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Soil water, ground water, and wetland seepage within an effluent-irrigated hillslope

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Abstract

Treated municipal wastewater from Rotorua, New Zealand, has been spray irrigated onto the soils of nearby Whakarewarewa forest at rates averaging 70 mm/week since 1991. Herein we describe soil water, ground water and wetland seepage responses to irrigation within a hillslope at this land treatment system, which was instrumented with small weirs to monitor seepage flows, and a grid of piezometers to monitor ground water response. Time domain reflectometry and tensiometers were used to monitor soil-water dynamics of an irrigated profile. Ground water levels and seepage discharge increased after onset of irrigation and peaked after about 30 hours. Seepage discharge was commonly more than 1 L/s, and, after winter irrigations, peaked at about 3 L/s. Peak seepage discharge could be predicted from antecedent profile water storage and irrigation loading, suggesting that irrigation could be managed to control seepage flows. Ground water responses were affected by layering of the volcanic soils and proximity to sprinklers. A gravel lapilli deposit appeared to be a preferential pathway for unsaturated movement of water downslope. Soil water dynamics were dominated by gravity drainage, and soils were usually at water potentials greater than field capacity. Upward movement of soil water from 0.52 m depth in response to evaporative demand was found only during summer and at least 3-4 days after irrigation. While the volcanic soils at this site can accept heavy irrigation loadings, the additional water influences soil water dynamics and hillslope seepage in ways that may be important to performance of the system.

Introduction

In New Zealand, irrigating land with treated sewage effluent onto land has become a popular alternative to discharge the effluent to surface waters.

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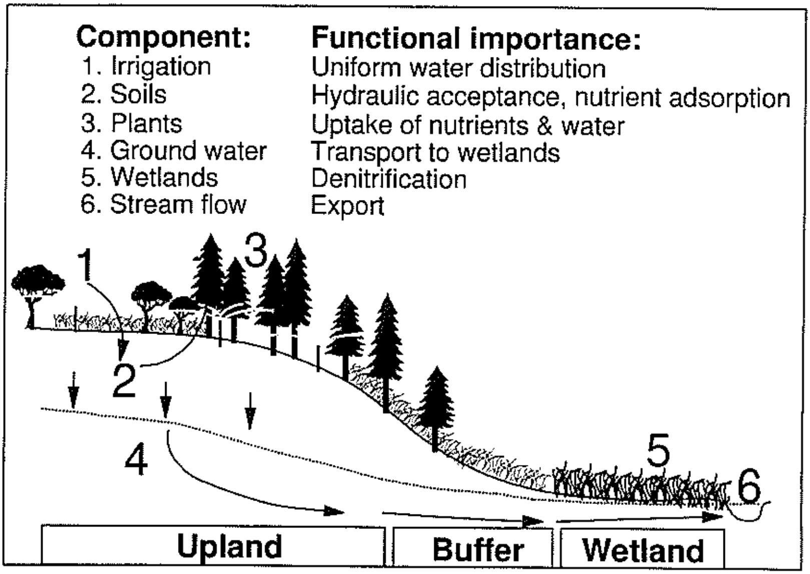
A recent survey of New Zealand's regional councils, which oversee consents for operating and monitoring effluent irrigation systems, shows that 37 communities irrigate land with their treated municipal wastewater (NZ Land Treatment Collective, unpublished data). This method conforms with Maori cultural preferences, and should help maintain the quality of New Zealand's surface waters, particularly those most vulnerable to pollution by nutrients in wastewater.

Most communities that use irrigation to treat and dispose of their municipal effluent are small. However, Rotorua, a city of 60,000 inhabitants in the central North Island, has been using a land treatment system since October 1991. The Rotorua Land Treatment System is located in Whakarewarewa Forest, and includes 193 ha of irrigated land, plus wetlands (47 ha), reserve irrigation blocks (28 ha), areas designated for future expansion (51 ha), and buffer zones. The irrigated area consists of 14 "blocks", each with an area of about 14 ha, with two blocks irrigated each day in a weekly rotation. During the first 6 years of operation, applications have averaged 70 mm of wastewater per week. The scheme is designed to take advantage of a range of natural processes that remove nutrients in different parts of the ecosystem (Fig.1). Wastewater is first treated by a biological nutrient removal system at the treatment plant, and then sprayed onto forested upland soils. Af-



Component:	Functional importance:
1. Irrigation	Uniform water distribution
2. Soils	Hydraulic acceptance, nutrient adsorption
3. Plants	Uptake of nutrients & water
4. Ground water	Transport to wetlands
5. Wetlands	Denitrification
6. Stream flow	Export

Figure 1 – Conceptual diagram of an effluent land treatment system that employs uplands and wetlands, with a listing of its major components, and key processes occurring in each.

ter being subjected to natural treatment processes in the soil, wastewater percolates to the ground water and moves to wetland areas, where denitrification can occur (Schipper *et al.*, 1994). These wetlands drain to the Waipa Stream, which flows to Lake Rotorua.

The goal of Rotorua's treatment system is to protect the water quality of Lake Rotorua, by limiting nutrient inputs from the effluent to the lake to less than 2.5 tonnes of phosphorus and 24.5 tonnes of nitrogen per year. According to system design, this means about 15% of the P and 33% of the N applied to the forest would eventually pass through the land treatment system and into the lake. In previous papers, we have described the various components of Rotorua's land treatment system (Tomer *et al.*, 1997b), and the performance of the scheme in terms of nutrient losses (Tomer *et al.*, 1997a). Although the scheme has performed very well for phosphorus removal, export of nitrogen via the Waipa stream has not always been within the 24.5 tonne guideline. There have also been large seasonal fluctuations in nitrogen export, with peak fluxes occurring in autumn and winter. Several factors could contribute to this seasonal pattern. First, nitrogen accumulates in the soils of the spray areas during summer (Lal, 1998), and is then susceptible to leaching during autumn and winter. Second, during winter, colder temperatures will slow biological activity, and probably cause reduced nitrogen uptake by plants and lower rates of wetland denitrification. Finally, less evaporation and greater hydrologic fluxes during cooler seasons may result in less retention of nitrogen in the system. Water movement through the upland and wetlands of the land treatment system will affect processes in each of these areas.

Our objective was to investigate the hydrology of an effluent-irrigated hillslope within Rotorua's land treatment scheme. When the scheme was being designed, there were preliminary investigations to determine the capacity of the volcanic soils of the irrigation site to accept large hydraulic loadings of irrigation water (Tomer *et al.*, 1997b). Results of these studies emphasised the high permeability and excellent drainage characteristics of these soils (Cook *et al.*, 1994, Tomer *et al.*, 1997b). Designers expected that these characteristics would largely eliminate any overland flow of irrigation water, and indeed, observations suggest that overland flow at the site only occurs from small disturbed areas during wet weather. Because of the soil's known capacity to accept large weekly loadings of irrigation water, there has been little investigation of the hydrologic impacts of irrigation at this site. As a consequence, little is known of the moisture regime of these soils under a weekly irrigation regime. The volcanic soils of the treatment area are very well drained, but they also have high water holding capacities (Cook *et al.*, 1994). We know that the upland soils, when irrigated, are well-enough aerated that soil denitrification rates are low (Barton, 1998). But there is little specific data on soil water dynamics within the areas being irrigated. Better information on soil water conditions under irrigation would be helpful for selecting and managing crops in land treatment systems. At the Rotorua site, increased mortality has been observed in *Pinus radiata* trees irrigated from age 1 year (Thorn *et al.*, 1997), mostly due to wind toppling. This problem may have been caused by limited rooting of the well-watered trees, and reduced strength of wetted soils.

The effects of effluent irrigation on hillslope hydrology are also not well known. Rapid movement of water through these soils could encourage preferential flow within irrigated hillslopes. Although there is a 20 m buffer between irrigated areas and downslope wetlands (Fig. 1), the wetlands tend to be narrow (<10 m wide), and the slopes above them are sometimes steep (> 23°). Layering of the volcanic deposits could allow preferential flow within these slopes. This is evidenced by the seepage zones found at wetland margins, predominantly below steeper slopes. These seepage zones provide a pathway into the wetlands that may reduce contact of effluent-derived water with the organic soils of the wetland, where the potential for denitrification is greatest (Hill, 1990). The timing of water flow through these seepage zones in response to irrigation is not known. We have noted, however, that seepage increased within one day after irrigation, and that there is significant seasonal fluctuation in seepage fluxes of both water and nitrogen (Tomer et al., 1996).

The specific aims of this study were to: (1) measure the extent and timing of responses in ground water levels to irrigation, (2) determine the soil water regime of a wastewater-irrigated soil profile at Rotorua's land treatment system, (3) measure the timing of seepage fluxes after irrigation, and (4) determine how irrigation loading and antecedent soil-water conditions affect seepage after irrigation.

Methods

Site characteristics

The research site is located about 4.5 km southeast of Rotorua. Average annual precipitation at Rotorua is 1491 mm; average monthly precipitation ranges from 94 mm in January to 161 mm in August. Mean annual temperature is 12.7° C, with monthly averages ranging from 17.8° C in February to 7.5° C in July. Pan evaporation varies from 186 mm in January to 28 mm in June (NZ Meteorological Service, 1983). The soil at the site is mapped as a Whakarewarewa sandy loam (Rijkse, 1979), which is derived from volcanic ash showers deposited during the past 20,000 years. It is classified as a Vitric Orthic Allophanic Soil under the New Zealand system (Hewitt, 1993), and as a Typic Udivitrands under the U.S. system (US Dept. of Agriculture, 1992).

Site instrumentation

The study site was established in 1993, after a reconnaissance survey of the treatment site's wetlands was conducted to locate areas with significant seepage. The site, located in irrigation block 4 (Tomer *et al.*, 1997b) contained four distinct seepage zones along the south side of an 8-10 m wide wetland (Knowles, 1995). These seepage zones were within about 10 m of one another. A grid of piezometers was installed across the hillslope above the seepage area and the adjacent wetland by hand auguring. Upland piezometers were placed along six transects, with piezometers installed 1, 5 10, 15, and 25 m from the wetland along each transect (Fig. 2). Transects are identified as T1 to T6, as indicated in Figure 2. Additional piezometers were installed 40 and 55 m upslope from the wetland along T1, and one and five m into the wetland along T1, T4, and T6 (Fig. 2). The transects were established 5 m apart and the entire site covered about 0.1 ha. The piezometers were installed in late summer, when water levels were at their

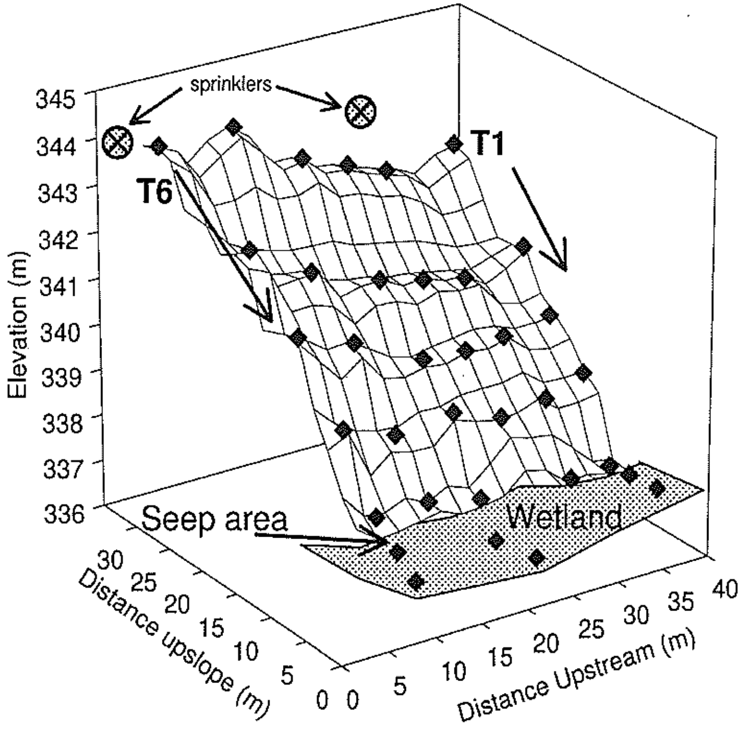


Figure 2 – Three-dimensional diagram showing relative locations of piezometers (diamonds) on the hillslope (within 25 m of the wetland), and in the wetland (shaded grey).

seasonal low, and were screened for 0.5 m below the depth where obvious saturation occurred. Gravel was used to screen the piezometers, and above the screening the annular space was filled with a bentonite plug and then compacted soil. Materials encountered during auguring were described and recorded, and the elevations and relative map positions of the piezometers were measured. Cross sections of the volcanic deposits within the hillslope were constructed from this information. Also, slug tests were conducted to determine the hydraulic conductivity of the saturated zone using the method of Bouwer and Rice (1976). Similar procedures were followed to install a transect of piezometers in a nearby, non-irrigated area. This transect was monitored to determine changes in ground water levels in the absence of irrigation.

Four small V-notch weirs were installed in the seepage zone to monitor flows. Measurements of discharge stage heights (h) of the weirs were converted to flow using the equation:

$$Q = (C_d\, 8/15)*(2g)^{0.5} *\tan(\phi/2)*h^{5/2} \qquad (1)$$

in which Q is water flow (m^3/s), g is acceleration of gravity, ϕ is the notch angle, and C_d is a coefficient that varies slightly with f (White, 1978). One weir had a ϕ of 45° and C_d of 0.580; the other three had a ϕ of 22.5° and C_d of 0.590.

Background

Four investigations have been carried out at this site to assess soil water, ground water, and seepage discharge responses to irrigation. One of these studies has been published (Tomer *et al.*, 1996) and will not be described here; it examined water and nitrate fluxes in seepage after irrigation, during 10-day monitoring periods within each season between winter 1993 and autumn 1994. The other three studies, described in detail below, examined changes in ground water levels, soil water storage, and soil water dynamics and seepage after irrigation, but were conducted on varying scales of time and space. In these studies, irrigation loading (mm/week) was determined from pumping records kept by the Rotorua District Council. In conjunction with this research, tracer studies were conducted in both soils and ground water using dyes and bromides. These efforts failed to show the timing of water movement through the volcanic soils, due to the soils' strong adsorption capacities (Knowles, 1995; unpublished data).

Ground water levels

This study aimed to determine spatial and temporal patterns of the responses in ground water levels to irrigation across the grid of piezometers.

Twenty-eight measurements were made of water levels in piezometers and seep weirs between 10 and 17 May, 1995 (Knowles, 1995). The readings were taken after an irrigation of 44 mm on 10 May. This application was less than average, but was typical in that it consisted of several applications made during the day, at a rate of 5 mm/hr. Irrigation usually began at 23:00 hours the prior day, and continued until the two storage ponds were emptied to a set level, but ceased during peak hours of electricity demand in Rotorua city (Tomer *et al.*, 1997b). There were 19 sets of water-level measurements made during 10-12 May, with the first of the readings at 19:50 hours on 10 May. An additional nine sets of measurements were then taken between 13 and 17 May. The water level data were used to map the extent and timing of changes in water table elevations that occurred after irrigation, and the timing of these changes was compared to the hydrograph of seepage flux at the base of the slope.

Soil water storage

This study aimed to determine increases in soil water storage from one day before to one day after irrigation, and compare these increases to changes in water table elevations and seepage discharge volumes. A neutron probe was used to measure soil water contents. Pre- and post-irrigation measurements were made during 17 weeks between May 1996 and April 1998. The neutron probe measurements were made in six access tubes installed at the top of the hillslope, at 0.15 m depth intervals between 0.15 and 0.90 m depth. Seepage flux measurements were also made, along with water level measurements in 17 piezometers (those in T1, T4, and T6, see Fig.1, plus additional piezometers placed 40 and 55 m from the wetland along Transect 1). Rainfall was measured between the two monitoring times with a standard rain gauge located in the non-irrigated buffer zone between the wetlands and irrigated uplands.

For the analyses, water contents determined from neutron probe measurements were summed to give total water storage in the soil profile. The neutron probe was field calibrated to estimate volume water content (θ) from the neutron count ratio (R). Volume water contents were summed to give total water storage in a 1-m profile (herein this is referred to as profile water storage). Average changes in soil water storage and ground water level were calculated, as well as changes in the rate of seepage discharge.

Data summaries were prepared to show pre- and post-irrigation profile water storage, and increases in ground water levels and seepage discharge resulting from irrigation. Regression analyses were carried out to determine if increases in ground water levels and seepage fluxes could be predicted from antecedent soil moisture, and irrigation plus rainfall data.

Soil water dynamics and seepage

This study provided more detailed temporal information on soil water and seepage dynamics on this hillslope. To monitor soil-water dynamics, a soil profile was instrumented for automated hourly measurement of soil-water potential using tensiometers, and soil-water content using time-domain reflectometry (TDR). Tensiometers were installed at 0.075, 0.225, and 0.525 m depths, and monitored using pressure transducers. The TDR probes were installed at 0.075, 0.225, 0.375, 0.525, 0.675, 0.825, and 0.975 m depths, which are the mid-depths of every 0.15 m depth interval from the surface to 1.05 m depth. Campbell Scientific model CS615 TDR probes were used; the dielectric constant was determined from the response time recorded by the probe, using an algorithm recommended by the manufacturer (unpublished brief), and water contents were then determined from the dielectric constant (Tomer *et al.*, 1999).

A piezometer 1 m upslope from the largest seepage zone (along Transect 6) was instrumented with a pressure transducer for hourly measurement of water levels. A linear relationship between seepage discharge and the piezometer water level was determined by least squares regression. This relationship was used to determine seepage discharge from the pressure transducer data. Overall, the data allowed us to determine, to within an hour, the changes in soil water, soil water potential, and seepage flux that occurred after irrigation. Monitoring was conducted between 12 August 1997 and 5 May, 1998.

Preliminary data plots were prepared, and from these plots 3-week periods in winter (12 August to 3 September) and summer (24 December to 13 January) were selected to determine the contrast between seasons. For these periods, profile water storage was calculated by multiplying the TDR-measured water contents by a 0.15 m depth increment and then summing for a 1.05 m profile. The data were then examined to compare the relative timing of soil-water and seepage responses to irrigation.

Tensiometric data, expressed as cm water tension, were evaluated to determine the soil water potentials occurring throughout the weekly cycle of irrigation, and the direction of water movement in the upper (0.075 to 0.225 m) and middle (0.225 to 0.525 m) parts of the soil profile. For example, if the water tension at 0.075 m depth is more than 15 cm greater than at 0.225 m depth, water is moving upwards from 0.225 m depth, given the gravitational gradient. Histograms of soil water tension were also prepared for each season and depth. We were particularly interested in determining how often the soil water tension exceeded 100 cm, or the "field capacity" of this soil.

Cumulative fluxes of soil water drainage were estimated using the SWIM model (Ross, 1990a,b). Soil hydraulic parameters for this model were determined at a level site about 100 m from the hillslope (Tomer, 1999). For the winter and summer periods, cumulative seepage discharge was divided by the cumulative drainage flux of soil water to estimate the size of the recharge area for the seepage zone.

The monitoring data were summarised to show pre-irrigation seepage flux and profile water storage, irrigation applied, rainfall (obtained from a climate station approximately 1 km distant), peak seepage flux and soil water storage, and the time between onset of irrigation and peak seepage flux. Regression analyses were used to determine if peak seepage flux could be predicted from antecedent water storage and irrigation loading. Such information could become useful in scheduling of irrigation at Rotorua's land treatment site.

Results and discussion

Layering and hydraulic conductivities of volcanic deposits

A cross-section of materials encountered while auguring T1 piezometers shows that the volcanic deposits essentially lie parallel with the land surface (Fig. 3). The Rotorua lapilli gravel is a prominent layer, and lies 2-3 m

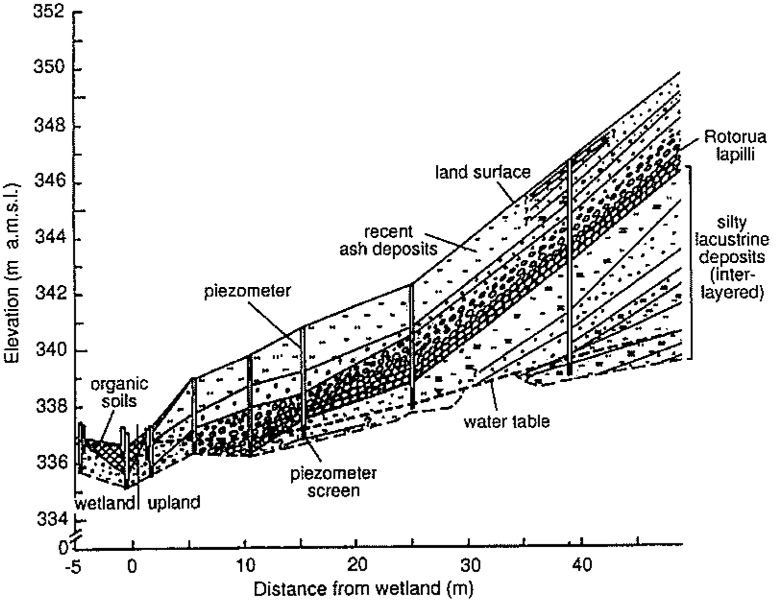


Figure 3 – Cross-sectional diagram along Transect 1, showing the layering of volcanic deposits within the hillslope. The Rotorua lapilli is found at 2-3 m depth, and the water table lies within this layer within 5-10 m of the wetland.

below the surface. Within 5 to 10 m of the wetland, the water table is within this lapilli; further upslope, it is within fine-sand-and-silt lacustrine deposits that underlie the lapilli. Hydraulic conductivities, calculated from slug-test data using the method of Bouwer and Rice (1976), varied with the material in which the piezometer screen was set. Piezometers penetrating to lacustrine materials showed conductivities between 0.05 and 0.93 m/day (n=4), whereas those set in sands showed conductivities between 0.24 and 5.8 m/day (n=4). Of nine piezometers set in the coarse lapilli, seven had conductivities too fast to measure, and the other two showed conductivities of 15.2 and 21.0 m/day (Knowles, 1995).

Ground water levels

At the end of irrigation on 10 May 1995, the variation in water levels across the grid of piezometers was about 2.5 m. An interpolated contour map of these water levels (Fig. 4a) shows a low hydraulic gradient within 5-10 m of the wetland margin, where the water table was in the coarse lapilli. The gradient was steeper (~0.1 m/m) further upslope, where the phreatic surface was within finer materials beneath the lapilli. The piezometer 10 m from the wetland on T4 showed an unusually low water surface. This piezometer was screened deeper below the phreatic surface than other piezometers, and the low water level in this piezometer therefore suggests a downward vertical gradient. This is not surprising, because the finer lacustrine sediments at that depth would probably be finely layered, as observed along road cuts in this forest.

Response of ground water levels to the 10 May irrigation was variable in extent and timing (Fig. 4b,c). Water levels increased following irrigation, peaking to as much as 0.11 m higher than those observed at the close of irrigation. The only piezometer showing no response was set near the centre of the wetland. The greatest responses occurred at the top of T2 and T6, where piezometers were close to sprinklers (Fig. 2) and at the lower end of T1 through T4 (Fig. 4.b). The lowest responses (<0.03 m) were in the wetland and along the upper 15 m of T3 and T4. During this period, there were only two small rainfall events (<10 mm), and piezometers along the non-irrigated transect showed that ground water levels were dropping throughout the period.

The peak water levels, on average, occurred 30 hours after irrigation ceased, or about 50 hours after irrigation began. The response times ranged from 12 to 69 hours after irrigation ceased. The fastest response was along the upper part of T2, T3, and T4 (Fig. 4c), probably due to the proximity of a sprinkler (as shown in Fig. 2). The responses in this area were not very large, except for the upper piezometer along T2, which was closest to the sprinkler. The slowest responses were along the upper parts of T5 and T6, where the elevation is slightly higher, the slope steeper, and the phreatic surface somewhat deeper.

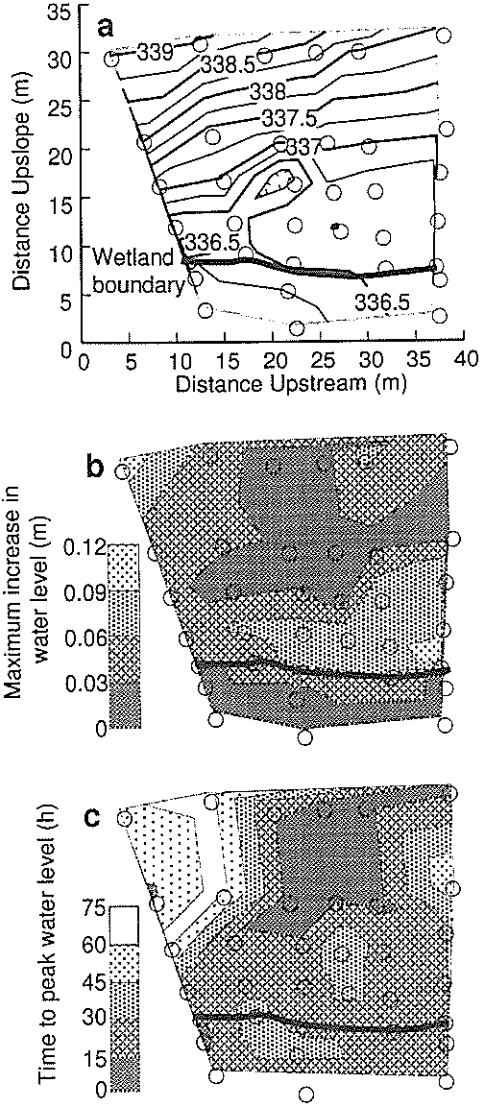


Figure 4 – Interpolated data maps from a series of piezometer water level measurements taken between 10 and 18 May 1995. The maps indicate: a) topography of piezometric surface at the time irrigation ceased (contours in m asl); b) the maximum observed increase in the height of piezometer water levels (m); and c) the number of hours transpired from cessation of irrigation until of water levels peaked. Locations of piezometers are indicated as circles, as is the location of the wetland boundary.

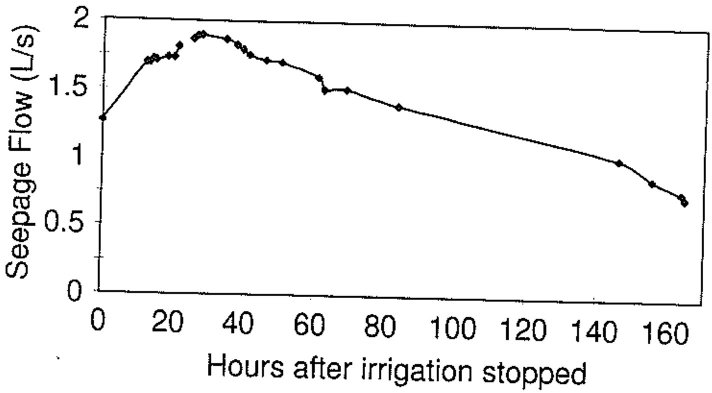


Figure 5 – Response of seepage discharge after irrigation on 10 May, 1995.

Seepage discharge showed a similar response to ground water levels in general, peaking 27.6 hours after irrigation ceased (Fig. 5). This discharge was well correlated (r>0.95) with water levels observed in upland piezometers within 5 m of the wetland, but was less correlated with water levels in the wetland (0.01<r< 0.92) and in piezometers more than 10 m upslope of the wetland (-0.70<r<0.75). This indicates that the gravel lapilli unit was the source of the seepage water. Most of the seepage flux occurred at the base of T6, where the slope is the steepest. This suggests that any preferential flow along the layered deposits was greater within the steeper slopes. The water level response in the piezometer 1 m from the wetland was more rapid than in the piezometer at the top of this transect, even though the top piezometer was close to a sprinkler.

Soil water storage

Soil water, ground water level, and seepage flux data were collected during 17 weeks between May 1996 and May 1998, with measurements made one day before and one day after irrigation each week. Across these weeks, irrigation loading averaged 77 mm, and varied between 37 and 144 mm. Rainfall received during the period between the two measurements across these weeks averaged 14 mm, but varied from 0 to 67 mm. Combined data for irrigation and rainfall are shown in Table 1. These loadings caused seepage flux to increase by 0.74 L/s, on average, and ground water levels to increase by an average of 0.11 m.

To explore the relationships between these data, a correlation matrix was prepared (Table 2). Correlations show fairly strong relationships between the total amount of irrigation plus rainfall received, and seepage flux after irrigation, increases in seepage flux, and increases in average ground water level.

Table 1 – Irrigation and rainfall during 17 weeks of monitoring between May 1996 and May 1998. Average profile water storage (measured by a neutron probe) and total seepage flux one day before and one day after irrigation are also given, plus the average increase in ground water level from before to after irrigation.

Date of Irrigation	Irrigation + Rain (mm)	Profile Water Storage Before (mm)	Profile Water Storage After (mm)	Seepage Flux Before (L/s)	Seepage Flux After (L/s)	Average Ground Water Increase (m)
29-May-96	59	395	440	1.41	1.51	0.00
05-Jun-96	64	392	430	1.17	1.34	0.00
12-Jun-96	78	401	434	1.06	1.72	0.24
17-Jul-96	181	436	435	1.46	3.86	0.31
14-Aug-96	76	402	425	1.52	2.02	0.05
25-Sep-96	69	388	425	1.86	1.78	0.01
04-Dec-96	72	403	407	0.87	0.92	0.01
11-Dec-96	63	385	415	0.76	1.13	0.03
19-Feb-97	158	373	436	0.80	2.01	0.14
15-Oct-97	37	397	411	1.40	1.73	0.00
12-Nov-97	83	405	452	1.07	2.10	0.10
10-Dec-97	77	397	436	1.07	1.50	0.08
14-Jan-98	79	384	431	0.87	1.78	0.17
04-Feb-98	56	388	429	0.95	1.67	0.13
11-Mar-98	146	404	446	0.99	3.41	0.27
08-Apr-98	134	396	447	1.03	1.60	0.11
06-May-98	110	393	436	0.95	1.77	0.15
Mean	91	396	430	1.13	1.86	0.11

Antecedent profile water storage was most strongly correlated with seepage flux after irrigation, and to a lesser degree with seepage and ground water level increases. Increases in seepage flux and ground water levels were strongly correlated with one another. Predictive equations to determine seepage flux, seepage flux increase, and ground water level increases, based on irrigation plus rainfall and antecedent profile water storage are shown in Table 3. Be-

Table 2 – Correlation coefficients amongst: (1) irrigation and rainfall received; (2) soil profile water storage before irrigation; (3) seepage flux after irrigation; (4) the increase in seepage flux after irrigation; and (5) the average increase in ground water level after irrigation. Data are for 17 weeks of monitoring between May 1996 and May 1998.

	Irrigation + rain	Profile water storage before	Seepage flux after	Increase in seepage flux
Profile water storage before	0.36	1		
Seepage flux after	0.73	0.63	1	
Increase in seepage flux	0.80	0.49	(n.a.)	1
Average increase in ground water level	0.73	0.43	0.77	0.88

n.a. = not applicable (one is calculated from the other)

Table 3 – Summary of regression equations predicting (1) the seepage flux after irrigation, (2) increase in seepage flux from before irrigation, and (3) average increase in ground water level from before irrigation, using irrigation and rainfall loading and antecedent profile water storage as independent variables. Data are for 17 weeks of monitoring between May 1996 and May 1998.

Dependent variable	Coefficients for independent variables: Intercept	Irrigation + rainfall (mm)	Antecedent PWS† (mm)	r^2
Seepage after irrigation (L/s)	-8.2	0.010	0.023	0.68
Increase in seepage flux (L/s)	-0.55	0.014	ns	0.64
Average increase in ground water level (mm)	-0.06	0.002	ns	0.53

† PWS = profile water storage

ns indicates not significant at the 0.05 probability level.

tween 53 and 68% of the variation in these dependent variables was predicted from irrigation/rainfall loadings, and, in the case of seepage flux, antecedent profile water storage. Variations not explained by the regressions could be due to measurement errors, seasonal dependencies, and differences between the timing of measurements and actual responses to irrigation. Although the data may be somewhat coarse in these regards, they indicate that, on average, an additional mm of irrigation or rainfall received would increase post-irrigation seepage flux by 0.01 L/s, increase the response in seepage from its pre-irrigation flux by 0.014 L/s, and increase ground water levels by 0.002 m. In addition, if antecedent profile water storage is increased by 1 mm, the seepage flux observed after irrigation is increased by 0.023 L/s. These results indicate that irrigation loadings could be managed to regulate seepage discharges to the wetland, and that antecedent profile water storage has an important effect on seepage.

Soil water dynamics and seepage

Soil-water contents and tensions were monitored on an hourly basis in a profile located near the top of T6, from 12 August 1997 to 5 May, 1998. Water levels in the piezometer 1 m from the wetland along Transect 6 were also monitored hourly. Irrigation occurred on Wednesday each week. Amounts of irrigation and rainfall received each week varied considerably (Fig. 6), averaging 71 mm and ranging between 4 and 127 mm. Some seasonality in effluent application is evident, i.e., irrigations exceeding 80 mm were rare during summer, but common during other seasons. Weekly rainfall (for 7-day periods beginning from the day of irrigation) averaged 23 mm, and ranged from 0 to 79 mm.

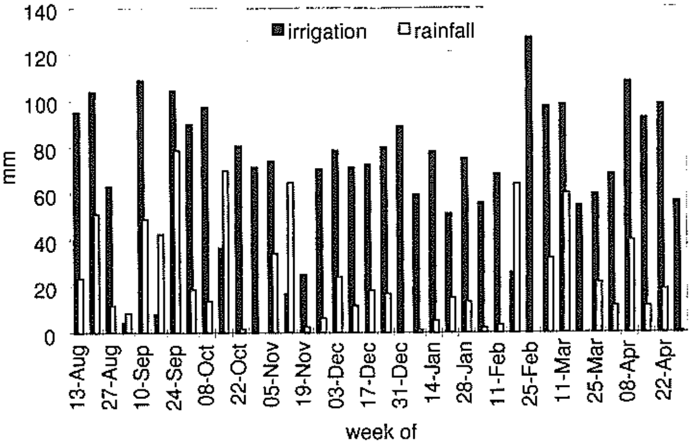


Figure 6 – Weekly irrigation and rainfall amounts at the study site during the weeks of continuous soil water and seepage discharge monitoring.

Rainfall also shows a distinct seasonal pattern with little rainfall during the summer, which was unusually dry and warm for Rotorua.

Estimation of seepage fluxes

We first calculated seepage flux based on the water level in the piezometer 1 m upslope from the seepage zone. Measurements taken during operation of the automated station showed a linear relationship between seepage discharge (calculated from the weir stage) and piezometer water level (Fig. 7a), which indicated that Darcy's law governed flow into the seepage zone. To validate use of data from this piezometer's pressure transducer to estimate seepage flux, the regression equation (shown in Fig. 7a) was used to estimate seepage

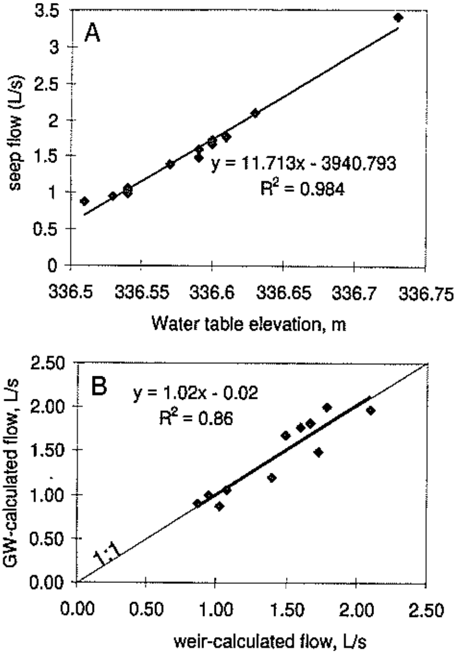


Figure 7 – Data validating use of water level in the piezometer 1 m upslope of seepage zone to estimate seepage discharge. A) Comparison of manual readings of piezometer water level with seepage discharge calculated from manual stage-height readings using Eq. 1. B) Comparison of seepage discharge from the same manual readings, with those calculated by piezometer water levels recorded by a pressure transducer at the same times (within 0.5 hours), using the regression equation shown in A. Conformance with the 1:1 line indicates the piezometer-based estimates of seepage flux are unbiased. The data point for the highest flow indicated in Fig. 7a is missing in Fig. 7b because the pressure transducer was not functioning properly at that time.

for the times of manual readings. The comparison of estimated and measured flows (Fig. 7b) shows a relationship not significantly different ($p < 0.05$) from a 1:1 line; the piezometer's water level was thus judged to be an unbiased and reasonably accurate estimator of seepage discharge.

Seepage and soil water contents

Seepage fluxes and profile water storage for the three-week monitoring periods during winter and summer followed one another closely (Fig. 8), and showed a distinct response to irrigation. Across all 38 weeks of monitoring, maximum seepage discharge occurred, on average, 28 hours after irrigation began (Table 4), which was an average of four hours after profile water storage began to decrease. There were strong seasonal differences in the range of profile water storage and seepage fluxes (Fig. 8), with greater profile water storage and seepage fluxes in winter. The increase in seepage flux after irrigation was greater in winter than in summer, as expected given the differences in loading and antecedent profile water storage.

A regression analysis was run on the weekly data to determine if peak seepage flux (PF) could be predicted from antecedent profile water storage

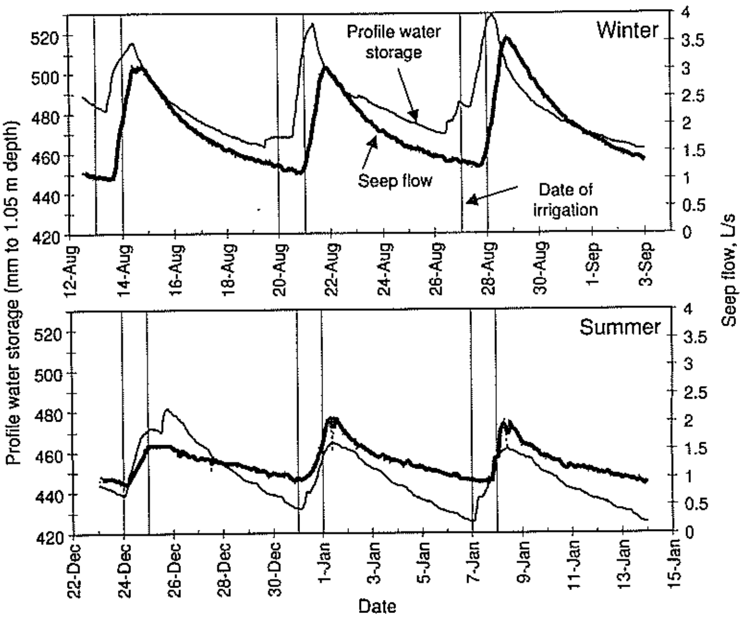


Figure 8 – Responses of total profile water storage and seepage flux to irrigation events in winter and summer. Dates of irrigation are indicated by vertical gridlines.

Table 4 – Descriptive statistics for weekly summaries of hourly data collected between 12 August 1997 and 5 May, 1998: (1) seepage discharge prior to irrigation, (2) maximum discharge after irrigation, (3) time elapsed between onset of irrigation and maximum seepage discharge, (4) profile water storage before irrigation and (5) maximum profile water storage observed during each week.

	Seepage discharge before (L/s)	Peak discharge after (L/s)	Time to peak (h)	PWS† before irrigation (mm)	Max. weekly PWS (mm)
Mean	1.0	2.4	28.1	447	486
Standard Deviation	0.2	0.7	8.1	19	21
Median	1.0	2.2	30	443	479
Minimum	0.63	1.34	13	421	457
Maximum	1.37	3.61	46	488	529

† PWS = profile water storage

(APWS) and irrigation plus rainfall received the day of irrigation (IR). The regression result was:

$$PF = -9.83 + 0.026\,(APWS) + 0.007\,(IR), \tag{2}$$

which had an r^2 of 0.60. The coefficients are similar in magnitude to those in Table 3; given that both APWS and IR are in units of mm, the larger coefficient for the antecedent water storage indicates its importance in determining the peak seepage flows.

Cumulative seepage fluxes during the three-week periods in winter (3510 m^3) and summer (2100 m^3) were divided by cumulative soil water drainage obtained by modelling (0.36 m during winter, 0.14 m during summer), thereby estimating the size of the recharge area to be 1.0 ha in winter, and 1.5 ha in summer. The difference between seasons could be due to: (1) seasonal differences in ground water storage, (2) differences in flow patterns between seasons (one-dimensional flow of the model, versus preferential or interflow), and (3) other errors, including difficulty in determining interception losses caused by a heavy understory vegetation during summer. Nevertheless, a significant portion of the 14 ha irrigation block appears to contribute to the seepage flows.

Flow along the Rotorua lapilli deposit is suspected of contributing most of the preferential flow within this hillslope. Data from several level sites in Whakarewarewa Forest have shown these sandy soils drain uniformly, and suggested that the lapilli layer is most likely to cause soil water accumulation (Tomer, 1999). However the possibility of interflow along shallower deposits should be acknowledged. Although low-permeability 'pan' layers have not been observed in these soils, there may be layers that in some areas have more clay, and are less permeable. During auguring of piezometers, some finer layers were encountered on occasion, as shown in Figure 3. This hillslope profile did show a distinctly layered soil-water profile during irrigation cycles in winter and summer (Fig. 9), with soil water accumulation observed at two different depths. The 3Bw horizon (Fig.9) was somewhat finer-textured and denser than others, and significant soil water accumulation was observed within it. This contrasts with the relative uniformity of a nearby level-site profile (see Tomer, 1999), and provides evidence that shallow interflow may have occurred above the lapilli.

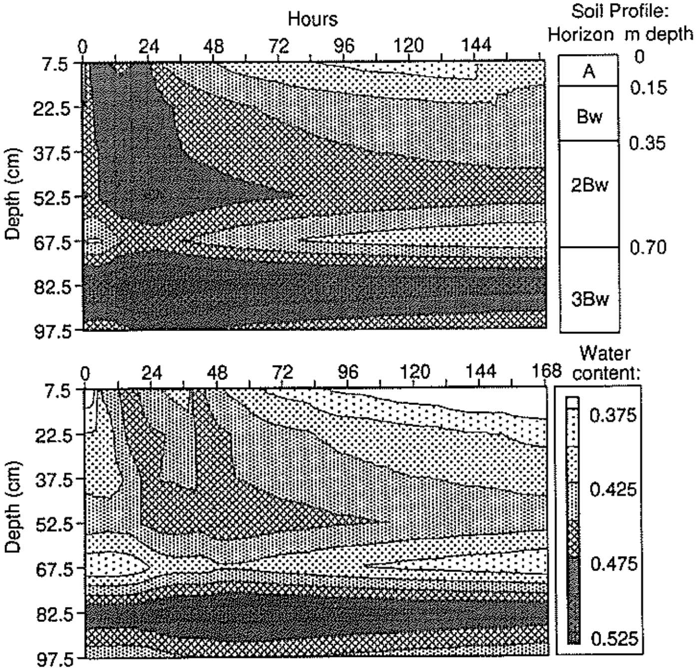


Figure 9 – Changes in water content with time and depth for weekly irrigation cycles in winter (top, beginning on 12 August) and summer (bottom, beginning on 24 December). Note there were two irrigations near the beginning of each period. Effects of soil layering (shown on the right) on water distribution in the profile are evident.

Tensiometric data

Histograms of soil water tensions measured during winter and summer show that these soils were wetter than 100 cm tension ("field capacity") most of the time (Fig. 10). During winter, at all three monitored depths, the soils were at water tensions less (wetter) than field capacity about 90% of the time. During summer, they were wetter than field capacity 50 to 60% of the time. This indicates that water was draining from the soils a majority of the time. A plot of soil-water tensions against time for winter and summer

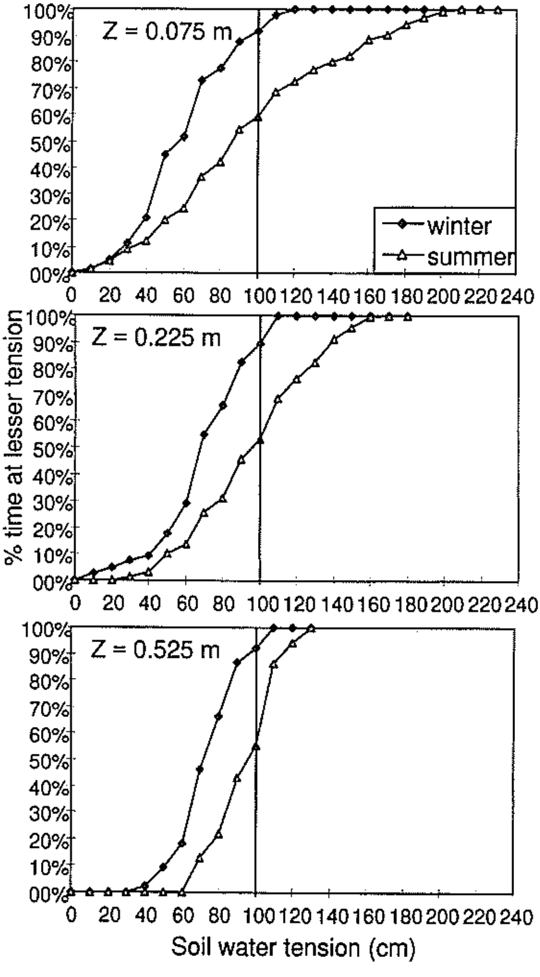


Figure 10 – Cumulative frequency distributions of soil water tension data for winter and summer at 0.075, 0.225, and 0.525 m depths. The vertical line corresponds to the "field capacity."

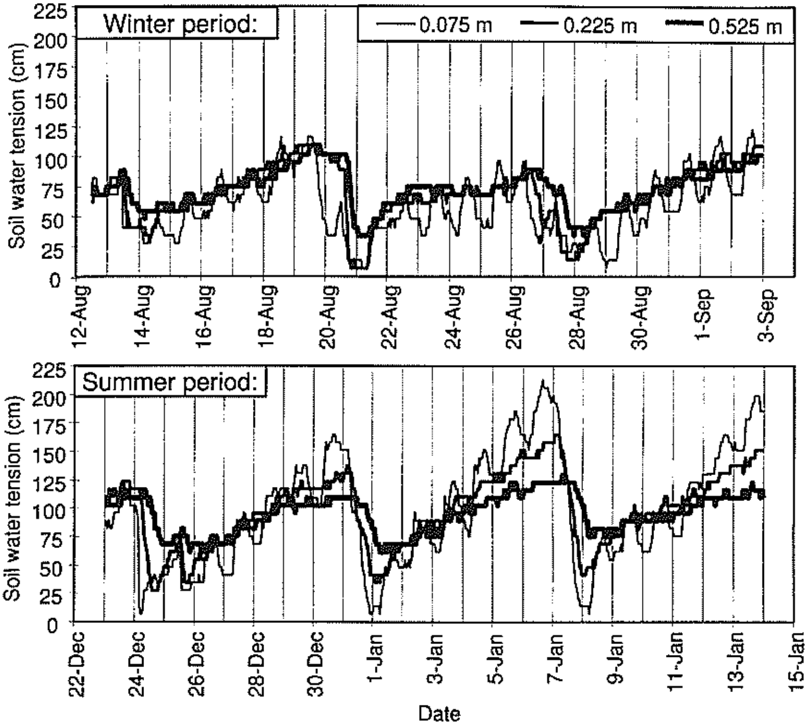


Figure 11 – Soil water tensions at 0.075, 0.225, and 0525 m depths during winter and summer monitoring periods.

monitoring periods verifies this (Fig. 11). During winter, water tensions at all three depths follow each other closely. The only exceptions were related to wetting-front movement during irrigation, and distinct diurnal changes at 0.075 m depth. Presumably, these diurnal changes are due to upward movement of water vapour during the night, which will occur in response to temperature gradients that develop as heat is lost from the soil. Most importantly, the similarity in soil water tension at different depths shows that gravity drainage of soil water occurred throughout the weekly irrigation cycles during winter. During summer, soil water tensions at the three depths closely followed one another for 3 or 4 days after irrigation, and then diverged as the tension exceeded about 100 cm (Fig. 11). This suggests that soil water drainage was dominant for three or four days after irrigation in summer. Tensiometric data further indicated that soil water seldom moved upward from 0.525 to 0.225 m depth. The tension at 0.225 m depth exceeded that at 0.525 m depth by at least 30 cm less than 5% of the time in any month, and never occurred during monitoring in August, September, October, or April. Upward water movement from 0.225 m depth, indicated by the tension at 0.075 m exceeding that at 0.225 m by at least 15 cm, occurred about 5% of the time during winter and 15 to 20% of the time during summer.

Summary and conclusions

These studies investigated the effects of weekly wastewater irrigation on the soil water, ground water, and seepage-flux hydrology of a hillslope within the Rotorua Land Treatment System. The results emphasise the rapid hydrologic response of the landscape to this practice. The irrigation loading averaging 70 mm/week is equivalent to more than 3600 mm of effluent per year, more than twice the annual rainfall of 1491 mm/yr. The soils are highly permeable and have the capacity to transmit this additional water, as overland flow is only observed from minor areas, which presumably were heavily trafficked by forest harvesting equipment. However significant discharge of water to wetlands occurs via seepage pathways that bypass the organic soils of the wetland. Modelling results suggest this seepage area was recharged by at least 1.0 ha of the 14 ha irrigation block, therefore these flow pathways could be important across the treatment site.

Ground water and seepage flux responded rapidly after irrigation, peaking within 30 hours on average. Responses in ground water levels ranged from 0.00 up to 0.11 m, with that response taking between 12 and 69 hours to occur. This variation in the timing and extent of response was related to the depth of the phreatic surface, proximity to sprinklers, and the volcanic sediments within which the phreatic surface occurred. This surface was within a lapilli gravel layer close to the wetland, and water levels in this lapilli responded quickly to irrigation. Seepage discharge was closely related to these water levels, such that the water level in one piezometer provided an excellent proxy for discharge measurement.

Seepage discharge was affected by irrigation loading, and regression equations indicate that seepage response could be predicted from irrigation loading and antecedent profile water storage data. Because seepage flows on top of, rather than through, the wetland's organic soils where denitrification may occur, a future aim for managing this land treatment site may be to minimise these flows. In that case, regression results could be used to suggest rules for modifying irrigation schedules in a way to achieve this goal.

Continuous monitoring of an irrigated soil profile showed that the soils were usually wetter than "field capacity," particularly in winter. These soils can transmit water rapidly when water contents are near saturation, but appear to retain water quite effectively at soil water tensions less than 100 cm. Tensiometric data conclusively showed that gravity drainage dominates the soil water regime in the upper half-metre of the soil profile during winter.

These wet conditions could affect rooting of perennial crops that are not adapted to wet soil conditions. Data on rooting distribution of *Pinus radiata* are needed to determine if this is occurring at Rotorua's land treatment system.

Acknowledgments

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