Using Simulation to Understand the Occurrence of Subsurface Lateral Flow in South-East Australia

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Abstract: Agroforestry has been identified as a possible solution to alleviate the water imbalance due to tree clearing in the agricultural landscapes of south-east Australia. One plantation design, known as 'break of slope', aims to intercept subsurface lateral flow on hillslopes. There is a need to be able to predict where this type of flow occurs in order to assist in the efficient identification of potential plantation sites. However, there is a lack of knowledge on the occurrence of subsurface lateral flow in this region. HILLS, a two-dimensional physically based model, was used to test the sensitivity of the occurrence of subsurface lateral flow to rainfall, soil, and topographic attributes. No attempt was made to calibrate the model. In this study, a 20% variation in the soil parameters had little effect on subsurface lateral flow, however, topography and rainfall did have an influence. Convex slopes generated more subsurface lateral flow than concave slopes, but the concave slopes had greater saturation. The volume of subsurface lateral flow increased with an increase in total annual rainfall and rainfall intensity. On average subsurface lateral flow accounted for 40mm of hillslope flow per annum, but vertical drainage clearly dominated, accounting for 862mm per annum. 271mm per annum was lost by evapotranspiration. Field observation suggests that subsurface lateral flow in the study region is greater than 40mm, suggesting that soil, topographical and rainfall conditions alone are not adequate to explain the occurrence of this type of flow. There is reason to believe that other factors, such as rising watertables and flow convergence, have a significant effect on initiating substantial subsurface lateral flow in south-east Australia, and these factors may need to be included in site descriptions in order to locate 'break of slope' plantations.

Keywords: Simulation; Subsurface lateral flow; Agroforestry

1. INTRODUCTION

Agroforestry has been identified as a possible solution to alleviate the water imbalance from tree clearing in the agricultural landscape of south-east Australia. The 'break of slope' (BOS) tree-belt has been specifically designed to intercept subsurface lateral flow (SLF) in the root zone along hillslopes, reducing the volume of water flowing to low lying areas [Clifton and Miles 1998]. Currently BOS plantations are located using surface topography, and evidence of waterlogging and salinity on the footslopes. However, waterlogging can occur due to regional groundwater systems without significant local hillslope recharge, so trees on the slopes may not address the problem [McJannet 2000]. In order to assist in the efficient identification of potential plantation sites, there is a need to be able to predict where SLF occurs.

There is a lack of data on the occurrence of SLF in south-east Australia. Most research has been in the United States and Europe, although there has been a study on hydrological flow paths in the Collie River Catchment, Western Australia [Turner et al 1987]. However, hydrological response varies with landscape and climate [Croke and Jakeman, 2001], so specific data are required for each focus area. The study reported here aimed to improve the understanding of the conditions required to initiate SLF in south-east Australia. Factors influencing SLF are reviewed, with reference to their capacity to generate saturated soil conditions. The potential for simulation as a research tool is discussed, followed by simulation results, using the HILLS model, which address the sensitivity to these factors in generating SLF in south-east Australia.

2. FACTORS GENERATING SUBSURFACE LATERAL FLOW

In this paper SLF refers to water movement in the potential root zone of a regolith, and not to deeper regional groundwater systems. Lateral flow can occur in unsaturated conditions [Anderson and Burt, 1977], however for rapid and significant flow, the soil must become saturated [Weyman, 1973; Anderson and Burt, 1978].

Research has shown duration and intensity of rainfall, soil hydraulic conductivity, soil storage capacity and topography as having critical influence on generating saturated conditions and consequential SLF. There is a greater potential for soil saturation if vertical drainage is impeded by an abrupt decrease in hydraulic conductivity [Lehman and Ahuja, 1985; Michiels et al., 1989]. SLF has been reported without an impeding layer however there may have been influence by a shallow watertable [McCord et al., 1987]. A rising watertable may increase the occurrence of SLF by pushing water through bedrock fractures, creating saturation and springs [Genereux et al., 1993].

The likelihood of soil saturation and SLF increases as soil depth decreases, or antecedent moisture increases, as this reduces the soil storage capacity [Hammermeister et al., 1982; Lehman and Ahuja, 1985]. While SLF has been recorded on convex slopes [Weyman, 1973; Hammermeister et al., 1982], it typically occurs in hillslope hollows, or concavities, where water accumulates [Woods and Rowe, 1996; Anderson and Burt, 1978].

The interaction between rainfall, soil hydraulic conductivity, soil water storage capacity and topography is complex, and the importance of each can vary with specific sites and situations. Hydraulic conductivity [Whipkey and Kirkby, 1978] and the presence of an impermeable layer [Weyman, 1973] have been noted for their crucial importance in generating SLF. But topography can override the effect of soil horizonation [Hammermeister et al., 1982]. It is also possible for geological and groundwater influences to dominate topographic effects [Genereux et al., 1993; Huff et al., 1982]. In order to find the key controls and conditions required to induce SLF in south-east Australia, a simulation experiment was undertaken.

3. SIMULATION AS A RESEARCH TOOL

Sensitivity analysis can be performed using analytical methods or simulations, though the latter may be preferred for complex, nonlinear models. All parameters are kept constant, except for the parameters being tested. In simple sensitivity testing, one parameter at a time is perturbed (Δp from p), in consecutive simulations to measure its effect on the outputs (ΔO from O) of the model, ie. to determine how 'sensitive' the output is to that parameter. A simple measure of this is $\Delta p/\Delta O$, where ΔO may represent a perturbation from O at a point in space or time, or some integration of such points. Simulations can also be run for changing inputs, to determine output sensitivity.

Simulation experiments have been used to gain site-specific information. In one example the parameters were set to field values observed on loessial hillslopes in the Netherlands, and simulations were used to determine the importance of lateral flow, compared with vertical flow during rainfall events [Ritsema et al,. 1996]. They found subsurface water movement was dominantly vertical.

4. THE HILLS MODEL

The HILLS model is a two-dimensional physically based hillslope hydrology model [Smith and Hebbert, 1983]. It describes water movement through a two-layered soil profile where important soil parameters, such as the hydraulic conductivities, soil depth and porosity can be defined. The timestep can be set to vary from minutes to days. The model quantifies surface runoff and saturated overland flow using a kinematic wave function. Water infiltrating into the topsoil is assumed to move as unsaturated vertical flow, according to Richard's Equation. If saturation occurs in the topsoil then saturated lateral flow occurs, at a rate determined by the Dupuit approximation of Darcy's Law. Evapotranspiration occurs between rainfall events from both the saturated and unsaturated soil. The rate is a function of root depth, potential pan evaporation, and moisture content. For a detailed description of the HILLS model see Smith and Hebbert [1983].

5. METHODS

The simulation experiment was focused on the Billabong Creek Catchment in southern NSW (Figure 1). It was conducted in three stages to test the sensitivity to soil properties, topography, and then an interaction between these properties and the volume and intensity of rainfall. Simulations were run for a period of 12 months.

5.1 Rainfall and Evaporation Inputs

Daily rainfall and evaporation data from the Holbrook Post Office, NSW (station 72022; 35.72°E, 149.32°N) were used for the simulations

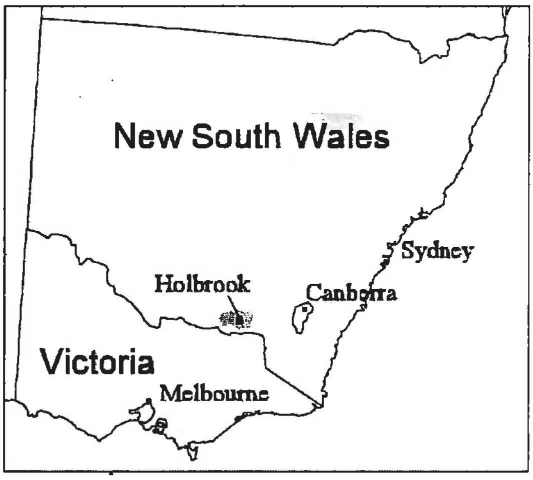

Figure 1. Location of Billabong Creek catchment (shaded area near Holbrook) in New South Wales, Australia.

[SILO Patched Point Dataset, 1999]. From these records an average [1951, 695mm], wet [1894, 1160mm] and dry [1967, 247mm] year were selected. The daily rainfall was defined to fall as one event that began at 9:00am, and finished at either 10:00am, or 12:00pm. By varying the length of the events from 1 to 3 hours, the sensitivity of SLF to rainfall intensity could be tested.

5.2 Soil Properties

Realistic values for the soil parameters were chosen using the mean of 16 detailed soil profile descriptions from the wheat-belt of southern NSW and Northern Victoria [Geeves et al. 1995] (Table 1). These values were varied by plus and minus 10%, to test their effect on SLF. The vertical saturated hydraulic conductivity of the lower soil layer was defined separately at the top and bottom of the slope. The rate at the bottom of the slope was called seepage. Soil depth sensitivity was tested as a uniform depth down the slope (+ and - 10%), and then varied from –10% (0.36m) at the top of the slope, to +10% (0.44m) at the bottom, and vice versa. Horizontal hydraulic conductivity of the topsoil is defined by specifying the ratio between the horizontal and vertical conductivity (h/v), which is limited by the model from 1 to 5. The volume of (h/v) was set at 1, as this was believed to be the most representative value for the study region. The lower hillslope boundary condition is defined by a head suction that must be overcome before SLF can flow at the base of the slope. This base value was set at 0.025m. The antecedent soil moisture condition, entered as a fraction of porosity at the beginning of each run, was set to a base value of 0.15. The soil input simulations were run on a 30% linear slope, using rainfall from the wet year (1894) at 1 hour intensity.

5.3 Topography

Concave, convex, linear and 'convex to concave' slopes (S) were tested at 5% increments from 5 to 30% gradients. The soil parameters were set to their base values given in Table 1, and the wet year (1894) at 1 hour intensity, was used for the rainfall input.

5.4 Interaction

Using the above data, a three-way matrix with soil, topography, and rainfall was run. The soil parameters were set at the base values given in Table 1. Topography was varied from shape and slope combinations that gave a high, medium and low SLF (see Section 5.3). Each combination of soil and topography was run with the wet, average and dry rainfall files, for both 3 and 1 hour events.

6. SIMULATION RESULTS AND DISCUSSION

6.1 Soil Properties

Using the base soil values given in Table 1, the SLF at the base of the slope was 40.2mm. The results from the soil sensitivity analysis, presented in Table 1, show the percent change in the total SLF compared to this value.

The most sensitive soil parameter was the saturated hydraulic conductivity of the upper soil layer, where a 20% change about the mean varied the SLF by 18.3%. However increasing the vertical conductivity of the upper layer, also increases the horizontal conductivity, because the two are linked by the h/v ratio.

For all other soil parameters (Table 1), a 20% change about the mean varied the SLF no more than 5% (2mm). However, the vertical drainage and evapotranspiration (Et) were substantially more responsive. The non-uniform soil depth caused the largest variation in vertical drainage and Et, where a 20% change in depth varied the outflow through these paths by 89mm and 88mm respectively. Further variation of the uniform soil depth shows that SLF does not significantly change, compared to the drainage and Et (Figure 2). Therefore the model is responsive to the changes in the soil parameters, but the differences are reflected in the drainage and Et, not in the SLF. Further testing of the vertical seepage at the bottom of the slope, showed that its sensitivity increased when it was less than 2mm/hr (Figure 3). SLF increased by nearly 20mm when seepage was reduced from 2mm/hr to 0.1mm/hr. However even with a very low vertical seepage only 57.8mm of SLF was generated.

Table 1 also clearly shows that vertical drainage is the dominate hillslope flow path, on average draining 862mm, compared to only 40.2mm SLF, and 271mm Et.

6.2 Topography

Both the shape and gradient of the land surface have strong influence on the amount of SLF (Figure 4). Convex slopes generated the most SLF, and linear slopes had the next greatest flow. On the convex slope a gradient greater than 5% was required to generate SLF. On the linear slope the threshold gradient was 10%. However, even with a 30% gradient, neither the concave nor (S) shape generated any SLF at the bottom of the hillslope. These results are at odds with other research where concave slopes generate more SLF than convex slopes [Woods and Rowe, 1996; Huff et al., 1982; Hammermeister et al., 1982; Anderson and Burt, 1978]. This difference may be due to the variation of hillslope shape that can be defined as a concave slope. The gradient at the bottom of the concave slope in this research may have been too shallow

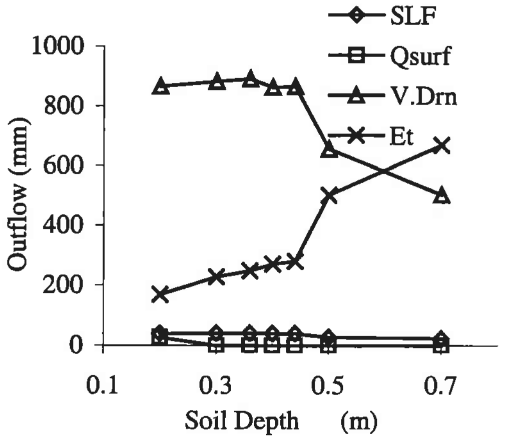

Figure 2. The effect of soil depth on SLF, surface runoff (Qsurf), vertical drainage (V.Drn) and evapotranspiration (Et) on a 30% linear slope, in a wet year, at 1 hour intensity.

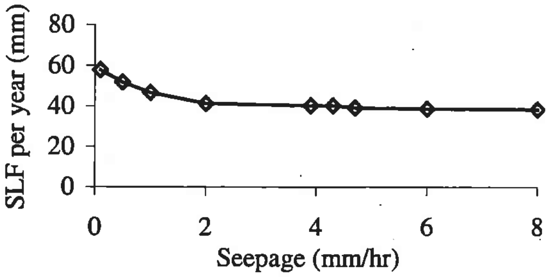

Figure 3. The effect of vertical seepage at the bottom of a 30% linear slope on SLF, in a wet year with 1hr rainfall.

Table 1. Soil parameter values used for simulations, and the percent change in SLF for – and + 10% of the base values, on a 30% linear slope, in a wet year (1894) with 1 hour events, as described in Section 5.2.

Parameter	Base Value	% change in SLF		Outflow (mm)		
				SLF	V.Drn	Et
Initial moisture [a]	15	-	0.5	40.5	858	254
		+	0.0	40.3	898	258
Soil depth [b]	0.40	-	1.0	40.7	891	249
		+	-0.2	40.2	866	281
	(c)	- to +	0.3	40.4	764	362
		+ to -	1.0	40.7	853	274
Porosity (%)	42	-	-3.5	38.9	875	263
		+	-1.5	39.7	890	252
Top soil K_{sat} [d]	37	-	-8.4	36.9	866	260
		+	9.9	44.3	849	285
Lower soil K_{sat} [d]	8.3	-	0.2	40.4	870	255
		+	-0.2	40.2	858	272
Seepage [d]	4.3	-	0.0	40.3	855	270
		+	-2.7	39.2	874	264
			average	40.2	862	271

[a] (% of porosity); [b] (m); [c] Depth varies top to bottom of slope: (–10%: 0.36 to 0.44m) (+10%: 0.44 to 0.36m)
[d] (mm/hr)

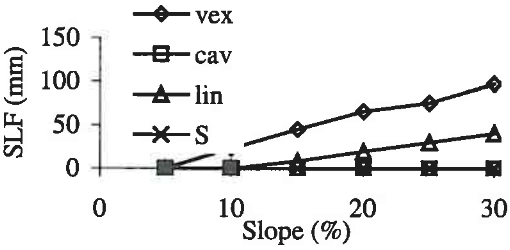

Figure 4. Effect of topography shape and gradient on SLF in a wet year at 1 hour intensity.

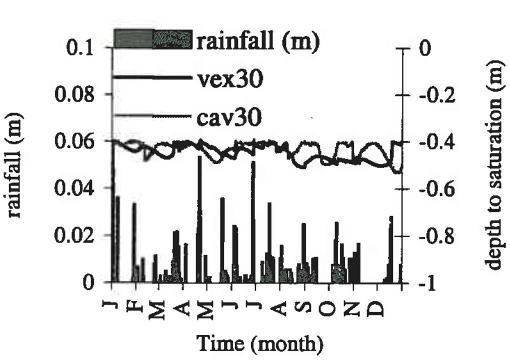

Figure 5. Depth below the surface (0m) to saturation at the break of slope for a 30% convex and 30% concave slope, with base soil values and 1hour intensity rainfall from 1894.

Table 2. Yearly SLF generated by wet, average and dry years where rainfall events are at 1 or 3 hour intensity. Soil parameters are set at base values (Table1). Topography is a 30% convex, 20% linear or a 30% concave slope.

Rainfall	Intensity	Topog	Outflow (mm)		
Total			SLF	V.Drn	Et
wet	1	vex30	97.0	865	204
wet	3	vex30	83.5	851	254
average	1	vex30	53.6	386	303
wet	1	lin20	19.7	911	248
wet	3	lin20	19.4	883	289
average	3	vex30	16.8	288	447
average	1	lin20	11.7	424	306
average	3	lin20	9.6	351	369
dry	1	vex30	8.4	66.6	243
dry	3	lin20	6.7	80.3	209
dry	3	vex30	6.4	78.6	220
dry	1	lin20	2.9	65.4	244
wet	1	cav30	0.0	837	351
wet	3	cav30	0.0	888	335
average	1	cav30	0.0	477	295
average	3	cav30	0.0	382	372
dry	1	cav30	0.0	92.2	221
dry	3	cav30	0.0	101	207

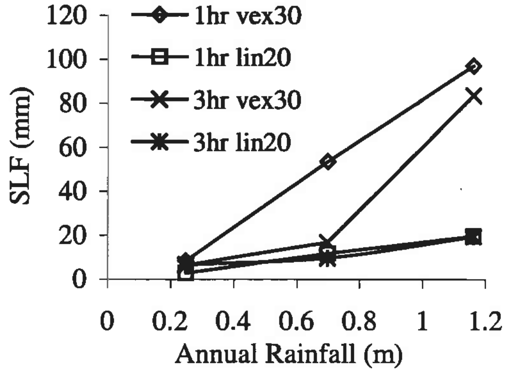

Figure 6. The effect of total annual rainfall on the SLF for the 30% convex, 20% linear and 30% concave slopes, with base soil values as defined by Table 1.

to maintain lateral flow so that water tended to pool and drain vertically, rather than move as SLF out the base of the slope, as on the convex slope. Figure 5 supports this suggestion, as it shows that the concave slope was more frequently saturated at the break of slope, than the convex slope. Both the volume and the presence of saturated zones should be used to site break of slope plantations as both can provide a valuable source of water.

SLF on convex slopes was most sensitive to changes in gradient. Linear slopes were also quite responsive, but concave and (S) slopes were insensitive to changes in the overall gradient. Again this may be due to the water accumulating at the bottom of the concave slopes regardless of the overall change in gradient.

6.3 Interaction

The 30% convex slope, 20% linear slope and 30% concave slope were chosen as the high, medium and low topographic combinations, respectively, to be used in the following interactions with the base soil property values, and the variations in the total and intensity of rainfall.

Table 2 presents results from the interactions between soil, topography and rainfall. The values are listed in order of descending SLF. For the 30% convex and 20% linear slopes, where some SLF occurred, generally the greater the total annual rainfall the more the SLF. Rainfall intensity also influenced the SLF, and appeared to have a greater effect on the convex slope than the linear slope (Figure 6). This is possibly because conditions on the convex slope were closer to a threshold value required for SLF, so change in intensity was sufficient to alter the resultant SLF. In general, 3 hour rainfall events resulted in approximately 15% less SLF than for 1 hour events. Supplying water at the higher intensity is more likely to generate saturated conditions, and initiate SLF.

Topography also has a strong influence on the SLF with the 3 greatest SLFs being associated with a 30% convex slope, and the 6 least SLFs with a 30% concave slope, while the 20% linear slopes yield values are scattered in between.

7. CONCLUSIONS

In this study, the most sensitive soil input was the saturated hydraulic conductivity of the topsoil, which may have been biased by the way (h/v) effects the horizontal conductivity. All other soil parameters tested with typical values for the study region had little effect on SLF. However, reducing vertical seepage at the bottom of the slope to values less than 2mm/hr increased its sensitivity to SLF.

Convex slopes generated the most SLF, and no SLF occurred out the bottom of the concave slopes, even with a 30% gradient. However, the concave slopes were saturated at the break of slope for extended periods. Both the volume of SLF and the amount of water held in saturation need to be considered when siting agroforestry plantations.

Total rainfall, rainfall intensity and topography influence the occurrence of SLF. In this paper a steep, sharp topography (30% convex slope), with a large rainfall falling at a high intensity was required to achieve more than 50mm of SLF per annum. It is clear that vertical drainage dominates subsurface water movement, agreeing with Ritsema's findings [Ritsema et al 1996]. However, pedological features (eg. bleached E horizons), and field observations suggest that a significant amount of SLF occurs in the study region. This suggests that other inputs, such as a rising watertable [eg. McCord and Stephens, 1987, Genereux et al., 1993], or convergence of flow, may be required to initiate significant SLF, and that considering soil, topographical and rainfall properties alone may not be adequate to site break of slope plantations. Further simulations and field experiments are being conducted to test this theory.

8. ACKNOWLEDGEMENTS

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