9.0 General discussion and conclusions

9.1 General discussion

The gleyed podzolic investigated in this study is a duplex soil having a moderately differentiated profile consisting of a sandy clay loam A horizon overlying a medium to heavy clay B horizon. The profile has a bleached A2 horizon, which is usually indicative of water ponding on top of the B horizon, resulting in the translocation of clay, iron and aluminium out of the horizon. Mottles are present in the B horizon indicating poor drainage and periods of waterlogging. Observation of the soil profile identifies some features of the soil's hydrology, but direct measurement of soil hydraulic properties is required to quantify these features.

Water entry, storage and movement in a soil can be described from a knowledge of the moisture characteristic and the hydraulic conductivity function. These two properties are affected by soil texture and structure.

There is an increasing concern that grazing animals cause soil structural damage. The ground pressures exerted by livestock are comparable to the pressures exerted by agricultural vehicles (Packer, 1988). Therefore, treading by stock can adversely affect soil physical properties, particularly when a soil is prone to compaction, thereby modifying the soil's hydrology.

In this study the hydraulic properties of the gleyed podzolic soil with and without grazing have been compared. The Soil Water Infiltration and Movement (SWIM) model was then used to examine the effects of grazing on the soil water balance, using inputs for soil properties measured in the field.

9.1.1 The hydrology of a gleyed podzolic soil

9.1.1.1 Moisture characteristic

The hydraulic properties differ markedly between the A and B horizons of the gleyed podzolic, mainly due to the large texture difference between these horizons. The clay content of the A horizon is around 20 per cent, whereas it is about 60 per cent in the B horizon (Schafer, 1980). The high clay content in the B horizon results in a predominance of small pores that hold onto water tightly, requiring large suctions (low potentials) for water to drain from these pores. The moisture characteristics show that the B horizon holds more water than the A horizon over a range of potentials (Chapter 6, Section 6.3.1). This has important implications for plant available water and drainage.

The air-entry potential of the B horizon is much lower (more negative) than the A horizon. The soil therefore remains saturated for longer periods of time after rainfall until the matric potential falls to the value at which the largest pores begin to drain.

Along with soil texture, soil structure also plays an important role in determining the shape of the moisture characteristic. Treading by grazing animals results in a reduction in the number of macropores and an increase in the number of smaller sized pores. A compacted soil will consequently retain more water at low potentials and less at high potentials compared to a well structured soil (Warkentin, 1971). Although no significant differences in the moisture characteristics were found in this study between the ungrazed and grazed treatment at either the 5 cm or 20 cm depths (Chapter 5, Section 5.3.2), Lemin (1992) found significant differences in bulk density between the ungrazed and high graze (20 DSE per ha) treatments at 1-2 cm and 6-7 cm. Air-filled porosity was greater in the ungrazed plot compared to the high graze at 0-4 cm, 4-8 cm and 8-12 cm. She also found that the greater the stocking rate, the closer the maximum value of cone penetrometer resistance came to the soil surface. In this study, undisturbed soil cores were taken using 4 cm deep cores at 5-9 cm, 20-24 cm and 30-34 cm. There were no significant differences in bulk density, porosity or the moisture characteristic at either the 5-9 cm or 20-24 cm. Either the effects of grazing did not occur at these sampled depths or the volume of soil sampled was too large and masked any grazing effects. That is, if the effects of grazing only occurred in the top 1 cm of the undisturbed core, the volume of soil in the core beneath this layer may have obscured any grazing effects. A better sampling method would have been to take soil cores that were divided into 1 cm deep cores, as Lemin (1992) did using a slicing technique. Measurements would be taken at several intervals (every 1 cm) close to the soil surface in order to examine the effects of grazing.

9.1.1.2 Hydraulic conductivity

Redistribution and drainage of water through the soil profile determines the quantity of water retained in the root zone and the available air-filled porosity for subsequent storage of water (Ward and Robinson, 1990). Drainage is also responsible for the removal of plant nutrients that are weakly adsorbed ions, such as nitrate.

The flow of water through the soil is in the direction of and at a rate proportional to the hydraulic gradient. The controlling factor is the hydraulic conductivity, which describes the soil's ability to transmit water. The conductivity of a soil is affected by the size, shape and continuity of pores, which depend on soil texture and structure. Water movement in the B horizon is restricted, as indicated by the low hydraulic conductivity values, compared with the A horizon. One reason for this is the high clay content of the B horizon, resulting in small pores that conduct water more slowly than large pores. The B horizon has a steep moisture characteristic and therefore a large change in matric potential results in only a small change in water content, indicating a predominance of small pores.

The low conductivity of the B horizon is an important factor determining the amount of drainage from the gleyed podzolic soil. A total of 31 mm of water drained below the root zone of a fully saturated soil profile over 286 hours. Of this about 15 mm drained within the first 24 hours (Chapter 7, Section 7.3.1.8). The advantage of slow drainage is that there would only be a small loss of nutrients through leaching and plants are given ample time to intercept water and nutrients. However, periods of waterlogging may occur, which result in anaerobic conditions that are detrimental to plant growth. Also, under these conditions nitrogen may be lost by denitrification.

A reduction in the number of macropores due to compaction by grazing animals can also affect hydraulic conductivity. The hydraulic conductivity was measured at the soil surface, and at depths of 20 cm and 30 cm for the two grazing treatments. Significant differences in hydraulic conductivity between the two grazing treatments were only found at the soil surface, with infiltration being significantly higher in the ungrazed treatment (Chapter 5, Section 5.3.3). This may be due to a larger number of macropores and/or the pores may be better connected at the soil surface resulting in more continuous pores that conduct water more easily in the ungrazed treatment.

9.1.2 An evaluation of SWIM's drainage prediction

Water balance models, such as SWIM, enable researchers to investigate hydrological processes which occur in the soil. They provide a means of increasing the understanding of the behaviour of water in the soil-plant system and can be used as a tool for improving water use efficiency. There are many advantages associated with the use of models. Much time and money can be saved by using models because data that have been collected in the past can be used to initialise the model. Given that the input data are available, output can be generated in a short time.

Modelling can overcome to some extent the problem of variability that confronts researchers when carrying out experiments in the field. A major source of experimental variation is climate. The results from an experiment carried out in a dry year can differ greatly from the results of the same experiment conducted in a wet year. Where climatic inputs are used in the model climatic variability is taken into account. Thus different scenarios can also be modelled to simulate hydrological processes under different conditions. For example, the effects of different rainfall events can be examined by using designed rainfall events, rather than waiting for that particular rainfall event to happen in the field before measurements take place.

The validation of models is essential in order to provide confidence in their use and application. Validation provides information on how well a model describes certain processes and whether or not model output is realistic. SWIM's prediction of drainage was evaluated in this study by measuring water content and drainage in the field and comparing it with prediction of these variables by SWIM (Chapter 7, Section 7.3.2). There was only a small difference between measured and simulated water content of soil profiles and drainage over time. It was concluded that for the gleyed podzolic soil SWIM provides reliable estimates of drainage, suggesting that the process of water movement is well described by the SWIM model, which simulates water movement through numerical solution of Richards' equation.

Differences between measured and simulated data could be due to error in the measurement of hydraulic properties, field measurements of water content and matric potential or wrong assumptions used in the simulation. Spatial variation in soil properties caused some problems in measuring soil hydraulic properties in this study. The main source of variation was the depth to the B horizon, which led to problems in determining a representative moisture characteristic for the A horizon (Chapter 7, Section 7.2.2.2). The *in situ* moisture characteristic and laboratory determined moisture characteristic were combined to provide input data for SWIM. The *in situ* moisture characteristic points did not match the points obtained in the laboratory at the 20 cm depth. The *in situ* measurements were taken in the drainage plot that was about 6 m from the soil profile pit, from which cores were taken for the laboratory determined moisture characteristic. The bulk density measurements made on cores taken from the soil profile pit also varied from the bulk density measured *in situ*, the difference being attributed to variation in the depth to the B horizon between the drainage plot and the soil profile pit.

Measurement techniques should be designed to reduce variability. For example, in this study, spatial variation in bulk density led to variation in volumetric water content and therefore error in the moisture characteristic at the 20 cm and 40 cm depth. The bulk density and moisture characteristic should be determined on the same core. This would indicate any variation that existed between cores and identify any outlying curves before the replicates were grouped together to give an average moisture characteristic for a particular depth.

The spatial variation in hydraulic properties resulting from soil texture and structure variability has important implications for models such as SWIM. An accurate description of soil hydraulic properties is required for SWIM to produce reliable output. Variability in soil properties may be so great over a large area that it would be wise to isolate smaller areas and model these separately, rather than using an average for the larger area, as the average may not be representative of the whole area.

9.1.3 Sensitivity analysis

A sensitivity analysis was carried out to determine the sensitivity of SWIM output to variation in the model's input parameters. Obviously more care needs to be taken in selecting parameter values if a small change in that parameter causes a large change in the model's output. The sensitivity analysis found SWIM's prediction of the soil water balance to be most sensitive to the soil input parameters, namely, initial matric potential, saturated water content, air-entry potential, *b* (the slope of the best fit line relating θ to ψ on a log-log scale), and saturated hydraulic conductivity (Chapter 8, Section 8.3.4).

SWIM's prediction of drainage was most sensitive to changes in saturated water content and *b* (Chapter 7, Section 7.3.2.5). A change in either of these inputs changes Campbell's (1974) water retention function and hydraulic conductivity function and thereby changes the water redistribution and drainage pattern.

SWIM was relatively insensitive to variation in runoff inputs. The runoff rate power and runoff rate factor are difficult to determine and, given that the model is insensitive to changes in these parameters, a small amount of error in their determination will not lead to significant changes in output.

9.1.4 Water balance predictions under two grazing treatments using SWIM

SWIM was used in this study to examine the consequences of changed hydraulic properties due to grazing on the soil water balance (Chapter 8). The grazing treatment was typical of the stocking rate used on the Northern Tablelands of NSW (10 DSE per ha). The simulated soil profile consisted of seven horizontally uniform layers. SWIM uses the equations of Campbell (1974, 1985) to define the soil moisture characteristic and hydraulic conductivity function. The equations require the following inputs: saturated water content, air-entry potential, *b* and saturated hydraulic conductivity. The initial matric potential was set at -100 cm H_2O throughout the soil profile. The SWIM output indicated that a stocking rate of 10 DSE per ha did not degrade soil structure enough to induce runoff until at least 43 mm of rain fell in one hour. However, it did show clear differences in the soil water balance between the two grazing treatments. The ungrazed treatment had a much higher infiltration rate compared to the 10 DSE per ha treatment. Grazing reduced infiltration leading to greater runoff and erosion hazard. The rainfall which runs off is a loss of potentially available soil water.

Difficulties in obtaining a reasonable estimation of infiltration with a disc permeameter were encountered (Chapter 8, Section 8.3.1.2). The infiltration rate at the soil surface of the 10 DSE per ha treatment measured using a disc permeameter was 71.9 mm per hour, whereas the infiltration measured in a similar plot using a drip infiltrometer was only 19.5 mm per hour. The differences are due to the different wetting mechanisms of the two methods. The soil is wet under tension using a disc permeameter. Wetting is therefore slower, and results in less breakdown of soil structure which commonly occurs under rainfall because of the impact of raindrops. The soil surface was also found to be hydrophobic during the initial stages of wetting under the drip infiltrometer. This natural water repellence is overcome using a disc permeameter because the ground is wetted for a longer time.

Two runoff mechanisms occurring in the gleyed podzolic soil were identified using simulation modelling: Hortonian flow, where runoff occurs when the rainfall intensity is greater than the conductivity of the soil surface, and saturation excess runoff, where runoff occurs once the A horizon becomes saturated. The intensity of rainfall in the Armidale district is relatively low. A storm of 43 mm/hr, which SWIM predicts should produce runoff, is an uncommon event, having an average recurrence interval, according to Pilgrim (1987) of once in every 20 years. Runoff is observed to occur at the experimental site more frequently than this. Runoff events are more likely to occur through saturation excess under low intensity rainfall that lasts for several hours. In this situation the A horizon tends to saturate during steady rainfall because of the low conductivity of the B horizon. Once the A horizon is saturated runoff will occur. Runoff by this mechanism is likely to occur at least once in every ten years.

One aspect of water movement that SWIM cannot model is lateral water flow. Given the low hydraulic conductivity of the B horizon compared with the A horizon, it is likely that water will pond on top of the B horizon as water moves through the A horizon relatively quickly. Lateral water movement along the top of the B horizon is therefore possible, particularly on a slope.

The effect of the dense clay B horizon on hydrology, as shown in this study, limits the land use potential of the gleyed podzolic soil. Water is strongly held by the B horizon so that the wilting point is high and plant available water is correspondingly reduced. Other problems include poor drainage resulting in waterlogging after rainfall causing anaerobic soil conditions that adversely affect plant growth. Entry of water draining through the A horizon into the B is restricted causing the A horizon to eventually saturate if rainfall continues. Once the A horizon is saturated further rainfall will be lost as runoff. To increase infiltration and water availability for the pasture, the hydraulic properties of the B horizon need to be improved. Deep ripping will create a temporary increase in pore space. However, once the soil is wetted soil structure may collapse and pore space is reduced. A more permanent measure would involve production of vigorously growing, deep-rooted perennial plant species that will create biopores and increase faunal activity in the B horizon thus increasing the hydraulic conductivity.

9.2 Conclusions

1) The hydraulic properties differ markedly between the A and B horizons of the gleyed podzolic soil due to the large texture difference in clay content. The hydraulic properties of the B horizon have a major influence on infiltration and water movement through the soil profile.

2) Although no significant differences in the moisture characteristic were found between the ungrazed and grazed treatments, infiltration at the soil surface was significantly greater in the ungrazed plot. This finding supports other research carried out on Big Ridge 1 which suggests that the effects of grazing occur close to the soil surface within a relatively narrow band.

3) The low hydraulic conductivity of the B horizon results in poor subsoil drainage. A total of 31 mm of water drained from below the root zone of a fully saturated soil profile over a 286 hour period. There is likely to only be a small loss of nutrients in drainage water. The low hydraulic conductivity of the B horizon slows down water movement through the soil profile enabling plant roots to intercept nutrients and water before they drain below the root zone. The disadvantage of poor drainage is the occurrence of waterlogging that adversely affects plant growth.

4) The SWIM model has found to give reliable predictions of drainage. There was little difference between measured and simulated water content profiles and drainage over

time. This indicates that the process of water movement is well described by SWIM, which simulates water movement by numerical solution of Richards' equation.

5) Spatial variation in hydraulic properties resulting from soil texture and structure variability has important implications for models such as SWIM, which require an accurate description of soil hydraulic properties to produce reliable output. Of the input parameters required to run the model, SWIM output is most sensitive to soil input parameters, namely, saturated water content, air-entry potential, b (the slope of the best fit line relating θ to ψ on a log-log scale), and saturated hydraulic conductivity.

6) Simulation by SWIM indicated that grazing reduced infiltration and increased runoff.

7) SWIM predicted two runoff mechanisms that occur on the gleyed podzolic soil: runoff by Hortonian flow and saturation excess runoff. Of these two mechanisms, runoff by saturation excess was more likely to occur. During prolonged low intensity rainfall the A horizon will saturate because drainage is impeded by the dense clay B horizon, once the A horizon is saturated further rainfall will run off.

8) To improve the hydrology of the soil, the hydraulic properties of the B horizon need to be improved. An increase in porosity through deep ripping, or production of deep rooted perennial plant species will increase infiltration and plant available water.

9.3 Further research

1) To fully assess the effects of grazing on soil hydrology all components of the soil water balance (precipitation, runoff, evapotranspiration, soil water storage and drainage) should be measured over an adequate time period.

2) The validation of the drainage component of SWIM should be extended to other components of the model. This would involve isolating each of the components as this study did for drainage and comparing modelled and measured values of runoff and evapotranspiration.

3) The amount and duration of lateral water movement within the soil profile should be measured. The low hydraulic conductivity of the B horizon compared to the A horizon is likely to result in water ponding on top of the B horizon causing lateral water flow. This could be an important process in the movement of water, nutrients and possibly soil particles over the landscape.

4) To aid soil management the soil water content at which the soil is vulnerable to compaction by treading should be determined. Where the opportunity exists, stock can be removed during times when the soil is prone to compaction.

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Appendix 1: Data from drainage plot

Appendix 1.1: Soil water contents and matric potentials used to derive water retention curves

Time	20 cm		40 cm		60 cm	
	ψm (mm H20)	θv (m^3 m^{-3})	ψm (mm H20)	θv (m^3 m^{-3})	ψm (mm H20)	θv (m^3 m^{-3})
0	-5.875	0.357	137.560	0.478	274.710	0.457
1	-56.155	0.333	106.135	0.478	287.280	0.457
3	-112.720	0.325	43.285	0.478	237.000	0.457
6	-166.143	0.313	-32.135	0.478	167.865	0.457
10	-206.995	0.307	-91.843	0.478	105.015	0.456
20	-298.128	0.293	-186.118	0.477	-20.685	0.456
28	-345.265	0.288	-233.255	0.476	-83.535	0.456
49	-439.540	0.277	-343.243	0.475	-202.950	0.456
74	-527.530	0.274	-450.088	0.473	-319.223	0.455
91	-562.098	0.269	-494.083	0.472	-366.360	0.455
116	-618.663	0.267	-547.505	0.470	-426.068	0.455
139	-684.655	0.263	-585.215	0.468	-460.635	0.454
163	-741.220	0.262	-619.783	0.466	-504.630	0.454
187	-766.360	0.263	-654.350	0.464	-542.340	0.454
212	-800.928	0.260	-688.918	0.463	-567.480	0.453
240	-804.070	0.260	-726.628	0.461	-605.190	0.453
286	-804.070	0.258	-770.623	0.457	-655.470	0.452
428	-1203.168	0.255	-965.458	0.460	-781.170	0.450
600	-1269.160	0.255	-1025.165	0.456	-884.873	0.455
764	-1551.985	0.251	-1103.728	0.451	-947.723	0.456
1123	-2532.445	0.250	-1326.845	0.455	-1173.983	0.456
1699	-2896.975	0.248	-1477.685	0.452	-1346.820	0.454
2083	-3173.515	0.246	-1669.378	0.453	-1560.510	0.452
2227	-3949.713	0.244	-1729.085	0.454	-1698.780	0.453

Time	80 cm		100 cm		120 cm	
	ψm (mm H20)	θv (m^3 m^{-3})	ψm (mm H20)	θv (m^3 m^{-3})	ψm (mm H20)	θv (m^3 m^{-3})
0	411.860	0.433	461.020	0.416	692.445	0.398
1	411.860	0.433	523.870	0.416	711.300	0.398
3	364.723	0.433	498.730	0.416	683.018	0.398
6	295.588	0.433	442.165	0.416	617.025	0.398
10	251.593	0.433	398.170	0.415	563.603	0.398
20	160.460	0.433	294.468	0.415	459.900	0.398
28	116.465	0.432	250.473	0.415	406.478	0.398
49	-21.805	0.432	137.343	0.415	261.923	0.398
74	-156.933	0.431	-19.783	0.415	98.512	0.398
91	-207.213	0.431	-88.918	0.415	19.950	0.398
116	-273.205	0.430	-151.768	0.414	-77.468	0.398
139	-342.340	0.430	-186.335	0.414	-146.603	0.398
163	-380.050	0.429	-227.188	0.414	-190.598	0.398
187	-389.478	0.429	-255.470	0.414	-231.450	0.397
212	-420.903	0.428	-286.895	0.413	-269.160	0.397
240	-452.328	0.427	-324.605	0.413	-288.015	0.397
286	-483.753	0.426	-381.170	0.413	-366.578	0.397
428	-612.595	0.430	-481.730	0.414	-517.418	0.397
600	-681.730	0.430	-582.290	0.414	-577.125	0.397
764	-735.153	0.430	-663.995	0.413	-643.118	0.397
1123	-838.855	0.430	-1053.665	0.413	-891.375	0.396
1699	-942.558	0.430	-1336.490	0.412	-1048.500	0.396
2083	-1014.835	0.430	-1569.035	0.411	-1343.895	0.395
2227	-1039.975	0.430	-1855.003	0.411	-1529.303	0.395

Appendix 1.2 : Calculation of soil water flux (q)
where: θv = volumetric water content,
W = cumulative water storage over time
$q = (W_{t-1}-W_t)/((t-1)-t)$

Time (Δtime) (hrs)	Depth (cm)	θv ($m^3\ m^{-3}$)	W (mm)	q (mm/hr)
0-1	20	0.333	69.404	2.437
(1)	40	0.478	144.487	4.540
	60	0.457	237.949	4.547
	80	0.433	327.456	4.551
	100	0.416	412.340	4.553
	120	0.398	493.779	4.554
	140	0.385	571.722	4.554
	180	0.400	729.594	4.554
1-3	20	0.325	68.542	0.431
(2)	40	0.478	142.963	0.762
	60	0.457	236.410	0.770
	80	0.433	325.910	0.773
	100	0.416	410.788	0.776
	120	0.398	492.226	0.777
	140	0.385	570.168	0.777
	180	0.400	728.041	0.777
3-6	20	0.313	66.179	0.787
(3)	40	0.478	139.252	1.237
	60	0.457	232.676	1.245
	80	0.433	322.165	1.248
	100	0.416	407.035	1.251
	120	0.398	488.471	1.252
	140	0.385	566.413	1.252
	180	0.400	724.285	1.252
6-10	20	0.307	65.837	0.086
(4)	40	0.478	138.441	0.203
	60	0.456	231.836	0.210
	80	0.433	321.311	0.214
	100	0.415	406.168	0.217
	120	0.398	487.601	0.217
	140	0.385	565.543	0.217
	180	0.400	723.415	0.217

Time (Δtime) (hrs)	Depth (cm)	θv ($m^3\ m^{-3}$)	W (mm)	q (mm/hr)
10-20	20	0.293	63.042	0.280
(10)	40	0.477	133.895	0.455
	60	0.456	227.215	0.462
	80	0.433	316.655	0.466
	100	0.415	401.484	0.468
	120	0.398	482.909	0.469
	140	0.385	560.849	0.469
	180	0.400	718.722	0.469
20-28	20	0.288	62.490	0.069
(8)	40	0.476	132.779	0.139
	60	0.456	226.040	0.147
	80	0.432	315.453	0.150
	100	0.415	400.258	0.153
	120	0.398	481.677	0.154
	140	0.385	559.616	0.154
	180	0.400	717.489	0.154
28-49	20	0.277	60.622	0.089
(21)	40	0.475	129.229	0.169
	60	0.456	222.334	0.176
	80	0.432	311.673	0.180
	100	0.415	396.417	0.183
	120	0.398	477.820	0.184
	140	0.385	555.757	0.184
	180	0.400	713.629	0.184
49-74	20	0.274	60.047	0.023
(25)	40	0.473	128.432	0.032
	60	0.455	221.350	0.039
	80	0.431	310.601	0.043
	100	0.415	395.273	0.046
	120	0.398	476.658	0.047
	140	0.385	554.591	0.047
	180	0.400	712.464	0.047

Appendix 1.2 : Calculation of soil water flux (q)
where: θv = volumetric water content,
W = cumulative water storage over time
$$q = (W_{t-1} - W_t)/((t-1)-t)$$

Time (Δtime) (hrs)	Depth (cm)	θv ($m^3\ m^{-3}$)	W (mm)	q (mm/hr)
74-91	20	0.269	58.991	0.062
(17)	40	0.472	126.808	0.096
	60	0.455	219.600	0.103
	80	0.431	308.791	0.106
	100	0.415	393.413	0.109
	120	0.398	474.785	0.110
	140	0.385	552.717	0.110
	180	0.400	710.589	0.110
91-116	20	0.267	59.428	-0.018
(25)	40	0.470	126.926	-0.005
	60	0.455	219.532	0.003
	80	0.430	308.636	0.006
	100	0.414	393.185	0.009
	120	0.398	474.539	0.010
	140	0.385	552.467	0.010
	180	0.400	710.340	0.010
116-139	20	0.263	58.168	0.055
(23)	40	0.468	124.584	0.102
	60	0.454	217.018	0.109
	80	0.430	306.042	0.113
	100	0.414	390.524	0.116
	120	0.398	471.860	0.116
	140	0.385	549.786	0.117
	180	0.400	707.658	0.117
139-163	20	0.262	57.845	0.013
(24)	40	0.466	124.371	0.009
	60	0.454	216.627	0.016
	80	0.429	305.567	0.020
	100	0.414	389.979	0.023
	120	0.398	471.297	0.023
	140	0.385	549.220	0.024
	180	0.400	707.092	0.024

Time (Δtime) (hrs)	Depth (cm)	θv ($m^3\ m^{-3}$)	W (mm)	q (mm/hr)
163-187	20	0.263	57.960	-0.005
(24)	40	0.464	124.574	-0.008
	60	0.454	216.651	-0.001
	80	0.429	305.507	0.003
	100	0.414	389.849	0.005
	120	0.397	471.149	0.006
	140	0.385	549.069	0.006
	180	0.400	706.941	0.006
187-212	20	0.260	57.460	0.020
(25)	40	0.463	123.557	0.041
	60	0.453	215.448	0.048
	80	0.428	304.216	0.052
	100	0.413	388.486	0.055
	120	0.397	469.767	0.055
	140	0.385	547.684	0.055
	180	0.400	705.556	0.055
212-240	20	0.260	57.093	0.013
(28)	40	0.461	122.773	0.028
	60	0.453	214.456	0.035
	80	0.427	303.126	0.039
	100	0.413	387.314	0.042
	120	0.397	468.574	0.043
	140	0.385	546.487	0.043
	180	0.400	704.360	0.043
240-286	20	0.258	57.196	-0.002
(46)	40	0.457	122.540	0.005
	60	0.452	213.880	0.013
	80	0.426	302.389	0.016
	100	0.413	386.443	0.019
	120	0.397	467.669	0.020
	140	0.385	545.576	0.020
	180	0.400	703.449	0.020

Appendix 1.3: Calculation of hydraulic gradients
where: ψm = matric potential
I = hydraulic gradient = $(\partial\psi m/\partial z)-1$
Mean I = $(I_{t-1}+I_t)/2$

Time (Δtime) (hrs)	Depth (cm)	ψm (mm H20)	I	Mean I
0-1	20	-56.155	0.000	0.000
(1)	40	106.135	-0.141	-0.220
	60	287.280	-0.236	-0.275
	80	411.860	-0.409	-0.471
	100	523.870	-0.251	-0.275
	120	711.300	-0.676	-0.629
	140	653.615	-0.587	-0.581
	180	959.340	0.000	0.000
1-3	20	-112.720	0.000	0.000
(2)	40	43.285	-0.126	-0.134
	60	237.000	-0.196	-0.216
	80	364.723	-0.346	-0.377
	100	498.730	-0.204	-0.228
	120	683.018	-0.519	-0.597
	140	691.325	-0.482	-0.534
	180	993.908	0.000	0.000
3-6	20	-166.143	0.000	0.000
(3)	40	-32.135	-0.165	-0.145
	60	167.865	-0.181	-0.189
	80	295.588	-0.314	-0.330
	100	442.165	-0.196	-0.200
	120	617.025	-0.456	-0.487
	140	659.900	-0.409	-0.445
	180	971.910	0.000	0.000
6-10	20	-206.995	0.000	0.000
(4)	40	-91.843	-0.220	-0.192
	60	105.015	-0.141	-0.161
	80	251.593	-0.267	-0.291
	100	398.170	-0.220	-0.208
	120	563.603	-0.440	-0.448
	140	622.190	-0.340	-0.374
	180	959.340	0.000	0.000

Time (Δtime) (hrs)	Depth (cm)	ψm (mm H20)	I	Mean I
10-20	20	-298.128	0.000	0.000
(10)	40	-186.118	-0.306	-0.263
	60	-20.685	-0.134	-0.137
	80	160.460	-0.212	-0.240
	100	294.468	-0.251	-0.236
	120	459.900	-0.432	-0.436
	140	521.630	-0.325	-0.333
	180	865.065	0.000	0.000
20-28	20	-345.265	0.000	0.000
(8)	40	-233.255	-0.346	-0.326
	60	-83.535	-0.126	-0.130
	80	116.465	-0.165	-0.189
	100	250.473	-0.275	-0.263
	120	406.478	-0.409	-0.420
	140	487.063	-0.299	-0.312
	180	827.355	0.000	0.000
28-49	20	-439.540	0.000	0.000
(21)	40	-343.243	-0.409	-0.377
	60	-202.950	-0.196	-0.161
	80	-21.805	-0.149	-0.157
	100	137.343	-0.291	-0.283
	120	261.923	-0.424	-0.416
	140	367.648	-0.147	-0.223
	180	773.933	0.000	0.000
49-74	20	-527.530	0.000	0.000
(25)	40	-450.088	-0.479	-0.444
	60	-319.223	-0.267	-0.232
	80	-156.933	-0.251	-0.200
	100	-19.783	-0.361	-0.326
	120	98.512	-0.385	-0.405
	140	226.235	-0.251	-0.199
	180	547.673	0.000	0.000

Appendix 1.3: Calculation of hydraulic gradients
where: ψm = matric potential
I = hydraulic gradient = $(\partial\psi m/\partial z)-1$
Mean $I = (I_{t-1} + I_t)/2$

Time (Δtime) (hrs)	Depth (cm)	ψm (mm H20)	I	Mean I
74-91	20	-562.098	0.000	0.000
(17)	40	-494.083	-0.511	-0.495
	60	-366.360	-0.283	-0.275
	80	-207.213	-0.306	-0.279
	100	-88.918	-0.432	-0.397
	120	19.950	-0.432	-0.409
	140	138.245	-0.272	-0.262
	180	456.540	0.000	0.000
91-116	20	-618.663	0.000	0.000
(25)	40	-547.505	-0.519	-0.515
	60	-426.068	-0.314	-0.299
	80	-273.205	-0.314	-0.310
	100	-151.768	-0.511	-0.471
	120	-77.468	-0.479	-0.456
	140	56.540	-0.262	-0.267
	180	365.408	0.000	0.000
116-139	20	-684.655	0.000	0.000
(23)	40	-585.215	-0.440	-0.479
	60	-460.635	-0.393	-0.354
	80	-342.340	-0.314	-0.314
	100	-186.335	-0.511	-0.511
	120	-146.603	-0.550	-0.515
	140	-6.310	-0.257	-0.259
	180	299.415	0.000	0.000
139-163	20	-741.220	0.000	0.000
(24)	40	-619.783	-0.409	-0.424
	60	-504.630	-0.401	-0.397
	80	-380.050	-0.306	-0.310
	100	-227.188	-0.526	-0.519
	120	-190.598	-0.566	-0.558
	140	-53.448	-0.299	-0.278
	180	230.280	0.000	0.000

Time (Δtime) (hrs)	Depth (cm)	ψm (mm H20)	I	Mean I
163-187	20	-766.360	0.000	0.000
(24)	40	-654.350	-0.440	-0.424
	60	-542.340	-0.338	-0.369
	80	-389.478	-0.283	-0.295
	100	-255.470	-0.605	-0.566
	120	-231.450	-0.691	-0.629
	140	-132.010	-0.351	-0.325
	180	158.003	0.000	0.000
187-212	20	-800.928	0.000	0.000
(25)	40	-688.918	-0.416	-0.428
	60	-567.480	-0.330	-0.334
	80	-420.903	-0.299	-0.291
	100	-286.895	-0.621	-0.613
	120	-269.160	-0.754	-0.723
	140	-188.575	-0.351	-0.351
	180	120.293	0.000	0.000
212-240	20	-804.070	0.000	0.000
(28)	40	-726.628	-0.503	-0.460
	60	-605.190	-0.314	-0.322
	80	-452.328	-0.299	-0.299
	100	-324.605	-0.589	-0.605
	120	-288.015	-0.723	-0.738
	140	-213.715	-0.372	-0.361
	180	88.867	0.000	0.000
240-286	20	-804.070	0.000	0.000
(46)	40	-770.623	-0.629	-0.566
	60	-655.470	-0.283	-0.299
	80	-483.753	-0.314	-0.306
	100	-381.170	-0.707	-0.648
	120	-366.578	-0.519	-0.621
	140	-188.575	-0.372	-0.372
	180	10.305	0.000	0.000

Appendix 1.4: Calculation of hydraulic conductivity function
where: q = soil water flux
I = hydraulic gradient
K = hydraulic conductivity, $K = -q/((\partial\psi/\partial z)-1)$
θv = volumetric water content
ψm = matric potential

Depth (cm)	Time (hrs)	q (mm/hr)	Mean I	K (mm/hr)	Meanθv	Mean ψm
40	0-1	4.540	-0.220	20.637	0.478	121.848
	1-3	0.762	-0.134	5.707	0.478	74.710
	3-6	1.237	-0.145	8.512	0.478	5.575
	6-10	0.203	-0.192	1.053	0.478	-61.989
	10-20	0.455	-0.263	1.727	0.477	-138.980
	20-28	0.139	-0.326	0.428	0.477	-209.686
	28-49	0.169	-0.377	0.448	0.476	-288.249
	49-74	0.032	-0.444	0.072	0.474	-396.665
	74-91	0.096	-0.495	0.193	0.472	-472.085
	91-116	-0.005	-0.515	-0.009	0.471	-520.794
	116-139	0.102	-0.479	0.213	0.469	-566.360
	139-163	0.009	-0.424	0.021	0.467	-602.499
	163-187	-0.008	-0.424	-0.020	0.465	-637.066
	187-212	0.041	-0.428	0.095	0.464	-671.634
	212-240	0.028	-0.460	0.061	0.462	-707.773
	240-286	0.005	-0.566	0.009	0.459	-748.625
60	0-1	4.547	-0.275	16.537	0.457	280.995
	1-3	0.770	-0.216	3.562	0.457	262.140
	3-6	1.245	-0.189	6.601	0.457	202.433
	6-10	0.210	-0.161	1.305	0.457	136.440
	10-20	0.462	-0.137	3.361	0.456	42.165
	20-28	0.147	-0.130	1.133	0.456	-52.110
	28-49	0.176	-0.161	1.096	0.456	-143.243
	49-74	0.039	-0.232	0.170	0.456	-261.086
	74-91	0.103	-0.275	0.375	0.455	-342.791
	91-116	0.003	-0.299	0.009	0.455	-396.214
	116-139	0.109	-0.354	0.309	0.455	-443.351
	139-163	0.016	-0.397	0.041	0.454	-482.633
	163-187	-0.001	-0.369	-0.003	0.454	-523.485
	187-212	0.048	-0.334	0.144	0.454	-554.910
	212-240	0.035	-0.322	0.110	0.453	-586.335
	240-286	0.013	-0.299	0.042	0.453	-630.330

Appendix 1.4: Calculation of hydraulic conductivity function

Depth (cm)	Time (hrs)	q (mm/hr)	Mean I	K (mm/hr)	Meanθv	Mean ψm
80	0-1	4.551	-0.471	9.654	0.433	411.860
	1-3	0.773	-0.377	2.050	0.433	388.291
	3-6	1.248	-0.330	3.782	0.433	330.155
	6-10	0.214	-0.291	0.735	0.433	273.590
	10-20	0.466	-0.240	1.943	0.433	206.026
	20-28	0.150	-0.189	0.797	0.432	138.463
	28-49	0.180	-0.157	1.146	0.432	47.330
	49-74	0.043	-0.200	0.214	0.432	-89.369
	74-91	0.106	-0.279	0.382	0.431	-182.073
	91-116	0.006	-0.310	0.020	0.431	-240.209
	116-139	0.113	-0.314	0.359	0.430	-307.773
	139-163	0.020	-0.310	0.064	0.430	-361.195
	163-187	0.003	-0.295	0.008	0.429	-384.764
	187-212	0.052	-0.291	0.178	0.428	-405.190
	212-240	0.039	-0.299	0.130	0.428	-436.615
	240-286	0.016	-0.306	0.052	0.427	-468.040
100	0-1	4.553	-0.275	16.560	0.416	492.445
	1-3	0.776	-0.228	3.406	0.416	511.300
	3-6	1.251	-0.200	6.244	0.416	470.448
	6-10	0.217	-0.208	1.040	0.416	420.168
	10-20	0.468	-0.236	1.988	0.415	346.319
	20-28	0.153	-0.263	0.582	0.415	272.470
	28-49	0.183	-0.283	0.647	0.415	193.908
	49-74	0.046	-0.326	0.140	0.415	58.780
	74-91	0.109	-0.397	0.276	0.415	-54.350
	91-116	0.009	-0.471	0.019	0.414	-120.343
	116-139	0.116	-0.511	0.227	0.414	-169.051
	139-163	0.023	-0.519	0.044	0.414	-206.761
	163-187	0.005	-0.566	0.010	0.414	-241.329
	187-212	0.055	-0.613	0.089	0.413	-271.183
	212-240	0.042	-0.605	0.069	0.413	-305.750
	240-286	0.019	-0.648	0.029	0.413	-352.888
120	0-1	4.554	-0.629	7.246	0.398	701.873
	1-3	0.777	-0.597	1.301	0.398	697.159
	3-6	1.252	-0.487	2.570	0.398	650.021
	6-10	0.217	-0.448	0.485	0.398	590.314
	10-20	0.469	-0.436	1.076	0.398	511.751
	20-28	0.154	-0.420	0.366	0.398	433.189
	28-49	0.184	-0.416	0.441	0.398	334.200
	49-74	0.047	-0.405	0.115	0.398	180.218
	74-91	0.110	-0.409	0.270	0.398	59.231
	91-116	0.010	-0.456	0.022	0.398	-28.759
	116-139	0.116	-0.515	0.226	0.398	-112.035
	139-163	0.023	-0.558	0.042	0.398	-168.600
	163-187	0.006	-0.629	0.010	0.398	-211.024
	187-212	0.055	-0.723	0.076	0.397	-250.305
	212-240	0.043	-0.738	0.058	0.397	-278.588
	240-286	0.020	-0.621	0.032	0.397	-327.296