Modelling Deep Drainage Under Different Land Use Systems. 2. Catchment Wide Application

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Abstract In the Liverpool Plains catchment of northern New South Wales, there is concern that current land uses are causing excessive deep drainage below the root zone which may be contributing to rising groundwater levels in some parts of the catchment and an increased risk of salinity. In parts of the catchment runoff can also contribute to groundwater recharge. The work described in this paper aims to identify which parts of the catchment are the main contributors to recharge and which parts might be best targeted for alternative land uses producing less deep drainage and runoff. The hydraulic properties of 30 major soil types were characterized using a mixture of measurement and empirical (pedotransfer) functions. The catchment was divided into 7 climate zones based on average annual rainfall with values from 626 mm to 950 mm. APSIM (Agricultural Production Systems Simulator) was used to estimate mean annual deep drainage, runoff and grain production over 41 years for 4 cropping systems for each combination of the 20 soil types and 5 climate zones suitable for cropping. The model had been locally calibrated and verified using data from a farming systems experiment. The model predicted that the traditional long fallowing system of the region, together with continuous wheat were likely to give more runoff and drainage and less grain production than opportunity cropping or continuous sorghum. Changing to opportunity cropping was particularly beneficial in the higher rainfall parts of the catchment. Soils classified as Vertosols were generally more productive and gave less drainage plus runoff than non-Vertosols. Individual non-Vertosols either had greater runoff due to poor infiltration or greater drainage due to low available water capacity. The benefits of changing to opportunity cropping or continuous sorghum were generally greater for non-Vertosols than for Vertosols.

1. INTRODUCTION

Dryland salinity is a major risk in the Liverpool Plains catchment (1.2 Mha) of northern New South Wales. There is concern that excessive drainage under current cropping practices may be causing rising water table levels and mobilizing salts in the lower parts of the landscape. In parts of the landscape runoff can also become recharge when it infiltrates at the base of the slope [Stauffacher et al., 1997]. Paydar et al. [1999] describe how the APSIM model (Agricultural Production Systems Simulator, McCown et al., 1996] was calibrated and verified for the Liverpool Plains using field experiments and used to investigate water use and productivity of various cropping systems. This paper describes how the verified model was used to investigate long-term deep drainage, runoff and productivity under various cropping systems for the range of soils and climates found in the Liverpool Plains. This follows work by Abbs and Littleboy [1998] by using a verified model, better estimates of soil hydraulic parameters and more detailed climate characterization.

2. METHODS

2.1. Soil Characterization

Thirty major soil profiles in the Curlewis and Blackville 1:100,000 soil-landscape maps [Banks, 1995, 1998] representing 94% of the mapped area were identified. A geographic information system was used to ensure adequate representation of all parts of the landscape. Representative profiles in the survey reports were re-sampled for hydraulic characterization. Analytical data for the sampled soil layers were obtained from the reports. Of the 20 profiles considered suitable for cropping 11 were classified according to Isbell [1996] as Self-mulching Vertosols, 5 as Chromosols, 2 as Sodosols, one as a Ferrosol and one as a Kandosol.

To enable a cost-effective measurement program, a variety of sampling and measurement intensities was used on each profile. The most intense involved taking undisturbed cores from each horizon and measuring near-saturated hydraulic conductivity in situ (7 profiles/25 soil horizons). For the remaining 23 profiles, undisturbed cores were taken from the upper horizons (51) and push-tube samples from lower ones (22). A total of 98 horizons were sampled, generally with 3 samples per horizon.

Table 1. Summary of climate data for seven locations in the Liverpool Plains for 41 years (1957-1997) generated by 'Data Drill' [Queensland Centre for Climate Applications, 1998].

Location	Elevation	Proportion of catchment represented	Mean annual:			Last frost*
			Rain	Potential evaporation	Frost*	
	m		mm/year	mm/year	days/year	95th %ile
Gunnedah	306	47%	626	1884	11.9	14 Sep
Quirindi	416	21%	652	1699	24.5	30 Sep
'Parraweena'	387	13%	680	1718	23.3	26 Sep
'Berwicks'	457	5%	718	1669	26.2	30 Sep
'Roscrae'	483	10%	744	1630	27.2	30 Sep
Willow Tree Highlands	892	3%	855	1419	42.8	20 Oct
Warung Forest	1211	1%	950	1366	68.1	17 Nov

*Frosts days were estimated as days with minimum ≤0°C.

2.1.1. Water Retention

For the 76 horizons from which undisturbed cores were taken, the soil water retention curve was estimated by measuring total porosity and water content at suctions of 5, 60 and 1500 kPa. Water content at saturation was assumed to be 93% of total porosity [Paydar and Cresswell, 1996]. Some samples had marked shrink/swell properties, so water contents at all suctions were expressed as a proportion of the sample volume at saturation. The Campbell [1985] water retention function was fitted to the data.

Only porosity, and water content at 1500 kPa suction were measured on the push tube samples. The parameters of the Campbell function were estimated using the 1-point method [Paydar and Cresswell, 1996] from 1500 kPa water contents and the particle size distributions given in the soil survey reports. This method was validated for the soils of this area using the previous 76 horizons by comparing the parameter estimates derived from measured water retention data with those from the 1-point method.

2.1.2. Hydraulic Conductivity

Near-saturated hydraulic conductivity was measured in the field using disc permeameters and the method of Reynolds and Elrick [1991] for 25 horizons, generally with 4 replicates. Hydraulic conductivity at 0.5 kPa suction ($k_{0.5kPa}$) was estimated for the remaining 73 horizons using the slope of the water retention curve and the porosity between saturation and 30 kPa suction. This was validated for the 25 horizons for which measurements are available.

2.1.3. APSIM Parameterization

Each soil was parameterized for the water balance module of APSIM (SoilWat2) by dividing the profile into a surface layer of 100 mm thickness and 15 layers of 200 mm. Soil water contents at saturation (SAT), field capacity (or drained upper limit, DUL) and wilting point (or lower limit, LL15) were derived for each layer from the measurements made on the appropriate horizon. SAT was estimated as 0.93×measured porosity; DUL as water content at 10 kPa suction estimated from the retention curve parameters; and LL15 as the measured 1500 kPa water content.

The lower limit for crop water extraction (LL) was estimated as LL15 for 0-0.5 m depth; 0.95×DUL for depths >1.7 m; and linearly increasing between these two extremes for 0.5-1.7 m. This minimizes plant water extraction at depths greater than 1.7 m.

The proportion of water in the drainable pore space (between DUL and SAT) that drains each day to the next layer (SWCON) was derived by scaling the hydraulic conductivity (mm/hr) between a minimum of 0.01 and a maximum of 0.9:

$$SWCON = \begin{Bmatrix} 0.01 & \vert D < 0.01 \\ D & \vert 0.01 \le D \le 0.9 \\ 0.9 & \vert D > 0.9 \end{Bmatrix} \qquad (1)$$

where

$$D = \frac{0.005 \cdot k_{0.5kPa}}{SAT - DUL}$$

The curve number (CN) for partitioning daily rainfall into runoff and infiltration was estimated from the surface condition and mean slope for the soil-landscape unit given in the survey reports using the method of Littleboy [1997].

2.2. Meteorological Regionalization

The climate within the Liverpool Plains catchment shows considerable variation. Mean annual rainfall varies from 625 mm at Gunnedah (306 m elevation) to over 1200 mm on the top of the Liverpool Ranges (>1400 m elevation). It was important to capture the range of climates across the catchment so that the relative impact of land use change in a given area could be determined. Although there are numerous rainfall stations within the catchment, there are only two meteorological stations with sufficient data to run APSIM. Therefore daily climate data for seven points across the catchment over a 41 year period from 1957 were generated using 'Data Drill'

Table 2. Sowing rules used in APSIM simulations

	Rainfall zone	
	Gunnedah	**Others**
Wheat		
Window for Sunco	1-31 May	1-14 Jun
Window for Hartog	1 Jun-31 Jul	15 Jun-31 Jul
Available soil water		
0-10 cm depth	50-99%	
0-50 cm depth	≥75%	
Sorghum		
Window	21 Oct-10 Jan	7 Nov-10 Jan
Available soil water		
0-10 cm depth	0-99%	
0-70 cm depth	≥75%	

[Queensland Centre for Climate Applications, 1998] which interpolates from recorded data (Table 1).

The pattern of rainfall is summer dominant across the whole catchment. Potential evaporation exceeds rainfall in all months except on the ranges. In the southern part of the catchment frosts occur more frequently than in the north (around Gunnedah) and occur later in the spring.

The catchment was divided into 7 corresponding rainfall zones each represented by the point with the closest annual rainfall. Only the five points with rainfall less than 750 mm/yr were used for crop simulations as the wetter two occur at higher elevations where there is no cropping.

2.3. APSIM Model Runs

Four cropping systems were simulated: long fallow (with three phases, LF1, LF2 and LF3); opportunity cropping (OP) with wheat and sorghum; continuous wheat (W) and continuous sorghum (S). Simulations were carried out for 1957-1997 using all combinations of cropping systems (6), climate zones (5) and soil types (20).

For W and S sowing could take place in the appropriate sowing window (Table 2) each year giving a maximum cropping frequency of 1/yr. For OP both wheat and sorghum sowing windows were available each year (provided the prior crop had been harvested) giving a maximum frequency of 2/yr. For LF the wheat and sorghum sowing windows were available alternately every 18 months, giving a maximum frequency of 2 crops every 3 years. In the southern rainfall zones the sowing windows are later than in Gunnedah to avoid the risk of frost during wheat flowering or soil temperatures too cool for sorghum germination and emergence.

Sowing rules were used to determine whether a crop was to be sown during an available sowing window (Table 2). During a window, a crop was sown if the available soil water (the proportion between LL15 and DUL) requirements were met.

Table 3. Mean annual predicted runoff, drainage and productivity of various cropping systems over 41 years, 20 soils and 5 rainfall zones in the Liverpool Plains. Also shown are the rates of increase (regression coefficients) as rainfall increases.

	LF	OP	S	W
Water balance terms				
Mean annual (mm/yr)				
Drainage	86	38	47	85
Runoff	39	26	34	31
Total	125	64	81	116
Rate of increase (mm/yr per mm/yr rainfall)				
Drainage	0.55	0.31	0.38	0.52
Runoff (n.s.*)	0.10	0.06	0.11	0.09
Total	0.65	0.36	0.49	0.60
Total grain production				
Mean annual (kg/ha/yr)	2100	3950	3350	2540
Rate of increase (kg/ha/yr per mm/yr rainfall)	6.5	19.3	13.1	7.6

*n.s.: not significant.

The surface soil had to be sufficiently dry to be trafficable and sufficiently moist to allow germination and emergence. Many farmers in the region assess the amount of available water in the soil profile before sowing using a push probe to measure the depth of 'wet' soil. They will sow only if a given depth is exceeded. These depths are commonly 0.5 m for wheat and 0.7 m for sorghum. For simulation purposes 'wet' was defined as >75% of available water.

3. RESULTS AND DISCUSSION

The results of all 600 model runs are summarized in Table 3 as long-term annual means over all soil types and rainfall zones for each cropping system. Note that the values for LF are the means of LF1, LF2 and LF3. Overall OP produces less runoff and drainage and more grain than LF. S behaves broadly like OP and W like LF. This analysis, consisting of a range of soil/climate combinations, extends the findings of Paydar et al. [this proceedings] for a single soil/climate combination. They found that the increased cropping frequency under OP resulted in increased mean evapotranspiration in particular by sorghum, whose peak water use coincides with the peak monthly rainfall in January.

Table 3 also shows how terms in the water balance change as mean annual rainfall increases broadly from north to south across the catchment. 10% or less of any extra rain becomes runoff. Under LF and W more than half becomes drainage compared to only about a third under OP and S. This is equivalent to an increase in drainage + runoff between Gunnedah and 'Roscrae' of 76 mm/yr for LF and 42 mm/yr for OP. Thus OP and S use a greater proportion of any extra rain for

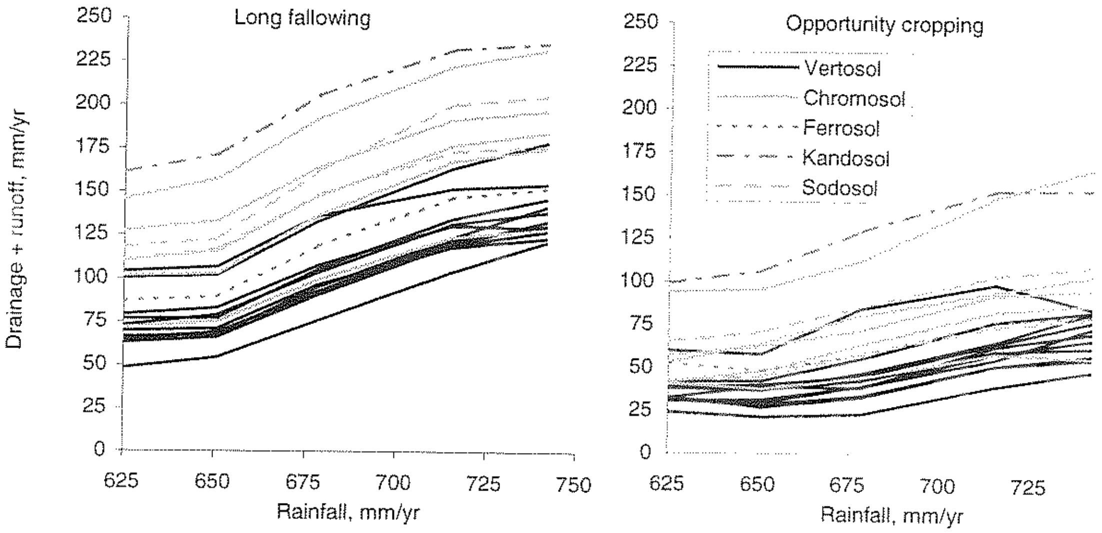

Figure 1. Variation in predicted mean annual drainage + runoff with rainfall in the Liverpool Plains for 20 soils (from 5 orders) and 2 cropping systems.

evapotranspiration and convert more into grain production. Predicted grain production increases between Gunnedah and 'Roscrae' by 760 kg/ha/yr for LF and 2240 kg/ha/yr for OP.

Figure 1 shows the variation in predicted mean annual drainage and runoff over 41 years for the 20 soils along the rainfall gradient. The variation between soils is at least as great as the variation with rainfall. The amount of drainage + runoff is generally less under soils classified as Vertosols than under non-Vertosols. However, individual non-Vertosols may have either runoff or drainage as low as the Vertosols, but not generally both. Some non-Vertosols have small runoff due to reasonable water entry but consequently have large drainage because their available water capacity (AWC) is small. Others have low drainage because of poor water entry, but consequently have large runoff.

The predicted reduction in drainage + runoff on changing from LF to OP is greater for non-Vertosols (mean reduction of 70 mm/yr) than for Vertosols (54 mm/yr). This suggests that in parts of the landscape where both drainage and runoff can contribute to groundwater recharge, changes from LF to OP should be targeted especially at non-Vertosols, depending on their relative areas. In parts where only drainage contributes, individual soils need to be targeted on the basis of the predicted reduction in drainage alone.

To demonstrate differences in behaviour between soil types, a comparison is made between two common soils in the Liverpool Plains: Lever Gully (profile type 1), a Self-mulching, Black, Vertosol, and Fullwoods Road, a Subnatric, Red Sodosol. Fullwoods Road has a hard-setting surface giving it poorer water entry than Lever Gully. Lever Gully also has greater AWC (Table 4).

Predicted long-term mean drainage and runoff are less for a Lever Gully soil than a Fullwoods Road soil under the same cropping system and rainfall (Figure 2). Changing from LF to OP reduces drainage and runoff for both soils. For both soils W is marginally better than LF in terms of unused water and S slightly worse than OP.

In the lower rainfall parts of the catchment, the reductions in drainage + runoff on changing from LF to OP are greatest for the Fullwoods Road soil. At Gunnedah the reduction is 45 mm/yr for Fullwoods Road compared to 34 mm/yr for Lever Gully. In higher rainfall zones ('Berwick'), the reduction in drainage + runoff on changing to OP is about 70 mm/yr for both soils.

To reduce drainage + runoff land use change from LF to OP should be directed at Fullwoods Road soil rather than Lever Gully over all but the wettest parts of the catchment. Conversely, to reduce drainage alone Lever Gully should be targeted over all but the driest parts.

As discussed earlier, water use under OP is more responsive to changes in rainfall over the catchment. These predictions also suggest there is an interaction between OP and the AWC of the soil, so that the responsiveness of OP to rainfall is greater for soils with larger AWC.

Table 4. Some properties of Lever Gully (profile type 1), lg1, and Fullwoods Road, fr, soils.

	lg1	fr
Slope	2-8%	2-8%
Bare-soil curve no.	72	83
Total AWC 0-3.1 m depth	441 mm	293 mm
Maximum available water content		
0-0.5 m depth	16.8%	16.6%
0.5-3.1 m depth	13.8%	8.1%

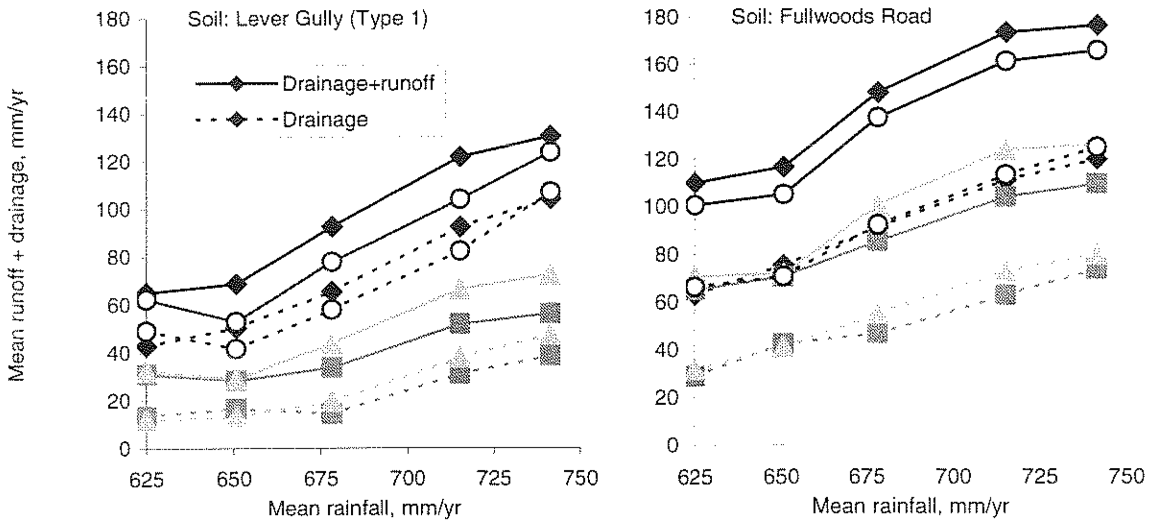

Figure 2. Variation in predicted mean annual drainage and runoff with rainfall in the Liverpool Plains for two soils and various cropping systems: ◆ long fallow (mean of LF1, 2 and 3); ▨ opportunity cropping; ▲ continuous sorghum and ○ continuous wheat.

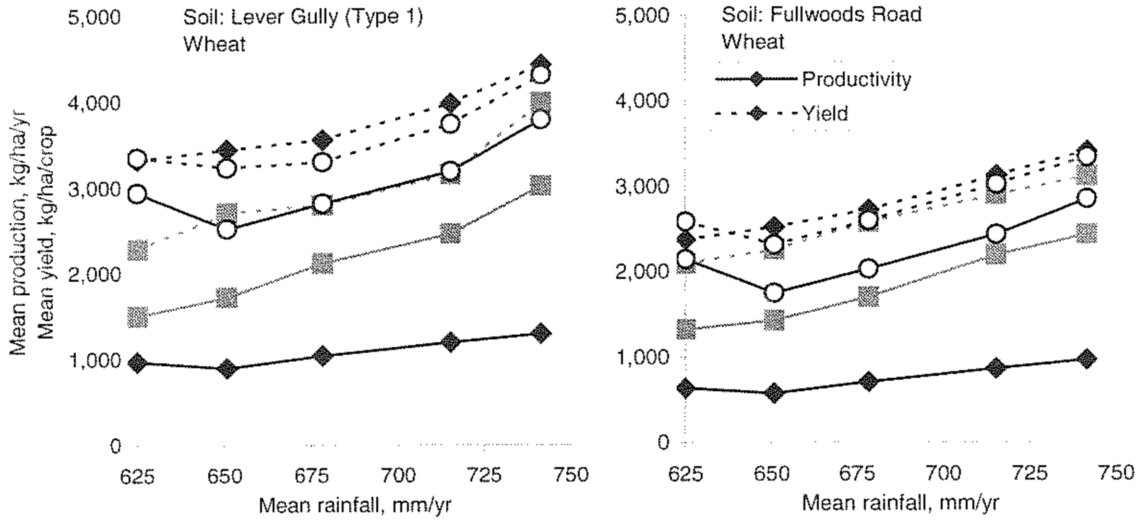

Figure 3. Variation in predicted mean wheat yields and annual productivity with rainfall in the Liverpool Plains for two soils and various cropping systems. (Symbols as for Figure 2).

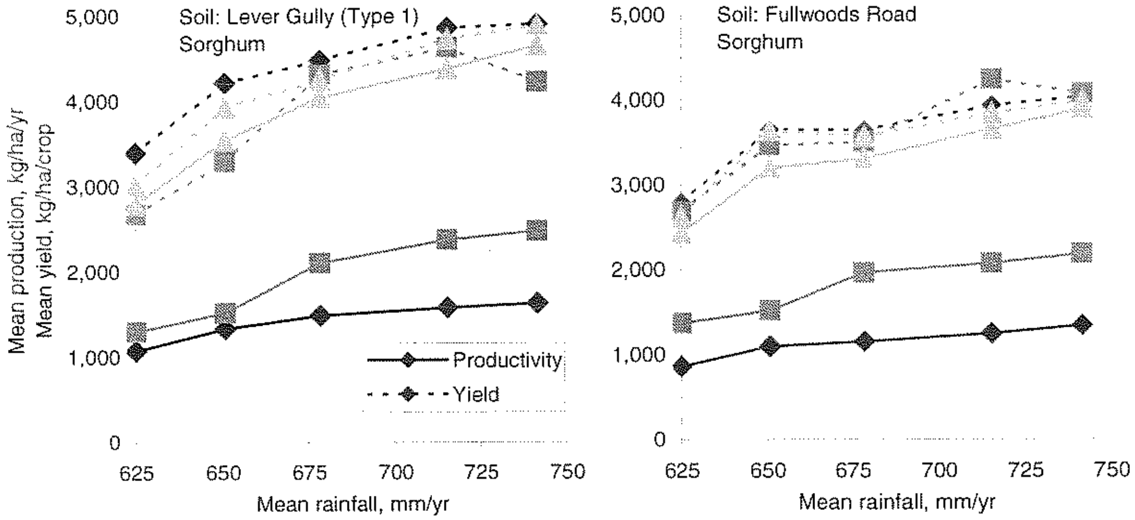

Figure 4. Variation in predicted mean sorghum yields and annual productivity with rainfall in the Liverpool Plains for two soils and various cropping systems. (Symbols as for Figure 2).

Lever Gully is more productive than Fullwoods Road (Figures 3 and 4), because its greater AWC buffers against year to year variation in rainfall. There is little yield advantage for either wheat or sorghum in long fallowing on Fullwoods Road because the AWC is too small to make use of all the rain during the long fallow. Cropping frequency increases from about 0.6 /yr under LF to 1.1 /yr in drier areas to 1.3 /yr in wetter areas under OP. Consequently, the total productivity of OP is much greater because of the greater cropping frequency. Therefore LF does not appear to have any advantages on this soil.

Long fallowing does give a yield advantage on Lever Gully because of its larger AWC. This is particularly so for wheat, which receives less growing season rain than sorghum. On this soil LF has the advantage of greater and more reliable individual yields. Nevertheless, the increase in total production under OP on Lever Gully is similar to that on Fullwoods Road. Cropping frequencies under LF and OP are similar to those for Fullwoods Road.

4. CONCLUSIONS

In the Liverpool Plains, the increased cropping frequency of opportunity cropping results in less runoff and drainage than the traditional long fallowing system. Because the maximum rainfall is in summer, continuous sorghum also appears a viable option. Opportunity cropping is especially beneficial in the higher rainfall areas in terms of reducing drainage and increasing production.

Long fallowing appears to have no advantages on non-Vertosols and changing to opportunity cropping or continuous sorghum reduces runoff and drainage and increases productivity. Vertosols are more productive and give less drainage and runoff under all systems. Changing to opportunity cropping is beneficial on Vertosols, but to a lesser degree than on non-Vertosols.

Water balance and productivity for alternative cropping systems with different soils and climates has been quantified which will enable assessment of the relative impacts of land use change in different areas of the catchment.

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