatic gradient in Israel. The results indicated that during the wet season, surface sealing could either increase or decrease water uptake depending on initial soil water content, rainfall intensity, and the duration of the subsequent drying intervals, thus affecting desertification processes [Assouline et al., 2015]. The seal layer was found to reduce the period where the vegetation was under water stress by 31% compared with unsealed conditions. This effect was more pronounced for seasons with total rainfall depth > 10 cm/yr, and was affected by interseasonal climatic variability. These results shed light on the importance of surface sealing in dry environments and its contribution to the resilience of woody vegetation.

In a similar work on plant consumption of water, *D'Onofrio et al.* [2015] have studied tree-grass competition over soil water in arid and semiarid savannas. For this purpose, the authors developed and used a simple implicit-space model which explicitly includes soil moisture dynamics, and life-stage structure of the trees. Comparison with observations indicates that the model, albeit very simple, is able to capture some of the essential dynamical processes of natural savannas. Their results show that precipitation intermittency affects savanna occurrence and structure, indicating a new point of view for reanalyzing observational data from the literature.

Yet in another work on water availability and plants response, *Siteur et al.* [2014] have studied the effect of rainfall intensity on the functioning of patterned semiarid ecosystems. This was done using a spatially explicit model that captures rainwater partitioning and runoff-runon processes with simple event-based process descriptions (Figure 1). This study is unique as rainfall intensity is a characteristic understudied in desertification science. Their results show that rainfall intensity can control patterning and the resilience of dry ecosystems. In other words, both an increase and a decrease in rainfall intensity can trigger desertification. In line with observations, three types of rain events were identified in their model.

Hausner et al. [2014] have studied the prospects for the endangered Devils Hole pupfish under changing climate conditions in Nevada. Numerical simulations were used to predict habitat temperatures under climate scenarios and combined computational fluid dynamic model with ecological modeling to quantify impacts of climate change. The results showed that Devils Hole could act as an indicator of changes expected in similar dry ecosystems. The sensitivity of Devils Hole to climate change means that the ecosystem can serve as a bellwether, providing an early indicator of ecological effects of climate change. The ecosystem's fast response to climate changes, however, also affords the opportunity to quickly examine the effects of climate change on a desert aquatic ecosystem, and the use of modeling in conjunction with ecological analysis offered good opportunity to examine the complex interactions between climate change and ecology.

Horvitz et al. [2014] introduced a simple model to discern the contribution of different dispersal mechanisms to the spread of invasive alien plant into new environments. The new method was used to examine spread

rate by various dispersal vectors. The results showed that extremely fast invasion of a plant species was attributed to dispersal by rivers. The main motivation was to fill the critical gap in assessing the mechanisms of large-scale invasive spread and to develop a predictive capacity to guide management control projects of invasive species.

Ebrahimi and Or [2014] have studied microbial dispersal in unsaturated porous media and the characteristics of motile bacterial cell motions in unsaturated angular pore networks. The authors used 3-D angular pore network model that mimic aqueous pathways in soil for different hydration conditions and an individual-based model that considers physiological and biophysical properties of motile and chemotactic bacteria. The modeling results allowed the evaluation of pore space geometry effects on microbial dispersal and to study the role of chemotactic motion versus random walk and the quantification of the role of aqueous phase fragmentation on microbial dispersal.

3. Concluding Remarks

Figure 1 recaps some of the salient processes and their spatial template covered in this workshop. The papers published in this special issue suggest causal links between the abiotic environment (e.g., rainfall or other ecosystem resources), dynamic hydrologic pathways linking rainfall to plant available water or other resource dynamics, spatial vegetation patterning, and ecosystem productivity. Catastrophic shifts in ecosystem goods and services appear to have precursors (environmental and soil conditions) and observable signatures of vegetation patterning in space that can be distinguished from natural variability. Some work also highlighted the significance of feedbacks (i.e., ecosystems can alter the atmospheric water vapor state and contribute to initiation of convective rainfall) and the significance of rainfall intensity on both biotic (e.g., microbial and plant, seed movement) and abiotic (e.g., soil surface sealing) processes that need to be incorporated in any future weather generators (e.g., Figure 1).

Innovative physically based modeling approaches proved to be effective when comparing their pattern-formation prediction against actual field measurements and remotely sensed data. Hence, there are strong grounds for claiming that mathematical models can contribute to greater understanding of ecosystem complexity through characterization of space-time dynamics.

However, it became also clear that the numerous processes involved in representing water fluxes and stores and biomass development in space and time mean that a “general” model for such systems will remain elusive in the foreseeable future. It is for this reason that improving merger between experiments—whether be the laboratory studies focused on specific mechanism or long-term experiments sampling a large ensemble of environmental conditions—and models of various degrees of complexity continue to shape the future research agenda.

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