# Measuring and Modelling water dynamics under effluent irrigated pine trees

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## Abstract
The rapid increase in water usage throughout the world demands safe and sustainable methods of waste-water disposal and recycling with minimal impact on the environment. A field experiment in the Large Lysimeter Research Facility, close to Rotorua, New Zealand, was conducted to quantify the water dynamics from an effluent irrigated pine tree plantation (*Pinus radiata*). The facility contained 2 soil types, the native volcanic soil, and a coastal dune sand. Secondary effluent, tertiary effluent, or fresh water was applied at the 3 different rates of 0, 30 and 60 mm/week. The annual average rainfall at Rotorua is 1335 mm/year and the reference ET is about 880 mm/year. Thus, there is the potential for large drainage losses through the soil profile.

Effluent irrigation increased the amount of drainage under all treatments. In the first years, drainage occurred also during the summer, indicating that the application was greater than the demand of the growing trees. By the third year no drainage was observed in the summer period , even when the application rate was 30 mm/week to the ash soil. This indicates that irrigation was beginning to match to tree's water demand.

Our SPASMO (Soil Plant Atmosphere System) model was used to predict the partitioning of rainfall and irrigation water to plant uptake and drainage beyond the root-zone of the pine trees. The model and measurement comparison of cumulative drainage was in good agreement for the different treatments, considering the large variations in the observations. This good result supports the use of SPASMO to predict the potential impact of effluent irrigation on drainage rates under an irrigated pine tree plantation. The model will form part of a decision support tool for developing sustainable effluent-application rates to land-based effluent disposal schemes.

## Key Words
Water balance, evapotranspiration, runoff.

## Introduction
Application of municipal effluent to land has become a popular option for disposal, nutrient re-cycling and water conservation in both developed and developing countries. While the irrigation of waste-water to agricultural land is quite widespread, the use of tree plantations has received less attention. Although, world-wide the area under effluent-irrigated tree plantations is rapidly increasing, research in these systems is still very limited. Generally effluent irrigation has shown to result in an increased tree growth, but the long term-effects of effluent irrigation on the soil have still to be determined. High concentrations of nitrate in the effluent pose the risk of excess nitrate leaching into the underlying groundwater, and several studies in NZ and Australia have shown elevated nitrate concentrations due to application of effluent to forested land (Tomer *et al*. 1997; Smith and Bond 1999). Results for the Wagga Effluent Plantation Project in Australia show that irrigation of treated effluent increased the level of nitrate leaching if the irrigation was twice as high as the water use by the Eucalyptus and pine trees (Bond *et al*. 1996). However if irrigation volume was matched to the demand of the plant and the time of the year, the groundwater quality was not affected (Bond *et al*. 1995). Fast growing plantations in Australia can use up to 8 mm/d in summer and as low as 0.5 mm/d in winter. Thus to ensure sustainability of effluent application to forested land it is necessary to properly understand the use and leaching of water in soil-plant systems. Then, guidelines tailored to specific soil-plant systems can be developed for sustainable effluent application to forest plantations, which minimises the risks of nutrient leaching.

In the land treatment system at Rotorua, secondary and tertiary-treated municipal waste-water from the City has been spray-irrigated onto a commercial Monterey pine forest since 1991. To better understand the water dynamics of this system, a detailed experiment was set up within the forested area. The experimental site is referred to as the large lysimeter research facility (LLRF). The present study deals with the sustainability of effluent irrigation which is assessed in terms of the site water balance. The objectives were to (i) quantify the water balance under various irrigation rates, and to (ii) to test the accuracy of our recently developed SPASMO model (Green *et al*. 2003) applied to an irrigated tree plantation.

The SPASMO model considers water and solute movement through a 1-dimensional soil profile that extends from the soil surface to a depth of 6.0 m. The model calculates the water balance of the vegetation by considering the inputs (rainfall and irrigation) and losses (plant uptake, evaporation, runoff and drainage) of water from the soil profile. SPASMO had been developed specifically to study land-use impacts in New Zealand. The model contains an extensive database of New Zealand soils (~150 profile descriptions of physical and hydraulic soil properties) and regional climates (~50 time series of daily weather spanning more than 30 years) from around the country. A detailed description of the model is given in Green *et al*. (2003).

**Methods and materials**

A replicated field experiment using small-plot lysimeters was set-up in the Whakarewarewa Forest, near Rotorua. In spring 1998, a total of 36 plots, each 5 by 5 m in size, were hydraulically isolated from the surrounding soil. One half of the plots contained the native Whakarewarewa soil, a volcanic pumiceous sandy loam (Typic Udivotrands, USDA), referred to as 'ash'. The other half of the plots contained a dune sand from a quarry located near Tauranga, some 50 km away, referred to as 'sand'. A total of nine 2-year-old clonal pine trees (*Pinus Radiata*) from the Forest Research nursery were planted into each plot in August 1999. The soil underneath the pine trees was left bare. Irrigation, either with fresh water, BNR (biological nutrient removal), or secondary-treated municipal effluent, began in July 2000 and continued on a regular, weekly basis through the course of the experiment. Application rates were set at either 30 or 60 mm/week, with control plots receiving no irrigation at all. The average annual rainfall in Rotorua is about 1335 mm/year while the average potential $ET_O$ (i.e. a reference value for pasture) is about 880 mm/year. Thus, even without irrigation there is likely to be significant drainage losses at the experimental site because annual rainfall often exceeds the potential ET. Applying a regular irrigation of 30 mm per week will contribute an additional 1560 mm of water annually to the soil profile, while regularly applying 60 mm/wk of irrigation adds an extra 3120 mm of water to the soil profile. The volume of soil water draining through the profile was estimated using 4 passive wick samplers installed into each plot at a depth of 0.9 m, see Figure 1. The samplers used a fibreglass rope (Amatex one inch, medium density) as the wicking material. Each sampler had a 1.0 m long wick and this provided a head (suction) of between 0.85 to 0.9 m. Hydraulic properties of the wick material were matched to those of the Whakarewarewa soil. The active area of each sampler was 0.2 by 0.2m, and so the four samplers potentially intercepted about 4% of the leachate water draining through each plot. Input values for the SPASMO model included measured hydraulic properties of the soil, local weather data, and measured leaf area.

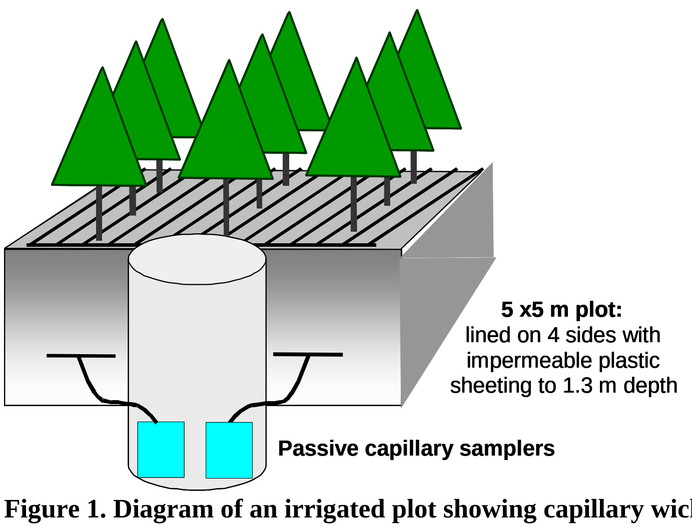


**Figure 1. Diagram of an irrigated plot showing capillary wick samplers and collection access chamber.**



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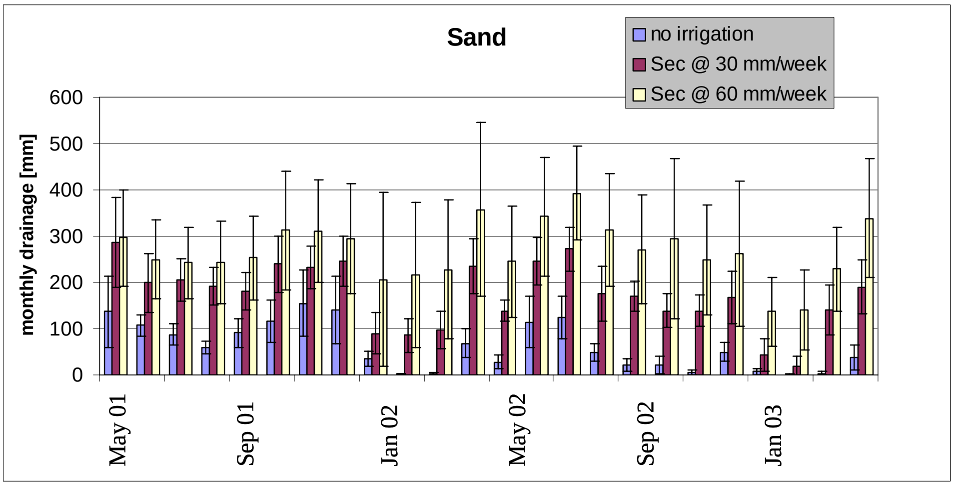
## Results

*Drainage losses*

Figure 2 shows the impact of different irrigation volumes on the temporal pattern of drainage each month under the sand and ash plots. These data cover just the last 2 years of the experiment (May 2001 to April 2003), soon after irrigation was first applied to the experimental site. The values in Figure 2 are calculated using the average determined from the leachate volumes collected by the four wick samplers installed into the three replicated plots. Results are shown only for the non-irrigated and secondary-effluent irrigated plots for the purpose of demonstrating the impact of irrigation intensity.

As expected, significant drainage losses were observed under both soil types. This is because total rainfall plus irrigation exceeds the combined evaporative losses from both the pine trees and the surface soil. In the first year of the experiment, when the trees were young and the canopy was quite open, large drainage events occurred throughout the whole year. However, towards the end of the last year (2003) the drainage rates tended to decline. This result is consistent with a higher rate of water use by the larger pine trees. Indeed, drainage losses practically ceased under the ash plots receiving both the zero and 30 mm/wk irrigation treatments. By the end of the third year 30 mm per week irrigation was approximately matching tree demand, at least over the summer period.

In general, drainage losses tended to be much higher under the sand plots compared to the ash plots receiving the same amount of irrigation. This is an expected result because the dune sand has a much lower water-holding capacity and a much higher hydraulic conductivity. Thus, the dune sand is of a more free-draining nature than the ash soil.



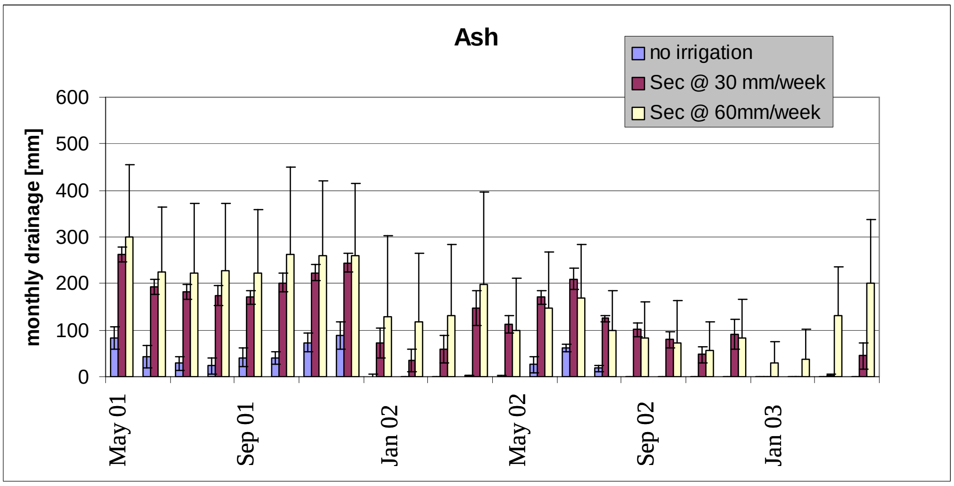




**Figure 2. Time course of drainage measured under the non-irrigated and secondary effluent-irrigated plots at the Whakarewarewa experimental site, for ash and sand soils.**

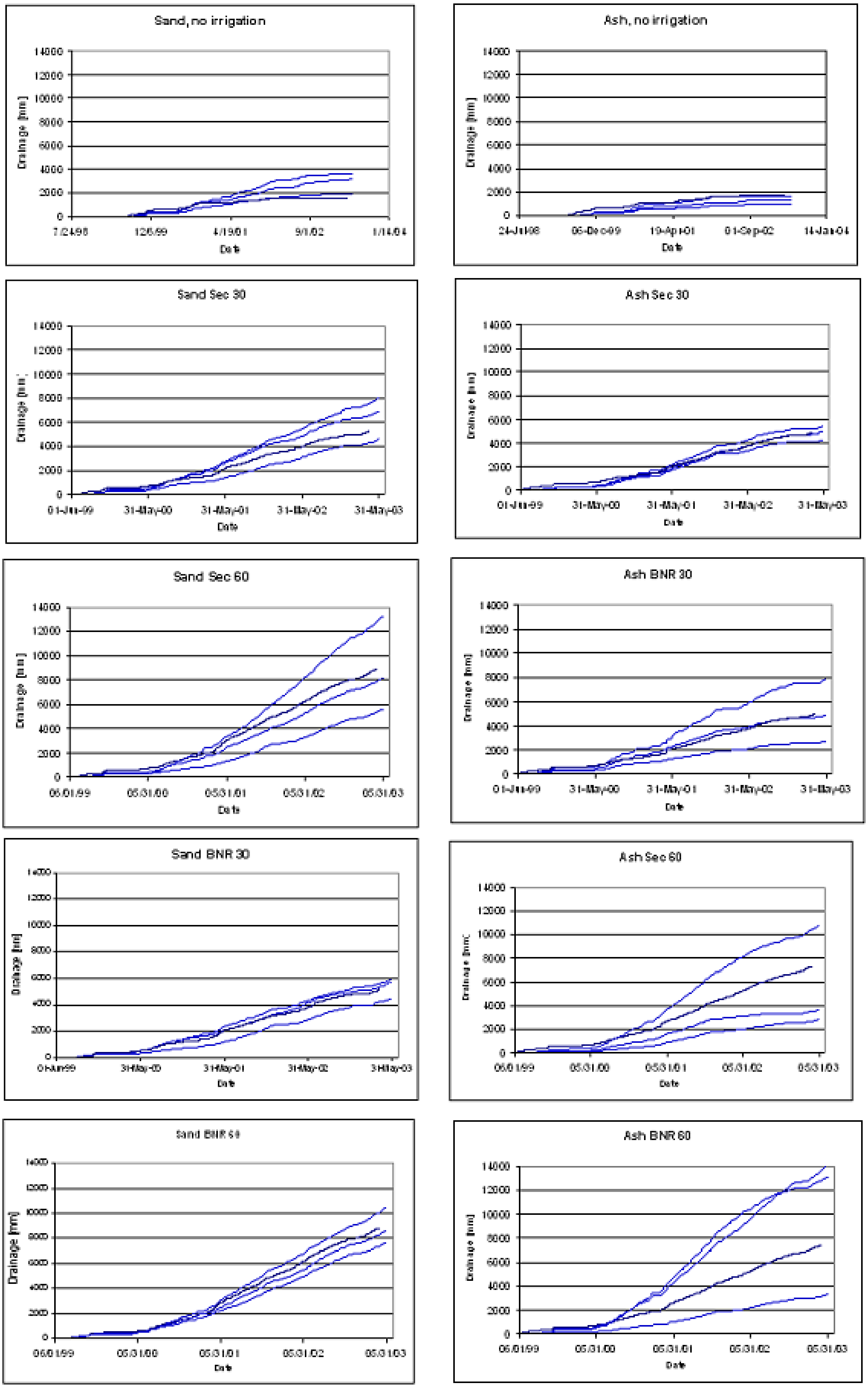



**Figure 3. The temporal pattern of measured, replicate plots (grey lines) and modelled (black lines) cumulative drainage under the three different irrigation treatments, for ash and sand soils.**

The temporal pattern of measured and modelled cumulative drainage under the three different irrigation treatments is shown in Figure 3. Generally the model results lie within the scatter of the measurements for all irrigation treatments, and both soil types. However, it should be noted that some treatments showed a very large variation between the 3 replicate plots. For example, results from the Ash BNR 60 treatment had a standard deviation of about 6000 mm in the cumulative drainage loss over the 3 year period; two of the measurements were almost double that calculated by SPASMO while measured drainage from the other plot was only half the calculated value (Table 1 & Figure 3). Similarly, the measured drainage under the Ash Sec 60 treatment also had a very wide scatter. One plot recorded about 50% higher drainage rates while the other two plots recorded 50% lower drainage rates compared to that calculated by the SPASMO model. The variation between plots is summarized in Table 1, where DR1, DR2 and DR3 are the drainages collected under the 3 different plots for each treatment. In general, the agreement between the modelled and measured drainage over the experimental period was very good. Poorest results were obtained from those treatments having a large variation between the replicate plots e.g. Ash BNR 60 and Ash Sec 60.

As expected, a greater amount of drainage was recorded, and modelled, under the treatments that received a larger volume of irrigation water. Over the experimental period of nearly 4.5 years some 1300 mm was collected from non-irrigated ash plots. By comparison, about 5000 and 10000 mm of leachate was collected from the other two ash plots irrigated at 30 and 60 mm/week, respectively. Those plots received, over the course of the experiment, an additional 4000 and 8000 mm of irrigation (Table 1). A considerable fraction of the irrigation simply drained beyond the root-zone soil to the receiving groundwater reservoir. While some flushing of the rootzone is essential in effluent irrigated plantations, to prevent the build-up of salts (Bond *et al.* 1995), excessive drainage losses can contaminate the underlying groundwater, especially if the drainage water is high in nitrate-nitrogen.

**Table 1. Summary of measured and SPASMO-modelled water balance for the different treatments. All Units in mm. DR is drainage, RF is runoff, ET is evapotranspiration. The total rainfall (period) was measured at 5556 mm.**

| Treatments | | Measurement | | | | | | Model | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Irrig. | DR1 | DR2 | DR3 | DR stdv | **DR avg** | **DR** | RF | ET |
| SAND | No Irrig. | 0 | 3896 | 1913 | 3252 | 924 | **2986** | **1579** | 35 | 3253 |
| | BNR 30 | 4331 | 5710 | 4398 | 5908 | 820 | **5339** | **5256** | 45 | 3359 |
| | BNR 60 | 7982 | 8653 | 7646 | 10450 | 3877 | **8916** | **8895** | 107 | 3359 |
| | Sec 30 | 4216 | 7946 | 6956 | 4633 | 1700 | **6512** | **5342** | 44 | 3359 |
| | Sec 60 | 7878 | 5662 | 8205 | 13278 | 1421 | **9048** | **8944** | 104 | 3359 |
| | No Irrig. | 0 | 1704 | 1304 | 915 | 394 | **1308** | **1808** | 324 | 2746 |
| ASH | BNR 30 | 4331 | 4924 | 2736 | 7899 | 2591 | **5187** | **5085** | 716 | 3254 |
| | BNR 60 | 7982 | 14229 | 13110 | 3317 | 6003 | **10219** | **7422** | 2029 | 3254 |
| | Sec 30 | 4216 | 5458 | 5054 | 4249 | 615 | **4920** | **4994** | 692 | 3254 |
| | Sec 60 | 7878 | 2848 | 3648 | 10829 | 4395 | **5775** | **7366** | 1982 | 3254 |

A summary of cumulative water balance, including totals for irrigation, rainfall and evapotranspiration, is presented in Table 1. These data cover the entire experimental period (June 1999 to April 2003) and allow us to compare actual measurements of drainage against the amounts calculated on a daily basis using the SPASMO model. Apart from those treatments where the measured drainage variability was high (e.g. ash Sec60 and Ash BNR60) the agreement between measured and modelled losses is good. SPASAMO appears to generate a reasonable water balance for the effluent-irrigated pine trees, at least in terms of the drainage losses that we have measured.

The SPASMO calculated evapotranspiration (ET) for the different treatments shows an increase of about 100 mm in the sand plots due to irrigation (Table 1). ET in the non-irrigated treatment was lower on the ash compared to the sand. However, the addition of effluent irrigation increased ET to about the same level as in the sand plots. The peak water use by the effluent-irrigated pine trees was calculated to be about 5 mm $d^{-1}$, in mid summer. Effluent irrigation increased the amount of runoff (RF) calculated by SPASMO, especially in the ash plots under the highest irrigation rate. Reduced runoff from the sand plots reflects the more free draining nature of the dune sand compared to the volcanic ash.

**Conclusions**

This study presents the results from field study set up to quantify the water balance from an effluent-irrigated pine tree plantation, using either secondary effluent, BNR-effluent, or fresh water, applied at 3 different rates of 0, 30 and 60 mm/week. Two different soil types, a volcanic soil, and a coastal dune sand were used. As expected, effluent irrigation increased the amount of drainage water under all treatments, and in the first years drainage also occurred during the summer periods, indicating that the application rate was higher than the demand of the growing pine trees. However, effluent irrigation also increased slightly the growth and evapotranspiration losses from the plots. And in the last year no drainage occurred in the summer period under the application rate of 30 mm/week to the ash soil, indicating that irrigation was matched to plant demand.

The computer model SPASMO (Soil Plant Atmosphere System Model) was used to calculate the water balance under the effluent-irrigated pine trees, and in general agreement between measurements and modelling results was good. Thus the SPASMO model can be used for designing a sustainable way of effluent irrigation to pine tree plantations with respect to water loadings.

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