5.3 Modelling the Growth of Irrigated Lucerne over a Shallow Saline Watertable

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Abstract

Shallow saline watertables underlie large areas of the Riverine Plains of the Murray Basin of southern Australia. It is believed that deep-rooted perennial plants in these areas are able to reduce recharge and use shallow groundwater, thus controlling groundwater levels. Lysimeters represent the best experimental technique for investigating capillary upflow from shallow watertables and the associated processes of salt accumulation, plant water use, and growth response. Techniques involving stable isotopes of water help determine the components of upflow due to vegetation. When combined with models that simulate salt and water movement in the soil zone and the plant water use and growth, we can thoroughly test our understanding of salinity processes and the ability of plants to control watertables. Results from WAVES simulations of plant growth, evapotranspiration, groundwater uptake, salt accumulation, and the impacts on lucerne growth are compared against measurements made in lysimeters at Griffith, NSW, Australia. With minimal calibration, WAVES was able to reproduce both the daily and seasonal variation in evapotranspiration, upward flux from the groundwater table, plant growth in terms of leaf area development, soil water profiles, soil water salinity, and root water extraction patterns. There was a decline of 36% in transpiration, 42% in leaf area growth, and 67% in upward flux after the salinity of the watertable was increased from 0.1 dS/m to 16 dS/m. Although upward flux of water was large, lucerne used little of it (< 20%), preferring 'fresher' rainfall and irrigation water near the surface. Given the tests presented in this work, we think WAVES is applicable to irrigated agricultural systems.

5.3.1 Introduction

Changes in agricultural practice in Southern Australia have led to increases in groundwater recharge, which in turn have led to rising watertables and increased salinisation. However, reducing groundwater recharge is not always the best way of controlling salinity. For regional groundwater systems the extractions must be increased; it is not enough to reduce inputs. The management of these groundwater systems relies on a combination of engineering options (pumping, drainage, disposal), biological controls (tree plantations, perennials on shallow watertables), and recharge reduction (increased irrigation efficiency).

The Riverine Plains in southern Australia is an example of an area underlain by regional groundwater systems. A combination of irrigation and increased pressures in the confined groundwater systems has led to large areas of shallow water tables. Plantation forests on farms with shallow saline watertables, revegetation of saline agricultural land and reduced leaching fractions are being proposed as part of the overall management options. These would create areas where there is a net flux of water from the groundwater into the soil zone. This water would be lost from the soil either by evaporation or by transpiration and the salt would accumulate and be concentrated in the root zone. There is concern that this will affect the sustainability of these management options.

Whereas there has been a number of past studies of plant response to salinity, few have dealt with the interactions between plant water uptake, salt accumulation, groundwater salinity and plant growth. For dryland areas, lucerne has been proposed as an option to not only reduce recharge but to access shallow groundwater. In the irrigation areas of the Riverine Plains, lucerne is commonly irrigated and it has been suggested that by reducing irrigation, lucerne may be able to use shallow fresh groundwater.

Capillary upflow from groundwater and salt accumulation in the soils are difficult parameters to measure in the field. Lysimeters offer an option for measuring these and other components of the water budget simultaneously in a field-like situation. The lysimeter facilities at Griffith, N.S.W, allow accurate measurement of capillary upflow and drainage, concurrent with measurements of rainfall, irrigation, evapotranspiration, soil moisture content, plant leaf area index, soil water salinity, and isotope analyses (Smith *et al.* 1996).

While a lysimeter can be used to measure capillary upflow, it can not be used for determining how much of this upflow is being used by the plant. Stable isotopes of water have been used in a number of recent experiments to help determine sources of water used by plants and plant water use strategies. Often the main limitation to successful use of isotopes is the similarity of the stable isotope composition of the various sources. This leads to poor discrimination of the relative importance of various sources. Within the lysimeter, it is possible to overcome this limitation by artificially enriching the isotope composition within the groundwater thus increasing the sensitivity of the technique (Thorburn *et al.* 1994).

The above processes are interlinked and complex and depend on a range of climatic, plant, soil, and groundwater factors. Physically based models can provide insights into the behaviour of this complex system provided that they are tested against measurements to check that they adequately simulate key processes. A tough test on any model is to predict the impacts of changing external conditions, particularly when these changes involve most of the key processes.

This paper describes a lysimeter, isotope and modelling study aimed at testing our understanding of lucerne grown over shallow water tables. It explores what happens to lucerne, a deep-rooted perennial, when irrigation is reduced to the extent that there is a net upward flux from the groundwater into the soil zone. During the course of a lysimeter experiment conducted at Griffith, NSW, the water table is changed in both depth and salinity and the groundwater is 'doped' with isotopically enriched water. A complex soil–vegetation–atmosphere transfer model, WAVES, is calibrated on pre-change data and only two parameters allowed to vary during this calibration. Model predictions of responses of transpiration, capillary upflow, lucerne growth and salt accumulation to changed water table conditions are compared with measured responses. If we can accurately model several different water balance responses, thus eliminating the possibility of compensating errors in other processes, we should feel confident in using WAVES to assess the suitability of lucerne, and perhaps other vegetation types, for management systems aimed at controlling groundwater levels.

5.3.2 Materials and methods

Field experiment

The field data collected has been presented in detail by Thorburn *et al.* (1994) and Smith *et al.* (1996). It was carried out during the period of 1990 to 1993 at CSIRO Land and Water, Griffith Laboratory, N.S.W., Australia (34°17′S, 146°03′E). Two weighing lysimeters each consisted of a concrete outer and steel inner box were installed. Each inner box encased an undisturbed soil core. The dimensions of the Lysimeter 1 (L1) are 1.2 m wide by 1.45 m long by 1.5 m deep, and those of Lysimeter 2 (L2) are 1.05 m wide by 1.3 m long by 1.7 m deep. The soil in L1 was Hanwood loam (Butler, 1979; Northcote, 1981), a Rhodoxeralf, and the soil in L2 was Mundiwa clay loam (van Dijk, 1961; Northcote, 1981), also a Rhodoxeralf. The Handwood loam has red-brown sandy loam (60% sand, 10% silt, and 30% clay) to 0.25 m depth and light brown clay (35% sand, 5% silt, 50% clay, and 10% calcium carbonate) from 0.25 to 1.5 m. The Mundiwa clay loam has brown sandy clay loam (60% sand, 23% silt, and 17% clay) to 0.2 m, a dark reddish brown heavy clay (25% sand 14% silt, and 61% clay) to 0.6 m and with mottled yellow red clay to 1.7 m (Loveday *et al*., 1984). Mass changes of both lysimeters were calculated daily from load cell output and resolution of the lysimeters was equivalent to 0.05 mm water depth. Upward flux from the watertable was measured daily as the volume of water supplied by the Mariotte tank to maintain a constant watertable.

The field had been fallow following a maize crop in 1989–90. Lucerne (WL Southern Special) was sown on 10 October 1990 in rows 175 mm apart. The leaf area index was determined using *in situ* tube solarimeters on each lysimeter and converting intercepted irradiance values using a locally calibrated function (Meyer *et al.*, 1990). Lucerne in both lysimeters were routinely cut and it took approximately one month for established lucerne to exceed a leaf area index of 3. The field was irrigated using a sprinkler system to maintain a high water status. Irrigation was applied to both lysimeters and the surrounding field with the application of irrigation based on a soil water deficit of 80 mm in L1. Soil moisture contents were measured using a field-calibrated neutron probe (Smith *et al*., 1996).

A non-saline watertable (EC 0.1 dS m^{-1}) at 60 cm below the soil surface was established before sowing and was dropped to 100 cm in March 1991 using the Mariotte tanks. In March 1992, a saline watertable was introduced (EC 16 dS m^{-1}) and maintained at 100 cm until the end of the experiment. Soil water was extracted from each lysimeter at seven depths using ceramic suction cups, and the electrical conductivity (EC) was measured.

An automatic weather station was located immediately adjacent to the field on the western side. Wet and dry bulb temperature was measured using temperature sensors with a standard muslin wick. A tipping bucket rain gauge recorded rainfall amount and duration. Solar radiation was measured 1 m above the canopy using a Delta-T[6] TS81L tube solarimeter.

Stable isotope ratios of hydrogen ($^2H/^1H$) and oxygen ($^{18}O/^{16}O$) were measured in the groundwater, soil water, and plants to trace the uptake of the saline groundwater by plants. To facilitate the tracing, the saline groundwater was made isotopically distinct from rainfall and irrigation water by doping with ^2H_2O. From February 1992 soil solution samples were extracted immediately after each irrigation application for isotopic analysis. Between irrigation events, samples of three plant crowns were taken on 15 occasions for isotopic measurements. The final four were taken weekly in April 1993, after irrigation ceased and the lysimeter soil was allowed to dry.

At each sampling time a section of the crown of the three plants was removed and placed in a jar containing kerosene (Thorburn and Mensforth, 1993). Water was extracted from the plant sample using azeotropic distillation (Thorburn *et al*., 1993). Analyses for ^2H was performed by reduction of 25 $\mu\ell$ of water to hydrogen gas over uranium at 800°C (Bigeleisen *et al*., 1952). Values of ^{18}O

were determined by a modification of the Epstein and Mayeda (1953) CO_2 equilibration technique using 1 mℓ of water. All isotopic ratios were expressed as standard δ notation:

$$\delta\ (‰) = (R_i/R_s - 1) * 1000 \tag{5.1}$$

where R is the ratio of heavy to light isotope, the subscript i indicates the isotope samples, and s the ocean water standard (V-SMOW).

Model calibration

The two WAVES vegetation parameters that dynamically allocate carbon, maximum above and below ground partition factors, were calibrated to match leaf area index over the period of 1990 to 1991. Solute concentration, upward water flux, leaf area index, evapotranspiration, and soil moisture contents for the period 1990–93 were used as a test of the model. Vegetation parameters for lucerne were initially set to those used by Zhang *et al*. (1999) in a dryland setting. The maximum assimilation rate of carbon and light extinction coefficient were taken from Whitfield *et al.* (1986). The saturated soil moisture content was set from measurements made with a neutron probe, and saturated hydraulic conductivity was estimated based on observed infiltration rates. The moisture characteristic shape parameters of the BW soil model were estimated from the texture profile description and fitted to observed capillary fringes in the soil.

Once the model was calibrated, it was run for the period 1990–93 using measured meteorological data, irrigation data, prescribed groundwater tables, and salinity data. No change was made to any parameter values after the saline groundwater table was introduced.

5.3.3 Results and Discussion

Leaf area development

During the period of the experiment, lucerne was routinely cut and the measured leaf area index varied between 0.05 and 4.0 (Fig. 5.16). Lucerne grown in L2 was less well established in the 1990–91 season with average leaf area index of 1.5 compared to 1.9 in L1. The maximum leaf area index in L2 was 2.8 compared to 3.7 in L1. The difference in leaf area index may be due to the soil conditions limiting seedling vigour and root growth (Meyer *et al*., 1996). The root length density in L2 was much lower than that in L1 due to the presence of a heavy clay layer (Smith *et al*., 1996). WAVES does not model root length density, but root carbon. There is no measured data against which to compare this.

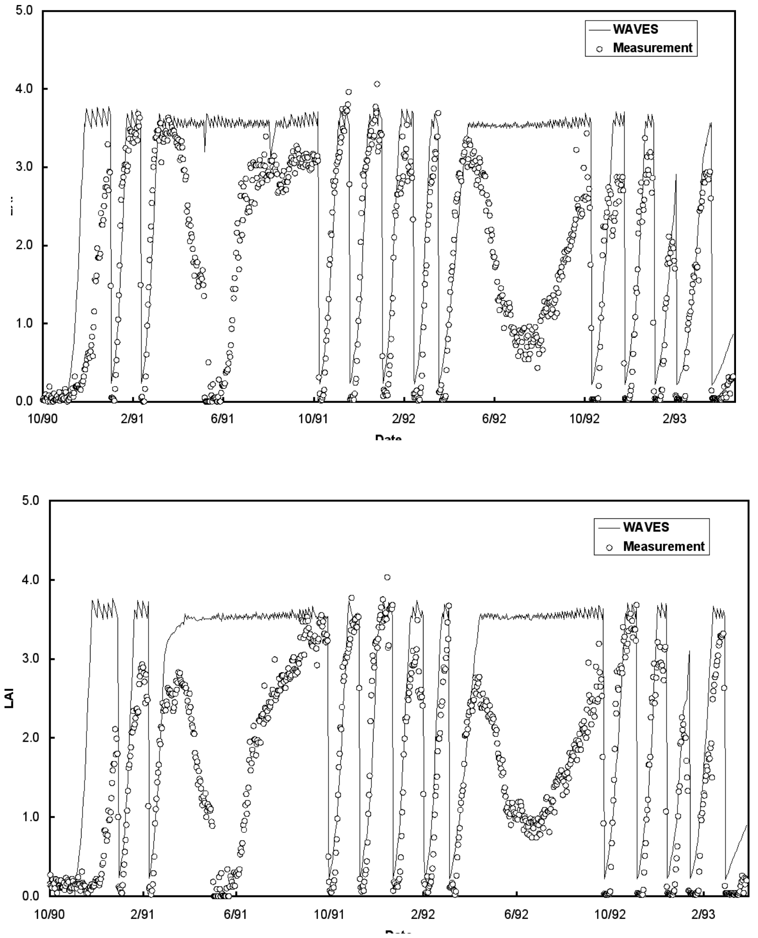
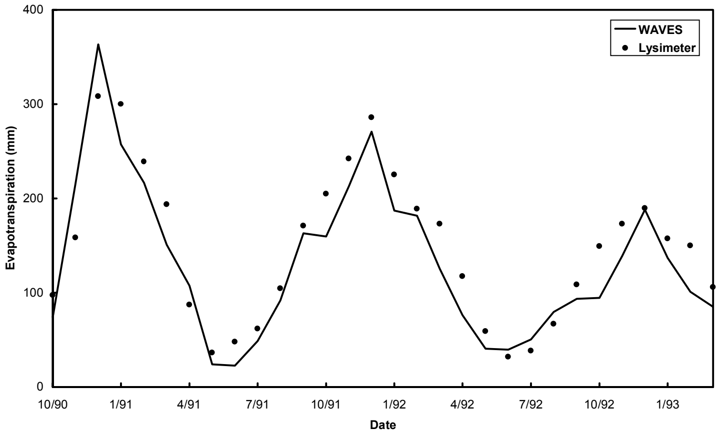


Fig.5.16. Comparison of modelled (—) and measured (○○○) leaf area index (LAI) for (a) Lysimeter 1 and (b) Lysimeter 2.

Once established as described in the previous section, lucerne exceeded a leaf area index of 3.0 by, on average, 28 days after a cut. The modelled leaf area index agreed very well with the measurements and they showed similar temporal patterns, except for the winter period (May to August) (Fig. 5.16). The large difference between modelled and measured leaf area index in winter was probably due to dormancy. If these winter periods are excluded, linear least-squares regression of modelled to observed leaf area index gives a slope of 0.91 with a zero intercept, regression coefficient (r^2) of 0.90, and root mean square error (RMSE) of 0.46. It was observed that the lucerne in the lysimeters started to lose leaves when the minimum air temperature was below 5°C. This specific dormancy behaviour is not modelled by the generic growth model in WAVES. In other models with specific modules to handle individual crop types, such as APSIM (McCown *et al.* 1996), such effects are incorporated with extra parameters in the detailed phenological descriptions. This period exhibits very low transpiration (1.2 mm day^{-1}) due to climatic controls not vegetation. Since WAVES incorporates the atmospheric demands directly, this period of low evaporation is modelled accurately in water-balance terms. Further, the fact that only allocation parameters needed to be calibrated implies the form and feedbacks within WAVES growth model are robust and appropriate.

Evapotranspiration and upward flux

There is good agreement between modelled and measured monthly evapotranspiration for both lysimeters (Fig. 5.17). For L1, least-squares linear regression yielded a slope of 1.06 with zero intercept, r^2 of 0.86, and RMSE of 0.96 mm day^{-1}. In L2, the slope was 1.06, r^2 of 0.82, and RMSE of 0.92 mm day^{-1}. Evapotranspiration showed significant temporal variations. In the summer months, daily evapotranspiration rate exceeded 15 mm day^{-1} and dropped to less than 1 mm day^{-1} in the winter periods.



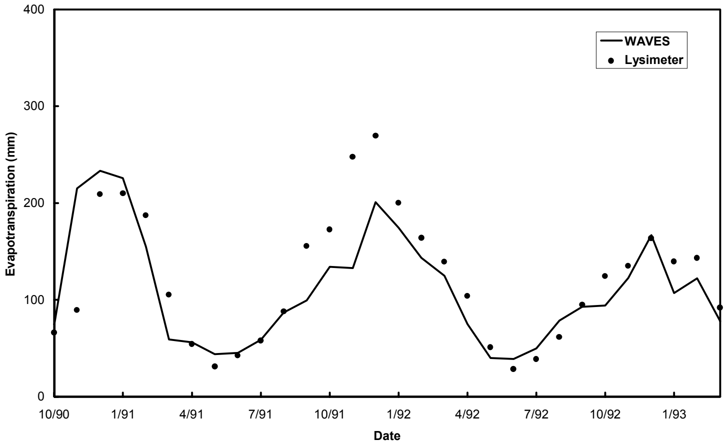


Fig. 5.17. Comparison of modelled (—) and measured (•••) monthly evapotranspiration for (a) Lysimeter 1 and (b) Lysimeter 2.

Evapotranspiration rates from L2 were consistently lower than those from L1, especially for the period of 1990–1991. For the entire period, observed evapotranspiration from L2 was 80% of that from L1. The difference between the two lysimeters may be due to the presence of the heavy clay layer in L2, which caused the lucerne to grow less vigorously than the surrounding plants (Meyer *et al.*, 1990). As a result, lucerne grown in L2 before saline watertable introduction had 10% less leaf area index than L1 (Fig. 5.16). Average annual irrigation for 1990–92 was 730 mm, and rainfall was 90 mm. Despite these inputs, average actual evapotranspiration rate (5 mm day^{-1}) was only half of the average potential evapotranspiration rate (10 mm day^{-1}) estimated using the Penman–Monteith equation with zero canopy resistance. Thus, evapotranspiration was supply limited and controlled by soil hydraulic properties. WAVES successfully modelled evapotranspiration from the two lysimeters with the only difference being soil profiles and properties (Table 5.5).

Table 5.5. List of Broadbridge–White soil parameters and soil layer depths used in the study

Site	Depth (m)	K_s (m/d)	θ_s	θ_d	λ_c (m)	C
Lysimeter 1	0–0.1	0.07	0.30	0.12	0.2	1.01
	0.1 – 0.3	0.05	0.35	0.20	0.3	1.05
	0.3 – 0.6	0.02	0.45	0.20	0.4	1.05
	0.6 – 1.5	0.02	0.38	0.15	0.3	1.05
Lysimeter 2	0 – 0.1	0.08	0.30	0.12	0.2	1.01
	0.1 – 0.2	0.04	0.35	0.20	0.3	1.05
	0.2 – 0.6	0.01	0.40	0.25	0.4	1.10
	0.6 – 1.7	0.001	0.40	0.25	0.4	1.10

The modelled monthly upward flux was also in good agreement with the measurements and showed similar trends to evapotranspiration (Fig. 5.18). The ratio of the upward flux to evapotranspiration varied between 25 to 65% and decreased after the saline groundwater table was introduced. These results suggest that the magnitude of upward flux was significant compared to the evapotranspiration (Table 5.6). However, it does not necessarily follow that upward flux accounted for up to 65% of the evapotranspiration.

The modelled and measured soil moisture contents at 10, 20, 60, and 100cm depths are shown in Fig. 5.19. It is clear that WAVES was able to accurately reproduce the daily and seasonal variations in soil moisture for two different soil types. The modelled soil moisture contents agree very well with the measurements with RMSE of 0.062, 0.063, 0.030, 0.008 respectively for the four soil depths shown in Fig. 5.19a. The modelled soil moisture contents for L2 showed better agreement with the measurements at 10 and 20 cm depths compared to L1, with RMSE of 0.060, 0.053, 0.035 and 0.016 at the four depths in Fig. 5.19b. The differences between modelled and measured soil moisture contents for L1 are relatively large at 10 and 20 cm depths for the period of October 1991 to February 1992 (Fig. 5.19).

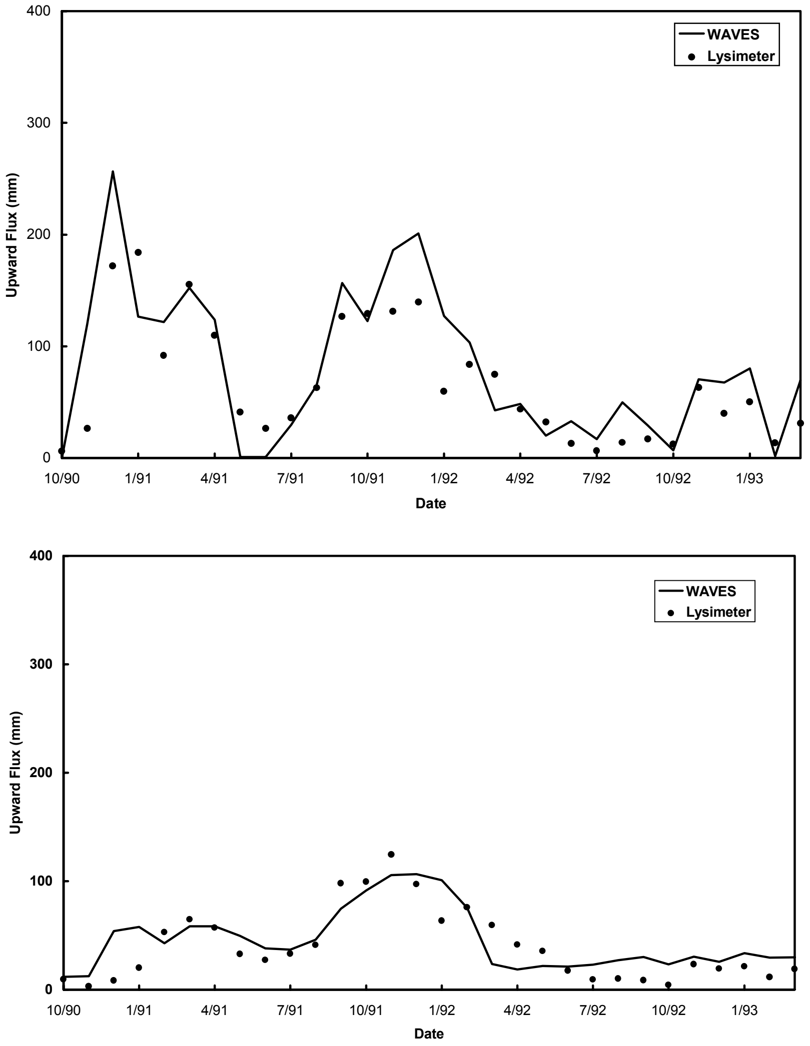


Fig. 5.18. Comparison of modelled (—) and measured (•••) upward flux for (a) Lysimeter 1 and (b) Lysimeter 2.

The distribution of root water extraction is a dynamic process influenced by soil water salinity, and root carbon distribution. Many functions have been proposed to represent water uptake by roots (Molz, 1981). The difficulty of incorporating microscopic variables such as root length and diameter into a macroscopic model is well known. Models that simplify the system, not requiring the measurement and modelling of these microscopic processes for a daily water-balance, offer the most practical tools. In WAVES, the proportion of transpiration taken from a depth node is a function of the amount of root present, and the osmotic and matric potentials at that node. Further, salinity in the root zone decreases apparent water availability, which feeds back to the plant as decreased assimilation and transpiration. WAVES assumes that matric and osmotic effects are identical to the plant in creating water stress, except that the sensitivity of the plant to salt may magnify or reduce the apparent osmotic potential. WAVES only simulates osmotic effects of salt on water availability, and not specific toxicity of high salt concentrations on roots. These approaches, and variations of them, are detailed in Meiri (1984).

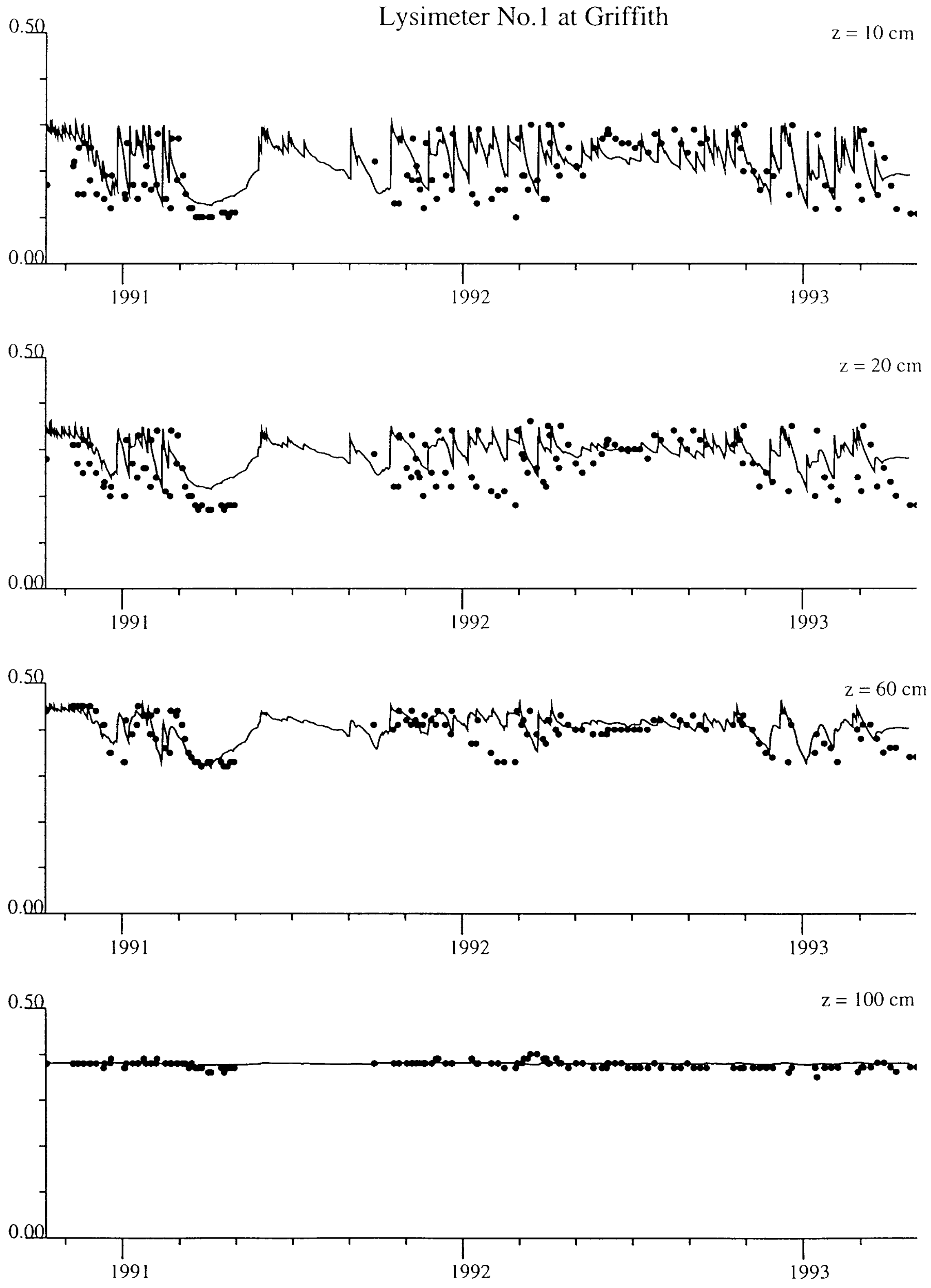


Fig. 19a. Modelled and measured soil moisture content at 10, 20, 60, and 100 cm (lysimeter 1)

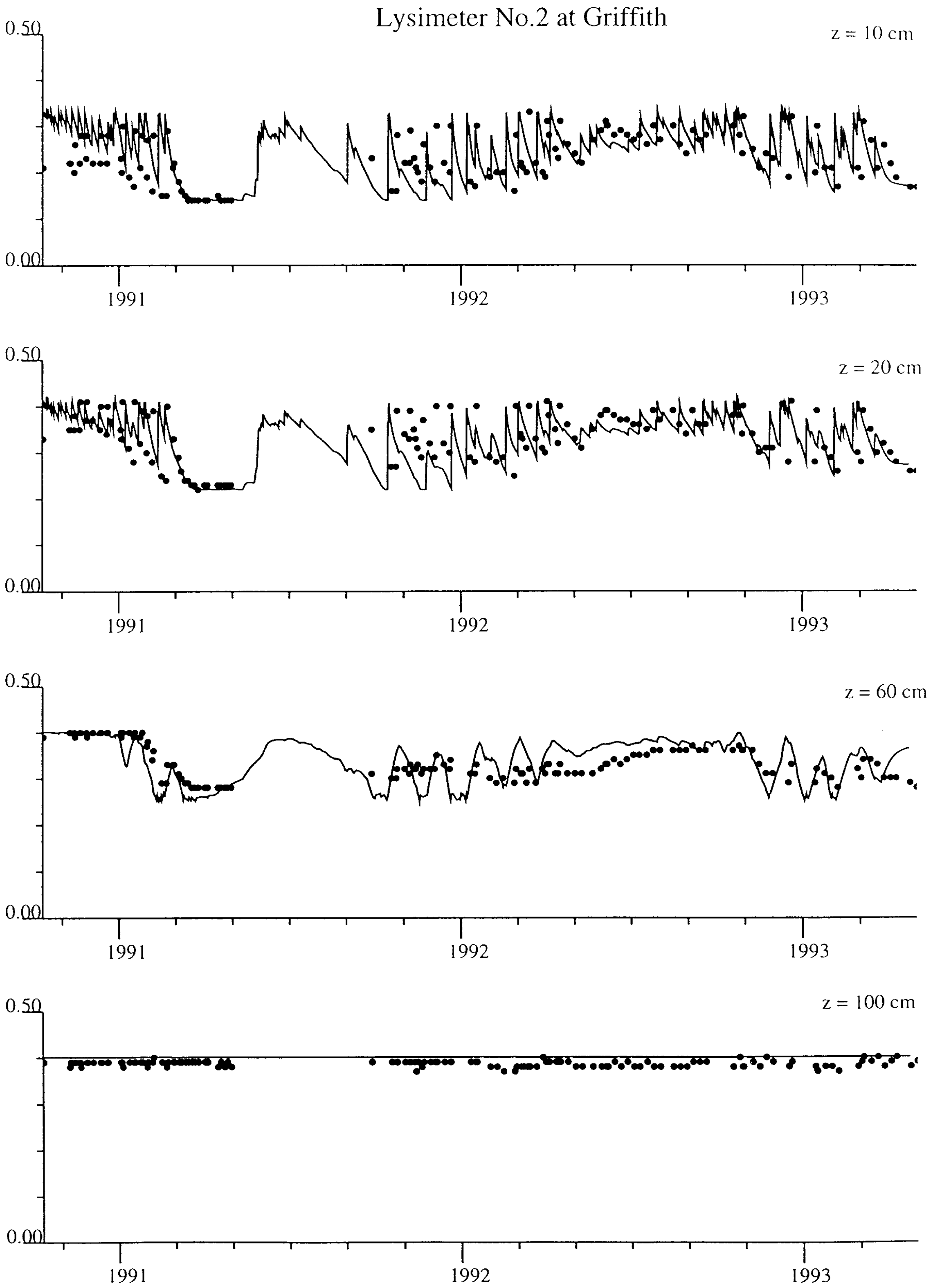


Fig. 19b. Modelled and measured soil moisture content at 10, 20, 60, and 100 cm (lysimeter 2)

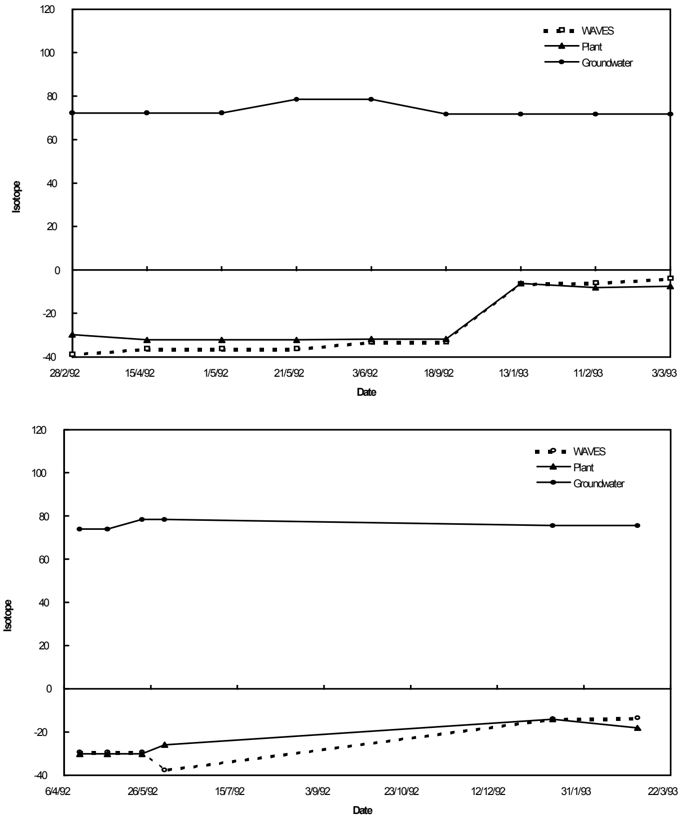


Fig. 5.20. Comparison of the δ^2H values of groundwater, water extracted from lucerne plants, and calculated from the WAVES model during the experiment for (a) Lysimeter 1 and (b) Lysimeter 2.

Root water extraction patterns

To evaluate the plant water extraction patterns in the root zone and groundwater uptake, the plant and groundwater δ^2H values were analysed. It is clear that plant δ^2H values were substantially different from those of the groundwater (Fig. 5.20) and Thorburn *et al.* (1994) concluded that only small (i.e. < 20%) proportions of saline groundwater were taken up by the plants. To compare modelled plant δ^2H values, we calculated the following:

$$\delta^2\overline{H} = \frac{\sum_{i=1}^{n} ET_i \delta^2 H_i}{\sum_{i=1}^{n} ET_i} \qquad (5.2)$$

where $\delta^2\overline{H}$ is the modelled average plant δ^2H value, ET_i is the plant water extraction at depth i simulated by WAVES, $\delta^2 H_i$ is the measured soil water values at soil depth i.

The results shown in Fig. 5.20 indicate that the modelled plant δ^2H values agree very well with the isotope measurements, and this provided an independent test for the model in terms of root water extraction. Using the water balance terms from WAVES, and assuming that irrigation, rainfall, and stored soil water were used in preference to saline groundwater, we estimate that 19% of the upward flux was actually used by the plants for transpiration. Saline water moving from the water table would have replenished soil water deficit caused by the plant water uptake of fresh water from rainfall and irrigation. Given that the potential evaporation was very high and the lucerne did not use appreciable amounts of groundwater, actual evapotranspiration and capillary upflow would have to decline. This is supported by the fact that both evapotranspiration and upflow decreased substantially when the water table was saline (see Figs. 5.17, 5.20, and Table 5.6). These results are consistent with the conclusions of Thorburn *et al.* (1994). Fig. 5.21 shows how the modelled root water extraction pattern changed as a result of the increase in salinity of the groundwater. These results indicate that WAVES accurately simulated the upward flux of groundwater, plant water extraction patterns, and salinity feedbacks to plants.

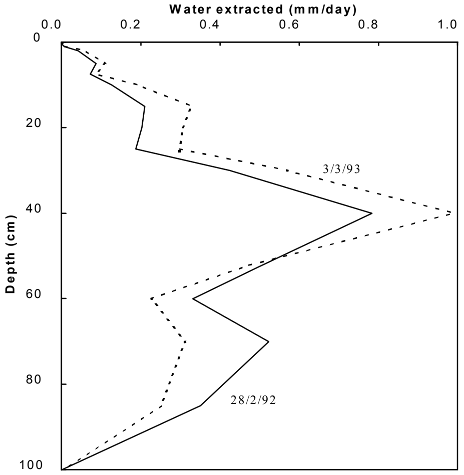


Fig. 5.21. Root water extraction patterns on 28 February 1992 (fresh water (—)) and on 3 March 1993 (saline water (- - -)) for Lysimeter 1. The saline water table was introduced on 4 March 1992 and maintained at 1.0 m until end of March 1993.

Impact of saline watertable on lucerne growth and water uptake

WAVES models coupled water and conservative solute dynamics (Dawes and Short, 1993). As described in the previous section, WAVES also models the osmotic feedback of salt in the root zone on carbon assimilation, transpiration, root growth, and root water extraction. The salinity in the root zone depends on groundwater salinity, upward water flux, root water extraction patterns, rainfall, and drainage. Fig. 5.22 shows good agreement between modelled and measured soil water salinity. While there appears to be some systematic error in the profile salinity, this could be due to collecting water samples by suction applied to ceramic cups.

The convection of solutes was the dominant process, while diffusion and mechanical dispersion played roles in reducing the solute gradients within the soil profile (Fig. 5.23). The magnitude of the errors in the modelled salt concentration due to neglecting either diffusion or dispersion was 5 dS/m. It has been suggested by Morris (pers. comm. 1997) that salt diffusion plays a significant role in the sustainability of vegetation. This measurement and modelling exercise suggests that this is not the case in this irrigated environment.

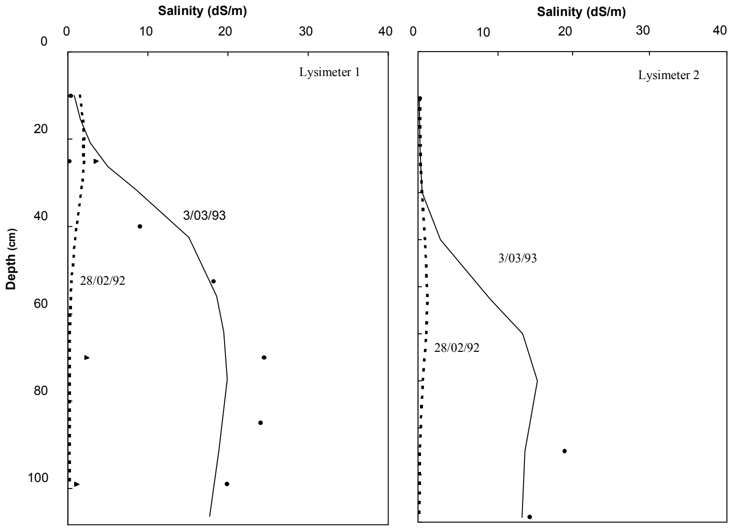


Fig. 5.22. Comparison of modelled and measured soil water salinity for (a) Lysimeter 1 and (b) Lysimeter 2.

Under drying conditions, diffusion and dispersion result in lower salt concentration around maximum root length density and higher salt concentration close to the surface (Fig. 5.22b) (Bresler, 1972). If these processes were not considered, plants would have had less uptake near the watertable, not use as much groundwater, and actual evapotranspiration rates could decline, as the surface soil store is depleted.

The introduction of a saline groundwater table in March 1992 had a noticeable impact on the leaf area index (Fig. 5.16), evapotranspiration rates (Fig. 5.17), and upward flux (Fig. 5.18). During the period of 1992–1993, average leaf area index was reduced by 41%, average evapotranspiration was reduced by 36% (potential ET dropped by 16%), and average upward flux was reduced by 67% (Table 5.6). These decreases can be attributed to an increase in salt in the root zone. Measurements showed that electrical conductivity (EC) of soil water in the root zone was very high, 25 dS/m, toward the end of the experiment (Fig. 5.22) as a result of saline groundwater movement. The high salinity of the soil water reduces the water availability to plants and hence limits plant growth (Hillel, 1980). WAVES was able to model these changes with the parameters measured and calibrated for the period 1990–1991, as outlined in section 5.2.

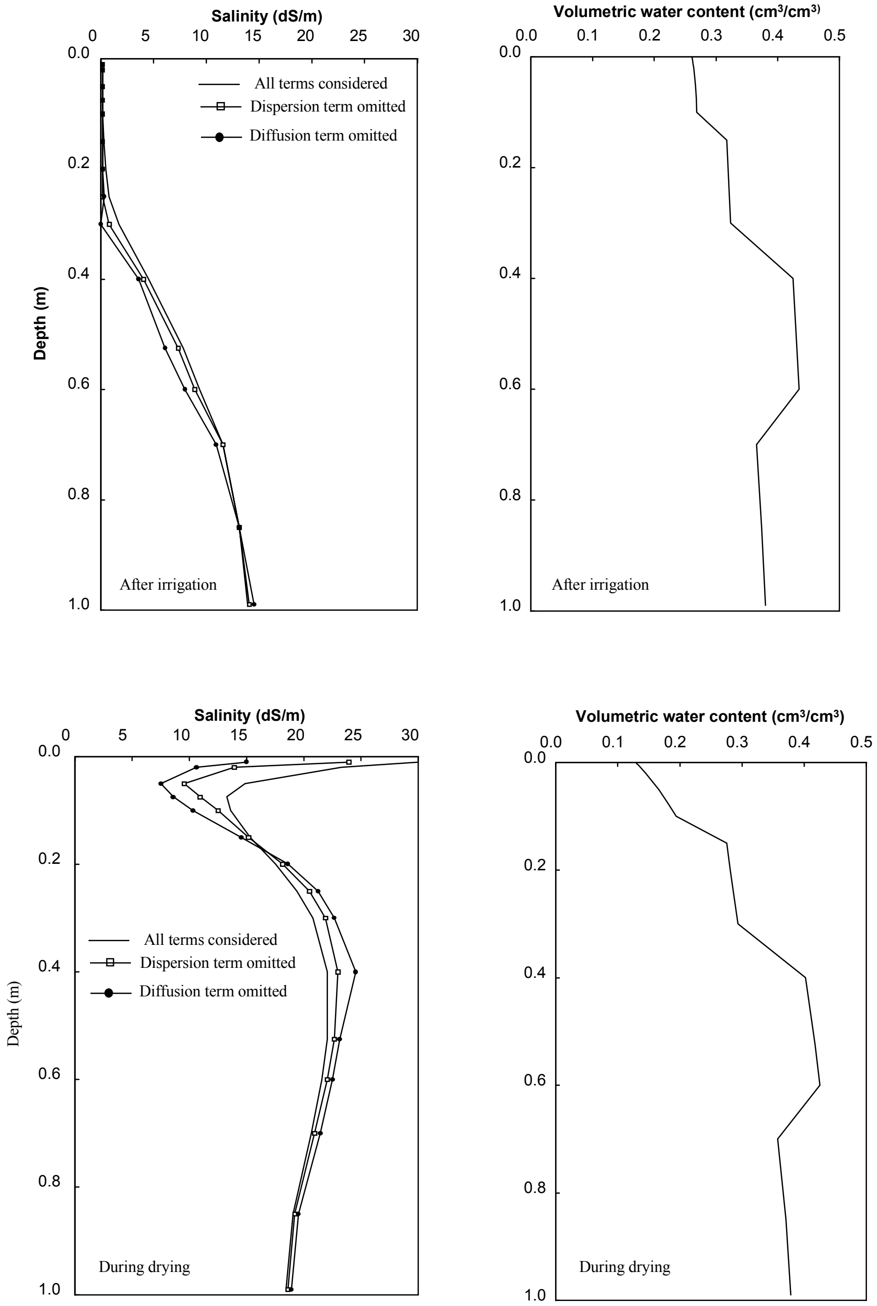


Fig. 5.23. Modelled soil water salinity and soil moisture content profiles after irrigation (a) and during drying (b). The convection, diffusion, and dispersion terms were considered (solid line), dispersion term was omitted (open square), and diffusion term was omitted (solid circle).

Table 5.6. Effect of saline groundwater table on evapotranspiration, upflow, and leaf area index.

	Before			After		
	ET	Upflow (mm/d)	LAI (mm/d)	ET	Upflow (mm/d)	LAI (mm/d)
Lysimeter No. 1	5.9	3.3	2.2	3.8	1.1	1.3
WAVES	5.3	3.7	2.4	3.7	1.3	1.7
Lysimeter No. 2	4.4	2.2	1.9	3.1	0.7	1.4
WAVES	4.1	2.3	2.3	3.0	0.8	1.8

Lysimeters are artificial environments. In the field where groundwater levels will fluctuate, we would expect a reduction in local groundwater levels to occur rather than the large fluxes of upflow as observed. This changes the short term behaviour significantly, but at some point in time, the lucerne will reach an impediment to root growth or meet the regional groundwater heads, and the salinisation of the soil will start at that level. As the deep environment becomes more prohibitive for root water extraction, water levels will start to rise again, and salinisation will creep toward the surface. This situation emphasises the need for an integrated approach to salinity mitigation, combining engineering (*e.g.* pumping), biological (e.g. deep rooted plants, perennial plants, grazing regimes, impact of grazing animals on surface soil properties), and irrigation controls (e.g. irrigation amount, and timing).

5.3.4 Conclusions

In the presence of a shallow saline groundwater table, lucerne does not appear to derive much of its water from the watertable directly, preferring to use 'fresher' water stored in the soil profile. The size and vigour of the canopy developed decreases with increased salt in the root-zone. Root water extraction patterns change as a result of an increase in salinity of the groundwater, and exaggerate drying at the surface. The process of drying out the soil water store causes upward capillary flow of groundwater, and can have a significant impact on groundwater levels in the short term. This capillary upflow causes salt to be brought into the soil and root zones, and this leads to a reduction in transpiration, plant growth, and upward flow. If this process operates without some irrigation, the lucerne crop would not be sustainable, or there would be a large reduction in leaf area.

The comparison between experimental results and those of the WAVES modelling showed that the assumptions inherent in the model capture the key processes relating to groundwater and salinity responses. Only two plant parameters were calibrated and good agreement was found for a wide range of measurements including trends in leaf area index, evapotranspiration, groundwater upflow, soil moisture and salinity profiles. The salinity impacts on water use, root water extraction patterns (from isotope data), and plant growth were fully explained by assuming only the osmotic effects of salt, and using the calibration obtained from the fresh groundwater case. WAVES also simulated the very different measured responses in a second lysimeter where the only difference was the soil profile and hydraulic properties. This gives us confidence that we understand the key processes and feedbacks and that the representations of these in WAVES is both adequate and appropriate. Thus we can use WAVES to investigate the effect of changing the irrigation or groundwater environment on lucerne. With sufficient data, we should be able to predict the long-term sustainability of lucerne under any specified management regime.