Simulating overland flow and soil infiltration using an ecological approach

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Abstract: Many ecological processes affect the amount of rainfall that infiltrates the soil profile and becomes available for plant production. These processes include those that affect macroporosity and the soil surface condition, which influence the movement of water across the landscape and time available for infiltration. Simulation modelling provides a valuable means of exploring the effect of these processes on the retention or loss of resources from a system. This paper describes the eco-hydrological processes implemented in the SAVANNA.AU model in order to represent soil hydrology using a simple ecological approach and utilizing variables that are easily measured by managers and field ecologists.

Keywords: *Eco-hydrology; Runoff; Soil hydrology; Simulation modeling; SAVANNA.AU*

1. INTRODUCTION

Rainfall records reported by the Bureau of Meteorology do not normally represent the amount of water entering an ecosystem that is available for plants. Many processes such as plant interception, evaporation, overland flows and infiltration rates may influence the actual amount of water available for plant growth in different parts of the landscape. These processes are influenced by factors such as the biomass and cover of vegetation and litter, the soil surface condition and soil structural properties. These in turn are susceptible to disturbances such as grazing and tree clearing.

Modelling plant available water is fundamental to providing realistic plant production models. To date, many process-based plant and crop models simulate available water in the soil using a tipping bucket approach. While the level of detail varies, most models use soil properties such as bulk density, field capacity and saturated capacity combined with rainfall to determine movement of water through the soil profile. This approach is sound, but, some simple assumptions and even the order in which processes are performed may lead to varying results. The most important of these may be the order and means by which infiltration and runoff are calculated.

Many models use various landscape properties to calculate runoff and assume the remainder of the rainfall infiltrates into the soil. This approach has most likely arisen due to the fact that runoff parameters and relationships have been published and may be more easily described than infiltration processes. If however, the amount of water which enters the soil is critical, as can be the case in many Australian landscapes with low or temporally patchy rainfall, we suggest that infiltration should be considered first and the water which cannot infiltrate then moves by overland flow. This approach also allows a range of factors which influence infiltration to be considered and modelled dynamically.

An understanding of infiltration and associated landscape processes has been documented by Tongway and Hindley (2000) who developed a field-based approach to measuring how prone a landscape is to leaking resources such as water and nutrients or conversely capturing resources. This approach has been incorporated in the eco-hydrology module of the SAVANNA.AU model, a detailed, process-based model for savanna landscapes of northern Australia (Liedloff *et al*, 2001, Ludwig *et al*, 2001). SAVANNA.AU aims to simulate mechanisms with a minimal set of parameters. The model also aims to use variables that can readily be measured in the field or obtained from published literature. Therefore, it wasn't deemed necessary to build sophisticated and complex models using the physics of soil water flows (e.g. Lane et al. 1988). Instead, we have developed the model based on the ecological understanding required to answer the management questions the model was designed for, such as determining the trade-off between fire and grazing and impacts of varying grazing intensities.

This paper considers simulating the influence of macroinvertebrate activity (macroporosity factor) and plant cover (soil surface condition factor) on infiltration using an ecological approach with easily measured variables.

2. METHODS

2.1. Model Concepts

The SAVANNA.AU model is based on the approach used by the SAVANNA model (Coughenour 1992) and simulates a landscape represented as a grid of cells. Flows of water, nutrients and litter occur between cells based on their relative elevation. Each cell is divided into two distinct facets (trees with grassy understorey and open grassy areas) as different processes operate between these areas (Ash et al. 2000). Most model processes including soil hydrology and plant growth occur on a daily time step.

In SAVANNA.AU, the potential rate of surface infiltration and soil hydraulic conductivity are provided to the model as measured properties or are estimated from bulk and particle densities and the percent clay, silt and sand in each soil layer (Smettem et al., 1999). These provide the potential infiltration rate based on the physical properties of the soil along with saturated holding capacity, field capacity and wilting point. These rates may then be enhanced or reduced by various eco-hydrological aspects such as macroporosity and the soil surface condition.

The presence of bio-macropores is known to increase the rate at which water can enter the soil profile and may increase infiltration by a factor of ten (Bristow et al. 1997; Smettem et al., 1999). SAVANNA.AU allows for soil macroinvertebrate activity to provide a macroporosity scaling factor for the infiltration rates. The abundance of macroinvertebrates (index 1-3 representing low to high macroinverebrate activity from field analysis, Tongway and Hindley, 2000) is used to estimate a soil macroporosity factor which is then used to modify infiltration in each soil layer (Figure 1).

The properties that define the soil surface condition, such as roughness, slope, plant cover and livestock impacts are used to provide a soil surface condition factor (Tongway and Hindley, 2000). The property that produces the greatest influence is used to estimate an infiltration multiplier (Figure 2). These factors also influence the sediment load carried by runoff, which is not covered in this paper.

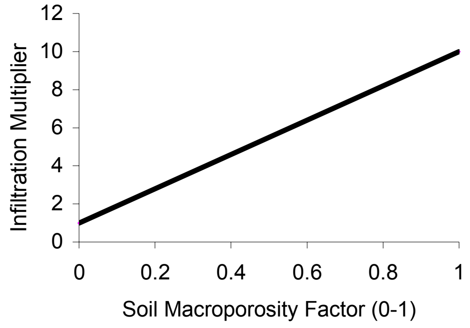

Figure 1. Multiplier for infiltration rate and hydraulic conductivity as a function of a soil macroporosity factor.

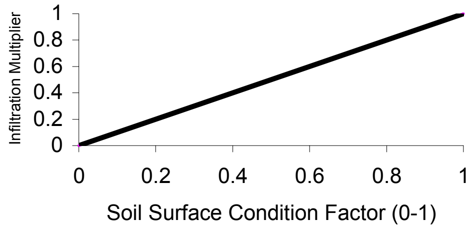

Figure 2. Multiplier for infiltration rate and hydraulic conductivity as a function of a soil surface condition.

The two multiplication factors (macroporsity effect and soil surface condition effect) are used to determine the daily infiltration rates and subsequent runoff. These are calculated for each cell in order from highest to lowest elevation. This ensures all cells receive runon from cells of higher elevation prior to considering water entering the cell as runon. Runoff is divided amongst adjacent cells of lower elevation in proportion to their elevation difference while also accounting for an extra distance required between diagonally adjacent cells. The model also accounts for creeks as defined by a creek map. For any cell designated as having a creek, a user defined proportion of any runoff is channelled to creek flow and is no longer assumed to be under overland flow processes, and is lost from the system.

2.2. Effect on soil water

While macroinvertebrate activity and weighted plant cover were altered, all other eco-hydrological processes were ignored in this analysis. A number of preliminary simulations were performed with the model using parameters estimated for Victoria River Research Station in the Northern Territory, Australia.

An area of 4 km^2 was modelled (1 ha grid cells) and included a digital elevation map to provide for flow of water between grid cells. Historic, daily, rainfall records were used based on those recorded at the nearby Victoria River Downs Station and representative month (February), when a total of 275.2 mm of rainfall was recorded, was used for all model display. This storm event driven rainfall was typical of that occurring in tropical Australia. The maximum fall on any day was 75.2 mm (mean = 21.2 s.d. = 23.1). With such variation in daily rainfall, any increase in infiltration can capture the larger rainfall events and result in more water infiltrating the soil profile. Parameters were estimated for infiltration calculations for the local soils (red loam soils and grey clay soils).

Plant cover was weighted to allow for known differences in the ability of plant cover to slow water movement and to improve infiltration between different plant functional groups with the same level of cover. Two arbitrary weighted plant covers (5% and 95%) were used to represent poor and good condition landscapes respectively. Then for each soil surface condition two macroinvertebrate activity levels (low and high) were used.

Other factors such as cattle grazing and root biomass were set to zero for ease of interpretation

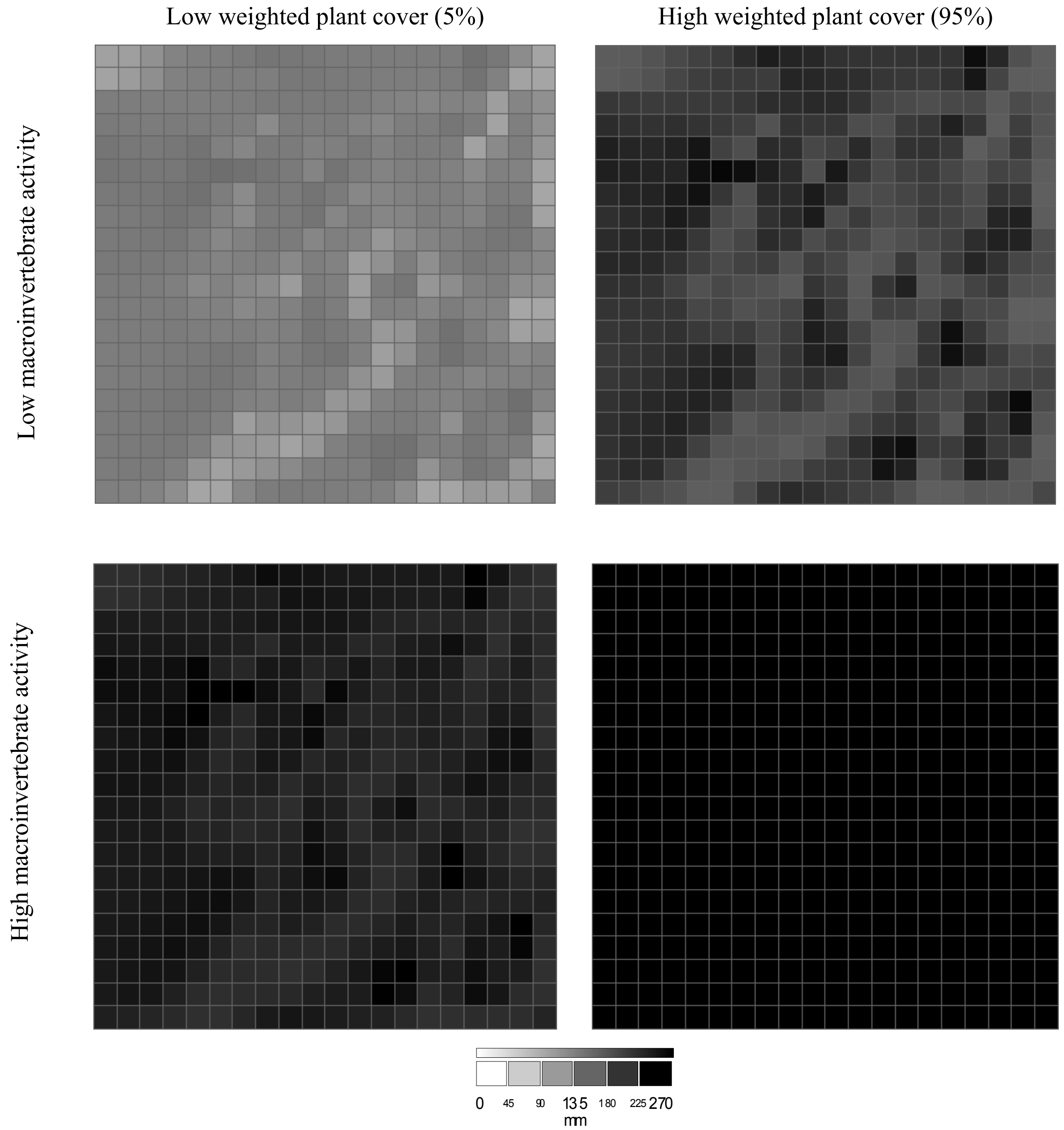

Figure 3. Total infiltration into each cell for combinations of low and high weighted plant cover and low and high macroinvertebrate activity where black represents 275 mm and white represents 0 mm infiltration.

and the slope was obtained from the elevation map. Soil water that infiltrated during a rainy day may be subject to deep drainage as the soil profile drains from saturated capacity to field capacity each day. This water is only available to plants on the day it fell. Plant water uptake was set for the single annual grass species growing in the current version of the model.

3. RESULTS

Figure 3 shows the results of four simulations and illustrates how changes in macroinvertebrate activity and weighted plant cover lead to varying amounts of water infiltrating the soil profile. Each of the four diagrams represents the simulated 4km^2 area with the infiltration recorded shaded on a continual scale from 0mm (white) to the full day's rainfall of 275mm (black). In all except the high weighted cover - high macroinvertebrate activity simulation, variation in the water infiltrated is the result of runoff and water being redistributed over the landscape.

Given that the condition of the landscape was explained by a macroporosity factor and the weighted cover of vegetation, a range of final infiltration scenarios were produced. The best condition (high weighted cover and high macroinvertebrate activity) simulation was found to produce infiltration rates in excess of the rainfall volume and intensity and thus all water infiltrated the soil (except that lost by plant interception and evaporation) and the system produced no runoff or associated sediment and nutrient loss from individual cells.

In many cases, cells in the low cover/low macroinvertebrate activity simulation were found to obtain less than half the water of the good condition run and thus plants had less water for production. The cells with the lowest infiltration in this simulation received only 50mm of the 275 mm which fell. This simulation also produced larger amounts of runoff and thus the system would potentially lose resources such as nutrients.

4. DISCUSSION

The SAVANNA.AU model was able to simulate the expected effect of the eco-hydrological processes on infiltration, and subsequent runoff, using a simple ecological explanation of hydrological processes. Although the results reported here need to be validated using experimental runoff plot data, we feel that the relative comparisons are indicative of likely real world responses.

The dynamic approach and the linking of hydrological processes with plant production and management outcomes (such as grazing impacts) allow the system to degrade or recover during the course of a SAVANNA.AU simulation. There is also potential to have both good and poor condition cells in the landscape with areas retaining and collecting nutrients from those losing resources.

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