IMPROVING WATER USE EFFICIENCY BY REDUCING GROUNDWATER RECHARGE UNDER IRRIGATED PASTURES

Final Report

December 2001

Hayden Kingston, Matthew Bethune, Jahangir Alam

Murray Dairy
Dairy Research and Development Corporation
Goulburn Broken Catchment Management Authority
NSW Agriculture
Murray Land and Water Management Plans
Land & Water Australia research • development • innovation
State Government Victoria Department of Natural Resources and Environment
National Program for Irrigation Research and Development

Improving Water Use Efficiency by Reducing Groundwater Recharge under Irrigated Pastures

FINAL REPORT
Project DAN 11

December 2001

Hayden Kingston
NSW Agriculture, Finley

Matthew Bethune
Institute of Sustainable Irrigated Agriculture, Tatura

Jahangir Alam
Formerly NSW Agriculture, Deniliquin

This report summarises work conducted between July 1997 and December 2001. This project was funded by, Land and Water Australia, the Dairy Research and Development Corporation (DRDC) through the Murray Dairy Regional Development Program, Murray Community Land and Water Management Plans, NSW Agriculture and the Victorian Department of Natural Resources and Environment.

For more information contact

Hayden Kingston
NSW Agriculture

241 Murray Street
Finley, NSW, 2713
Phone 03 5883 1644
Fax 03 5883 1570
Email hayden.kingston@agric.nsw.gov.au

Matthew Bethune
Institute of Sustainable Irrigated Agriculture, DNRE
Private Bag 1, Ferguson Road
Tatura, Vic, 3616
Phone 03 5833 5222
Fax 03 5833 5299
Email Matthew.Bethune@nre.vic.gov.au

Executive summary

The project, 'Improving Water Use Efficiency by Reducing Groundwater Recharge Under Irrigated Pastures' (DAN11), was established to quantify recharge under well-managed flood irrigated pasture. A range of approaches, from field based experimental programs to lysimeters, was used to quantify recharge under flood irrigated pasture. The project focussed on the Berriquin and Shepparton irrigation areas.

Recharge was estimated to be less than 0.2 ML/ha/y on most of the soils examined. The results indicate that recharge on the lighter soils was higher in 1996 than during 1998, 1999 or 2000 on the lighter soils in the Berriquin and Wakool areas. The reduced recharge is associated with drier than average climatic conditions over the study period, and is mirrored by the reduction in regional groundwater levels in both the Berriquin and Shepparton irrigation areas. A review of previous studies identified that recharge in excess of 3 ML/ha/y had been measured on one fine sandy loam soil. However, there is very little supporting information describing recharge under such sandy soils. Irrigation water quality had a large impact on recharge.

Models describing infiltration under flood irrigated pastures needed to account for soil cracks to quantify the rapid initial wetting to depth following irrigation. The SWAP model, which accounts for infiltration through cracks, provided a good description of the soil water dynamics when tested against lysimeter and field data. However, uncertainties in parameters that describe soil hydraulic properties were the major limitation to the practical application of the model at a wider scale. This limitation was also identified at a national workshop, 'Modelling water movement in cracking soils,' organised by the project team.

The model was used to assess the impact of a range of irrigation schedules on recharge. Recharge levels were found to be relatively insensitive to irrigation schedule on the heavier clay loam soils. However, irrigation schedule had more of an impact on recharge on a fine sandy loam. An appropriate framework is required that delineates soils that are suitable for flood irrigation, soils where we can reduce recharge by improving irrigation management, and soils unsuitable for flood irrigation. The main impediment to developing such a framework is the lack of good data describing soil hydraulic properties.

Policy implications

- Good management of flood irrigated perennial pastures on heavy clay loam soils in Northern Victoria and southern NSW will not result in excessive recharge.

- Recharge under flood irrigated sandy soils is likely to be excessive in many areas. Improved scheduling of flood irrigation had only limited scope to reduce recharge. Alternative irrigation systems, use of deep-rooted perennials such as lucerne, modified layouts or land use change may be options to reduce recharge in these areas.

- Increasing water salinity will increase recharge under irrigated pasture. Water managers need to assess the risk of increased water salinity resulting from regional salt disposal and reuse schemes and dryland salinity. Increased irrigation water salinity resulting from any of these factors will inevitably result in increased recharge.

- Pasture water use was well defined by the reference crop evapotranspiration (ET_o- FAO-56). Therefore, ET_o provides an upper limit on pasture irrigation requirements and should be adopted for setting maximum annual irrigation intensities. The setting of maximum irrigation intensity can be refined further if the amount of rainfall that contributes to plant water use is quantified.

- There is some scope to reduce recharge during winter by drying the soil profile in autumn. However, the pasture rootzone is too shallow to prevent recharge every winter. Limiting the time for infiltration through good surface drainage still offers the best method for reducing recharge during winter.

- Recharge occurred over the spring period as a result of increased soil water storage over winter. Improved irrigation scheduling during spring may encourage plant water extraction of this excess stored water and reduce recharge.

- The SWAP model could be used to inform policy decisions. It described the key components of the water balance, including infiltration through soil cracks. Small conceptual changes to the SWAP model were required to enable its use in the irrigation region, and these should be formalised to provide a robust tool for assessing policy options.

- A major limitation to the use of models for informing policy and management is the lack of good data describing the soil hydraulic properties affecting water movement. A methodology to transfer soil properties across spatially varying soils is also required.

- Farm management practices (such as nutrient management) have a large impact on the amount of dry matter produced per unit of water.

Recommendations

- Evapotranspiration and effective rainfall data should be used to set maximum irrigation intensities for irrigated perennial pastures. A practical process to measure actual irrigation intensity on irrigated dairy farms should be developed. This requires measurement of the irrigated area of perennial pasture and water applied to this area. The setting of this maximum irrigation intensity is the first step in identifying which farms are over irrigating and potentially have high recharge.

- A maximum acceptable level of recharge needs to be defined for irrigated pastures. This level would provide a basis for targeting farms to change management where unacceptable recharge levels occur.

- The extent of light sandy soils with potential for high recharge needs to be appraised. This will allow management on these areas to be assessed and modified if necessary to reduce recharge. It will also be useful information for long term planning and consideration of future irrigation development.

- Changes made to the SWAP model, so that it could be applied to flood irrigation, should be clearly documented and formalized with the original model developers for incorporation in future releases of the model. This will benefit future studies looking at the water balance of cracking soils. Funding for a visiting scientist may be an effective method to achieve this.

- Further investigation of the hydraulic properties of soils in this region should be undertaken. The appropriate scale for such investigations should be considered, as data describing hydraulic properties is also limiting in many other irrigation areas. Improved understanding of hydraulic properties of soils would enable the application of models such as SWAP for use in assessing the impacts of management and policy decisions on recharge.

- Continued promotion of Best Management Practices for irrigation management and pasture production is required. These practices will increase the production per unit of water.

Acknowledgments

We would like to thank the following organisations for their support for this project: Land & Water Australia, Dairy Research and Development Corporation (DRDC), Murray Dairy (MD), Murray Irrigation Land & Water Management Plans, Department of Natural Resources and Environment, Victoria and NSW Agriculture. There are many people who have had input into or assisted during the course of the project: Firstly, the steering committee who provided valuable insight and direction, from the initial project development through to submission of the final report. A special mention must go to the farmers whose co-operation was invaluable to the running of the field sites and to Tony Cook whose hard and tireless work was largely responsible for the successful running of the lysimeter experiment. We also acknowledge the input of Iain Hume and David Mitchell who assisted in setting up and developing methodology for running and interpreting the field sites, Garry Bond for assistance with running the field sites, Barbara McAllister for clerical support and Dr Leigh Callinan for biometric support.

Steering committee members and affiliation

Member	Affiliation
Nick Austin	NSW Agriculture
Martin Blumenthal	NSW Agriculture
Neil Campbell	Dairy farmer
Keith Nicol	Dairy farmer
Alfred Heuperman, replaced by QJ Wang	DNRE
Maurice Incerti	Murray Dairy
Warren Mason	DRDC
Geoff Mcleod	Murray Irrigation Limited
Brett Tucker, replaced by Murray Chapman	NPIRD-L&W Australia

Main Report

Improving Water Use Efficiency by Reducing Groundwater Recharge Under Irrigated Pastures

Introduction

Approximately 65% of water extracted for irrigation in Northern Victoria and over 30% in the NSW Murray Valley is applied to pastures. In 1996, Murray Irrigation Limited (MIL) introduced a Total Farm Water Balance Policy which aimed to limit farm water use to sustainable levels and hence to reduce groundwater recharge to the district watertable. The dairy industry had some concerns with the original limit of 4 Ml per hectare and initiated discussions between NSW Agriculture, MIL, Murray Dairy and farmers to evaluate the implications of the policy for the dairy industry in the Southern Riverina. This process highlighted the lack of knowledge of recharge beneath flood irrigated perennial pastures.

This project was developed to measure recharge beneath irrigated perennial pastures on a range of soil types in the region, assess management practices that minimise groundwater recharge and to provide vital information for refinement of policy and adoption of improved practices by irrigation managers and farmers.

Project objectives

1. Quantify groundwater recharge under well managed irrigated perennial pasture for a range of soil types.
2. Delineate and quantify the contributions of physical processes and management practices on groundwater recharge.
3. Use measured recharge levels to test the ability of existing models to predict recharge under a range of field conditions.
4. Determine practices that minimise groundwater recharge while optimising pasture production and water use efficiency.
5. Evaluate the sustainability of perennial pasture production under different scenarios.
6. Through a participative approach assist irrigation managers and farmers to develop sound water use policy and the adoption of improved irrigated pasture management practices.

Project framework

Three field sites in southern NSW and a lysimeter facility at Tatura, Victoria, were established to quantify groundwater recharge on a range of soil types (Objective 1). Data from previous experiments were reviewed and re-analysed to provide additional information on recharge over a wider range of soil types. The key physical processes affecting recharge were assessed using results from the lysimeter and field sites (Objective 2). Data collected at the field sites were used to test the WAVES model. Through this testing it was identified that soil cracking was an important process affecting water movement in these soils. Another model that incorporated soil cracking (SWAP, developed in the Netherlands) was tested using the lysimeter and field site data (Objective 3). A national workshop was organised to assess the ability of current models to simulate the water balance in cracking soils, and practical limitations in the application of models. SWAP was then used to simulate the impact of different management scenarios over a fifteen year period to assess the impact on groundwater recharge and pasture productivity (Objective 4). The sustainability of pasture production was assessed in terms of the ability of soils to achieve the leaching requirement necessary to maintain soil salinity within acceptable levels (Objective 5). The results from the project have been communicated to farmers, water managers and scientific audiences (Objective 6).

Report structure and definitions

This report addresses each of the project objectives individually. Supporting information and details of project work are attached. Reference to these attachments is indicated by (#), with # indicating the attachment number. A summary of abbreviations and definitions is provided at the end of the report.

Objective 1

Quantify groundwater recharge under well managed irrigated perennial pasture for a range of soil types

Methods

- Three dairy farms using 'best farm management practices' were selected from the Wakool and Berriquin Irrigation Districts in southern New South Wales. Two sites were monitored on each property, corresponding to the heaviest and lightest soils on the farm. Soil moisture, watertable level and dry matter production were measured over the period 1/96 to 10/00. Recharge was estimated using Darcy's law and salt balance techniques (1).
- A lysimeter experiment was conducted at Tatura to quantify recharge. Twenty-four intact soil cores of 2m depth and 0.75 m diameter were extracted from a Gl soil with established pasture. The lysimeter water budget was monitored from 1/99 to 7/01. The impact on recharge of watertable depth and irrigation were assessed (2).
- A review of studies quantifying recharge under flood irrigated pasture was conducted (3).
- Results from a leaching study conducted prior to DAN11 were reanalysed to understand factors affecting recharge at a sub-catchment scale at Tongala in northern Victoria (4).

Results

- Recharge was less than 0.5 ML/ha/y for the majority of soils examined (Table 1).
- The variability in recharge estimates (Table 1) cannot be solely explained by differences in soil texture. Site conditions, such as depth to watertable, irrigation intensity and water quality, can override the impact of texture on soil water movement and thus recharge. High watertables (<2m) were present in all of the measurements.
- The estimates of recharge made in DAN11 may be less than in an average climatic year due to drier climatic conditions and limited irrigation allocations. Recharge for the Sms was estimated to be 0.7 ML/ha/yr in 1996 and 0.2 ML/ha/yr in 1999.
- Recharge estimated by Darcy's law was typically greater than that measured by salt balance. This difference is attributed to the uncertainty in hydraulic properties used to calculate the Darcian flux.
- There is little information on recharge under sandy soils. Recharge exceeding 3 ML/ha/yr was recorded on a fine sandy loam (not in this study). There is also anecdotal information suggesting recharge rates up to 5 ML/ha/yr could occur on the lightest sandy soils. Irrigation intensities of 15ML/ha have been recorded in small areas such as the Campaspe area of northern Victoria. Irrigation audits have also revealed that up to 40 % of applied water has passed below the rootzone on sandy soils in the Kiewa Valley and Gippsland area.

Table 1. Recharge rates for a range of soil types under flood irrigated pasture (ML/ha/yr).

Soil type	Gl DAN 11	Sms DAN 11	Wl DAN 11	Cl DAN 11	Cl DAN 11	Bl DAN 11	Bl DAN 11	Efsl	LL	SFSL	NFSL
Average	0.2	0.3	0.07	1.2*	1.2*	0.15	0.2	0.05	0.05	0.10	3
Standard error		0.14	0.04	0.5	0.3	.07	.13	0.02	0.03	0.05	

Gl=Goulburn loam, Sms =sandmount sand. Wl =Wakool loam, Cl =Cobram loam, Bl =Birganbigil loam, Efsl-east shepparton fine sandy loam, GL-goulburn loam. LL = lemnos loam, SFSL= shepparton fine sandy loam. NFSL = naneela fine sandy loam. *Groundwater was used for irrigation at these sites.

Conclusions

- Considerable variation in recharge was observed. Generally, recharge on the clay loams and heavier soils was small (less than 0.2 ML/ha/y).
- There is very little information about recharge on the lighter sandy soils. The existing recharge measurements vary considerably from 0.05 to 3 ML/ha/y on a FSL. This highlights that many others factors, in addition to soil texture, impact on recharge.
- The magnitude of recharge under light sandy soils needs to be better quantified. The extent and environmental implications of high recharge rates need to be addressed and understood.
- The spatial variability in recharge is high. The reported results are point estimates and may not apply at the field scale. Techniques need to be developed that allow field estimates of recharge to be made from point measurements.

Objective 2
Methods

Delineate and quantify the contributions of physical processes and management practices on groundwater recharge

Results from the lysimeter [2] and field experiments [1] were analyzed to identify the timing of recharge and factors affecting recharge. Results from a leaching study in northern Victoria were reanalysed to assess factors influencing recharge [4]. The impacts of management practices are considered under Objective 4.

Results

- Watertable depth and irrigation deficit had only a small impact on recharge in the lysimeters. It is thought that the low conductivity of the soil overrided the impact of the watertable depth and irrigation deficit. This will not always be the case for more permeable soils [2].
- Recharge at the field sites was greater in areas with the shallowest watertables, indicating that localised recharge is contributing to a groundwater mound under these lighter soils [6]. This same trend was observed in the Tongala area [4].
- Infiltration through cracks explained the rapid watertable fluctuations following irrigation on a cracking soil.
- Recharge occurred during the irrigation season at the NSW field sites, particularly on the sandier soils. Recharge in the lysimeters predominantly occurred during the winter period, when the soil was wet for long periods due to low potential plant water use (ET_o). Differences in rainfall and soil permeability between sites explain these trends. The difference between ET_o and rainfall (ET_o-R) indicates that rainfall exceeds ET_o over winter, by on average (over years 1986-2000) 50 mm at Tatura, and 15 mm at Finley. ET_o exceeded rainfall in 4 of the last 5 years at Finley (Fig 2). This lower winter rainfall is reflected in lower recharge on the fine sandy loam soils (FSL). This lower recharge may also result from lower water allocations over the same period. No difference was observed in the heavier clay loam soils.
- The high recharge rate measured in 1996 in the FSL soils followed two consecutive wet winters. A reduction in measured recharge on the FSL since 1996 was matched by a lowering in regional watertables since 1995. No reduction in recharge was seen in the heavy soils over this period.
- Recharge can be restricted by layers of low permeability or by high groundwater pressures in regional aquifers. Such restrictions can substantially reduce recharge. Information describing the nature of the restriction is usually not collected or available to modelling studies. More effort needs to go into describing the nature and impact of sub-surface restrictions to groundwater flow if accurate prediction of recharge is to be achieved.
- Irrigation water salinity had a large impact on recharge at both the Finley and Tongala areas. This occurs as a result of increased soil permeability and reduced plant water use.
- High recharge is associated with the lighter prior stream soils [10]. The soils near the prior stream bed being the most permeable, with recharge decreasing with distance from the prior stream (Fig 1). The higher recharge in these soils is also reflected in the watertable levels, with higher groundwater pressures forming under the prior stream soils [10].

Fig 1. Impact of prior stream activity on soil texture and recharge.

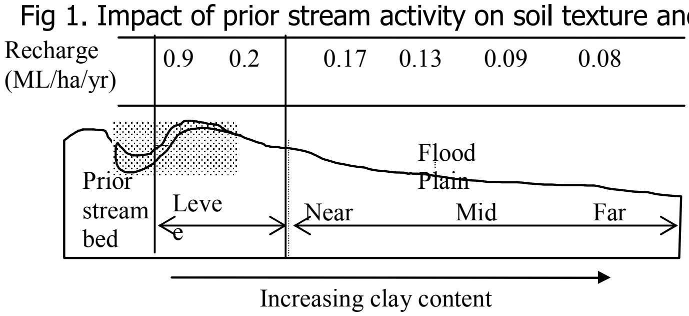
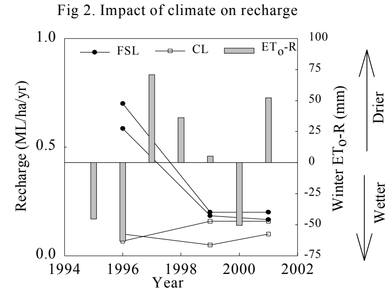


Fig 2. Impact of climate on recharge



Conclusions

- Soil texture, irrigation water quality and underlying groundwater pressures all have large impacts on recharge.
- Recharge predominantly occurred during winter at Tatura, and during the irrigation season at Finley. This results from differences in rainfall and soil properties between the Finley and Tatura sites.
- Measured reductions in recharge over the last five years are reflected in the observed falls in regional watertable levels, and correspond to a period of low winter rainfall.
- Recharge estimates in DAN11 may underestimate the long-term average recharge due to drier conditions.
- Prior stream activity is linked to recharge processes. Recharge resulting from irrigation is much more likely on the texturally lighter soils close to the bed of the prior stream.

Objective 3
Methods

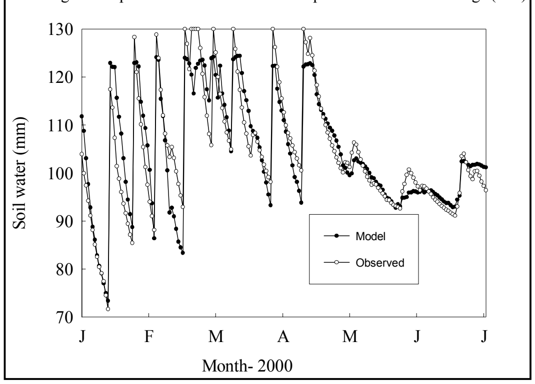
Use measured recharge values to test the ability of existing models to predict recharge under a range of field conditions.

- The WAVES model was initially used to model the soil water balance. It requires inputs describing soil hydraulic properties, irrigation, climate data, grazing and watertable depth. Outputs from the model include pasture growth, soil moisture and water balance data.
- The lysimeter data set was used to test the model on a cracking soil (5).
- The model was tested against measurements of soil storage and pasture production at the field sites (6). No component of the soil water balance (other than soil water storage) was measured. Therefore, the ability of the model to simulate other components of the water balance could not be fully tested against the field data.
- A national workshop was conducted to identify technical and functional weaknesses in modelling approaches and the ability of existing models to underpin water policy and planning (7).

Results

- The WAVES model predicted dry matter production well. However, it was not able to predict the rapid changes in soil water following infiltration through soil cracks. This process is not simulated in WAVES. Soil properties had to be adjusted to account for infiltration through soil cracks. The impact of this adjustment was to over predict recharge.
- The SWAP model, which accounted for the impact of infiltration through cracks, was tested against lysimeter data. It provided a good description of components of the water budget. Therefore, it was considered that the model could adequately describe the soil water balance and recharge processes under flood irrigated pasture (5).
- The SWAP model provided a good description of the soil water dynamics (Fig 3) at the NSW field sites (6). The definition of the lower boundary condition (depth to watertable) had a major impact on predicted recharge levels. Therefore, use of the model for predictive applications needs to ensure that the lower boundary condition is well defined. The model needed to be adjusted to predict dry matter production at each site. This was attributed to differences in fertiliser management, soil salinity levels and pasture composition.
- The modeling workshop identified that model development had exceeded the available data

Fig 3. Comparison between observed and predicted soil water storage (200)



required to run and test the models. A clear recommendation was that good descriptive information, in particular, well-documented case studies of the water balance in cracking soils, are required. We also need good hydraulic data that characterise the soil water relationship. Without such information, it is not possible to develop or verify models describing water movement in cracking soils, nor apply them to practical problems, such as predicting recharge, with confidence [7].

- SWAP predicted the relative reduction in pasture yield observed in the lysimeters resulting from water stress.
- SWAP predicted lower recharge since 1995, which matches reductions in regional watertables since this time.

Conclusions

- Soil cracking dominated infiltration into the majority of soils studied. Adjusting hydraulic properties to compensate for infiltration of water through soil cracks resulted in over prediction of recharge. Models that do not conceptually capture key processes affecting the soil water balance should not be used for predictive analysis of different management scenarios.
- The SWAP model described the key components of the water balance well, including infiltration through soil cracks. The model also prediction relative reductions in pasture yield well. Small conceptual changes to the SWAP model were required to enable its use in the irrigation region.
- Uncertainty in model inputs, particularly describing soil hydraulic properties, was the major limitation to the practical application of the model to quantitative studies.
- Good experimental programs are required that characterise soil properties affecting water movement. A process to transfer soil properties across spatially varying soils is also required.
- The correct definition of the lower boundary conditions is a limitation to the practical application of models for predicting recharge. Field trials need to place greater emphasis on measurement of data that allow accurate definition of this lower boundary condition.
- Given the above limitations, it was considered the SWAP provided a useful tool for qualitative studies of recharge.

Objective 4

Determine practices that minimise groundwater recharge while optimising pasture production and water use efficiency

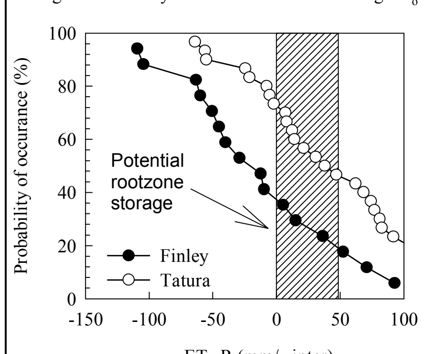
Methods

The SWAP model was used to assess the impact of a range of irrigation practices on recharge over a 15-year period, from 1986 to 2000 [(8)]. The testing was conducted for two soil types for which hydraulic data were available, a Clay Loam (CL) and a fine sandy loam (FSL). A fixed pressure, equivalent to observed watertable levels, was applied to the bottom of the soil profile (2.5 m deep). Management options considered were: 1) Irrigating on an E-R of 50 mm (I_{50}), irrigation on an E-R of 80 mm (I_{80}), irrigation on a fixed interval (I_{day}), no autumn irrigation after 15th April (I_{aut},) and no spring irrigation before 15 September (I_{spr}). The potential to reduce recharge using sprinkler irrigation was also tested. The outputs from the simulations should be viewed in a qualitative manner due to uncertainties in model inputs.

Results

- Average recharge on the CL was 0.6 ML/ha/y for I_{day}, varying between 0.2 and 1.1 ML/ha/y. The other irrigation schedules reduced recharge by 30 % to 0.4 ML/ha/yr. This estimate is similar to that measured in the lysimeter experiment and does not represent a large water saving
- Average recharge for I_{day} and FSL was 2.0 ML/Ha/y, ranging between 0.9 and 2.7 ML/Ha/y. Improved scheduling techniques reduced recharge by 30 % on this soil. However, recharge under these improved techniques was still too high. The area of such permeable soils that are flood irrigation needs to be identified, as does the potential impact of this high recharge surrounding lands.
- The modelling did not account for the increased groundwater pressure that would have resulted from the high recharge under the FSL. This impact of this pressure would be to reduce recharge. The interaction between vertical movement of water in a point model such as SWAP and a 3-D groundwater system is still a major limitation to the application of models to describing recharge.
- For the FSL, I_{days} had higher recharge than the other treatments (2 ML/Ha/y). This indicates that scheduling can reduce recharge on the FSL. Recharge is likely to be excessive under FSL even under good flood irrigation management. A hypothetical simulation, where frequent, small, sprinkler irrigations were applied, reduced recharge to under 1 ML/ha/yr on the FSL. This indicates the scope for reducing recharge on FSL using sprinklers. This requires further assessment before management practices and policy changes are recommended.
- Average lysimeter dry matter production in year 3 (20 tDM/ha) was twice that observed in year 2 (10 tDM/ha), even though plant water use was the same. This change corresponded to a substantial increase in fertiliser application and highlights the importance of nutrient management on WUE.
- There is an 80 % probability of winter rainfall exceeding ETo (ETo-R <0) at Tatura, and a 40 % probability at Finley (Fig 4). By not irrigating close to winter, pasture could potentially dry the soil profile sufficiently to store 50 mm of excess rainfall. This would reduce the probability of occurrence of winter rainfall exceeding soil water storage and plant water use (ET_o-R <50) recharge to 5 in 10 years (Tatura) and 2 in 10 years (Finley). This highlights that drying the rootzone prior to winter has scope to reduce, but not eliminate winter recharge [(3)].

Fig 4. Probability of winter rainfall exceeding ET_o



Conclusions

- Scheduling irrigation reduced recharge on the CL. The magnitude of recharge was small and only small water savings would be realised. The potential environmental benefits from reducing recharge may be more important.
- Irrigation scheduling reduced recharge on the FSL, however recharge was still excessive. If pasture is to be grown on such soils then alternative irrigation systems need to be considered to reduce recharge. The alternative systems need to offer control over both timing and depth of irrigation water application. Further testing of the potential to reduce recharge on SFL soils using alternative irrigation systems is required.
- Soils vary considerably spatially in the field. Lack of good soil hydraulic data prevents testing the impact of irrigation management on transitional soils, which texturally fall between a CL and FSL.
- Acceptable levels of recharge need to be defined, based on the resulting environment and production costs. A framework should then be developed to identify which soils have acceptable levels of recharge, and when changes to management, irrigation system or enterprise are required.
- Increased nitrogen application led to twice the production from the same amount of water. This highlights the potential for large increases in WUE efficiency through improved nutrient management.

Objective 5

Evaluate the sustainability of perennial pasture production under different scenarios.

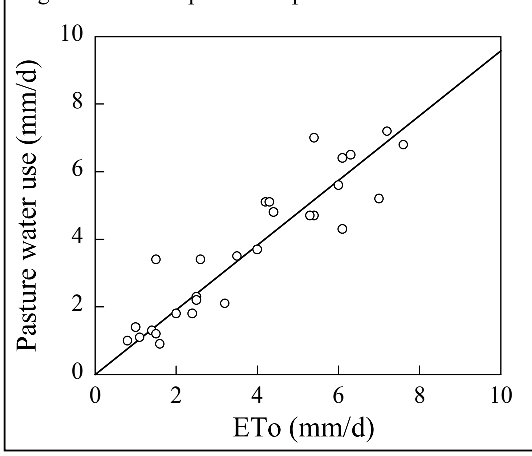
Methods

The sustainability of perennial pasture is assessed in terms of the ability to maintain soil salinity at acceptable levels and the irrigation requirement to maintain pasture production. The amount of recharge required to keep soil salinity at acceptable levels was calculated using Rhodes equation and measured recharge rates were compared with required leaching rates. Pasture water requirements were assessed using lysimeter data. Temporal and spatial trends in watertable data were examined to assess the impact of recharge on groundwater hydrology and surrounding areas.

Results

- Only 0.1ML/ha/y of leaching is required to prevent salt stress on a clover based pasture where irrigation water salinity is 0.1 dS/m. The leaching requirement increases with irrigation water salinity, such that 1 ML/ha/y of recharge is required for an irrigation water salinity of 1.0 dS/m. The sandy loam soils can achieve this level of leaching. Leaching appears to be restricted on many of the heavier clay loam soils, and thus pasture production may be compromised.
- Increases in irrigation water salinity will lead to greater recharge and therefore greater environmental problems associated with irrigation (viz high watertables).
- High recharge close to the prior stream results in the formation of a groundwater mound. This results in net movement of groundwater from the prior stream soils to the lower, heavier soils. It is

Fig 5. Relationship between pasture water use and ET_o



considered that recharge management should target these areas of lighter prior stream soils. This may reduce the need for sub-surface drainage in the heavier soils at distance from the prior stream. This process has been observed at a number of sites in northern Victoria. The extent to which it occurs in other localities needs to examined prior to recommendations being made.

- The upper limit to pasture water use was well defined by ETo (FAO-56) [#], with pasture water use equalling 0.96 ETo (Fig 5). This relationship held in both the lysimeter experiment and on a district farm when pasture water use was measured using Bowen Ratio technology. Average required irrigation intensities (for the last 16 years) were calculated for different percentages of effective rainfall (the percentage of rain utilised by the pasture. Table 2). 75% of rainfall was effective in the lysimeters. However, lysimeter runoff may not be typical of field conditions. The level of effective rainfall needs to be quantified so that sensible caps on irrigation intensities can be calculated.

Table 2. Required irrigation for different amounts of effective rainfall

Location	100 %	75%	50%
Tatura	7.5	8.5	9.3
Finley	10	10.5	11

Conclusions

- Sufficient leaching can be achieved on the studied soils to maintain soil salinity at acceptable levels providing leaching is not restricted further due to the development of high watertables.
- Increased irrigation water salinity is a threat to the sustainability of pasture production. This results from potentially limited leaching achievable on the heavy soils.
- Increased irrigation water salinity will lead to greater recharge and potentially increased areas with high watertables.
- Pasture water requirements are well defined by reference crop evapotranspiration (FAO-56). Therefore, irrigation limits for pasture in northern Victoria and southern NSW should be based on ET_o[#].
- High recharge on prior stream soils could potentially affect the sustainability of pasture production on the lower, heavier soils, which occur at distance from the prior stream.

[#] Many areas of southern NSW use a locally calibrated form of the Penman equation to estimate potential plant water use (ET_p). ET_p and ET_o (FA0-56) are closely related, with ET_p being 25% higher that ET_o. Therefore, crop coefficients will need to be adjusted accordingly where ET_p is used to estimate potential plant water use.

Objective 6

Through a participative approach, assist irrigation managers and farmers to develop sound water use policy and the adoption of improved irrigated pasture management practices

Methods

- This project has developed information for input into a policy framework. Communication of this information was managed through a Steering Committee, which was responsible for monitoring project progress and inputting to the strategic directions and policy implications. Irrigation managers and farmers were represented on this committee.
- A considerable number of presentations and field visits were conducted during the project. Presentations on the project's progress have been made to Land and Water Management Plan (L&WMP) Groups, L&WMP Annual Research and Develop (R&D) Updates and to farmer groups. Milestone reports and progress reports have been provided to the Murray L&WMP R&D Committee when produced.
- DAN11 was linked to the Improved Irrigation Practices (IIP) for Forage Production project. IIP integrates social, economic and research issues relevant to the dairy industry. Results from DAN11 were incorporated into communication activities of the IIP project and have been widely disseminated through this forum [(9)].
- Experimental results have been presented in conference papers and will be submitted for journal publication in 2002. Eight journal papers are currently in preparation [(9)].
- A national workshop on modeling water flow in cracking soils was conducted in May 2001 at the request of Land and Water Australia (L&WA). A report summarizing this workshop [(7)] is available through the L&WA web site This report has been widely disseminated.

Policy implications

- A maximum acceptable level of recharge needs to be defined for irrigated pastures. This level would provide a basis for targeting farms to change management.
- Recharge under the heavy clay soils was small. The management options considered did not reduce recharge greatly. Therefore, changes to land and water management offer little scope to reduce recharge on these soils.
- The biggest benefits in reducing recharge are likely to occur in areas of sandy soils that are flood irrigated. The extent of flood irrigation on light sandy soils needs to be appraised. This will allow management on these areas to be assessed and modified if necessary to reduce recharge. It will also be useful information for long term planning and consideration of future irrigation development.
- Further investigation of the hydraulic properties of soils in this region should be undertaken. The appropriate scale for such investigations should be considered, as data describing hydraulic properties is also limiting in many other irrigation areas. Improved understanding of hydraulic properties of soils would enable the application of models such as SWAP for use in assessing the impacts of management and policy decisions on recharge. Decisions can then be made on whether recharge can be controlled for a particular soil through improved management, or whether changes in irrigation system and/or changes in land use are required. Soil hydraulic properties are not well defined in most irrigation areas in Australia. Consideration is required towards a larger scale study into soil hydraulic properties, including methodologies that allow hydraulic properties to be transferred across data poor areas.
- Potential evapotranspiration (FAO-56 - ETo) and effective rainfall data should be used to set maximum irrigation intensities for irrigated perennial pastures. The setting of a maximum irrigation intensity based on actual plant water use is the first step in identifying which farms over-irrigate and potentially have high recharge.

- A practical process for assessing which farms use more water than the maximum irrigation intensities should be developed. Farms using excess water can then be target for improved management.
- The SWAP model was an effective tool for assessing the impacts of policy decisions on recharge. The modifications made to the SWAP model so that it could be applied to border irrigation on cracking soils should be clearly documented and preferably formalized with the model developers so that the changes are included in future releases of the model. This would allow the experiences gained in this project to be built on by future research investigating the water balance of irrigated cracking soils. Funding for a visiting scientist would allow the model developer to visit Australia, and would be an effective method for achieving this.
- Continued promotion of Best Management Practises for irrigation management and pasture production is required to increase production from a land and water perspective.

Conclusions

- Clear policy directions have been developed for water managers.
- The results and recommendations have been presented to the L&WMPs in southern NSW and northern Vic.
- Further support is required to ensure that this information is incorporated into the policy making process.
- Consultation with farmers should be a joint initiative between the project team and water managers to ensure a balanced perspective is presented on the implications of the results for policy development.

Definitions

Best management practices- Farms using current best management practices were selected for field sites. This required that the sites have a whole farm irrigation plan, be landformed and have a surface water drainage and recycle system. Additional requirements were that the farms were highly productive with higher than average inputs of fertiliser and stocking rates and finally that the farmers were also required to be active members of dairy discussion groups.

Clay loam soil (**CL**) defines a soil that is on the heavier end of soils flood irrigated for growing perennial pasture. A lemnos loam soil would be considered typical of this soil group.

Fine sandy loam soil (**FSL**) is on the lighter end of soils flood irrigated for growing perennial pasture. A Shepparton fine sandy loam is representative of this soil group.

Land and Water Management Plans (**L&WMP**). This project worked with Murray and the Shepparton Land and Water Management Plans.

Recharge is used in this report equates to the difference between drainage losses below the rootzone and capillary rise into the rootzone.

Reference crop evapotranspiration (**ET_o**) defines the evapotranspiration from a well-watered reference crop. ET_o in this report is calculated using the procedure documented in FAO Irrigation and Drainage Paper 56, 'Crop evapotranspiration- Guidelines for computing crop water requirements. This assumes the reference crop is grass. A locally calibrated form of the Penman equation is used in many areas of southern NSW to calculate reference crop evapotranspiration (ET_p). ETo and ETp are strongly related, with ET_p being 25 % higher that ET_o.

E-R is the cumulated difference between pan evaporation and rainfall

List of attachments

1 NSW field sites
2 Quantification of the water balance of border check irrigated perennial pasture
3 A review of groundwater recharge studies below flood irrigated pasture
4 Factors affecting recharge under border check irrigation of pasture
5 Simulating the water balance of flood irrigated pasture on a cracking soil
6 Model testing against field sites
7 Modeling water movement in cracking soils – Workshop proceedings, 16-17 May 2001
8 Assessment of scheduling options to reduce recharge under border irrigated pasture
9 Communication activities in DAN11 and IIP project
10 Relationship between recharge, watertable levels and prior stream activity in Northern Victoria, Australia

IMPROVING WATER USE EFFICIENCY BY REDUCING GROUNDWATER RECHARGE UNDER IRRIGATED PASTURES

Report on NSW Field Sites

Attachment 1

Hayden Kingston, NSW Agriculture, Finley
and
Jahangir Alam, Formerly NSW Agriculture, Deniliquin

introduction

Murray Irrigation Ltd (MIL) introduced a Total Farm Water Balance Policy in 1996. The policy aims to limit on farm water use intensity to sustainable levels and hence to reduce accessions to the district water table.

The original limit was set at 4 ML per hectare and this was of concern to the dairy industry as many farms were currently using between 4 and 6 ML of water per hectare. Discussions were held between NSW Agriculture, dairy farmers, MIL and Murray Dairy to evaluate the implications of the policy for the dairy industry in the Southern Riverina. These discussions and consultation with researchers highlighted the lack of knowledge of groundwater accession beneath flood irrigated perennial pastures.

Community consultation since the inception of the Total Farm Water Balance Policy has led to its modification. It is now less rigid and account is taken of good management and the level of farm development in setting the target water limit of an individual farm. This raising of irrigation intensity was based on the assumption that recharge is least beneath "best practice" dairy farming. This project was developed to measure groundwater accessions under "best practice" dairy farming. Recharge benchmarking of best practice is an important step in justifying the current Total Farm Water Balance Policy and vital information for refinement of that policy.

Earlier Victorian work suggests that recharge is higher where the watertables are deep. Research into recharge beneath rice growing has shown the recharge increases as the clay content of the soil decreases. Dairy farming is practiced on the lighter soils of the riverine plain and these are the most texturally variable and are commonly underlain by prior streams (Butler, 1950). Shallow watertables are common beneath the parts of the landscape used for dairy farming and these watertables are used in some areas as a source of irrigation water. The exploitation for irrigation and therefore depth of these watertables varies both in time and space, this variation must be evaluated, its effect on recharge estimated and these effects "factored" into a more targeted sustainable farm water use value.

Site selection

Farms using current best practice were identified for use in this study. To be selected a farm had to have a whole farm irrigation plan, be landformed and have a surface water drainage and recycle system. In addition to having a high standard of irrigation development and management the farms had to have highly productive perennial pastures with higher inputs of fertiliser and stocking rates than the district average. In addition the farms managers-owners had to be active members of dairy discussion groups, be willing participants in training activities and be leaders in the implementation of new technology. Considering these criteria for farm selection, three farms were selected in the Murray Valley region, one in the Wakool Irrigation District and two in the Berriquin Irrigation District. On each farm two locations were selected based on EM 31 survey depending on the extremes of frequency distribution. The upper point was designated as site H (heavier soil) and the lower point site as L (lighter soil) at each site. At Farms 1 and 2, H and L sites were in the same bay; at Farm 3 H and L sites were in two different bays.

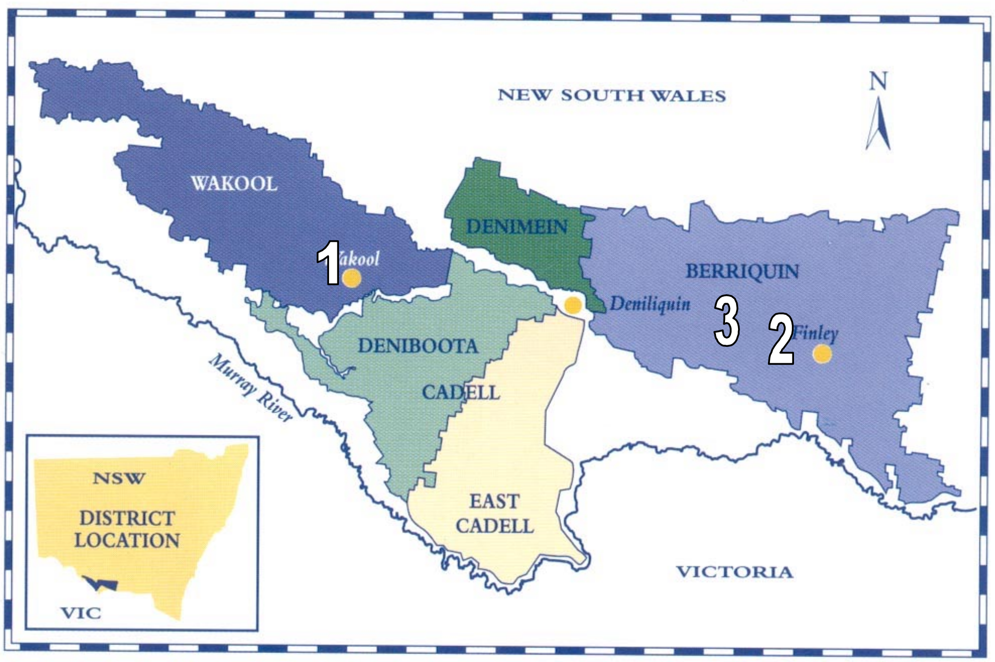


Figure 1. Location of field sites.

Site description

Farm 1

The site lies within the Deltaic Deposits and Aeolian Sandhills physiographic subdivision of Smith et al. (1945). The deposits of this subdivision were associated with the change in course of the old Cochran Creek watercourse; they slope gently westward and are situated above the "treeless plain". The deposits of this subdivision consist of gravel beds, fine and coarse sands, loams and silty clays. The natural topography of the area was of low rises, gentle slopes and low depressions of heavy soils. The landscape had only internal drainage to the small depressions. These were filled with water by heavy rain and the ponds formed in this way were slowly exhausted by evaporation or slow percolation into the subsoil.

The experimental site traverses the catenary sequence of the red-brown earths identified by Smith et al. (1945). The soils trend from almost pure Sandmount Sand at the highest point of the site through to a Wakool Loam at the lowest.

Farm 2

This site lies on the old flood plain of the Murray River. The soil of the site is classified as the Cobram-Katunga series (Smith, 1945) these soils are all red-brown earths dominated by Cobram loam. Smith (1945) suggested that the soils of this material were all derived from the same parent material, consisting of "mixed light sediments". He identified a number of soils, which developed in a catenary sequence ranging in soil texture from fine sands (Sandmount Sand) to the fine sandy clays (Cobram Loam).

The experimental site showed no obvious differences (colour changes or differential growth of pasture) in soil type. There were, however, marked changes in the colour of the banks delineating irrigation "bays" within the experimental site suggesting that the soil was spatially variable.

Farm 3

This site is also located on flood plain of the old Murray River. Its soil is mapped as the Birganbigil-Wandook series (Smith 1945). This soil catena parallels the Cobram group, but comprises heavier textured soils intermediate between the soils of the channel deposits and those of the flood plains. The series contains three soils. In increasing order of clay content and decreasing rate of internal drainage these are Birganbigil Loam, Tuppal Loam and Wandook Loam.

This experimental site also showed no obvious differences in soil type and there was also no evidence of colour change in the irrigation earthworks of the site.

Soil sampling and analysis - soil texture and salinity

Methods

The soil at each measurement location was sampled to a depth of 120 cm in 15 cm increments by hand auger. All soil samples were sub sampled in the field and the gravimetric soil water content of the sub sample measured. The main samples were air dried, ground by jaw crusher to pass a 2 mm sieve. All chemical analyses were of the soil water extract obtained by tension wetting and centrifugation (Slavich and Pettersen, 1993). The electrical conductivity of the soil water extract was measured with a conductivity meter (Metrohme model). Soil texture was determined from its saturated water content (SP) by the relationship developed by Slavich and Pettersen (1993).

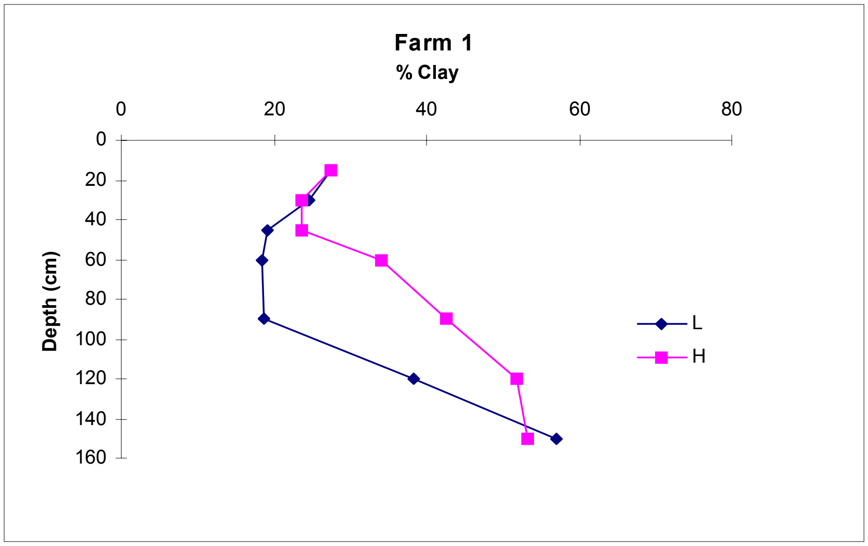
Results

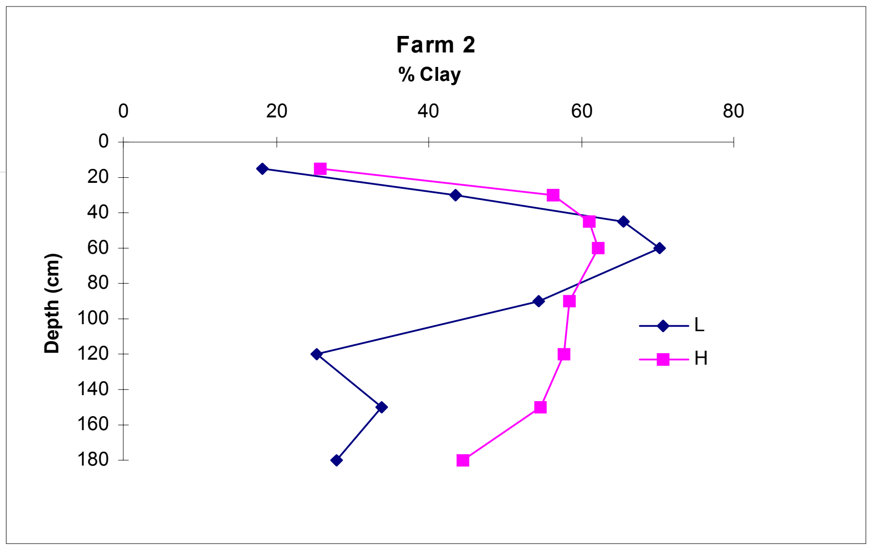
There was considerable difference in both the textural and salinity profiles of the soil sampling sites. At each of the farms the average texture of the soil profile of the H sites was always heavier (containing a higher proportion of clay) than the L sites (Figure 2) and the soil salinity of the H sites was higher (Figure 3). These differences were tested formally by analysis of variance (Genstat, 1989). Differences in texture between sites were found to be significant at the 5% probability level and differences in salinity were more pronounced being significant at the 1% level.

Two different shapes of textural profile were found; one where the clay content increased gradually with depth (Farms 1 and 3) and another with a pronounced peak in clay content (Farm 2). The soil of the H and L sites at Farm 1 had similar texture at the surface (< 30 cm deep). The clay content of the soil of the H site increased gradually with depth below 40 cm. The clay content of the L site declined between 20 and 40 cm and increased between 80 and 160 cm at which depth the soil had the same clay content as the H site. The H and L sites of Farm 3 had similar shaped soil textural profiles, rising gradually in clay content with depth. The clay content of both sites was the same at the surface (<30 cm) below this depth the H site had a consistently and significantly higher clay content.

Both the H and L sites at Farm 2 exhibit a peak in clay content of similar size at a depth of 50 cm. The peak of the L site is more pronounced because the soil beneath the peak had a significantly lower clay content than the soil of the H site.

At all three farms the depth weighted average salinity was higher at the high EM31 site. There was a general trend for soil salinity to increase with depth, there were however a few exceptions (Figure 3). Soil salinity at the L site at Farm 1 showed the opposite trend with higher soil salinity near the soil surface. The soil salinity profile of the L site at Farm 2 showed a pronounced peak between 40 and 60 cm with a marked decline in soil salinity below this peak. The salinity profile of the H site was more uniform showing a slight peak at 40 cm, a decline between 40 and 80 cm and increasing once more below 80 cm. The salinity of the H site was significantly higher, in a statistical sense, than that of the L site below 120 cm.





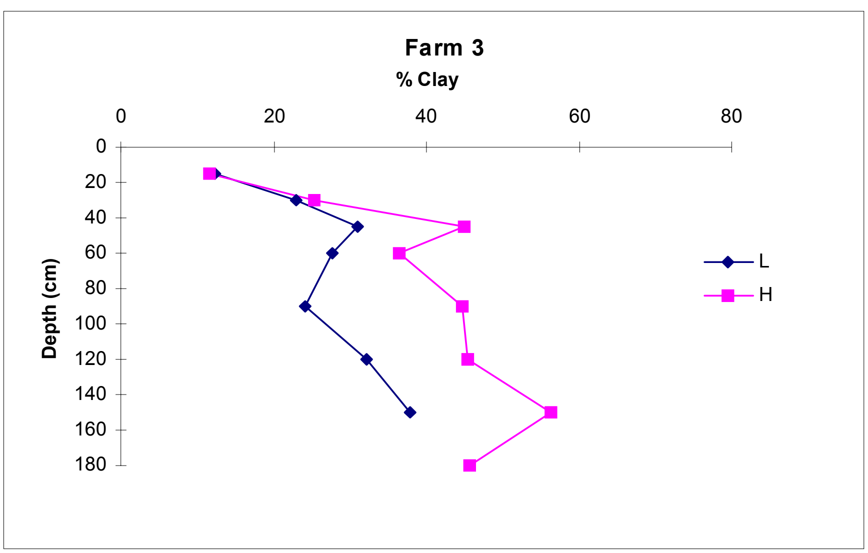
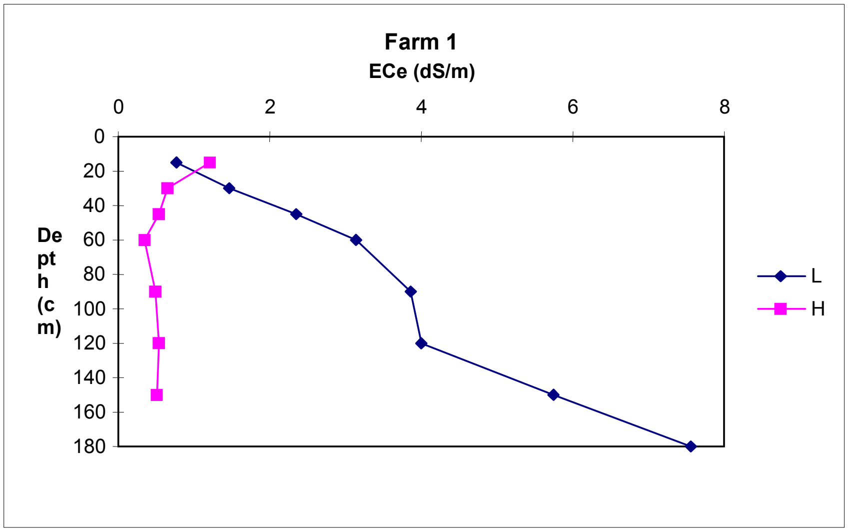
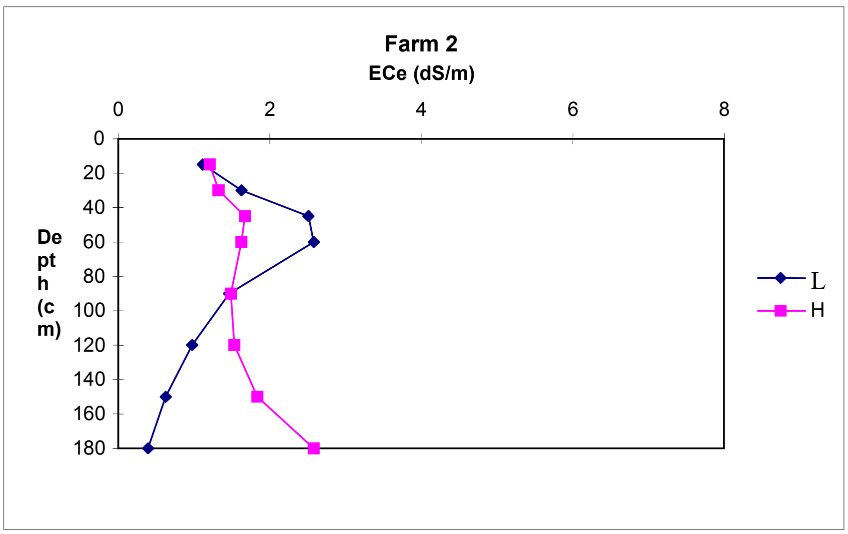


Figure 2: Soil textural profile at the recharge measurement locations





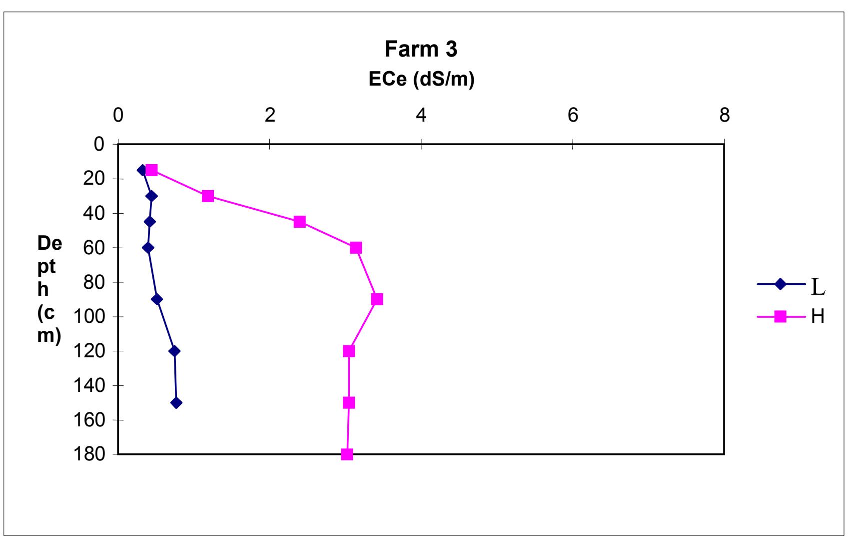


Figure 3: Soil salinity profiles at the recharge measurement locations

Measurement of soil water content

Soil water content was measured at both high and low EM sites on all three farms using EviroSCAN. The EnviroSCAN sensor measures the complex dielectric constant of the soil-water-air medium and consequently, its water content (Sentek 94). Six sensors were mounted on each probe at depths of 10, 20, 30, 50, 90 and 140 cm. The moisture content was recorded every six hours.

Soil was sampled before and after irrigation to get the wettest and driest field conditions to calibrate EnviroSCAN soil water content to actual moisture content. A push tube sampler with 5 cm diameter was used and soil was sampled up to a depth of 90 cm with 10 cm increments. In each location, three cores of the soil profile were collected. Water content was determined gravimetrically. Bulk density was estimated from the 10 cm long segments and considered that the diameter of soil sample was 5 cm. Volumetric soil water content was calculated by multiplying gravimetric soil water content by soil bulk density.

The relationship between soil water content predicted by the EnviroSCAN instrument and volumetric soil content was determined by linear regression.

The sites were calibrated during the pilot project and the calibrations are documented in the report. (Hume et al 1997) The calibration was repeated at Farm 2.

Measurement of watertable

Piezometers were installed to measure soil water pressure levels. Initially one piezometer at 2m depth was installed at all sites. Later three more piezometers at depths of 20, 40 and 70 cm were installed to check for any possibility of perched watertables. The piezometer tubes were constructed from 5 cm diameter class 5 PVC water pipe. Slots were cut in the lower 25 cm of the pipe and the lower end was sealed to stop water entry inside the piezometer tube from the bottom. The piezometer tubes were installed in oversized hand auger holes. The bottom 25 cm slot was surrounded with coarse sand and a sodium bentonite cap was placed above the sand to protect any flow downward adjacent to the piezometer tube. Then the auger hole was backfilled up to a depth of 10 cm from the soil surface where another bentonite cap was placed and then again filled with soil up to the surface.

Soil water pressure was measured as the standing water level in the piezometer. A fox whistle attached to a tape was used to measure water level. Initially measurements were made infrequently when visiting the experimental sites for pasture cuts or other measurement purposes. From the end of August 1998, dataflow loggers were used to measure the watertable in the 2.0m depth piezometer at an interval of 8.0 hours.

The main points to note in this chart of watertable movements is the responsiveness of the watertable to irrigation or rainfall events, with a rapid rise in watertable height occurring after an event and the seasonal trend of falling watertables during the winter and higher watertables during the irrigation season. It should be noted that winter conditions during these years were relatively dry and this seasonal trend may not be so pronounced during a wet winter. These trends were observed at all sites.

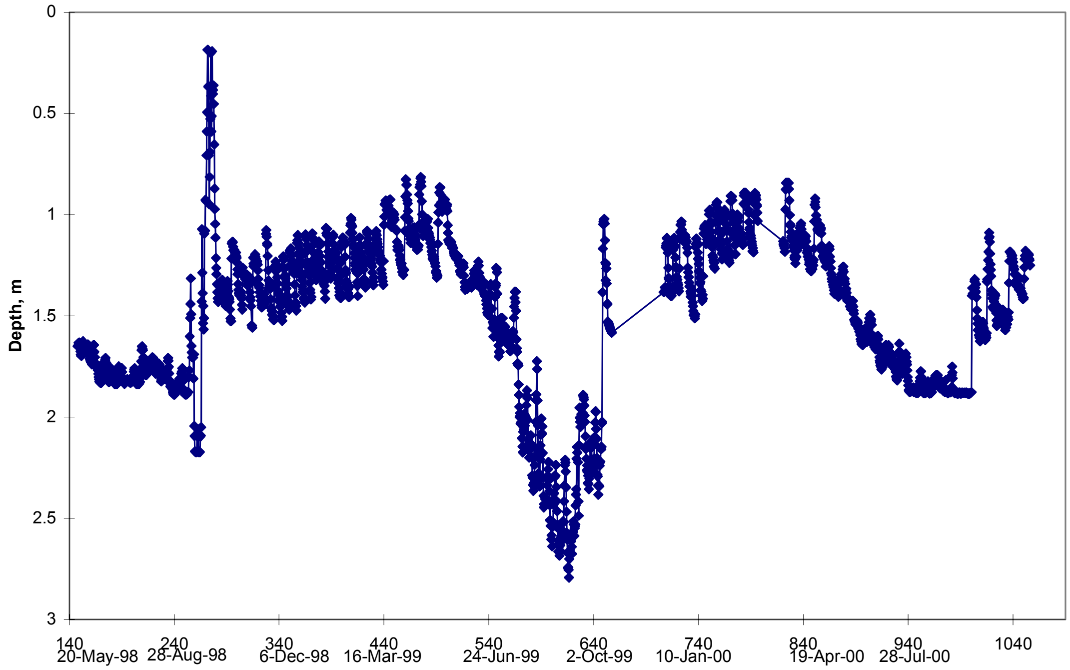


Figure 4. Water table depth at Farm 3 High EM site.

Pasture production

Steel pasture exclusion cages (60 x 120 cm) were used to protect pasture from grazing stock. There were four cages at each location. Fifty by fifty centimetre quadrants were used to take pasture cuts just after grazing. Pasture samples were taken from both inside and outside of the cages to give pre and post grazing pasture mass. Dry matter was determined by drying the samples at 70 degrees C for 24 hours. During 1998-99 the pasture species were separated and dry matter was determined separately, for the remainder of the experiment only total pasture dry matter was measured.

Pasture production data is summarised in table 1.

At farms 1 and 3 the trend was that the heavier soil produced less pasture than the lighter soil, but at Farm 2 where the soils were less variable pasture production was similar for both sites. Pasture production was higher on Farm 2 and 3 this was mainly due to higher fertiliser inputs, particularly nitrogen, on these farms and was also influenced by pasture composition.

Pasture composition

During 1998-99 pasture samples were separated by species. The pasture at Farm 1 which had been established longer was paspalum dominant whilst pastures at Farm 2 and 3 were ryegrass dominant. Separation of pasture samples was discontinued after the first year as it was determined that the pasture growth would be modelled as a mixed sward rather than as individual species.

	Farm 1		**Farm 2**		**Farm 3**	
1997-98	**Light**	**Heavy**	**Light**	**Heavy**	**Light**	**Heavy**
Pasture Growth	16852	13024	25418	26043	21231	20083
Pasture Utilised	12369	10177	19975	20252	18473	16978
1998-99 Pasture Growth	19743	15718	20781	20770	23724	19056
Pasture Utilised	13465	11055	15678	14792	16714	14096
1999-2000 Pasture Growth	21019	14450	30899	31485	26987	22307
Pasture utilised	14785	8977	22071	21201	17909	15506

Table 1. Summary of Dry Matter Production (kg DM/ha) at each site

Soil water flow/flux

Soil matric potential (Ψ), total potential (h) (matric, Ψ + Gravitational potential, Z) and unsaturated hydraulic conductivity were predicted from the measured profiles of soil moisture content by the Broadbridge and White soil model. Matric potential is related by the equation:

$$\Psi = \lambda_c \{ (T - 1)/ (T) - 1/c \, In \, [C - T)/ T (C-1)]\}$$

where, T = effective saturation of the soil = $(\theta_s - \theta)/ (\theta s\_\theta_r)$,$\theta s$ = saturated water content, θ_r = residual water content, λ_c and **C** are fitted parameters.

Broadbridge and White describe unsaturated hydraulic conductivity by the following equation:

$$\mathbf{K}_T = \mathbf{K}_s \, (T)^2 \, (\mathbf{C-1})/(\mathbf{C} - T)$$

Where, **K**s = saturated hydraulic conductivity

The instantaneous vertical flow rate of water in the soil ($q_{i(1-2)}$) between adjacent depths at which soil water content measurement was measured was calculated by Darcy's Law:

$$\mathbf{q}_{i(1-2)} = K_\theta[(h_1 - h_2)/z_1 - z_2)]$$

Soil moisture content, θ were made daily by picking one value close to midday everyday out of four six hourly readings in 24 hours. The instantaneous flow rate, qi(1-2) was assumed to be in effect for one day. The depth of the flow measurement was considered at the deepest point in the soil, which remained saturated throughout the measurement period. The height of the piezometer pressure was used to represent the saturated zone.

Table 2. Recharge (ML/ha) estimated from soil water flux

	Farm1		Farm 2		Farm 3	
	L[1] (15)	H(70)[2]	L (25)	H(40)	L(40)	H(70)
96-97 Irrigation[3]	1.34	-0.25	0.006	-0.44	- 0.55	-0.40
97 Winter	1.16	-0.07	-0.0005	-0.18	0.03	-0.10
97-98 Irrigation	2.74	-0.37	0.012	-0.86	- 0.56	-0.70
98 Winter	0.99	-0.09	0.01	-0.14	- 0.04	-0.20
98-99 Irrigation	xxxx	-0.39	0.03	-0.73	- 0.78	-1.00
99 Winter	1.52	-0.09	0.01	-0.11	-0.13	-0.21
99-00 Irrigation	xxxx	-0.27	0.03	-0.66	-0.74	-0.85
2000 W	-0.01	-0.07	0.005	-0.22	-0.34	-0.20
00-01 Irrigation	xxxx	-0.36	0.007	-0.60	xxxx	xxxx

Notes: 1. L = Low EM Site and H = High EM Site
2. Depth (cm) at which drainage/recharge is estimated
3. Irrigation season September 1- May 31
4. Minus figures are downward flow

* No data available for estimating recharge for farm 3 for the irrigation season 2000-2001

Comments and recommendations

Using this methodology to calculate soil water flux and to estimate recharge has several limitations under the field conditions that are experienced on flood irrigated perennial pastures in this region.

Soil hydraulic properties/characterisation – the soil hydraulic properties used to estimate recharge have a big impact on these estimates. For this project soil hydraulic properties were determined by evaporating profile (Hume et al 1997). Further investigation of the soil hydraulic properties that should be measured and the methodology to measure them was a key recommendation from the national workshop on the modelling of soil water movement in cracking soils (Bethune and Kirby, 2001)

Water table fluctuations – the height of the watertable at the 3 sites and the responsiveness of the watertable following irrigation meant that at times the watertable was within the rootzone of the pasture during the irrigation cycle. To take account of the variable watertable conditions at each site recharge estimates had to be made at different depths in the profile. This introduced more variability and less confidence in the results particularly at the sites with very shallow water tables where estimates of recharge were made at shallow depths that were within the rootzone of the pasture.

The following table shows the recharge estimated at all sites at a depth of 70cm, this depth is below the rootzone of the pasture but at the sites with shallow water tables would be within the water table for part of each irrigation cycle.

Table 3. Recharge (ML/ha)estimated from soil water flux at a depth of 70 cm

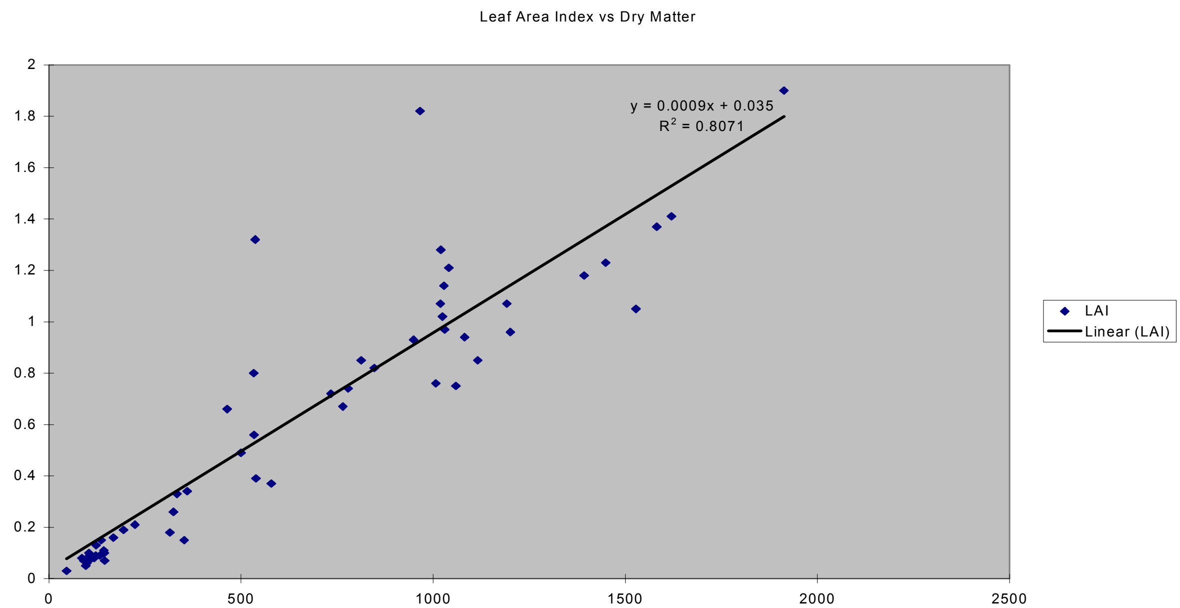
	Farm 1		Farm 2		Farm 3	
	L[1]	H	L	H	L	H
96-97 Irrigation[2]	0.36	-0.25	-0.04	-0.75	-0.64	-0.40
97 Winter	0.10	-0.07	-0.01	-0.30	-0.06	-0.10
97-98 Irrigation	-0.22	-0.37	-0.07	-1.14	-0.63	-0.70
98 Winter	0.00	-0.09	-0.03	-0.33	-0.05	-0.20
98-99 Irrigation	-0.67	-0.39	-0.09	-0.79	-0.15	-1.00
99 Winter	-0.06	-0.09	-0.02	-0.18	-0.08	-0.21
99-00 Irrigation	-0.33	-0.27	-0.09	-0.73	-0.98	-0.85
2000 Winter	-0.01	-0.07	-0.01	-0.22	-0.16	-0.20
00-01 Irrigation	-0.28	-0.36	-0.08	-0.73	xxxx	xxxx

Notes (1) L = Low EM site and H = High EM site
(2) Irrigation season September 1 – May 31

Leaf area index

Information on Leaf Area Index (LAI) and Specific Leaf Area (SLA) for the pastures at the experimental sites was required for the modelling component of the project and our inquiries showed that there was very limited data available in this region or Australia. Sarah Dickson collected this data as part of a student summer project and the project team collected further data. The following chart shows the relationship between LAI and pasture dry matter production based on the data collected.

Data was collected for individual species in the pasture, but for the modelling component of the project we have considered the pasture as a mixed sward. The LAI of our pastures was generally lower than those reported in the international literature.



WAVES modelling

The WAVES model

WAVES stands for Water Atmosphere Vegetation Energy and Solute transport modelling. WAVES is a complex biophysical process-based model that simulates movement of water, energy and solutes in a vertical system involving interactions within the soil-vegetation atmosphere system on a daily time step (Hatton et al. 1995). The model consists of four sub-models, which simulate the energy, water, carbon (plant growth) and solute balances. The model energy balance partitions net radiation into canopy and soil available energy. Evaporation and transpiration are calculated using the Penman-Monteith equation using available energy, air temperature and vapour pressure deficit. (Dawea and Hatton 1993)The plant growth stresses induced by the availability of light, water and nutrients are modified by air temperature and salt in the rootzone, feedback to carbon assimilation and plant growth and ultimately to stomatal conductance and transpiration (Hume et al. 1998). Soil water movement is described by Richards equation. This module handles rainfall infiltration, runoff, evaporation and water extraction, moisture distribution and groundwater recharge (Zhang et al. 1998). The Broadbridge and White (BW 1988) soil model was used to describe the relationships between water potential, volumetric moisture content and hydraulic conductivity to solve the Richards equation. The BW model has five parameters: saturated hydraulic conductivity (K_s), saturated volumetric moisture content (θ_s), air-dry volumetric water content (θ_r), capillary length (λ_c) and a shape parameter (C). The solute in the WAVES model is considered to be sodium chloride and does not interact with or affect the soil hydraulic properties. Solute transport is solved using the convective-disperse equation (Slavich et al. 1998).

Model calibration

The WAVES model was calibrated for the Farm 3 high EM site for a three-month period from December 1997 to February 1998. Although the pasture was a mix of different species, it was considered as a single species for the purpose of calibration purpose. Leaf Area Index (LAI) from the model was converted into dry matter production and compared with field measured dry matter production. Dry matter production, soil moisture content and evaportranspiration for the three month period were used as a test of the model. Vegetation parameters were initially set from the C3 per veg file provided by the model developer and these were changed to fit the actual pasture in the field. Soil hydraulic properties were used from the pilot project report which were determined by inverse modelling. One of the hurdles to fitting the hydraulic properties was saturated hydraulic conductivity. The actual saturated hydraulic conductivities were very low at all sites. Cracking or macropore flow is significant on these soil types but the WAVES model has no capacity to handle this crack flow. To allow water to pass through the soil profile and incorporate the cracking effect, the saturated hydraulic conductivity was increased several times to reduce runoff to reasonable levels. Otherwise most of the irrigation or rainwater escaped as runoff from the field. Data from a nearby weather station were used as the climatic data file. Irrigation dates were derived from the EnviroScan data and measured watertable data was interpolated for use in the calibration.
After calibration of the model it was run for the period of 1996 to 1998 for all sites.

Results and discussion

Calibration

Dry matter production

Pasture was cut regularly before and after grazing throughout the experimentation period and dry matter production was calculated. The aim of calibration for dry matter production was to determine the appropriate vegetation growth parameters for pasture and apply them for the longer term simulation. Figures 1 and 2 showed the calibration results for perennial pasture at Farm 3 high EM site. The modelled yield agreed well with these field values. For the calibration period, pregrazed production was higher at the start and gradually decreased with time. This was probably due to the impact of higher temperatures on pasture production later in the calibration period.

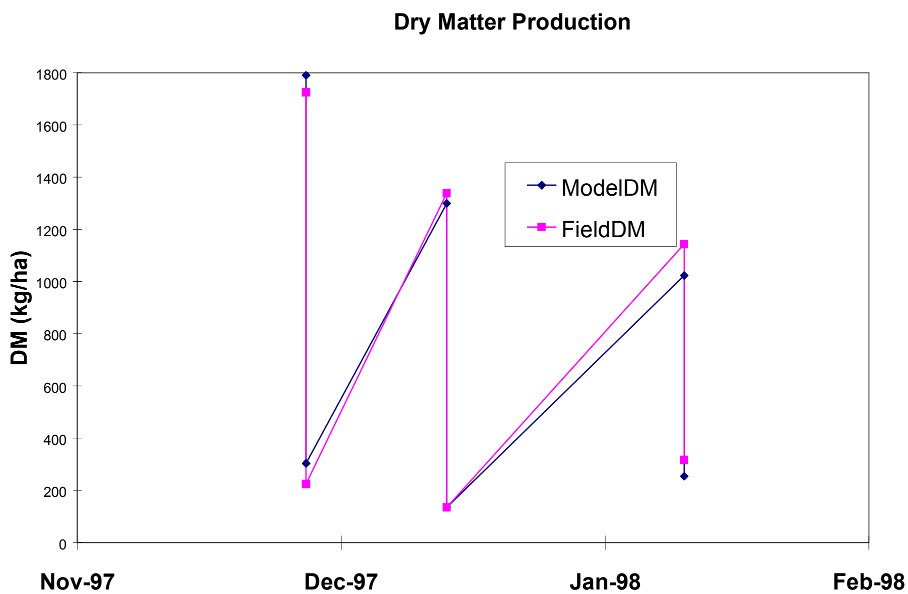


Figure 5. Comparisons of the modelled and field pre and post grazed dry matter production.

There was also a good agreement between pre and post graze cumulative dry matter production (Figure 6). WAVES successfully modelled pasture production.

Cumulative dry matter production

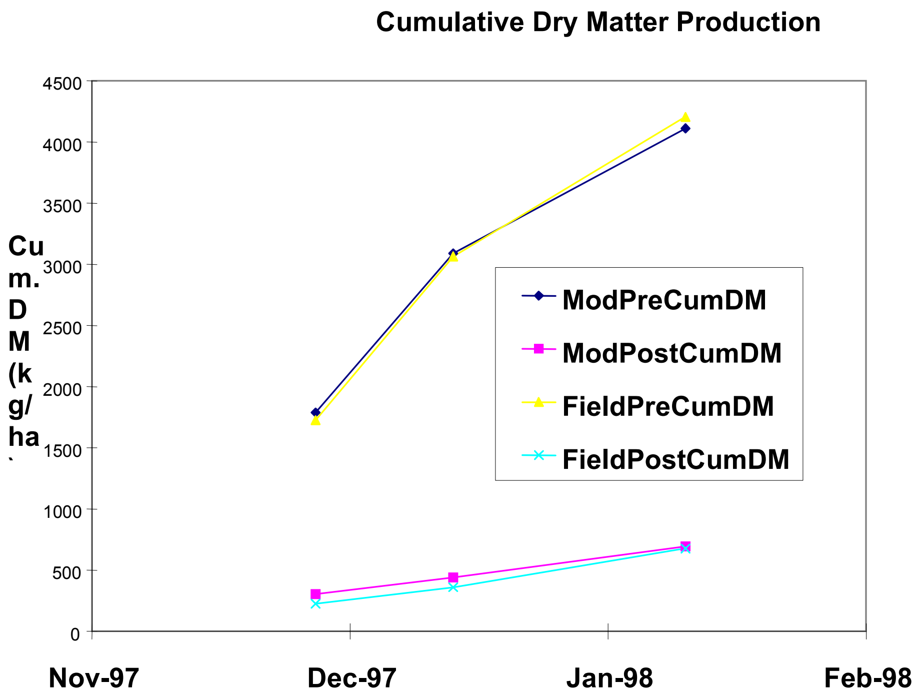
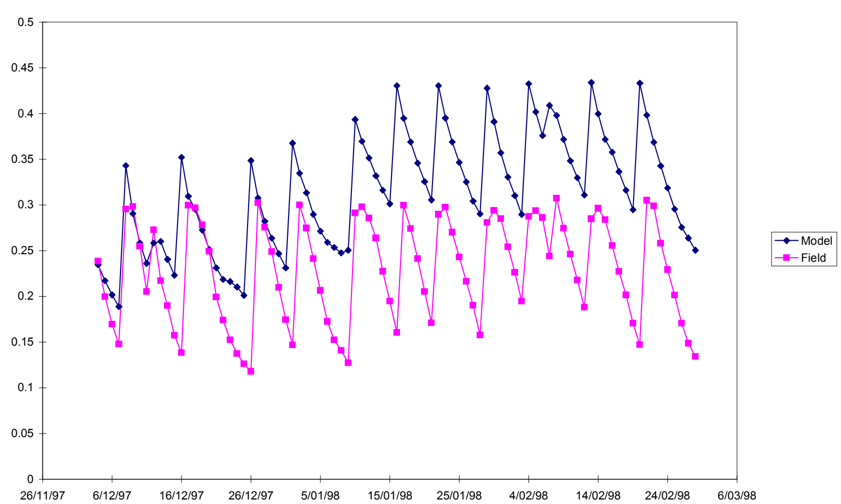


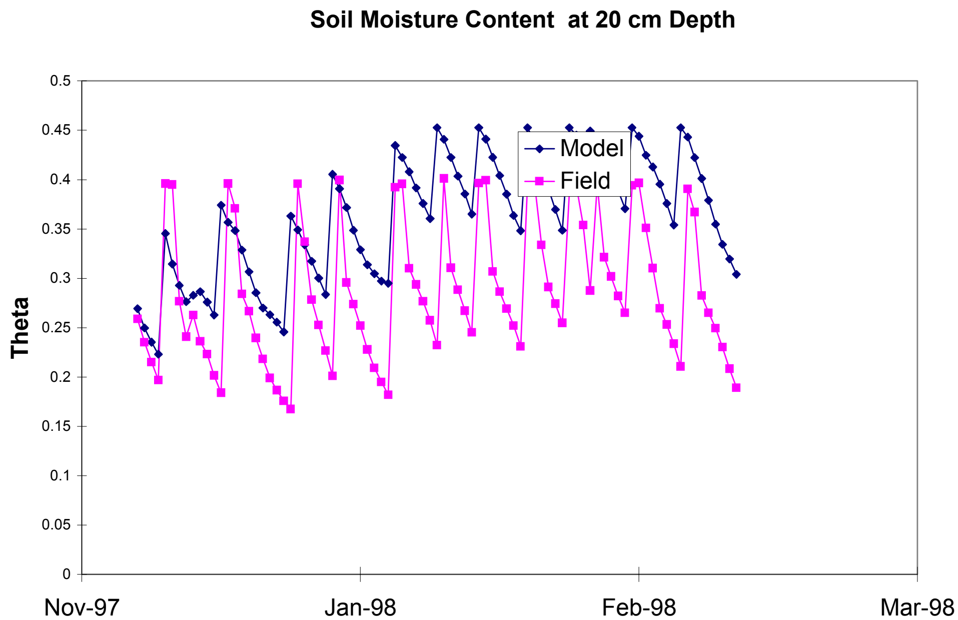
Figure 6. Comparisons of the modelled and field cumulative dry matter production.

Soil moisture content

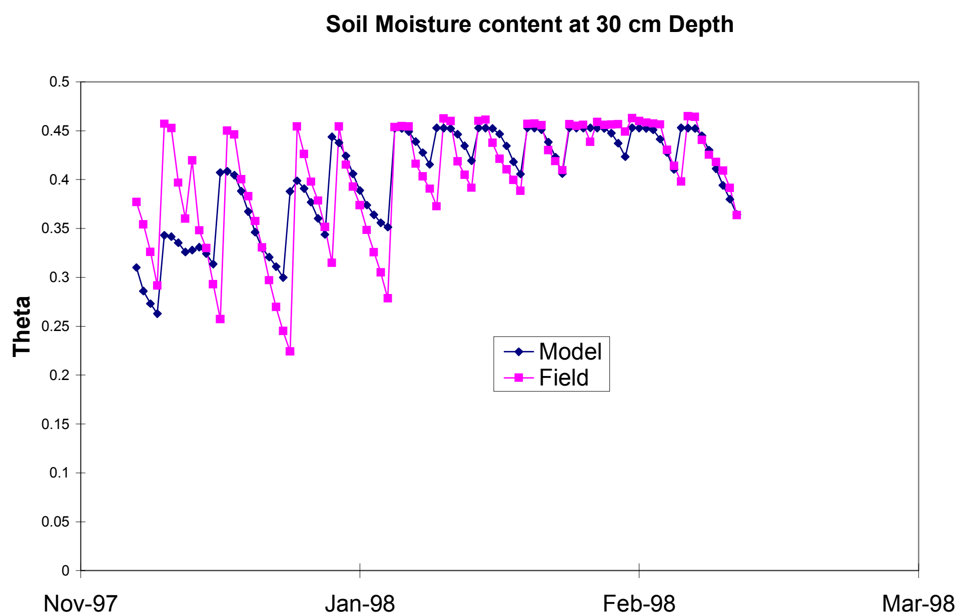
The modelled and field (measured) soil moisture content at 10, 20, 30 and 50 cm depths are shown in Figure 7. The modelled soil moisture contents showed better agreement at the deeper depths than at the shallower depths.



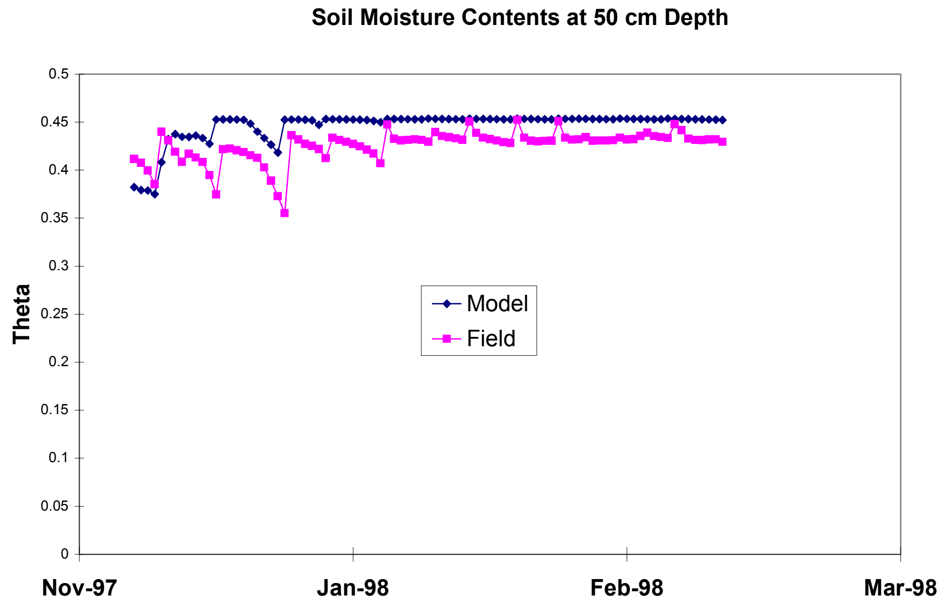
a) 10cm



b) 20cm depth



c) 30cm depth



d) 50cm depth

Figure 7. Field and modelled soil moisture content at different depths.

The changes in soil moisture content following irrigation occur more rapidly in the field than in the model prediction (Figure 7b and 7c). This is due to the difficulty of accounting for macropore (crack) flows in the WAVES model. Cracks appeared to be dominant in the upper part of the soil profile therefore macropore flow is significant on these types of soils. There was a general tendency of increasing modelled soil moisture content with time at 10 and 20 cm depths. At deeper depths (30 and 50 cm depths) it was adjusted with time. Overall, modelled soil moisture content agreed with field measurement although there were variations observed at different depths as outlined above.

Evapotranspiration

An example of calibration results of potential evapotranspiration for pasture at Farm 3 high EM site is given in Figure 8. The ET_{POT} and modelled daily evapotranspiration generally agreed well.

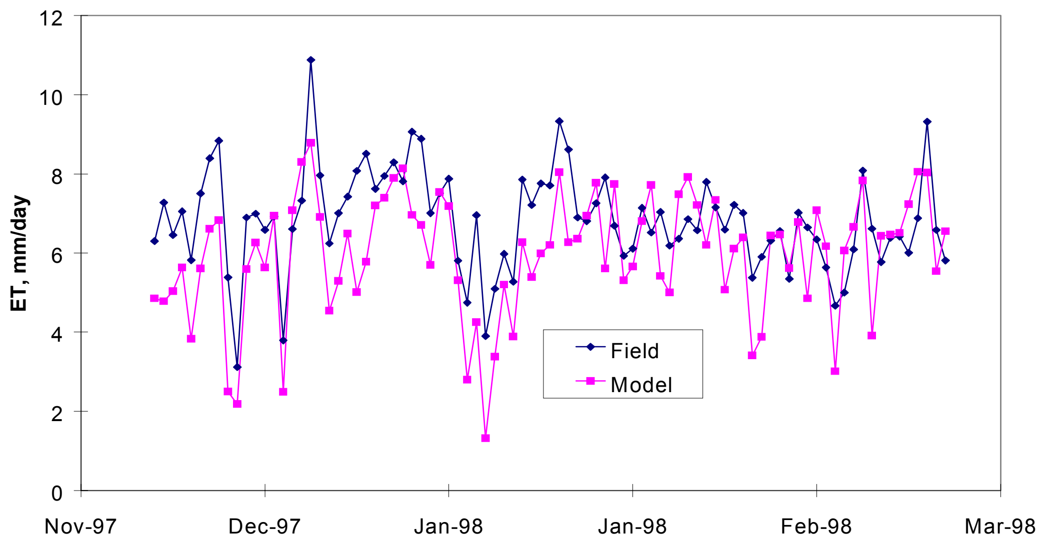


Figure 8. Comparison of modelled and field evapotranspiration

Model output

Once the model was calibrated it was run for the period of 1996 to 1998 for all sites. The field and modelled value of evapotranspiration, dry matter production, rainfall and irrigation and drainage (recharge) is given in Table 4. The field drainage value reported here is different from the value in Table 2, the drainage value in Table 4 was based on our initial estimation and it was later recalculated after the Waves modelling had been completed. Negative drainage indicates downward water movement and positive drainage indicates upward water movement. There was a good relationship between the modelled and field dry matter production for all sites. Based on the initial estimation of field recharge, the model can handle the drainage below the rootzone well. Recharge patterns during the simulation periods were associated with irrigation patterns for both the model and in the field.

Farm No			Rain + Irrigation (mm)	ET (mm)	Drainage (mm)	DM Production (kg/ha)	
						Pre-graze	Post-graze
1	High	Model	2197	1968	-110	30002	8587
		Field	-	2502	-77	29562	7673
	Low	Model	2046	2023	602	33283	9501
		Field	-	2502	625	35716	9408
2	High	Model	3285	2198	-422	41537	13596
		Field	3285	2496	-474	44758	11812
	Low	Model	-	2210	-48	42733	10559
		Field		2496	3.5	43399	9558
3	High	Model	3195	1865	-453	33304	7198
		Field	-	2496	-385	33537	7192
	Low	Model	2980	2119	-256	35879	7485
		Field	-	2496	-152	35896	6199

Table 4. Comparison of modelled and field out puts on evapotranspiration, dry matter production, rainfall + irrigation and recharge.

Scenario modelling

An attempt was made to evaluate dry matter production and recharge under different management scenarios and the outputs are presented in Table 5. parameters are. Nutrient levels of 1.0, grazing rotations of 3 weeks and calibrated irrigation are considered as best practice management for the experimental sites.

		Dry matter production (kg/ha)		Recharge (mm)
		Pre graze	Post graze	
Nutrient	1.0	33304	7198	-453
	0.9	32103	7065	-454
	0.5	27131	7037	-458
Grazing	3 weeks rotations	33304	7198	-453
	2 weeks with light grazing	29496	9997	-483
				-453
Irrigation	Calibrated	33304	7198	-453
	E-R = 50 mm	31824	7083	-500
	E-R = 80mm	37154	7020	-412

Table 5. Dry matter production and drainage under different management scenarios.

As the nutrients decreased, dry matter production also decreased and recharge increased. The three week grazing rotation showed better performance than the other two modelled rotations. Irrigation at an evaporation and rainfall deficit of 80 mm proved to be better than current practices applied by the dairy farmers. This was in contrast to the findings reported by Dunbabin et al. (1997). They found that dry matter production was significantly increased by frequent irrigation and produced the highest yield at 50 mm E - R treatment. It could be due to the fact that the WAVES model cannot handle macropore flow and hold water longer for pasture use whereas in the field, macropore flow is a dominating process in this situation. For that reason frequent irrigation treatments in the WAVES model might have resulted in waterlogging leading to reduced yields and contributing more recharge. It was clear that optimum application of nutrients and proper grazing management produced high yields and reduced annual recharge.

Conclusions from the WAVES modelling

The interactions between soil, water, plant and climate is a complex process. 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 (Zhang et al. 1998). The prediction of the impact of changing external conditions is not possible with limited field studies. Once calibrated, models are an excellent tool for planning and management of land use. The good agreement between field and modelled dry matter production has suggested that the model can handle pasture growth and production well. Low nutrient input and poor management produced less dry matter and increased groundwater recharge giving reasonable confidence to use the model in different changing conditions. As the saturated hydraulic conductivity was increased to incorporate macropore flow, the model produced high recharge. Therefore, the WAVES model may not be suitable for predicting recharge under this particular situation, but it can be argued that the model out put was indicative if not quantitative. The general agreement between field and modelled processes gave reasonable confidence that the WAVES model provided an adequate prediction of growth and water use under the irrigated pasture conditions.

References

Bethune, M and M. Kirby, (eds)2001. "Modelling water movement in cracking soils" Workshop Proceedings, 16-17 May 2001, Melbourne, Victoria.

Broadbridge, P. and I. White. 1988. "Constant Rate Rainfall Infiltration; a Versatile Non Linear Model. 1. Analytic Solution." *Water Resources Research* 24:145-54.

Butler, B. E. 1950. "A Theory of Prior Streams As a Causal Factor of Soil Occurrance in the Riverine Plain of South Eastern Australia." *Australian Journal of Agricultural Research* 11:231-52.

Dawes, W. R. and T. J. Hatton. 1993. *TOPOG_IRM: 1. Model Description*. Technical Memorandum 93/5. Canberra: CSIRO Division of Water Resources.

Dunbabin, J. S., I. H. Hume and M. E. Ireson (1997). Effects of irrigation frequency and transient waterlogging on the production of a perennial ryegrass-white clover pasture. Australian Journal of Experimental Agriculture. Vol 37, pp165-71.

Genstat 5. 1989. *Genstat 5, Reference Manual* The Genstat 5 Committee. Oxford: Oxford University Press.

Hume, I H., D. C. Mitchell and H. Kingston (1997). "Groundwater Recharge Beneath Best Management Dairy Farming – A Pilot Study." Final Report, NSW Agriculture.

Hume, I. H., D. C. Mitchell, P. L. Milthorpe, M. Yea, M. O'Connell and L. Zhang (1998). Episodic recharge under crops and shrubs in the Mallee zone. Final report. NSW Agriculture

Richards, L. A. 1931. "Capillary Conduction of Liquids Through Porous Mediums." *Physics* 1:318-33.

Sentek. 1994. *EnvionSCAN RT5 (Software Manual for Customers)*. Kent Town , South Australia: Sentek, Pty. Ltd.

Slavich, P. G. and G. H. Pettersen. 1993. "Estimating Electrical Conductivity of Saturated Paste Extracts From 1:5 Soil Water Suspensions and Texture." *Australian Journal of Soil Research* 31:73-81.

Slavich, P. G., T. J. Hatton and W. R. Dawes (1998). The canopy growth and transpiration model of WAVES: Technical description and evaluation. CSIRO Land and Water. Technical Report No 3/98 (January).

Smith, R. 1945. *Soils of the Berriquin District, N.S.W.* Bulletin No. 189. Melbourne: Council for Scientific and Industrial Research.

Smith, R., R. J. Herrioit, and E. J. Johnstone. 1943. *The Soil and Landuse Survey of the Wakool Irrigation District, N.S.W.* Bulletin No. 162. Melbourne: Council for Scientific and Industrial Research.

Hatton, T, P. Dyce, L. Zhang and W. Dawes (1995). WAVES – An ecohydrological model of the surface energy and water balance: sensitivity analysis. CSIRO Division of Water Resources. Technical memorandum 95.2, February.

Zhang, L., W. R. Dawes, P. G. Slavish, W. S. Meyer, P. J. Thorburn, D.J. Smith and G. R. Walker (1998). Growth and groundwater uptake response of lucerne to change in groundwater levels and salinity: lysimeter, isotope and modelling studies. CSIRO.

The water balance of border check irrigated perennial pasture measured using lysimeters

Attachment 2

Introduction

Production from the Australian dairy industry is almost exclusively based on pasture. Northern Victoria and southern New South Wales has the largest concentration of dairy production in Australia, with over one-quarter of the national production (ADC 1997). Rainfall is insufficient to meet pasture water requirements during the summer period. Therefore, dairy production in these two areas relies heavily on irrigation and the dairy industry is a major user of irrigation water in these areas. Approximately 65 % of water extracted for irrigation in northern Victoria and over 30 % in the NSW Murray Valley is applied to irrigated pastures.

Salinity is a major threat to the economic sustainability of productive dairy farming in these irrigation areas. Salinity problems are largely associated with shallow watertables that restrict leaching of the soil profile. The development of high watertables in these areas is attributed to increased recharge, resulting from the combined impact of irrigation and the replacement of deep-rooted native vegetation with shallow rooted plant species (GHD 1983).

Numerous studies have been conducted to assess the relative magnitude of recharge under irrigated perennial pasture. These studies were confounded by the difficulty in directly measuring recharge. Rather, recharge was inferred using either salt balance approaches (Lyle *et al.* 1986b; Prendergast 1995), water balance approaches (GHD 1970)or modelling approaches (Schwamberger *et al.* 1994). Typically, the uncertainty in these estimates was of a similar order of magnitude as the actual measurements of recharge. Recharge also varies considerably temporally as a result of changes in climate (Lyle et al, 1986), watertable levels (Schwamberger *et al.* 1994) and irrigation frequency (Bartels 1965).

A further constraint on the irrigated dairy industry is that the diversions of irrigation water in southern NSW and northern Victoria is limited. A Cap on diversions was introduced in 1995, limiting annual diversions to those that would have occurred with the level of irrigation infrastructure that existing in 1993/94 (MDBMC 1996). There is also increasing demand for some existing irrigation allocations to be used to increase environmental flows in the rivers. The competing needs of increased environment flows and agricultural expansion can only be achieved through the more efficient use of existing irrigation allocations. This has resulted in a major push for increased water use efficiency (WUE) in the irrigated dairy industry.

Organisations responsible for managing land and water resources are developing and implementing policy to counter the problems posed by high watertables and limits on irrigation allocations. This policy will limit the intensity of irrigation water applied to dairy pastures. The development of such policy requires information describing the water balance of an irrigated pasture. In particular, information is required describing pasture evapotranspiration (ET), irrigation requirements and recharge losses. This information needs to account for the complex interactions between ET, recharge, climate, watertable levels and irrigation frequency.

Lysimeters are currently the only feasible method to directly measure recharge and to quantify all components of the water balance. This paper summarises a lysimeter trial that was undertaken to provide qualitative and quantitative information on the water budget of border check irrigated pasture. The interactions between depth to watertable, irrigation frequency, recharge and ET are investigated.

Methods

The experiment was conducted in a lysimeter facility located at Tatura (36° 26′ S, 145° 16′, altitude 114 m) in south-eastern Australia. The lysimeter facility consists of 24 underground concrete silos (0.8 m diameter and 2.2 m depth); with each silo opening into an underground central tunnel (Fig

1a). Underground access allowed installation of instruments into the side of the lysimeters (Fig 1c). The top of the silos is level with the surrounding land.

Twenty-four undisturbed soil cores of 0.75 m diameter and 2.2 m depth were extracted in August 1997, from a field where perennial pasture had been grown for over 10 years. Profiles of soil salinity and texture measured prior to core extraction indicated that soil properties were relatively uniform across all cores. The soil was a Goulburn Clay Loam and consisted of a shallow loam A-horizon underlain by a heavy impermeable B-horizon (Skene and Poutsma 1962). The soil permeability increases and texture lightens below the B-horizon (Table 1). The soil is representative of the less permeable floodplain soils in the region. The soil cores were encased in a steel cylinder and a drainage base was added to the bottom of the lysimeters. This base consisted of screened drainage pipes surrounded by fine sand. The soil cores were installed into the lysimeter facility (October 1997) such that the top of the cores was level with the soil surface in the surrounding field.

Table 1. Textural properties of a Goulburn Clay Loam (Skene and Poutsma 1962)

Depth (m) m	Field texture	Bulk density g cm^{-3}	Coarse Sand %	Fine sand %	Silt %	Clay %	K_s [#1] mm/d
0-0.15	clay loam	1.53	10	39	24	26	20
0.15-0.6	medium clay	1.61	8	29	18	45	1
0.6-0.8	medium clay	1.71	8	33	20	40	8
0.8-1.0	light clay	1.71	9	33	22	35	8
1.0-1.2	light clay	1.71	6	31	19	43	8

[#1] saturated hydraulic conductivity

Experimental design

Six treatments were imposed using a randomised block design; each treatment replicated four times. The six treatments (Table 2) consisted of different combinations of depth to watertable (3) and irrigation schedule (2). The depth to watertable (**WTD**) was set by applying a constant water pressure to the base of the lysimeter using a marriotte bottle. This fixed water pressure was equivalent to the watertable levels listed below (Table 2). The salinity of water in the marriotte bottles was 5 dS/m, which is typical of regional groundwater salinity in the area (Ife 1988).

Two different schedules (**S**) were employed to determine when irrigation occurred. Irrigation was triggered in both S when accumulated evaporation minus rainfall (**E-R**) since the last irrigation exceeded a threshold value (Table 2). **E-R** of 50 mm is the recommended irrigation frequency for pasture in northern Victoria. A pond of water was maintained on the lysimeter surface for 6 hrs during an irrigation event. After this time, remaining surface water was drained and measured as runoff. The ponding of water for 6 hours was adopted to represent border check irrigation practices found on district farms in northern Victoria.

Table 2. Experimental treatments imposed onto the lysimeters.

Schedule-Watertable	S_{50}-WTD_{600}	S_{50}-WTD_{1200}	S_{50}-WTD_{1800}	S_{80}-WTD_{600}	S_{80}-WTD_{1200}	S_{80}-W_{1800}
Watertable depth (mm)	600	1200	1800	600	1200	1800
E-R (mm)	50	50	50	80	80	80

Lysimeter setup.

The lysimeters had established perennial pasture consisting of ryegrass, white clover and paspalum. Pasture was established in the area surrounding the lysimeters to reduce the impact of fetch on lysimeter plant water use. The area surrounding the lysimeter was irrigated when cumulated E-R since the last irrigation exceeded 50 mm. Fertiliser was applied intensively from February 2000 (Urea at 50 kg/ha/harvest). No fertiliser was applied prior to this date.

Soil moisture was measured using TDR, with probes installed into the side of the lysimeters at depths 0.1,0.2,0.3,0.4,0.6,0.9,1.2,1.5 and 1.8 m (Fig 1c).

Experimental measurements

Experimental treatments were applied to the lysimeters in March 1998. Experimental measurements did not commence until January 1999 due to difficulties with instrumentation. This 8 month period allowed time for the lysimeters to come into equilibrium with the imposed experiment treatments.

The volume of effective irrigation (I), recharge (R), change in soil water storage (ΔSWS) and surface runoff (R_u) were measured for each lysimeter pre and post irrigation, and following large rainfall events. I is the depth of applied water that infiltrates the soil during irrigation, equalling the total depth of applied irrigation water less irrigation runoff. Reported R_u data results from rainfall runoff events only. Recharge was defined as the difference between water leaving and entering the base of the lysimeter, with net water leaving the lysimeter measured as positive recharge. Precipitation (P) was measured at a Bureau of Meteorology Climate Station, located within 100 m of the experimental site. Evapotranspiration (ET) from each lysimeter was calculated by volume balance (eq 1). Reference crop evapotranspiration (ET_o) was calculated from daily climate data measured at the weather station using the approach recommended in FAO-56 (Allen *et al.* 1998).

$$ET = I + P - R_u - R - \Delta SWS \qquad (1)$$

Pasture was harvested when the ryegrass had approximately reached the three-leaf stage. This corresponded to a 21-day interval over summer and approximately 60 days over the winter period. Dry matter production (DM) was measured by drying the harvested pasture in the oven at 105 ^oC for 48 hours. Pasture composition was measure every 3 months, with the harvested DM partitioned into ryegrass, clover, paspalum and weeds.

Data and statistical analysis

There were 3 irrigation seasons (IS) and 3 winter seasons (W) during the experiment (Table 3). Data describing ET, R, I, R_u, WUE and DM were totalled for each of the 6 seasons. IS1 was not a full season due to experimental measurements not commencing until 1/1/1999. Analysis of variance (ANOVA – level of significance = 0.05) was used to assess treatment impacts on total I, R_u, SWS, R, ET, DM for each season. Experimental treatments (E-R and WTD) were specified as factors in the ANOVA. The relationship between ET, ET_o and DM was appraised using regression analysis. Water use efficiency (WUE) defines the slope of a linear model of DM and ET, with ET being the explanatory variable. Analysis of SWS data was limited to be the top 0.4 m of the soil profile where the pasture rootzone is concentrated. SWS were averaged over each season (SWS_{av}) to assess treatment impacts on rootzone water storage. The impact of S and WTD on SWS prior to irrigation (SWS_{prior}) and post irrigation (SWS_{post}) was also analysed using ANOVA. The crop factor K_c was calculated from the ratio ET to ET_o. All statistical analysis was undertaken using Genstat 5 version 4.2 (Lawes Agricultural Trust, Rothamstead Experimental Station).

Table 3. Start and end dates of seasons used in statistical analysis, with corresponding P and ET_o.

Period	IS1	W1	IS2	W2	IS3	W3
Start	1/1/1999	16/5/1999	16/8/1999	16/5/2000	16/8/2000	16/5/2000
End	15/5/1999	15/8/1999	15/5/2000	15/5/2000	15/5/2001	15/5/2000
P (mm)	106	190	353	131	459	71
ET_o (mm)	607	121	1109	102	1187	102

Results

Irrigation

There was more irrigation events under S_{50} than S_{80} in each season (Table 4). Less frequent irrigation in S_{80} was associated with a significantly ($p<0.001$) higher I per event than for S_{50} (Table 4). However, total I applied over the whole season was higher ($p<0.001$) in S_{50} (Fig 2). Therefore, the increased I per event in S_{80} was insufficient to compensate for the reduced frequency of irrigation. The average difference in I between S_{50} and S_{80} was 100, 220 and 160 mm for seasons IS1, IS2 and IS3 respectively. WTD had no significant impact on I in any season ($p=0.6$). The combined interaction of S and WTD was not significant during any season ($p=0.4$)

Table 4. Number of irrigations, average I per event and date of last irrigation in each of the season.

	IS1			IS2			IS3		
	number	mm/event	last irrigation	number	mm/event	last irrigation	Number	mm/event	last irrigation
S_{50}	11	50	4/5	18	47	27/4	16	52	18/4
S_{80}	7	64	29/4	11	57	27/3	11	61	20/4

Figure 2a. Impact of watertable depth on effective irrigation on 50 mm (E-R) irrigation schedule

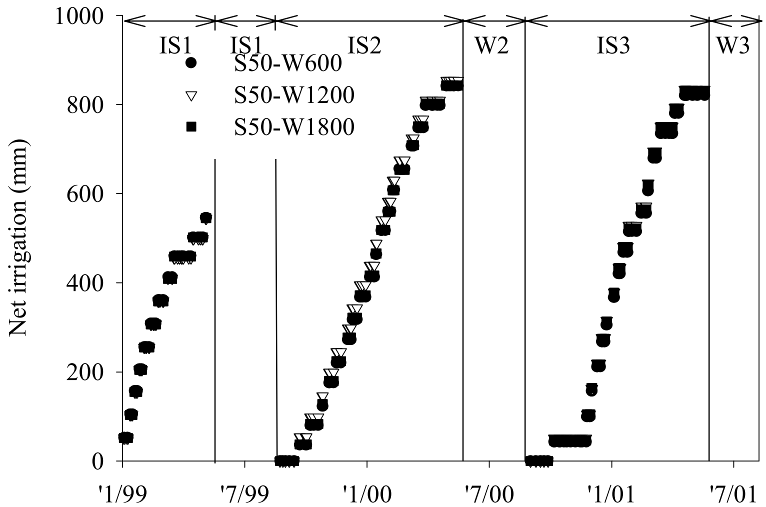
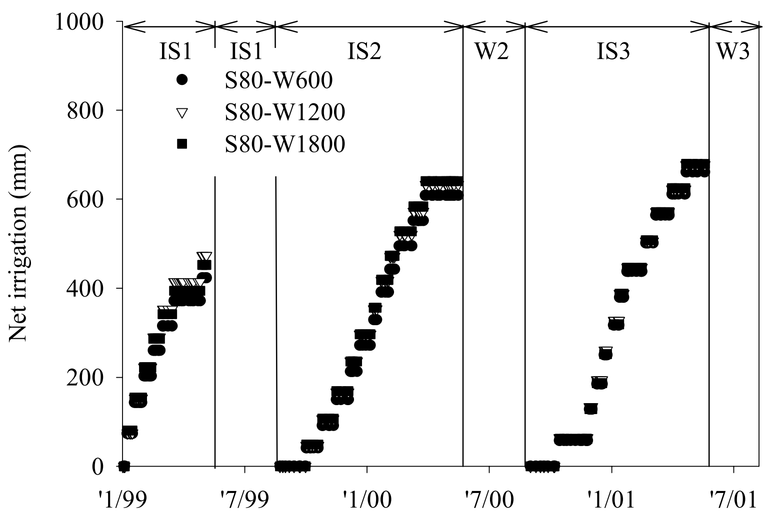


Figure 2b.Impact of watertable depth on effective irrigation on 80 mm (E-R) irrigation schedule



Soil water storage

SWS was generally higher during the winter period, and reduced over the irrigation season (Fig 3). SWS peaked during W1, which was relatively wet due to P exceeding ET for an extended period of time. P was less in W2 and W3 relative to W1 and thus SWS was not as high as during W1. Very dry conditions during W3 resulted in low SWS during this period.

The impact of S and WTD on SWS_{av} was not large. SWS_{av} was significantly affected by the interaction between S and WTD during IS1 (p=0.05), W1 (p=0.04), IS2 (p=0.04), and to a lesser degree in W2 (p=0.08) and IS3 (p=0.07). SWS_{av} decreased with increasing depth to watertable in S_{50}, while increasing with WTD in S_{80}. The greatest difference between S_{50} and S_{80} in SWS_{av} occurred at WTD_{600}. S, WTD and the interaction between S and WTD did not impact on SWS_{av} during W3.

Figure 3a. Change in soil water storage at different water table levels and irrigation schedule of 50 mm (E-R)

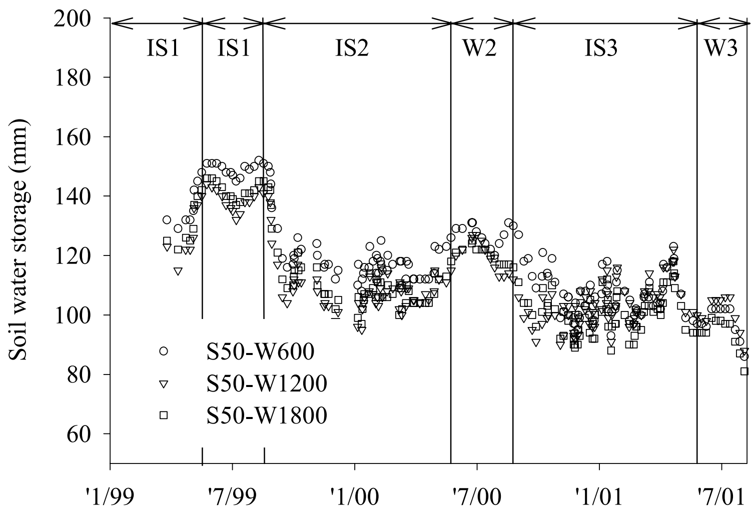
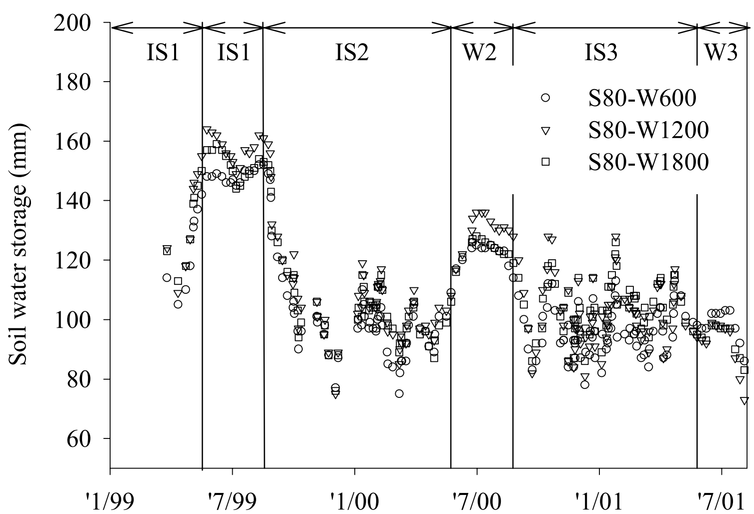


Figure 3b. Change in soil water storage at different water table levels and irrigation schedule of 80 mm (E-R)



SWS_{prior} was greater under S_{50} than S_{80} ($p<0.001$), reflecting the more frequent irrigation. SWS_{prior} was also greater at shallow watertable levels ($p<0.001$) indicating that WTD impacted on drainage below the rootzone or resulted in capillary rise into the rootzone. There was also a significant interaction between S and WTD on SWS_{prior} ($p<0.001$). SWS_{prior} increased with increasing WTD for S_{80}, while the opposite was observed for S_{50}. SWS_{post} was greater under S_{80} ($p<0.001$), even though the magnitude of the difference was small (Table 4). SWS_{post} decreased with increasing WTD ($P<0.001$). The same interaction between S and WTD on SWS_{prior} was observed for SWS_{post}. The average change in SWS resulting from an irrigation event (Table 5) was in good agreement with I (Table 3).

Table 5. Water storage in rootzone pre and post irrigation

	S50	S80
SWS_{prior}	82	68
SWS_{post}	127	129
SWS_{post}-SWS_{prior}	45	61

SWS was less at the end of IS1 ($p=0.04$) and IS2 ($p=0.003$) under S_{80} than S_{50}. There was no difference in SWS between S_{80} than S_{50}at the end of IS3 ($p=0.5$). This means that the rootzone would be drier entering winter under S_{80} in IS1 and IS2, but not IS3. The varying impact of S on SWS was caused by different last dates of irrigation in the different seasons (Table 4). S_{50} was irrigated 7 days later than S_{80} in IS1 and 24 days later in IS2. There was only 2 days difference between the last irrigation date in IS3 and therefore SWS was similar between S_{50} and S_{80}.

Rainfall runoff

Average Ru across all treatments accounted for 6,25,24,10,30 and 0 % of rainfall in IS1,W1,IS2,W2, IS3, and W3 respectively (Fig 4). Ru in S_{80} was significantly less in IS2 than S_{50} ($p=0.002$) and resulted in an additional 20 mm of rainfall being captured and utilised. Both S and WTD impacted on Ru during W2. Ru was greater under shallow watertable conditions ($p=0.03$). A wetter soil profile leading into winter under S_{50} resulted in greater Ru than S_{80} ($p=0.01$). S and WTD did not impact on Ru at any other time.

Figure 4a. Impact of depth to watertable on rainfall runoff for S_{50}

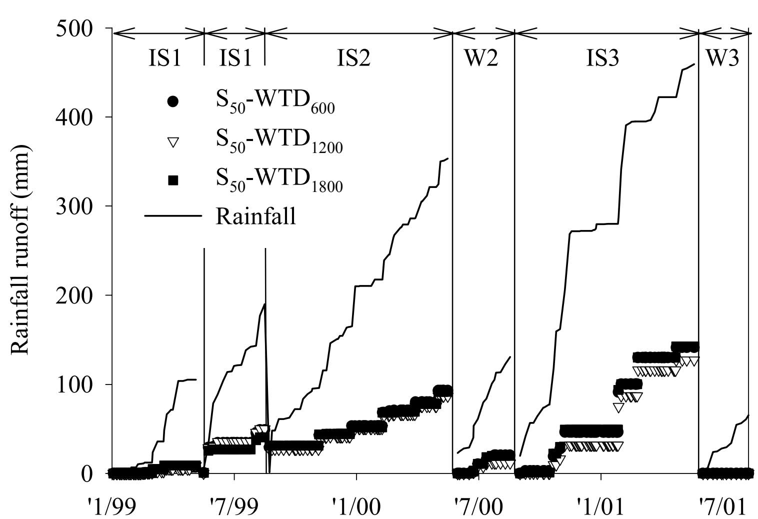
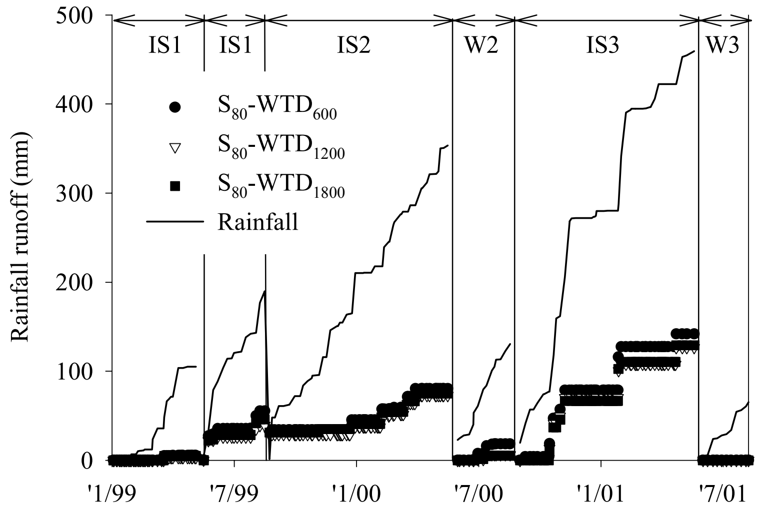


Figure 4b. Impact of depth to watertable on rainfall runoff for S_{80}



Recharge

Recharge was the smallest measured component of the water balance, averaging 2 mm/y across all treatments (Fig 5). All lysimeters had negative recharge (capillary rise) during IS1 and W3. The capillary rise during IS1 is indicates that watertables and soil water in the lysimeters had not equilibrated with the water pressure imposed on the base of the cores. Capillary rise during W3 results from low rainfall, which led to a soil water deficit over an extended period of time. R increased with greater WTD during IS1 (p=0.03), W1 (p=0.03), IS2 (p=0.04) and IS3 (p=0.03). The pattern of increasing R with WTD was also followed during W1 (p=0.125) and W2 (p=0.2) to a lesser degree. S had no significant impact on R over the duration of the experiment (Fig 5).

Figure 5a. Impact of depth to watertable on recharge for S_{50}

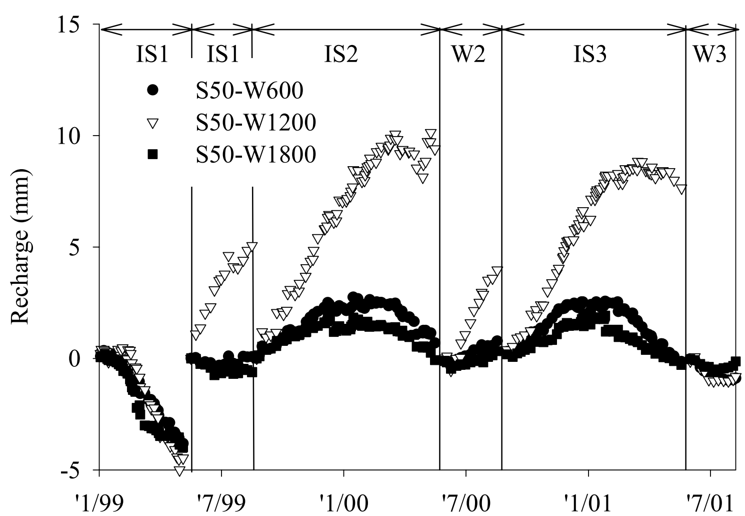
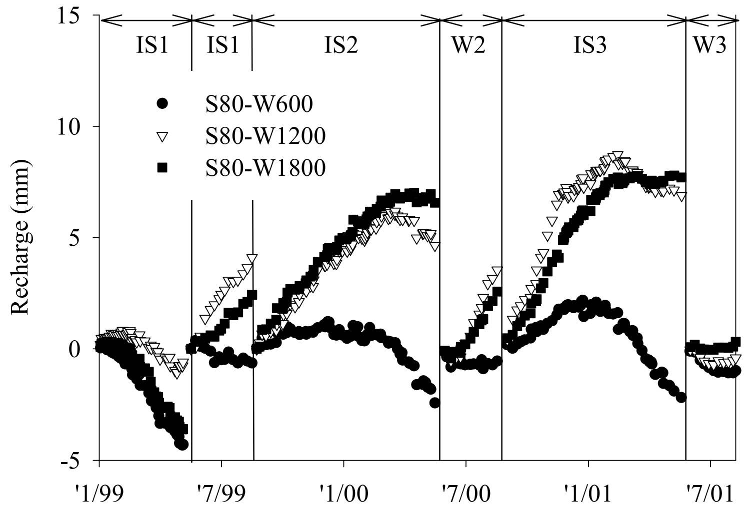


Figure 5b. Impact of depth to watertable on recharge for S_{50}



ET

ET was the largest component of the water balance. ET was significantly higher for S_{50} (Fig 6a) than S_{80} (Fig 6b) during IS1, IS2 and IS3 ($p<0.001$). S did not impact on ET during the winter periods. WTD had no impact on ET during the experiment. ET for S_{50} was well predicted ($r^2=0.86$) by ET_o (Fig 7). Low SWS and insufficient irrigation in S_{80} restricted ET and consequently ET_o over predicted ET by 20 %. The S_{80} results indicate that capillary rise from the watertable was insufficient to meet plant water requirements at all WTD. Low soil permeability most likely limited capillary rise.

Figure 6a. Cumulated ET 50 mm deficit during the 6 seasons

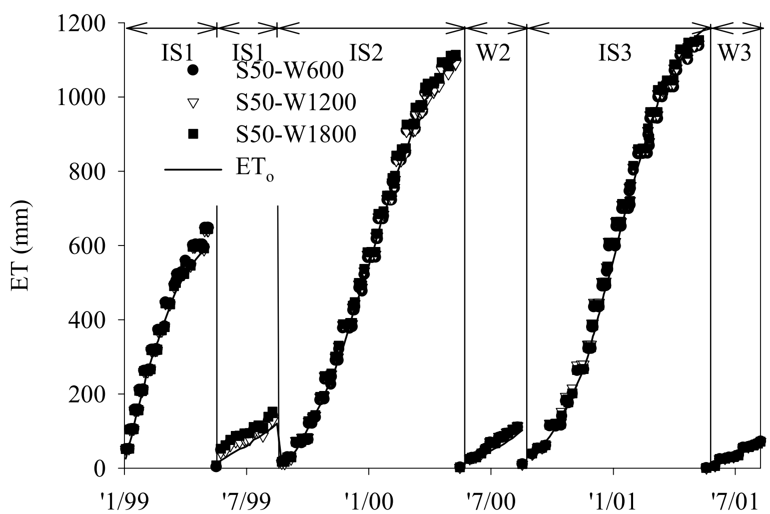
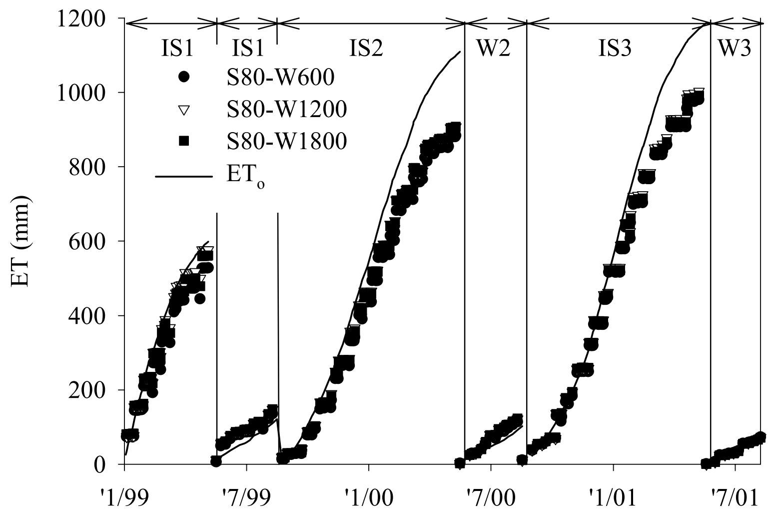
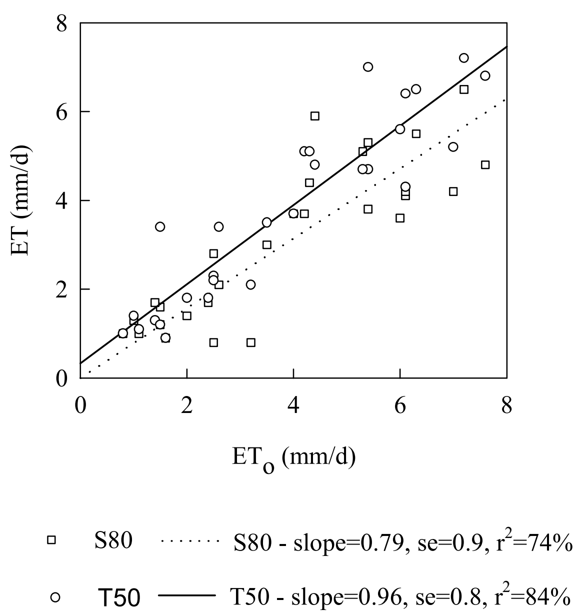


Figure 6b. Cumulated ET 80 mm deficit during the 6 seasons



There was a significant difference ($p<0.001$) in K_c between S_{50} (1.0) and S_{80} ($K_c=0.87$) for the total monitoring period. K_c was less in IS3 than IS2 for both S_{50} and S_{80} ($p=0.01$). Measured ET was not different between seasons. Therefore, the variation in K_c between seasons results from differences in ET_o.

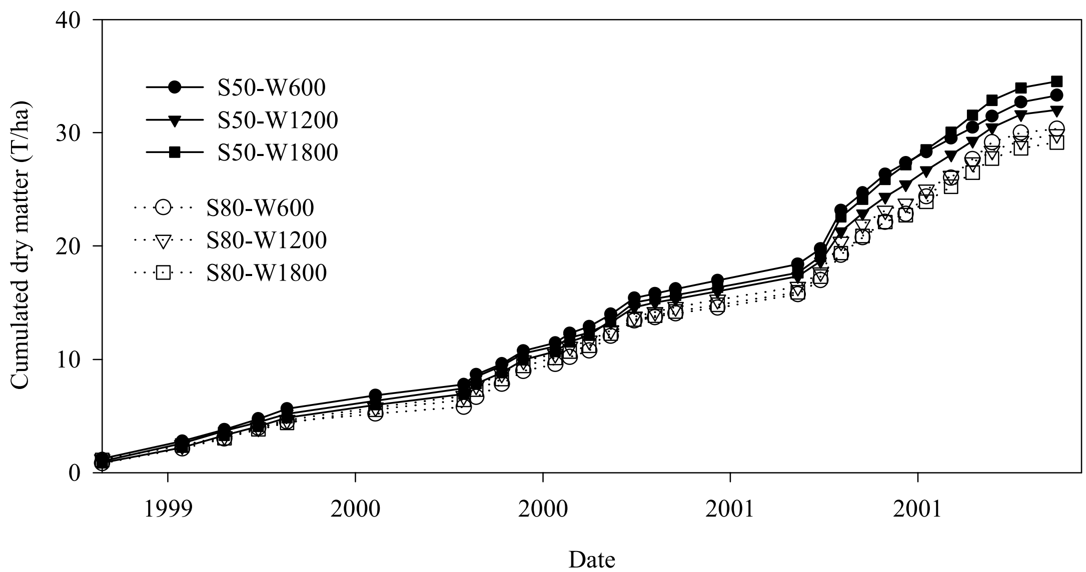
Figure 7. The impact of irrigation deficit on the relationship between pasture water use and ET_o..



Pasture growth

WTD and S did not have a large impact on DM (Fig 8). At no time during the experiment did either S or WTD affect pasture composition ($p>0.1$). However, pasture composition did affect DM. The percentage of ryegrass was the most strongly correlated plant species with DM. The percentage of ryegrass at the commencement of each sampling period was included as a co-variate into the ANOVA to assess the relationship between DM and experiment treatments. The co-variate significantly impacted on DM during all periods of the experiment. S_{80} had significantly less DM than S_{50} during IS1, W1, W2 and IS3 (Fig 8). WTD had no impact on DM during the experiment

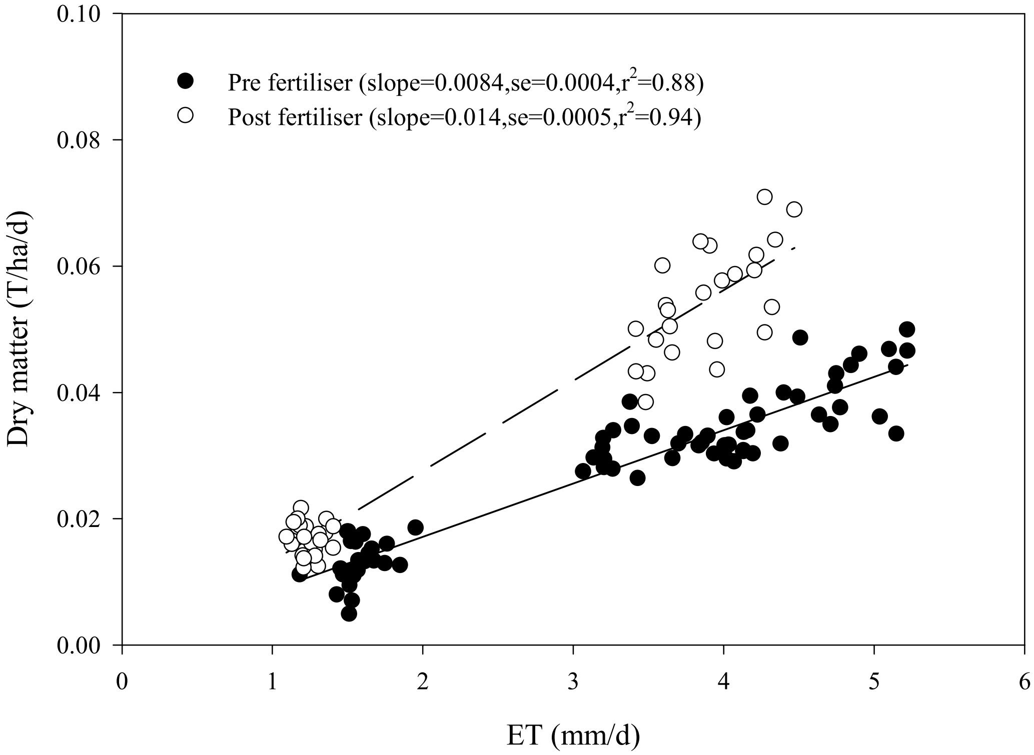
Figure 8. Impact of depth to water table and irrigation schedule on pasture production.



WUE

S or WTD did not affect WUE throughout the experiment. However, there was a large temporal change in WUE ($p<0.001$) that coincided with the implementation of an intensive fertiliser application regime (in February 2000). WUE efficiency, defined by the slope of a linear model between DM and ET, was compared pre and post intensive fertiliser application (Fig 9). Low ET and DM data correspond to winter periods, while high ET and DM data correspond to irrigation seasons. The WUE almost doubled following the initiation of the intensive fertiliser application regime. This means almost twice as much DM being grown from the same amount of water.

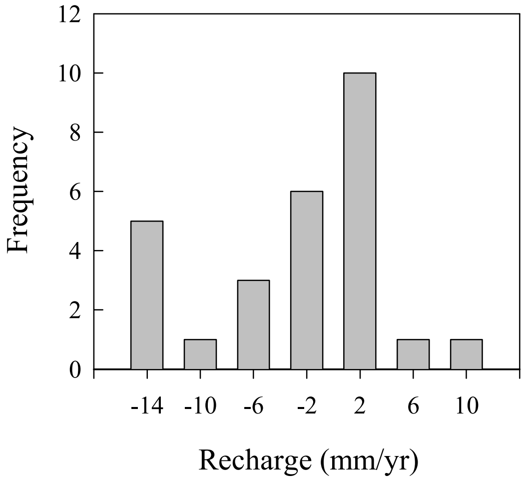
Figure 9. Change in the relationship between DM and ET pre and post intensive fertiliser application.



Discussion

Measured recharge was small in magnitude and contained considerable variability (Fig 10). This variability highlights the difficulty in measuring recharge, even under extremely controlled environments such as in the lysimeter facility. The large variability in measured recharge would also be expected under field conditions. Most methods for estimating recharge rely on either field scale water balance or point measurements of soil moisture and chemistry. Predicting recharge from a field scale water balance will be plagued by uncertainties in the estimation of the major components of the water balance, particularly plant water use, irrigation and runoff. Estimates based on one point in the landscape would have the same difficulties in quantifying components of the water balance, and the extra uncertainty resulting from the large spatial heterogeneity found under field conditions. Approaches are required that allow confident predictions of recharge under field conditions. The development of reliable micrometeorology tools, such as Bowen Ratio, for direct measurement of plant water use will improve confidence in field scale estimates of ET and thus recharge.

Figure 10. Histogram of measured recharge.



Timing of recharge

Monthly averages of R and SWS were calculated from the lysimeter data. R was greatest in August for all treatments (Fig 11a), which follows the winter period when P exceeds ET and SWS is high for an extended period (Fig 11b). R was relatively high during September, October, November and December compared to the rest of the year. This reflects the long period of time required to drain a wet soil profile. R decreased into the irrigation season as the soil became drier and surplus P was utilised or drained. R was a minimum in March when there was negative recharge (net capillary rise) into the lysimeters. This suggests that lysimeter ET was greater than infiltrated water during this period and capillary rise occurred to compensate for the water deficit.

Fig 11a. Relationship between R and surplus rainfall (P-ET_o)

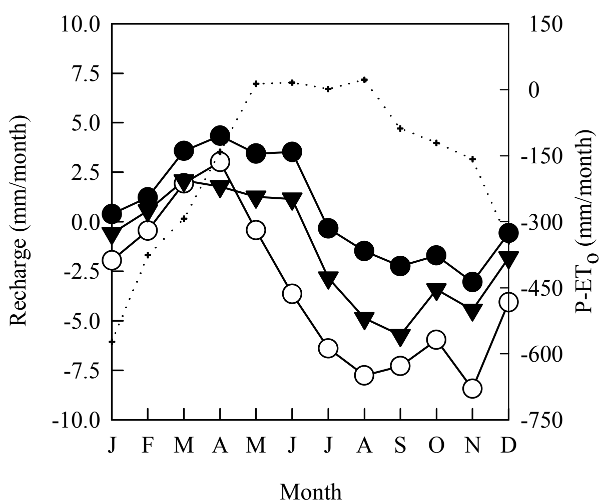
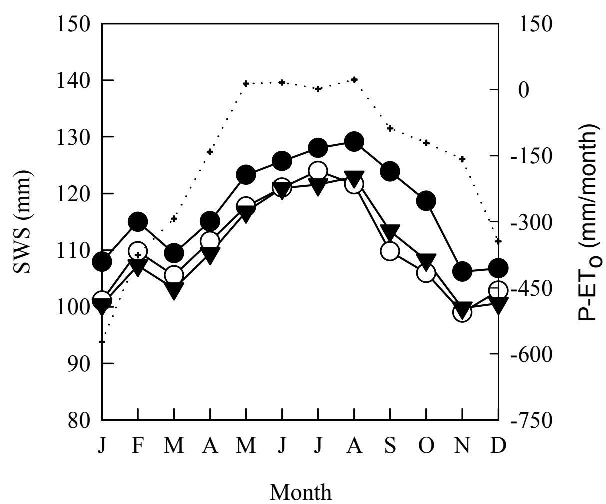


Fig 11b. Relationship between SWS and surplus rainfall (P-ET_o)



Recharge lagged behind the climatic drivers, as indicated by the difference between ETo-P. This occurred because soil water storage increased over the winter period and took an extended period to drain. The soil in the lysimeters had a very impermeable subsoil that restricted water flow, with a saturated hydraulic conductivity (K_s) less than 1 mm/d. Therefore, the soil rootzone must be saturated for extended periods of time for measurable quantities of water to move to depth and lead to recharge. High plant water use during the irrigation season resulted in the rootzone being saturated for only short periods of time. However, low plant water use during winter lead to the soil being close to saturation for extended periods of time.

Potential to reduce recharge through irrigation scheduling
The timing of recharge in this experiment indicates that the majority of recharge is not a direct consequence of irrigation on the studied soil. Rather, recharge is a consequence of rainfall during periods of low evaporative demand resulting in a wet soil for extended periods of time. This finding supports previous work that concludes that the majority of groundwater recharge under heavy soils is attributable to rainfall (Lyle *et al.* 1986a). These results indicate that there is only limited scope to reduce recharge on this soil by improving irrigation management. The greatest scope is offered by creating a soil water deficit prior to winter to store surplus winter rainfall. The irrigation scheduling options tested in this experiment did not impact on winter recharge. This is because SWS entering winter, and thus soil water deficit, is driven by the last date of irrigation rather than the irrigation frequency. An earlier end to the irrigation season may be a better option for reducing recharge during the winter months. The impacts of this option on pasture growth needs to be appraised prior to recommendations been made to the farming community. There is also potential to reduce recharge by delaying irrigation in spring to encourage uptake of surplus soil water. Again, this impact of such an option on pasture growth requires consideration.

Good irrigation scheduling practices were employed in this study. Dairy farms do not typically schedule irrigation using climatic data. Rather a fixed irrigation interval is adopted, which may be adjusted for large rainfall events or during the spring and autumn months. Such an irrigation schedule is likely to result in higher recharge than observed in this experiment due to increased potential for irrigation to be applied to wet soils and for soils to remain wet for longer periods of time.

The majority of soils in the irrigated dairy areas in northern Victoria and southern NSW are more permeable than assessed in this study. The potential to recharge through irrigation scheduling is likely to be higher on more permeable soils.

Recharge requirements to prevent salinisation
The average depth of leaching across all lysimeters was 2 mm/y. The leaching requirement for ryegrass/clover based perennial pasture is 10mm/yr for the irrigation water salinity (0.1 dS/m) used in this experiment (Prendergast 1993). Therefore, on average there was insufficient leaching to prevent salt accumulation and salinity would impact on pasture growth at some stage in the future.

Pasture water requirements

The annual irrigation requirement can be estimated from the difference between pasture water use and effective rainfall. Pasture ET (ET) was well approximated by ET_o and a K_c of one in this experiment. Effective rainfall is the amount of rain that infiltrates and contributes to ET. The irrigation requirement was calculated from the difference between the 20-year average of ET_o and effective rainfall during the irrigation season (Table 6). The average irrigation requirement for Tatura is 830 mm/y, based on the level of effective rainfall (80 %) measured in the lysimeter experiment. This level of effective rainfall is similar to that reported from a survey of district farms in northern Victoria and southern NSW(Armstrong *et al.* 2000). The irrigation requirement in Finley is higher due to lower rainfall.

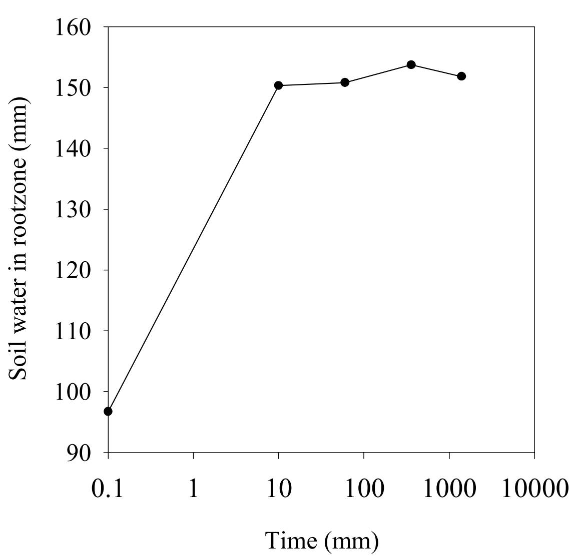
Table 6. Irrigation requirement for Tatura and Finley.

Rainfall efficiency (%)	100%	80%	60%
Irrigation requirement –Tatura (mm)	776	830	890
Irrigation requirement –Finley (mm)	980	1030	1090

Impact of cracking on infiltration

Soil water stored in the rootzone increased rapidly following irrigation (Fig 12). There was no increase in soil water storage below the rootzone. These results indicate that nearly of the infiltration occurred within 10 minutes of the application of irrigation water. This initial wetting is attributed to infiltration through soil cracks. This phenomenon is widely recorded for border check irrigation on duplex red brown earths (Austin and Prendergast 1997; Ross and Bridge 1984). Soil cracking results from the soil shrinking as water is extracted from the soil matrix. The size of the crack is related, amongst other things, to the soil moisture status of the soil (Yule 1984; Bronswijk 1988). Therefore, soil cracking would be most extensive over the depth of the rootzone where soil water extraction is concentrated. The low soil permeability in the lysimeters limits the rate of water redistribution. Reductions in soil water content below the rootzone would not be expected in areas with heavy soils, higher watertables and where irrigation is applied to meet plant water requirements. Soil cracking and infiltration of water to depth would be more likely to occur under conditions where deep soil drying occurs. This is more likely to be encountered when deeper rooted crops are grown or when there is long periods where plant water use exceeds irrigation and rainfall.

Figure 12. Change in water stored in the rootzone following irrigation.



Potential for swelling to impact on soil water movement and recharge

Watertable level and irrigation schedule had a relatively small impact on the water balance of the lysimeters. It is considered that the impact of the imposed treatments was limited by the low permeability of the soil, particularly the sub-soil (K_s=1 mm/d). The impact of treatments on recharge may be further reduced as a result of the soil swelling. Soil swelling introduces an additional pressure head term to the total soil water potential. This term describes the overburden potential, which represents the work done in displacing soil when a unit quantity of water is added at a defined point in the soil (Philip 1971). The overburden potential can be calculated from knowledge of soil shrinkage characteristic and the wet specific density of the soil (Talsma 1974). Typical values for a Shepparton Fine sandy loam (SFSL) are provided by Olsson and Rose (Olsson and Rose 1978). The overburden potential was calculated using the data of Olsson and Rose for a saturated soil profile. The impact of the calculated overburden pressure under saturated conditions was to reduce the gradient in soil water potential ($d\Phi/dz$) from unity (gravitational only) to 0.25. This would quarter the drainage rate through the soil profile under saturated conditions. The soil in the lysimeter has similar origins to the SFSL, being formed through prior stream deposition. However, the GL soil has greater clay content and is likely to demonstrate a greater level of swelling. Therefore, it is likely that the overburden potential could have substantial impacts on soil water movement in the lysimeters, especially under conditions were the soils are close to saturation.

Conclusions

The water balance of flood irrigated pastures was measured using a replicated lysimeter experiment. Watertable level and irrigation schedule only had a minor impact on the measured components of the water balance. Increasing the time between irrigation resulted in reduced plant water use and pasture production. While this saved irrigation water, it did not lead to reduced recharge. Watertable level had a small impact on recharge and runoff resulting from winter rainfall. It is considered that the low permeability of the heavy soil in the lysimeters restricted soil water fluxes and reduced the impact of the imposed experimental treatments on components of the water balance.

Pasture water use was well approximated by ET_o. Testing of this relationship under field conditions is required before sensible limits on irrigation intensities can be developed. However, assuming pasture water requirements equal ET_o is a good first approximation until better information is available.

Recharge was found to be greatest following winter, where the soil profile in the lysimeters was wet as a result of an extended period where rainfall exceeded pasture water use. There was net capillary rise from the watertable into the rootzone during the peak of summer indicating that the infiltrated of irrigation water was insufficient to meet plant water needs. Measured recharge were small (5 mm/yr) and contained considerable variability. The cause of the variability could be either measurement errors or soil heterogeneity. These results highlight the difficult nature in measuring recharge. On average, the measured level of recharge was insufficient to meet the leaching requirements of the pasture. Therefore, salinisation and reduced pasture growth would occur under these low recharge rates.

Soil water infiltration occurred rapidly following irrigation, with the soil profile become saturated with 10 minutes of the irrigation over the depth of the rootzone. No further changes in soil water occurred. This suggests that the initial infiltration was dominated by crack flow, with very limited infiltration occurring after the initial crack filling. The cracking was limited to the depth of soil water extraction (the plant rootzone). Therefore, cracking is unlikely to directly lead to recharge.

Reference List

ADC (1997) 'Dairy compendium 1997.' (Australian Dairy Corporation, Victoria)

Allen RG, Smith M, Perrier A, Pereira LS (1998) 'Crop evapotranspiration, Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56.' (United Nations: FAO Rome)

Armstrong D, Knee J, Doyle P, Pritchard K, Gyles O (2000) Water-use efficiency on irrigated dairy farms in northern Victoria and southern New South Wales. *Australian Journal of Experimental Agriculture* **40,** 643-653.

Austin N, Prendergast JB (1997) Use of Kinematic wave theory to model irrigation on cracking soil. *Irrigation Science* **18,** 1-10.

Bartels LF (1965) Estimation of soil drainage losses following irrigation. *Australian Journal of Experimental Agriculture and Animal Husbandry* **5,** 59-64.

Bronswijk JJB (1988) Modelling of water balance, cracking and subsidence of clay soils. *Journal of Hydrology* **97,** 199-212.

GHD (1970) 'Murray Valley Salinity Investigations.' (River Murray Commission, Canberra)

GHD (1983) 'The application of salinity control techniques in Victoria. A report prepared for the Salinity Committee of the Victorian Parliament.'

Ife D (1988) 'Geomorphic and hydrogeological mapping of the upper Shepparton formation, Shepparton Region.' (Rural Water Corporation, Melbourne, Australia)

Lyle CW, Chalmers DJ, Wildes RA, Heuperman AF (1986a) Causes of shallow watertables in the irrigation areas of the Shepparton Irrigation Region of Northern Victoria. *Journal of the Australian Institute of Agricultural Science* **52,** 23-27.

Lyle CW, Mehanni AH, Repsys AP (1986b) Leaching rates under a perennial pasture irrigation with saline water. *Irrigation Science* **7,** 277-286.

MDBMC (1996) 'Setting the Cap. Report of the Independent Audit Group, November 1996.' (Murray Darling Basin Ministerial Council, Canberra, Australia)

Olsson KA, Rose CW (1978) Hydraulic properties of a red-brown earth determined from in-situ measurement. *Australian Journal of Soil Research* **16,** 169-180.

Philip JR (1971) Hydrology of swelling soils. In 'Salinity and Water Use'. (Eds T Talsma and JR Philip) pp. 95-107. (Macmillan: London)

Prendergast JB (1993) A model of crop yield response to irrigation water salinity: theory, testing and application. *Irrigation Science* **13,** 157-164.

Prendergast JB (1995) Soil water bypass and solute transport under irrigated pasture. *Soil Science Society of America Journal* **59,** 1531-1539.

Ross PJ, Bridge BJ (1984) Ross P.J. and Bridge B.J., in Eds. McGarity J.W., Hoult E.H. and So H.B., 1984. MICCS: a model of infiltration into cracking clay soils. Rev. Rural Sci. 5, Univ of New England, Armidale 155-163. In 'The properties and utilization of cracking clay soils'. (Eds JW McGarity, EH Hoult, and HB So) pp. 155-163. (University of New England: Armidale, Australia)

Schwamberger EC, Meyer WS, Prathapar SA (1994) 'Determination of water flux past 800 mm depth under different combinations of soil, crop, water table depth and rainfall in the riverina. Final Report to the Murray Darling Basin Commission.' (CSIRO Division of Water Resources, Griffith, Australia)

Skene JKM, Poutsma TJ (1962) 'Soils and land use in part of the Goulburn Valley, Victoria. Technical Bulletin No 14.' (Department of Agriculture, Victoria, Australia)

Talsma T (1974) Moisture profiles in swelling soils. *Australian Journal of Soil Research* **12,** 71-75.

Yule DF (1984) Volumetric calculations in cracking clay soils. Reviews in Rural Science 5. (Eds JW McGarity, EH Hoult, and HB So) pp. 136-140. (University of New England: Armidale, New South Wales, Australia)

A Review of Groundwater Recharge Studies below Flood Irrigated Pasture

Attachment 3

Matthew Bethune,
Institute for Sustainable Irrigated Agriculture, Tatura, VIctoria

CONTENTS

1. Summary

The dairy industry in Australia is predominantly pasture based. Irrigation is used to supplement rainfall and increase pasture production in areas where rainfall is insufficient to meet pasture water requirements. Irrigation water is typically applied using the border-check irrigation system. Irrigated pastures occupy 0.7 million hectares of land in Australia High watertables and associated salinity problems have developed over the major irrigation areas in Australia. These high watertables occur as a result of excessive recharge. This paper reviews studies of recharge under border check irrigated pasture and discusses the factors affecting recharge.

The majority of recharge studies have concentrated on heavy soils, as they contain the majority of border check irrigated pasture. The available information indicates that there is little recharge under flood irrigated pasture on these heavy soils. There is only limited information describing recharge under border check irrigation on light soils. The available information indicates that high recharge rates would be expected.

Large differences in recharge occur between heavy and light soils. However, no framework has been developed that identifies what level of recharge is acceptable and under which soils border check irrigation can be managed to maintain acceptable levels of recharge. This framework would also need to consider the impacts of management, watertable conditions, climate, soil chemistry and irrigation water salinity; which have all been found to impact on recharge. Such a framework is the first step towards the irrigated dairy industry managing recharge in an environmentally responsible manner.

2. Introduction

Production from the Australian dairy industry is almost exclusively based on pasture. These pasture-based systems require a year round supply of water to meet plant water requirements. Such conditions are found in coastal areas where rainfall is relatively high, or where irrigation can be applied to supplement rainfall. Over one-quarter of dairy production in Australia comes from northern Victoria and southern New South Wales (ADC 1997). Production in these areas is heavily dependent on irrigation. However, irrigation is intrinsically linked to rising watertables and salinisation (GHD 1983).

Salinity is a major threat to the economic sustainability of irrigation catchments, resulting in reduced production, decreased water quality and environmental degradation. These salinity problems are largely a consequence of high watertables that restrict leaching of the soil profile. High watertables are prevalent across most irrigation areas in South Eastern Australia. Watertables were 40 m below the surface in the Tatura area in the early 1870's (Bossence 1969). Watertable levels are now within in 2 m of the surface over a large part of this area. Watertable levels have stabilised between 1-2 m below the surface over most of the Shepparton Irrigation Region (SIR). The stabilisation of watertable levels has occurs as a result of groundwater discharge equalling groundwater accessions. This example is typical of most irrigation areas of the southern Murray Darling Basin in Australia. The development of high watertables resulted from the clearing of deep-rooted native vegetation and replacement with shallow rooted plant species(GHD 1983). This had led to greater drainage losses below the plant rootzone. These drainage losses, which are exacerbated by irrigation and channel seepage, contribute to groundwater accessions (GHD 1983).

Deep percolation (DP) describes the magnitude of drainage losses below the rootzone. Deep percolation below the rootzone results in either a watertable rise, groundwater movement away from the site where deep percolation occurred, or moves back into the rootzone through capillary rise. **Recharge** is used in this report to describe the net drainage (deep percolation minus capillary rise) out of the rootzone at a particular point in the landscape. Deep percolation is often expressed in terms of the **leaching fraction**, which represents the proportion of water entering the soil that drains below the rootzone. Recharge can be calculated by multiplying the leaching fraction and depth of infiltrating water.

Numerous studies have been conducted to assess the relative magnitude of recharge that are relevent to the irrigated dairy industry (Brown 1978; GHD 1970; McMahon 1984). However, these studies were confounded by the difficulty in measuring recharge, which cannot be directly measured under field conditions. Rather, recharge is usually inferred from measurement of the water or salt balance, or from modelling approaches. Typically, the uncertainty in estimates of recharge made using methods is greater that the magnitude of the accessions trying to be measured. However, the purpose of this paper is not to review techniques for estimating recharge. Gee and Hillel (Gee and Hillel 1988) provide a review of field techniques for estimating recharge in arid areas. Rather, this paper attempts to summarise our current qualitative and quantitative understanding of recharge processes under irrigated pasture.

Studies quantifying recharge

A technical workshop was conducted to review the current knowledge on the sensitivity of watertables to irrigation practices (McMahon 1984). The sources of and relative magnitude of recharge to the watertable were summarised for the Shepparton Region (Fig 1a), Kerang Region (Fig 1b) and from a modelling study of the Bar Creek Catchment (Fig 1c) (McMahon 1984). The review compiled the current knowledge at that time, much of which has never been published.

Therefore, the source of this data and techniques used to estimate recharge is summarised below. Studies conducted after this technical workshop are also summarised (Table 1).

DP was estimated to be between 8-17 % of irrigation water that infiltrated the soil, on a Red Brown Earth at Werribee in southern Victoria (Bartels 1965). He assumed that DP was equal to the unaccounted water in the water balance. The impact of rainfall on recharge was ignored, as was the impact of capillary rise and water redistribution. He found DP to be less under drier soils by comparing losses under different irrigation frequencies. Using a water balance approach, recharge was found to be negligible under irrigated pasture near Murray Bridge in South Australia (Holmes and Watson 1967). In this instance groundwater pressures were influenced by the Murray River and watertable levels were close to the surface. This would have restricted downward drainage. However, DP must have occurred to provide leaching so that soil salinity could be maintained at a suitable level for pasture production. It is considered that DP moves laterally under the rootzone, discharging into deep surface drains that run parallel to the border check fields. This highlights an interesting question: Is the magnitude of DP or the fate of DP more important?

Recharge under pasture was estimated to be between 50 and 80 mm/y, using a catchment scale water budget approach (GHD 1970). A catchment scale estimate of the percentage of irrigation and rainfall lost in runoff was made in this study. The likely errors in the runoff and evapotranspiration components of the water balance would be of the same magnitude as estimated recharge. This study highlights the difficulty in measuring recharge by water balance. GHD (GHD 1970) consider that the major losses occurred on prior stream soils. However, no measurements were taken to support this suggestion. No attempt was made to differentiate the impact of rainfall and irrigation on recharge.

The drainage flux below the rootzone was estimated following irrigation from measured soil suction gradients and known hydraulic properties (Brown 1978). Less than 1 mm of water passed below 1 m following irrigation. From this flux, annual DP below the rootzone resulting from irrigation was estimated to be 15 mm/y, by assuming 20 irrigations in a season (Lyle *et al.* 1986a). This drainage flux does not take into account the impact of capillary rise of water back into the rootzone or the impact of winter rainfall on drainage fluxes.

Rises in watertable were observed at distances of up to 60m from the bay following irrigation in the Kerang area (Roufail 1980). This indicates that recharge was occurring following irrigation but does not actually quantify accessions. Watertable changes following irrigation were found to be restricted to the irrigation area in a separate study on a similar soil (Sampson 1975). The different behaviour between these two studies may result from the presence of a shallow permeable aquifer in the first study that allowed rapid lateral sub-surface water movement. However, no information was provided to clarify this perspective.

Leaching fractions of 4%, approximately equating to 40 mm/y of recharge, were measured on a Red Brown Earth near Kyabram (Lyle and Mehanni 1984). Leaching fractions were found to increase from 2% (20 mm/y) for plots irrigated with channel water, to 17% (170 mm/y) for plots irrigated with saline water (4.8 dS/m). Lyle et al. (Lyle *et al.* 1986a) reviewed previous work, in conjunction with some of their own data, to estimate that recharge varied between 50 and 100 mm/y on the heavier soils that occupy 70% of the SIR.

A combination of lysimeters and chloride profiles were used measure recharge in the Kerang area (Girwood 1984). Recharge under perennial pasture underlain by shallow watertables was between 20 and 50 mm/y. Recharge under annual pasture in similar soils and watertable conditions was negligible. Capillary rise and evapotranspiration (ET) from bare soil was 0.1 mm/d for a watertable 1 m deep. Groundwater pumping increased accessions under annual pasture to 30 mm/y, however, the impact of pumping on recharge was less under perennial pasture (Girwood 1984).

A study near Deniliquin measured leaching fractions on a sandy loam. Leaching fluxes by were measured to vary between 200 and –115 mm/week (unpublished data, Slavich). These high rates were attributed to difficulties in applying leaching fraction equations to fields with large amounts of spatial variability. The spatial variability was measured using an EM38. Regression relationships between EM38 reading and measured LF were developed, and a field-average leaching fraction calculated using this regression relationship and a field average EM38 reading. The average leaching fraction was (1.8± 4 mm/wk). A key implication of this work is that a large sample size needs to be taken to account for spatial variability when using chloride profiles to estimate leaching fraction.

The temporal and spatial pattern in watertable levels were analysed to estimate recharge in the Girgarre area of Northern Victoria (Prathapar and Erskine 1991). Recharge was calculated from the difference between change in storage, lateral groundwater flow and groundwater pumping. They found considerable variation in recharge, varying from –220 mm/y to 310 mm/y. On average, the area had net negative recharge across the region, with only a few areas having greater than 100mm/y recharge. This estimate of recharge is influence by channel seepage and regional groundwater flows. Again, this work highlights the high level of spatial variability in recharge.

A range of point-scale modelling approaches have also been used to quantify recharge under flood irrigated pasture. These studies are usually conceptual, as there is insufficient data to test and verify the model being used. Recharge was found to vary between -30 and 260 mm/y in the Riverina (Schwamberger *et al.* 1994). Rainfall had a large impact on recharge, as did watertable and soil type. The authors acknowledged that there were insufficient data to test the model.

Recharge was estimated at 250 sites, over a 650 ha area in northern Victoria, from chloride profiles. (Bethune 2002). The average depth of recharge over the study area was 40 mm/y, ranging from 1 to 190 mm/y. This work again highlighted the large spatial variability in recharge.

A lysimeter study conducted between 1997 and 2001 quantified all components of the water balance for an irrigation pasture on a heavy soil (Goulburn Loam). This study found recharge was small, averaging 5 mm/y (Bethune and Cook 2002). However, there was considerable variation in accessions between lysimeter cores.

3. Factors affecting recharge

3.1 Soil factors

Most studies quantifying recharge under irrigated pasture focus on heavy clay soils, which occupy the greatest spatial extent of irrigation areas in the southern Murray Darling Basin. Estimated recharge on heavy soils generally are in reasonably good agreement, typically being less than 5% of applied irrigation and rainfall in the Shepparton area (Lyle *et al.* 1986a; Prendergast 1995). Similar levels of recharge were reported for the Kerang area (Girwood 1984; Poulton 1984) and in southern NSW (Bethune-unpublished data).

There are very few sources of information on recharge under lighter soils. The hydraulic gradient of soil water potential below the rootzone of a prior stream soil was measured to be approximately five times that of Lemnos loam following irrigation (Brown 1978). This indicates potential for greater losses, but no hydraulic properties of the soil were available to calculate the actual deep percolation for these soils. In addition, hydraulic gradients following rainfall events and during winter were not measured. Therefore, no inference on recharge as a consequence of rainfall can be made from this study. Recharge on intensively irrigated light soils were estimated to be between 100 and 200 mm/y (Anon 1977; Trewhella 1981). These estimates were based on the analysis of groundwater pump test results. They would overestimate recharge that occurs directly under border check irrigated pasture as they include the impact of channel seepage and regional groundwater flows. In addition, recharge estimates based on pump tests would be higher as a result of the impact of groundwater pumping on recharge.

One published study on light soils (Naneela Fine Sandy Loam) recorded leaching fractions of 30% (Lyle and Wildes 1986). The depth of irrigation was not reported, however this leaching fraction would correspond to approximately 300 mm/y of recharge. A groundwater pump operated at the site and may have lead to higher levels of recharge. This estimate of recharge does not include the contribution of channel seepage, which would also be quite high in areas of such permeable soils. Leaching fractions in the Deniliquin area on a sandy loam soils were found to be around 10% (Slavich, unpublished data). Considerable spatial variability was measured over small distances in this study. Recharge was estimated from steady state leaching fractions in the Campaspe area to be 240 mm/y for light sandy loams, 110 mm/y loams and 64 mm/y for clay loams (Bridley 1985).

Using a modelling approach, recharge for Shepparton Fine Sandy Loam (SFSL) was found to be approximately twice that of Lemnos Loam (Lyle 1988). However, the author acknowledged that he did not have hydraulic properties defining a Lemnos Loam. Some evidence supporting these results can be drawn from the leaching studies on Lemnos Loam (Lyle *et al.* 1986b"afdasf") on a sandy loam soil. Leaching fraction for Lemnos loam was typically less than 5 % and for the sandy loam, 10 %. A recent study of leaching studies in the Tongala area found that leaching fractions of SFSL were on average twice that of a LL (Bethune 2002). However, leaching fractions in areas irrigated with low salinity water were less than 1%, which is considerably less than measured by Lyle et al (Lyle *et al.* 1986b) and Slavich (unpublished data). This source of this discrepancy is unclear, but may result from restricted drainage in the Tongala area as a result of high watertables.

Bakker and Cockcroft (Bakker and Cockcroft 1974) suggest that the small areas of light soils in the area Shepparton area act as intake areas, with high levels of recharge. This recharge then moves laterally and impacts on watertable levels under the heavier, less permeable soils. Further support for this argument was provided through interpretation of watertable level data in the Tongala area (Bethune and Heuperman 2002). Watertable levels were found to be strongly associated with prior stream activity, with a groundwater pressure mound forming under the lighter prior stream soils. This pressure mound most likely results from high recharge through the permeable prior streams. Recharge under the lighter prior stream soils were twice that under the heavier soils at distance from the prior stream (Bethune 2002). This mound results in a groundwater movement towards the heavier soils found away from the prior stream.

Only 10% of the Shepparton area has soils lighter than SFSL (Lyle *et al.* 1986a). From simple calculations, it can be estimated that 40 % of the farm recharge could result from 10 % of the irrigation area, by assuming that 90 % of the region has leaching fractions of 5 % and 10 % has leaching fractions of 30 %. This does not consider the impact of channel seepage, which again would be expected to be considerably higher on the lighter soils. While this calculation is only approximate, it highlights that there may be considerable environmental benefits in targeting recharge reduction in areas of very light soils. However, there is unlikely to be large water savings as the areas of light soils

The available literature indicates that flood irrigation on heavy clay soils does not lead to large amounts of recharge. However, it does not provide an assessment of whether the observed recharge rates under these heavy soils are acceptable or sustainable from an environmental management perspective. There is some evidence that flood irrigation on permeable sandy soil results in excessive amounts of recharge. However, the spatial extent of the intersection of flood-irrigated pastures and these permeable soils is relatively small. Nevertheless, the environmental consequences of flood irrigation on the relatively small areas of permeable soils are largely unknown. A framework needs to be developed that clearly defines an acceptable recharge rate below flood irrigated pasture. It would then be possible to identify under which soils border check irrigation of pasture could be managed to within this limit.

3.2 Cracking and bypass flows

Soil shrinkage and crack formation are a function of soil wetness in swelling clay soils, with the degree of shrinkage increasing with increasing soil drying (Stirk 1954; Yule 1984). As a result, there is scope for rapid losses of water below the rootzone through cracks in dry soils. Prendergast (Prendergast 1995) measured bypass flows below 1 m, which was attributed to rapid flow through soil cracks. The magnitude of bypass flows below 1 m was less than 1 % of water applied 3 days after irrigation, and approximately 5 % of irrigation water had drained below 1 m after 210 days. This bypass flux is similar in magnitude to the total leaching fraction measured at the experimental site. Sampson (Sampson 1975) found that watertables rose quickly following irrigation as a result of water flow through soil cracks. The watertable quickly receded as a result of the crack water being absorbed into the soil matrix. In both of these studies, cracks lead to rapid water fluxes. However, the impact of cracking on recharge was not assessed.

Cracks form as a result of soil drying and shrinkage (Yule 1984). No cracks will be present when the soil is at saturation. Therefore, crack depth is limited to the depth of the watertable. In ares with shallow watertables, soil cracks will most likely be restricted to the depth of water extraction by the crop when irrigation water is applied to meet plant water requirements. Prior to irrigation in the Shepparton area, the landscape was covered with deeper rooted vegetation. These deep-rooted plants could have extracted water to greater depth than shallow rooted pasture species, therefore resulting in greater crack formation to depth. Irrigation of these deeply cracked soils could have led to large amounts of recharge passing to depth before the soil profile wet up and cracks closed. Some evidence of this process was recorded on a flood irrigation rice farm. The area had never been sown to rice before and had deep watertables. A large amount of water (150 mm) was lost below 2 m depth within the first 24 hours of ponding (Bethune *et al.* 2001). This loss was attributed to soil cracking. The following season, losses in the first 24 hours of ponding were negligible because the soil profile was still wet and there were no cracks to depth.

Annual pastures are typically irrigated in the autumn to improve germination and growth during the winter period. These pastures are inactive and not irrigated over summer. Therefore, there is an extended period of high evaporative demand to dry out the soil profile. Such a dry profile may lead to the formation of deep cracks in a cracking soil. High water use is often recorded in the first irrigation on annual pasture, 200-300mm in a cracking soil and 100-150mm in duplex soil. The fate of this water is largely unknown. Questions rise over whether the water use is restricted to wetting up the soil profile (limited recharge) or contributes directly to recharge. Even if the water use is restricted to wetting up the profile, it is likely to lead to increased recharge over the winter due to reduce storage capacity of the soil. Whether capillary rise and evaporation the following summer balance this recharge out is unknown. The area of winter pastures is greater than the area of summer pastures in northern Victoria. Therefore, it would appear warranted to establish some well designed experimental programs to measure recharge under annual pastures and the likely impacts on the surrounding area.

3.3 Soil sodicity

Soil sodicity is widely recognised as leading to soil structural problems. Sodic soils have poor soil structure (Rengasamy and Olsson 1991), and reduced soil permeability to water and air (van Hoorn and van Alphen 1994). This restricts water movement and thus may lead to reduced recharge. Leaching of soluble salts from a saline-sodic soil by rainfall and irrigation with low salinity water will result in degraded soil structure (Quirk and Schofield 1955; Rengasamy and Olsson 1991). Leaching studies in the Tongala area found a net negative correlation between recharge and soil sodicity (Bethune 2002). However, increases in soil salinity and sodicity are a consequence of restricted recharge. Therefore, it was not known whether restricted recharge led to elevated sodicity levels, or sodicity related structural decline restricted recharge.

Recharge was found to reduce from 200 mm/y in the first year of irrigation to 50 mm/y in the fourth year on a tile drained site in the Kerang area (Poulton 1984). The reduction in recharge was attributed to the development of a throttle in the soil profile, associated with sodicity problems resulting from leaching a saline-sodic soil. The throttle formed over four years of irrigation after which recharge became limited by the infiltration characteristics of the soil (Poulton 1984). However, no supporting chemical or physical data was collected to verify this hypothesis.

The impact of sodicity on recharge was captured in an empirical leaching fraction model developed in Queensland (Shaw and Thorburn 1985). The model was based on a study of leaching under 766 soils, and expressed leaching fraction as a linear function of rainfall and soil sodium levels within a soil group, the soil group being classified by clay content, cation exchange capacity and soil sodicity.

3.4 When does recharge occur?

Brown (Brown 1978) estimated that 0.8 mm of DP (below 0.7 m) occurred per irrigation on a Lemnos Loam, quantified by measuring the hydraulic gradient and soil hydraulic properties. This would equate to a total of around 15 mm/y of recharge that result directly from irrigation (Lyle *et al.* 1986a). Based on these results, they stated that the majority of recharge under heavy soils result from rainfall, with only between 10 and 20 mm/y recharge resulting from irrigation. They suggest than winter and spring rainfall is a major cause of rises in watertables as opposed to irrigation. Modelling studies also support these findings, indicating that recharge predominantly occurs during winter, with the greatest accessions occurring in wet winters (Lyle 1988). These modelling studies were theoretically based with little practical testing. More recent lysimeter experiments support these earlier findings that recharge occurs mostly during winter and spring on a heavy clay soil (Bethune and Cook 2002). Recharge during the irrigation season was small in the lysimeter experiment.

Given the low permeability of the subsoil, substantial amounts of recharge are only likely to occur when the soil is wet for long periods of time. This is most likely to occur during winter and spring when rainfall typically exceeds the evaporative demand of the crop. This impact of winter rainfall can be observed in regional watertable behaviour with times of high watertable reflecting periods of high recharge. Watertable levels have monitored in the SIR since 1982, with each year a watertable map being produced for the region. The correlation between winter rainfall and the area with high watertables was assessed (Table 2). The area with watertables within 1m of the surface was most strongly correlated with winter rainfall. Areas with deeper watertables were less strongly correlated with winter rainfall. Irrigation would also be expected to influence on the area with high watertables. The irrigation intensity was calculated by from the total deliveries and the total area of the SIR (including non irrigated areas). The impact of the total irrigation water allocation available to the SIR on watertable levels was also assessed (Table 2). The irrigation allocations reflecting water storage in the reservoirs, which is a function of climatic conditions over several years. The irrigation allocation was more strongly correlated to the area with high watertables than the actual irrigation water delivered to the region. This suggests that the area with high watertables was more strongly correlated with water availability for irrigation than actual irrigation water use. This may reflect a lagging impact of past climatic conditions that have contributed to the formation of the current water allocation for irrigation. In any year, the percentage of the irrigation region with watertables within 2m of the surface is strongly correlated with winter (May –August) rainfall and the regional allocation of irrigation water (Fig 2). Multi linear regression analysis of winter rainfall and irrigation allocation accounted for 73 % of the variation in the area with watertables within 2 m of the surface over the 20 years of records. Consideration of rainfall over the irrigation season did not improve the model fit. This results from the relatively small contribution rainfall makes to total applied water during the irrigation season. The above analysis of areas with high watertables was done in conceptually simplistic manner. Further analysis and interpretation of the watertable data is required. This analysis should consider both temporal and spatial factors (such as soils and land use)

It is likely that considerable amounts of recharge occur during the irrigation season on light sandy soils, in addition to recharge that occurs during the winter. Water use data from dairy farms clearly identifies that some farms have greater irrigation application that potential pasture water use (Terry *et al.* 2001). However, it is not possible to identify from these studies whether the water surplus to the plants needs is lost in runoff or DP. No systematic study has been conducted in this area to identify why water use is greater that potential water use, and what impact this high water use has on the timing and magnitude of recharge. One recent study on a light sandy soil in the Campaspe area measured a water balance over a 10 ha area. Recharge was estimated from the difference between irrigation intensity and pasture water use to be 30 % of applied water, or between 300-500 mm/y (Douglass 2000). These results indicate that high levels of recharge can occur under border check irrigation on highly permeable soils.

Historical data on trends in groundwater level highlight that significant recharge occur during 'discrete recharge events' that occur as a result of high rainfall and surface flooding across northern Victoria (Macumber 1984). This behaviour was evident during the wet period between 1973 and 1975 in northern Victoria.

3.5 Irrigation management

Bartels (Bartels 1965)found that deep percolation was reduced when the interval between irrigations was increased and the soils drier. Watertable levels, and by inference, recharge, were found to be adversely affected by poor irrigation management (Sampson 1975). This observation was made by comparing watertable levels under good and bad flood irrigation management on 1 ha plots. He found watertable level response to be similar under sprinkler and well managed flood irrigation in the same experiment. A quadratic response in leaching fraction to increasing irrigation interval was observed by Prendergast and Noble (unpublished data- 1990). Irrigating when pan evaporation minus rainfall (E-R) exceeded 40 mm and when E-R exceeded 85 mm resulted in the highest leaching fractions. The two intermediate intervals (E-R = 50 and 65 mm) had lower leaching fractions. The increased leaching at 85 mm irrigation frequency was attributed to greater crack formation. This work also found that increasing the interval between irrigations resulted in greater pasture root density at 0.5 m depth. This occurred because the pasture was under water stress in this treatment (20% reduction in dry matter production) and new roots are being grown to try and source more water. This greater root development has potential benefits in that it could allow the soil profile to dry out further prior to the wet winter. Recharge would also be expected to increase with increasing irrigation intensity. This impact can be assessed by comparing recharge measured under perennial and annual pasture. Girwood (Girwood 1984)measured annual accessions for perennial pasture to be between 2 and 5 cm. He found annual accessions under annual pasture to be negligible. Leaching fractions in the Tongala area were also found to increase with irrigation intensity (Bethune 2002). However, the impact of irrigation intensity on recharge was small

3.6 Irrigation water salinity

There are several examples of the impact of increasing irrigation water salinity on (Lyle *et al.* 1986b; Prendergast 1995). The causes for higher leaching are increased hydraulic conductivity, reduced plant water use and increased hydraulic gradients and reduction in diffuse cation layer thickness (Lyle *et al.* 1986b). Increasing the irrigation water salinity above a threshold will prevent soil dispersion and restricted drainage. This threshold for Lemnos Loam occurs between 0.2 and 0.6 dS/m (Lyle *et al.* 1986b). Hydraulic conductivities did not increase further at irrigation water salinities above 0.6 dS/m. Further evidence of this can be observed in a study on the impact of saline irrigation on soil hydraulic properties (Bethune and Batey 2002). Steady state infiltration and permeability of the sub soil were found to increase as a result of irrigation with saline water when compared to areas irrigation with low salinity channel water. However no difference in either steady state infiltration rate of subsoil permeability were measured between plots irrigation with 2.5 and 4.5 dS/m water salinity.

3.7 Surface drainage

Good bay slope minimises surface storage, duration of ponding and recharge (Poulton 1984). While this applies in theory, it is very difficult to measure in practice. No direct measure of this has been made under field conditions. Modelling studies have attempted to quantify the impact of surface roughness on recharge by changing the depth of water ponding on the surface after the cessation of runoff (residual depth). Increasing the residual depth from 10 to 20 mm resulted in an increase in accessions from 75 to 115 mm/y for a sandy loam soil (Lyle 1988).

3.8 Watertable level and subsurface drainage

Girwood (Girwood 1984) measured accessions in the Kerang area using a combination of lysimeters and chloride profiles. Annual accessions for perennial pasture underlain by shallow watertables was between 20 and 50 mm/y. Groundwater pumping did not increase recharge. Net groundwater movement must have occurred away from the study site. Recharge under annual pasture increased as a result pumping from zero to 30 mm/y. Approximately 6 % of applied water contributes to recharge under a non-saline-sodic tile drained soil near Kerang (Poulton 1984). This compares favourably with the 50 mm/y measured by Girwood (Girwood 1984), where recharge under the permanent pasture would have resulted in groundwater discharge in the surrounding dryland areas.

A model was used to assess the impact of watertable level on recharge for soils typical to the Shepparton area (Lyle 1988). The results indicated that only the lightest soil (East Shepparton fine sandy loam-Efsl) had positive recharge during a wet winter at watertable depth of 0.5 m. Recharge was negative for all other soils and seasons assessed at this shallow watertable depth. At a deeper watertable level (1.5 m), recharge was positive during both the irrigation season and winter, with greater recharge under lighter soil types. The same trend was seen for a modelling study in the Riverina where recharge was negative for watertables within 0.75 m of the surface under all soil types and seasonal conditions studied (Schwamberger *et al.* 1994). Conversely, recharge estimates were positive for all seasonal conditions and soil types when watertables were below 1.25m depth. For both modelling studies described above there were limited data (or none) for model testing and verification. In addition, the impact of increasing soil salinity on plant water use resulting from capillary rise was not considered. Therefore, these outputs should only be considered in a qualitative manner. Absolute values of recharge predicted by the models need to be treated with caution. In both models, the groundwater level was fixed, where under natural conditions the watertable level would fluctuate in response to drainage or capillary rise. The authors of both studies recognise this as a limitation and indicated that the model needs to allow the watertable to respond to water movement.

A lysimeter study at Tatura found that recharge rates were generally positive for watertable depth increasing from 0.6 to 1.8 m (Bethune and Cook 2002). No difference in recharge levels was measured between watertable depths at 1.2 and 1.8 m. Recharge was less at watertable depths of 0.6 m.

3.9 Agronomic potential to reduce recharge

The potential for recharge can be assessed by investigating the relationship between rainfall and plant water use. Pasture water use is assumed to equal reference crop evapotranspiration (ET_o), calculated from pan evaporation and a pan factor of 0.85 (Allen *et al.* 1998). The difference between ET_o and rainfall (R) was calculated using monthly climatic data for the period between 1970 and 2000. Calculated R-ET_o were ranked in ascending order and the probability of occurrence calculated for each winter period (15 May to 15 August). On average, winter rainfall exceeded pasture water use by 42 mm. There was an 80% probability of winter rainfall exceeding plant water use over winter (Fig 4). This means that in 8 out of 10 years, more rain will fall than can be used by pasture. Two issues affect this calculation. Firstly, it was assumed that all of the rainfall infiltrated the soil. The second is that the pan coefficient is the same all year and that the pasture is transpiring at potential rate over the winter period.

One option often considered to reduce recharge is through drying the soil profile prior to winter. The maximum storage capacity of the rootzone can be approximated from the difference between field capacity and permanent wilting point, multiplied by the depth of the rootzone. This is approximately 50 mm, assuming field capacity of 34 %, permanent wilting point of 20% and a rooting depth of 400 mm. This potential water storage in the rootzone is of a similar order of magnitude to the average difference between winter pasture water use and rainfall (42 mm). This indicates that on average surplus rainfall during winter could be stored in the rootzone providing the rootzone is dry prior to winter. However, the probability of R-ET_o exceeding rootzone storage is 50% (Fig 4), resulting in low potential for the shallow rooted pasture crop to store the surplus rainfall falling during winter periods.

4. Conclusions

Recharge is very difficult to measure and there are few good data sets describing recharge under perennial pasture that are suitable for model testing and verification. Most recharge studies report annual water balances or estimates of recharge which are not informative about options to reduce or manage recharge.

The available information implies that little recharge occurs under flood irrigated pasture on heavy soils (<5 % of applied rainfall and irrigation). However, some recharge must occur to provide leaching and prevent salinisation. There is only limited information describing recharge under light soils. This available information suggests recharge rates under flood irrigation light soils can be very high (>300 mm/y). High recharge levels through these small areas of light soils could potentially impact on a large area. There may be considerable benefits in targeting these areas with more efficient irrigation practices or techniques.

Large differences in recharge occur between heavy and light soils. This begs the question of what is a heavy soil and what is a light soil. Approaches need to be developed that allow recharge to be estimated on transitional soils. Acceptable recharge limits need to be defined. These limits should be based on the leaching requirement of the crop. Alternative irrigation technologies should then be applied to areas where recharge is higher than this limit. Such a systematic approach has not been applied to irrigation areas in the southern Murray Darling Basin.

Irrigation water salinity has a large impact on recharge rate. Therefore, deteriorating water quality through impacts of dryland salinity and disposal of groundwater through the channel supply system will lead to increased accessions. The implications of this on future watertable levels, salinisation, drainage requirements and salt export have not been considered in the formulation of land and water management plans in south eastern Australia.

Large databases of temporal and spatial watertables levels have been collected. This information, in conjunction with other hydrologic and management data may indicate where and when recharge is occurs and provide a tool to target high recharge areas. To date, no systematic analysis of these watertable data has been conducted.

Table 1. Studies of recharge under border check irrigation pasture.

Source	Crop	Scale	Soil	Water-table	Location	Recharge (mm/y)	Method
(Bartels 1965)	PP	Point	WL	?	Werribee	7-360	water balance
(GHD 1970)	Var	Region	Var	Var	Shepparton	150-300	water balance
(Anon 1977)#	PP	Sub-Reg	Heavy-Light	S	Shepparton	110 (HS)-200 (LS)	Pump test or water balance
(Brown 1978)	PP	Point	LL	S	Kyabram	1.5mm/irrigation	flux-gradient
(Trewhella 1981)	Var	Sub-Reg	SL	S	Shepparton	200	pump test
(Girwood 1984)	AP & PP	Point	MC	S	Kerang	Neglible	Lysimeter & chloride
(Girwood 1984)	AP & PP	Point	MC	GWP	Kerang	20-50	chloride profiles
(Poulton 1984)	PP	Field	MC	TD	Kerang	50-200	tile drain outflow
Trewhella (1984)		Sub-Reg	Var	shallow	Bar Creek	30	water and salt balance
(Bridley 1985)	PP	Sub-Reg	Heavy-Sandy	?	Campaspe	90(HS), 115(SS), 2(DL)	chloride profiles
(Lyle and Wildes 1986))	PP	Field	NFSL	shallow (1m)	Shepparton	360-600	chloride profile
(Lyle *et al.* 1986a)	PP	Point	LL-SL	shallow	Shepparton	50-100 mm/y	review
(Lyle *et al.* 1986b)	PP	Plot	LL	shallow	Kyabram	34 (up to 230)	chloride (3 methods)
(Prathapar and Erskine 1991)	PP	Sub-Reg	Var	GWP	Gigarre	5-6	spatial model
Prendergast and Noble (unpublished data)	PP	Plot	LL	GWP	Tatura	24 (up to 280)	chloride profiles
(Schwamberger *et al.* 1994)	PP	Point	var	Var	Various (NSW)	-30-260	modelling
(Prendergast 1995)	PP	Plot	LL	GWP	Tatura	24 (up to 500)	chloride profiles
Gilfedder et al., (2000)	PP	Field	heavy	shallow	Kerang	neglible	bay water balance
Slavich and Yang (UP)	PP	Field	SL	shallow	Deniliquin	100	chloride profiles
(Bethune 2002))	PP	Sub-Reg	var	shallow	Tongala	40 (up to 200)	chloride profiles
(Bethune and Cook 2002)	PP	Point	GL	Var	Tatura	20 (range (-50-100)	lysimeter

Abbreviations. PP (perennial pasture), AP (annual pasture), PC(preclearing), SL(sandy loam), LL(Lemnos Loam), NFSL (Naneela Fine Sandy Loam), WL (Werribee Loam-similar to Lemnos Loam), Var=various, GL(Goulburn Loam)

Table 2. Correlation matrix of relationship between areas with high water tables, irrigation allocation, irrigation delivery and winter rainfall in the SIR

		A	B	C	D	E	F
Irrigation water allocated	A	1					
Irrigation water delivered	B	0.4	1				
Winter rainfall	C	-0.10	0.25	1			
Watertables within 1 m of surface	D	0.50	0.33	0.66	1		
Watertables within 2 m of surface	E	0.66	0.22	0.51	0.92	1	
Watertables within 3 m of surface	F	0.5	0.09	0.27	0.59	0.75	1

Table 3. The effect of landforming on accessions, based on modelling studies (mm/y) After McMahon (McMahon 1984)

Condition	Pre Landforming	Post land forming
PP-Light soil	110-120	120
PP-Heavy soil	70	60
AP-Heavy soil	90	30

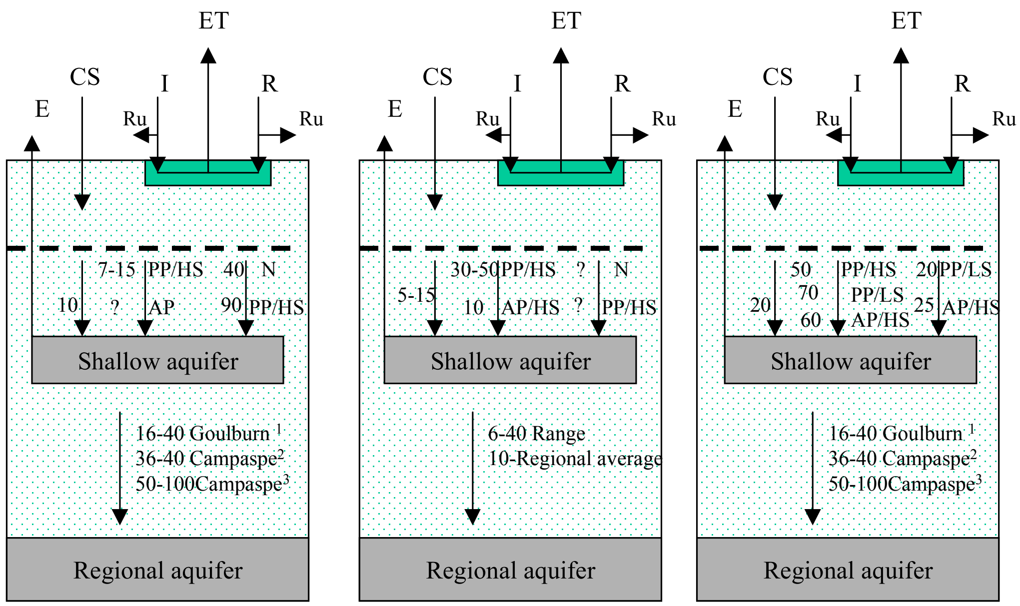


Fig 1a. Groundwater accessions in Shepparton Region (mm/yr), I-AP 200-400mm/yr, I-PP 500-800 mm/yr, R - 400-500 mm/yr

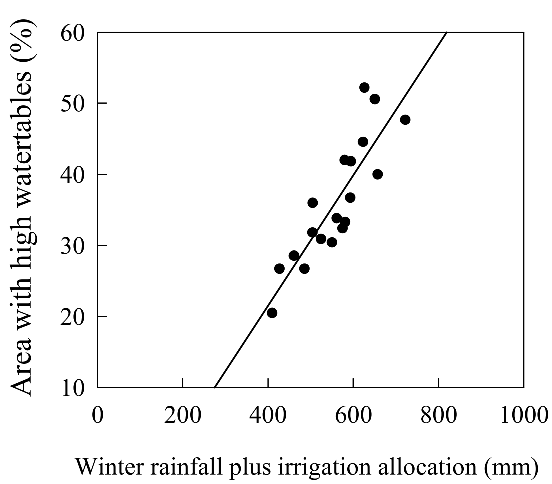
Fig 1b. Groundwater accessions in Kerang Region (mm/yr), I-AP 200-400mm/yr, I-PP 500-1000 mm/yr, R - 350-430 mm/yr

Fig 1c. Groundwater accessions in Bar Creek catchment model (mm/yr)

Footnotes:
AP = annual pasture
PP = perennial pasture
N = non irrigated land
HS=heavy soil
LS = light soil
E=evaporation
R=Rain

ET=evapotranspiration
Ru=runoff
CS=channel seepage
I=Irrigation
1 = regional range - irrigated and non irrigated
2 = Regional average - irrigated and non irrigated
3= Average under irrigated land

Figure 1. Summary of recharge in Northern Victoria, after McMahon (McMahon 1984).



.

Figure 2. Impact of winter rainfall and irrigation allocation on areas with high watertables in the SIR (r^2=0.73).

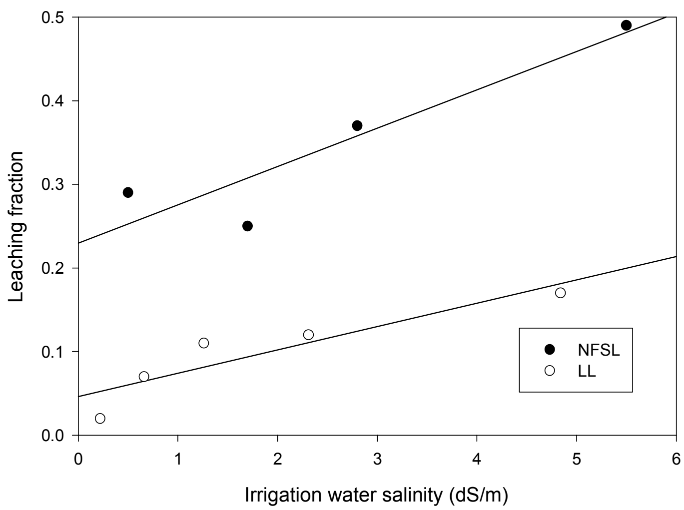


Figure 3. Impact of irrigation water salinity on leaching fraction, data from Lyle and Wildes (Lyle and Wildes 1986)and Prendergast (Prendergast 1995)

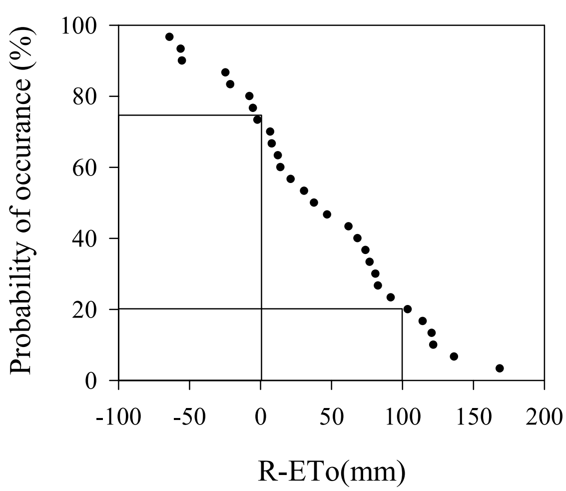


Figure 4. Probability of occurrence of the difference between rainfall and potential pasture water use (R-ET$_o$) exceeding a specified value during the winter.

References

ADC (1997) 'Dairy compendium 1997.' (Australian Dairy Corporation, Victoria)

Allen RG, Smith M, Perrier A, Pereira LS (1998) 'Crop evapotranspiration, Guidelines for computing crop water requirements. FAO Irrig. and Drainage Paper 56.' (United Nations: New York)

Anon (1977) 'Shepparton Region Water Table Control Programme-The need for water table control.' (State Rivers and Water Supply Commission Investigation Division Report, Victoria)

Bakker AC, Cockcroft B (1974) Salting in the Goulburn Valley. *Victorian Horticultural Digest* **62**.

Bartels LF (1965) Estimation of soil drainage losses following irrigation. *Australian Journal of Experimental Agriculture and Animal Husbandry* **5,** 59-64.

Bethune M (2002) Factors affecting recharge under border check irrigation of pasture. *In preparation*.

Bethune M, Austin N, Maher S (2001) Quantifying the water budget of irrigated rice in the Shepparton Irrigation Region, Australia. *Irrigation Science* **20,** 99-105.

Bethune M, Batey T (2002) Impact on soil hydraulic properties resulting from irrigating saline-sodic soils with low salinity water. *Australian Journal of Experimental Agriculture and Animal Husbandry* **42,** 999.

Bethune M, Cook A (2002) Quantification of components of the water balance of irrigated pastures using lysimetry. *In preparation*.

Bethune M, Heuperman AF (2002) Interactions between watertable levels, salinisation and prior stream activity in Northern Victoria, Australia. *In preparation*.

Bossence WH (1969) 'Tatura and the Shire of Rodney.' (Hawthorn Press: Melbourne)

Bridley SF (1985) 'Groundwater recharge in part of the Campaspe Irrigation District.' (Rural Water Commission, Armadale, Australia)

Brown SA (1978) 'Percolation losses under perennial pasture irrigation in the Shepparton region. Project Report-In-service training Project.' (Irrigation Research Station, Kyabram)

Douglass W (2000) 'ISU4: Improving water use efficiency of borderch irrigation on light soil types.' (Goulburn Murray Water, Tatura, Victoria)

Gee CW, Hillel D (1988) Groundwater recharge in arid regions: review and critique of estimation methods. *Hydrological Processes* **2.,** 255-266.

GHD (1970) 'Murray Valley Salinity Investigations.' (River Murray Commission, Canberra)

GHD (1983) 'The application of salinity control techniques in Victoria. A report prepared for the Salinity Committee of the Victorian Parliament.'

Girwood G (1984) 'Measurements of components of the water balance by means of lysimeters.' (State Rivers and Water Supply Commission of Victoria, Armadale, Australia)

Holmes JW, Watson CL (1967) The water budget of irrigation pasture land near Murray Bridge, South Australia. *Agricultural Meteorology* **4,** 177-188.

Lyle CW (1988) 'The quantification of on-farm options for salinity control. A working paper prepared by DARA for the Project Management Advisory Committee of the Shepparton Irrigation Region Land and Water Management Plan.' (Rural Water Commission, Tatura, Australia)

Lyle CW, Chalmers DJ, Wildes RA, Heuperman AF (1986a) Causes of shallow watertables in the irrigation areas of the Shepparton Irrigation Region of Northern Victoria. *Journal of the Australian Institute of Agricultural Science* **52,** 23-27.

Lyle CW, Mehanni AH (1984) Leaching rates under perennial pastures grown on clay soil and irrigated with saline water in northern Victoria. p. -303. Brisbane)

Lyle CW, Mehanni AH, Repsys AP (1986b) Leaching rates under a perennial pasture irrigation with saline water. *Irrigation Science* **7,** 277-286.

Lyle CW, Wildes RA (1986) Irrigation of permeable soils with saline groundwater in the Shepparton Region of Victoria. pp. 103-115. Toowoomba)

Macumber P (1984) 'The Implications of northern Victorian regional hydrogeology for salinity control.'

McMahon TA (1984) 'Irrigation and groundwater accessions. A report prepared for the Salinity Committee of the Victorian Parliament on the Proceedings of a Technical Seminar.'

Poulton DC (1984) 'Hydrology of an experimental tile drainage system and Kerang, 1975-79.' (State Rivers and Water Supply Commission of Victoria, Armadale, Australia)

Prathapar SA, Erskine D (1991) 'Estimating net recharge to the watertable in the Girgarre project area using historic piezometric data and linear programming. Technical Memorandum 91/7.' (CSIRO, Griffith, Australia.)

Prendergast JB (1995) Soil water bypass and solute transport under irrigated pasture. *Soil Science Society of America Journal* **59,** 1531-1539.

Quirk JP, Schofield RK (1955) The effect of electrolyte concentration on soil permeability. *Journal of Soil Science* **6,** 163-178.

Rengasamy P, Olsson KA (1991) Sodicity and Soil Structure. *Australian Journal of Soil Research* **29,** 935-952.

Roufail (1980) '***Need correct title.*** In 'The salinity problem in the Goulburn-Murray irrigation district, with particular references to agricultural research relevant to salinity control'.' (University of Melbourne: Melbourne)

Sampson K (1975) 'Water table movements under an irrigated perennial pasture on Macorna clay. In 'The salinity problem in the Goulburn-Murray irrigation district'.' (University of Melbourne: Melbourne)

Schwamberger EC, Meyer WS, Prathapar SA (1994) 'Determination of water flux past 800 mm depth under different combinations of soil, crop, water table depth and rainfall in the riverina. Final Report to the Murray Darling Basin Commission.' (CSIRO Division of Water Resources, Griffith, Australia)

Shaw RJ, Thorburn PJ (1985) Prediction of leaching fractions from soil properties, irrigation water and rainfall. *Irrigation Science* **6,** 73-83.

Stirk GB (1954) Some aspects of soil shrinkage and the effect of cracking upon water entry into the soil. *Australian Journal of Agricultural Research* **5,** 279-290.

Terry A, Mann L, Heuperman AF, Morris M (2001) 'The Tongala groundwater pumping and reuse project- 20 year review 1980-2000.' (Department of Natural Resources and Environment, Tatura, Australia)

Trewhella W (1981) (1981) Problems in design of groundwater pumping schemes in the Shepparton Region. Melbourne. pp 148-159. pp. 148-159. (ANCID: Melbourne)

van Hoorn JW, van Alphen JG (1994) van Hoorn JW and van Alphen JG (1994) Salinity Control. In 'Drainage Principles and Applications'. (Eds HP Ritzema) pp 533-600. (ILRI Publication 16). In 'Drainage Principles and Applications'. (Ed. HP Ritzema) pp. 533-600. (ILRI: Wageningen, The Netherlands)

Yule DF (1984) Volumetric calculations in cracking clay soils. Reviews in Rural Science 5. (Eds JW McGarity, EH Hoult, and HB So) pp. 136-140. (University of New England: Armidale, New South Wales, Australia)

Recharge under Flood Irrigated Pasture

July 2001

Attachment 4

Matthew Bethune,
Institute of Sustainable Irrigated Agriculture, Tatura, Victoria

Abstract

Soil sampling was undertaken to determine groundwater recharge in an area where groundwater pumping and reuse for irrigation of pasture has been practiced for more than 10 years. Factors affecting recharge (viz. irrigation management, soil type, soil chemistry and groundwater pumping) in these areas were investigated. Recharge rates were on average 38 mm/yr, varying between 2 and 190 mm/yr. Applied water salinity had the greatest impact on recharge. Soil type, irrigation intensity and soil sodicity also impacted on recharge, but to a lesser degree. No relationship between groundwater pumping and recharge was observed.

Introduction

Salinity is a major threat to the economic sustainability of irrigation catchments, resulting in reduced production, decreased water quality and environmental degradation. These salinity problems are largely a consequence of high watertables that restrict leaching of the soil profile. High watertables are prevalent across most irrigation areas in south eastern Australia. The development of high watertables resulted from the clearing of deep rooted native vegetation and replacement with shallow rooted plant species (GHD, 1983). By example, watertables were 23 below the surface prior to the introduction of irrigation in the Rodney Shire, by 1970 the average depth to the watertable was 3 m (Bakker and Cockcroft, 1974). The watertable has now stabilised between 1-2 m below the surface over most of this area. This example is replicated in most irrigation areas of the southern Murray Darling Basin in Australia.

Rises in watertables result from recharge to the groundwater system. Recharge has increased as a result of irrigation and channel seepage (GHD, 1983). A key objective of land and water management plans is to reduce groundwater recharge. However, there is very little information on the magnitude of recharge, or what factors influence the location and magnitude of groundwater accessions. Three factors that impact on groundwater recharge are soil type, irrigation management (including water quality) and drainage (both surface and sub-surface). This study quantified groundwater recharge under flood irrigated pasture over a 600 hectare area in northern Victoria. Factors affecting recharge were also assessed.

Materials and methods

Location of experiment

The Tongala groundwater / reuse project area was initiated in 1980 to combat salinity problems arising from high watertables. It is located in the Shepparton Irrigation Region of northern Victoria, just east of the township of Tongala. The project area is approximately 600 hectares in size, with most of the land being layed out for border check irrigation, growing perennial pastures. The project area contains 14 farms, 13 being dairy farms that flood irrigate perennial pasture and one horticulture farm. The first groundwater pump was installed in the project area in 1980. Seventeen groundwater pumps were installed by the end of the 1994-95 irrigation season. Historically, most of the pumped groundwater has been reused on farm for irrigation. A significant decrease in soil salinity has been recorded since the commencement of groundwater pumping.

Groundwater recharge

Groundwater recharge was calculated from the leaching fraction (LF) and total volume of applied water. LF calculated using a steady state model closely approximates LF calculated using non-steady state theory once a steady state soil salinity had been achieved (Prendergast et al. 1995, Lyle et al., 1986 and Noble et al., 1989). Soil salinity had reached steady state in the Tongala project area after two years of reuse (Norman et al., 1993). Groundwater reuse has been practiced in the area since the early 1980's. Therefore, it was considered appropriate to calculate LF in the project area using the well accepted steady state model. This model assumes that the total mass of chloride stored in a finite volume of soil is constant over time, and that groundwater flow occurs only in the vertical direction (1-dimensional flow). The finite volume used to calculate LF in this instance is the top 90 cm of the soil profile, over a unit area. Annual chloride input to the finite volume is through irrigation and rainfall, and is calculated by multiplying the total annual volume of applied water by the average chloride concentration of applied water (Ci). Annual chloride output will be through deep percolation of groundwater (below 90 cm). The chloride concentration in the deep percolation (Cz) was measured by soil sampling. Groundwater recharge is calculated by multiplying LF by the total depth of applied water (irrigation and rainfall)

Soil sampling

Two hundred and forty two soil samples were taken in May 1994 from within the Tongala project area. Samples were taken in the centre of border check irrigated bays to 0.9 m depth. Soil samples were divided into four depths (0-0.15,0.15-0.3,0.3-0.6 and 0.6-0.9 m). Soil sampling was repeated in May 1995 at the same location as in 1994.

Soil salinity and exchangeable cations were measured in a saturated extract to calculate the sodium absorption ratio (Sar) and soil salinity (EC_{se}) in the rootzone (0-0.3m) and subsoil (0.3-0.6m). The soil chloride concentration was measured in a 1:5 soil/water suspension for the 0.6 to 0.9 m depth range. Gravimetric soil moisture was also measured on the 0.6-0.9 range to enable conversion of the measured chloride concentration to an equivalent concentration of chloride in the soil water solution.

Irrigation management

A survey of farmers was conducted to identify irrigation management practices on each farm in the project area. Three different irrigation water sources were identified in the survey. These are low salinity channel supply water (CW), groundwater (GW) and water diverted from surface drains (DW). Typically the groundwater was diluted (DGW) prior to reuse for irrigation, although undiluted groundwater was used for irrigation on a couple of bays within the project area.

Areas of similar irrigation management were identified on each farm. The proportion of different irrigation water sources applied to these management areas was identified and average applied water salinity calculated (adjusted for rainfall). Irrigation water was assumed to be uniformly applied across the farm. This was considered a reasonable assumption as irrigation management and frequency was consistent across the whole farm, regardless of the irrigation water source. These calculations are summarised in Table 1.

Table 1. Annual irrigation details per farm and irrigation management area

Farm	Area	I	Area per irrigation management (%)				C_i (dS/m)			
	Ha	ML/ha	CW	GW	DGW	DW	CW	GW	DGW	DW
1	10.8	8.3	11.7	12.1	76.2	-	0.07	-	0.64	-
2	41.0	7.8	39.7	-	60.3	-	0.07	-	0.39	-
3	24.7	6.2	63.3	-	36.7	-	0.06	-	1.15	-
4	36.2	10.8	100.0	-	-	-	-	-	0.13	-
5	61.8	5.7	28.0	-	51.3	20.7	0.06	-	1.20	0.37
6	19.2	4.5	100.0	-	-	-	0.05	-	-	-
7	8.0	5.1	89.0	-	11.0	-	0.06	-	5.44	-
8	9.8	8.3	100.0	-	-	-	0.07	-	-	-
9	10.7	5.4	100.0	-	-	-	0.06	-	-	-
10	8.9	6.5	100.0	-	-	-	0.06	-	-	-
11	48.0	9.6	45.2	4.0	47.0	3.9	0.07	1.13	0.57	0.07

12	66.9	12.0	34.8	-	59.2	6.0	0.07	-	0.42	0.42
13	52.4	8.5	51.0	-	35.1	13.8	0.07	-	0.68	0.37
14	16.4	12.6	39.0	-	61.0	-	0.08	-	0.81	-

Soil type

Two predominant soil types were found in the project area, Shepparton fine sandy loam (Sfsl) and Lemnos loam (Ll). In addition, smaller areas of East Shepparton fine sandy loam (Efsl), Goulburn clay loam (Gl) and Sandmount sand (Sms) were found in the project area. Some soil physical properties for these soil types are summarised in Table 2. Sms is the lightest of these soils, typically found in the bed of a prior stream. Efsl, Sfsl and Ll have red-brown clay subsoils and grade into each other texturally, Efsl being the lightest and Ll the heaviest. Texturally there is vary little difference between Ll and Gl, the main difference being the colour of the subsoil which changes from a red (Ll) to a brown (Gl) (Skene and Poutsma, 1962).

Table 2. Physical characteristics of soil types found in the study area (After Skene and Poutsma,1962).

	Sms		Efsl		Sfsl		Ll		Gl	
	Top	Sub	Top	Sub	Top	Sub	Top	Sub	Top	Sub
Sand	86	86	69	30	49	29	36	14	43	18
Silt	4	3	20	21	31	14	38	21	29	18
Clay	10	12	10	48	20	56	23	64	27	63

Groundwater pumping

The average pumped volume over the last 6 years was calculated for each of the groundwater pumps. An estimate of the area of influence around each pump was made based on this average pumped volume. A GIS was used to map the area of influence of each pump in relation to soil sampling sites in the project area. A score for each soil sampling site was made based on the number of times the area of influence of a groundwater pump overlapped a sampling point. The higher the score, the greater the groundwater extraction.

Statistical analysis

Soil salinity measurements in 1994 and 1995 were compared using a two-sampled T-test to test the assumption that soil salinity was at a steady state. The project area was divided into areas of similar irrigation management and soil type. This resulted in 36 different combinations of soil type and irrigation management. Analysis of variance was used to assess the relationship between recharge and soil type. Regression analysis was used to assess relationships between recharge, irrigation salinity, groundwater pumping volume, irrigation intensity and soil chemistry. Genstat 5 (Release 3.1), Lawes Agricultural Trust (Rothamsted Experimental Station) was used for statistical analysis.

Results and discussion

There was no difference in soil salinity ($p=0.31$) between 1994 and 1995. This supports the assumption that soil salinity was at a steady state in the study area, and gives confidence in the use of the steady state leaching model to predicted recharge levels.

Considerable variation in recharge levels was measured (Table 4). Mean recharge across the whole area was 38 mm, ranging between 2 and 199 mm/yr. Almost half of the sites sampled had recharge rates less than 10 mm/yr.

Table 4 Distribution of measured recharge.

Recharge (mm/yr)	<10	10-30	30-50	50-70	70-90	>90
Number of sites	15	7	3	3	4	4

Applied water salinity

Recharge was strongly correlated with the salinity of irrigation water. Recharge in areas irrigated with channel supply water has a mean recharge level of 8 mm/yr. Recharge increased linearly with salinity of irrigation water to 100 mm/yr at an irrigation water salinity of 1.2 dS/m (Fig 1). A linear model of recharge as a function of irrigation water salinity accounts for 60% of the variation in the data set. Two points heavily influence this function (Fig 1), these points corresponding to light, sandy soils in the project area. The linear model between recharge and irrigation water salinity accounts for 83 % of the variation if these two points are excluded from the analysis. These results are supported by a serious of plot experiments where increasing irrigation water salinity was found to increase groundwater accessions (Prendergast, 1995, Lyle et al 1986a). The causes for higher leaching and accessions are increased hydraulic conductivity, reduced plant water use and increased hydraulic gradients and reduction in diffuse cation layer thickness (Lyle et al, 1986b).

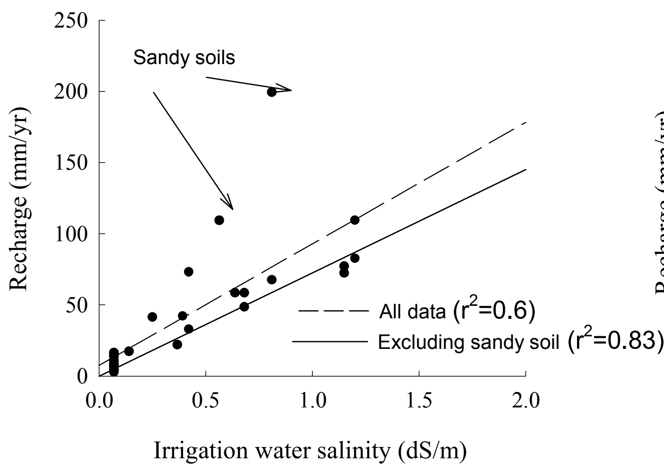


Fig 1. Impact of irrigation water salinity on recharge

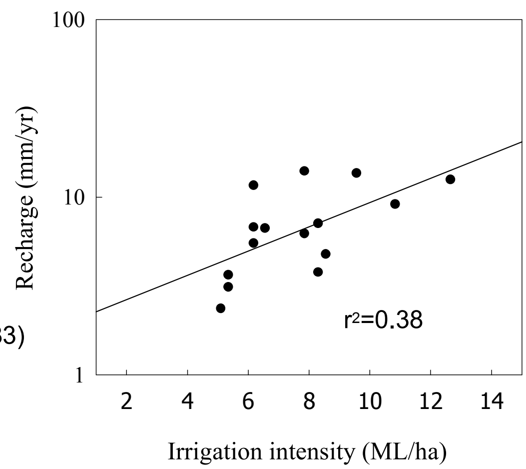


Fig 2. Impact of irrigation intensity on recharge

Soil type

Recharge under different soils was compared for areas irrigated with low salinity channel water and areas irrigated with groundwater reuse (Table 5). The impact of irrigation water salinity was removed (using the function derived from Fig 1) in the presented recharge levels. Recharge for Sfsl was twice that of the LL ($p<0.05$) in areas with groundwater reuse and areas irrigated with low salinity channel water. Limited sampling points for GL, Efsl and Sms restricted the analysis and no significant contrasts were observed between these soil types. Two higher that average recharge estimates were observed (Fig 1). These sites corresponded with light soils and high irrigation intensities (Fig 1).

Table 5. Mean recharge levels (mm/yr) for different soils in the project area, range of recharge in brackets.

Soil	Gl	Ll	Sfsl	Efsl	Sms
Channel water	14 (10-20)	7(2-19)	13(2-37)	7(2.5-13)	no samples
Groundwater reuse	21(-1-31)	19(3-32)	37(21-85)	22(21-24)	87(21-154)

Groundwater pumping
No significant relationship was observed between groundwater extraction intensity and recharge levels across the project area. Groundwater pumping extracts on average 200 mm/yr across the project area. However, watertables were still within 2 m of the surface across the project area. Therefore, there was potential for plant water extraction from the watertable when plant water requirements were not met by irrigation. The pumping rate of 200 mm/yr greatly exceeds the average groundwater recharge rate (40mm/yr). This indicates that groundwater does not contribute to leaching in the project area (non leaching recharge or NLR) is approximately 150 mm/yr. The source of this NLR occurs through channel seepage and regional groundwater flows into the project area and is the major cause of increases in pumped groundwater salinity in the project area.

Irrigation intensity
Increasing irrigation intensity lead to increases in recharge across the project area ($p=0.002$). Inclusion of the impact of irrigation intensity into the relationship between recharge and irrigation water salinity improves the fit of the data. However, the impact of intensity on recharge was small compared to that of irrigation water salinity. On average, recharge increased by 1mm/yr for a 100 mm/yr increase in irrigation intensity in areas irrigated with low salinity channel water (Fig 2). However, an increase in irrigation intensity from 400 1200 mm/yr results in a tripling of annual recharge in areas irrigated with low salinity channel water.

Soil chemistry
The combination of high Sar and low EC_{se} potentially leads to sodicity related soil structural decline and restricted recharge. Multiple regression analysis was used to assess the relationship between recharge, EC_{se} and Sar. EC_{se} and Sar were individually correlated with recharge ($p<0.01$), however there was no combined impact on recharge. The combined impact of Sar (negative) and irrigation intensity (positive) provided the best description of recharge measured in areas irrigated with low salinity channel water, accounting for 70% of the variability in the data. There was also a significant negative correlation between Sar of the subsoil and recharge in areas irrigated with groundwater ($p<0.01$). However, the impact of Sar on recharge was small in comparison to irrigation water salinity.

Conclusions

The average groundwater recharge over the 600 hectare area study area was 38 mm/yr. There was considerable variation in recharge levels. Irrigation water salinity resulted in increases in recharge from 8 mm/yr in areas irrigated with low salinity channel to 100 mm/yr in areas with irrigation water salinity of 1.2 dS/m. The impact of irrigation water salinity explained 60 % of the measured variation in recharge levels. The highest measured recharge rate was 190 mm/yr, which occurred on a Sms (a sandy soil). Recharge rates for Sfsl were twice that of a Ll. Comparison with other soils types did not reveal any clear trends.

Recharge increased by 1 mm/yr for a 100 mm/yr increase in irrigation intensity in areas irrigated with low salinity channel water. This impact is small compared to the impact of irrigation water salinity. Sub-soil sodicity was negatively correlated with recharge in both areas irrigated with low salinity channel water and areas with groundwater reuse. The impact of sodicity on recharge was also small in comparison to irrigation water salinity.

No trend was observed between groundwater extraction rates and recharge. Groundwater pumps were extracting on average 200mm/yr, while recharge rates were only 38 mm/yr. This indicates that the majority of groundwater extracted did not contribute to leaching of crops in the project area.

Acknowledgments

Funding for this project was provided by Land and Water Australia and the Catchment and Water Division of the Victorian Department of Natural Resources and Environment. Biometric support was provided by Leigh Callinan.

References

Bakker, A.C. and Cockcroft, B (1974). Salting in the Goulburn Valley”. Vic Hort. Dig. 62.

Gutteride Haskins and Davey (1983). The application of salinity control techniques in Victoria. A report prepared for the Salinity Committee of the Victorial Parliament.

Lyle, CW, Chalmers DJ, Wildes RA, Heuperman AF (1986a). Causes of shallow watertables in the irrigated areas of the Shepparton Irrigation Region of Northern Victoria. Journal of the Australian Institute of Agricultural Science 52:23,27

Lyle CW, Mehanni AH, and Repsys, AP (1986b) Leaching rates under perennial pastures irrigated with saline water. Irrig. Sci. 7:1-10

Noble, CL. Prendergast, J.B., and Z. Xiao. (1989). Irrigation management of perennial pasture. Proc. "Salinity in S.E. Aust. ", Albury. Soil Sc. Soc. pp 181-190.

Norman C. (1993 Ed.). The Tongala groundwater pumping / reuse project. Department of Agriculture, Victoria, Australia. 70p.

Prendergast 1995. Soil water bypass and solute transport under irrigated pasture. Soil Scientist Society America J. 59:1531-1539

Prendergast, JB., Rose, CW., Hogarth, WL., (1994). Sustainability of conjunctive water use for salinity control in irrigation areas; Theory and application to the Shepparton region, Australia. Irrig. Sci. 14:177-187.

Skene, JKM and Poutsma, TJ (1962). Soils and land use in part of the Goulburn Valley, Victoria. Technical Bulletin No. 14. Department of Agriculture, Victoria, Australia

Simulating the Water Balance of Border-Check Irrigated Pasture on a Cracking Soil

Attachment 5

Introduction

Over 40 % of water diverted for irrigation in the Murray Darling Basin of Australia (MDB) is applied to pasture (Crabb 1997). This pasture is mostly irrigated using the border-check system and is the main feed source for the irrigated dairy industry (Austin 1998). The sustainability of the dairy industry in the MDB is threatened by shallow watertables and land salinisation. Shallow watertables result from recharge to the groundwater system. Increased recharge resulted when deep-rooted native vegetation was replaced by shallow rooted annual crops and pastures (Crabb 1997). Irrigation resulted in further increases in recharge (GHD 1970). Options to reduce irrigation recharge and alleviate salinity problems arising from shallow watertables are required. Improving irrigation management through better scheduling practices is one option for reducing recharge. However, the farming community will resist changes to irrigation management if pasture growth is compromised. Therefore, the appraisal of options for reducing recharge needs to consider pasture growth aspects. Experiments that assess how irrigation management impacts on recharge and crop growth are costly and difficult to implement. As an alternative, simulation models can be used to assess the impact of irrigation management on recharge and evapotranspiration (ET), using ET as an indicator of pasture growth (Doorenbos and Kassam 1977). However, such models are only informative if they are conceptually sound, and capture the impact of management on recharge and ET.

This paper investigates the potential for using a simulation model to assess the impact of irrigation management on ET and recharge under border irrigated pasture. Model outputs were compared with water balance data measured in a lysimeter experiment. The importance of (i) seasonal variation in pasture crop factor and (ii) infiltration through soil cracks were appraised. The following two subsections describe why these two aspects were investigated in this study.

Seasonal variation in pasture crop factor

Potential ET (ET_{pot}) is usually calculated by multiplying reference crop evapotranspiration (ET_o) by a crop factor (K_c) (eq1). ET_o defines the ET rate from a reference crop, this crop being similar to an extensive well watered grass of uniform height (0.12 m), fixed surface resistance (70 s m^{-1}) and an albedo of 0.23 (Allen *et al.* 1998). K_c integrates factors that differentiate a particular crop from the reference crop (Allen *et al.* 1998). An irrigated dairy pasture varies from the hypothetical reference crop in a number of ways. The crop height (and thus leaf area index) changes temporally in response to grazing. Rotational grazing causes K_c to vary between 0.4 and 1.05 (Allen *et al.* 1998). The surface resistance (r_s) of an irrigated pasture varies temporally due to changes in air temperature, radiation intensity and vapour pressure deficit (Dingman 1994). The response of r_s to these factors is species dependent and is integrated into K_c, with K_c decreasing as r_s increases. Measurements of r_s over a irrigated pasture in Denmark indicate that K_c varies seasonally, with a lower K_c during the peak of summer (Szeicz and Long 1969). Seasonal variation in K_c of irrigated pasture was observed in the Murray Swamps of South Australia (source Thomson, unpublished data) and in this study (see Material and Methods) where ET was measured using lysimeters (Table 1). The available data indicate seasonal variation in K_c. The importance of accounting for such seasonal variation in K_c in a simulation model of pasture ET needs to be investigated.

$$ET_{pot} = K_c . ET_o \qquad 1$$

Table 1. Seasonal variation in pasture K_c.

Source	Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Field water balance[1]		0.7	0.6	0.67	0.5	0.4	0.44	0.48	0.78	0.96	0.81	0.71	0.67
Lysimeter[2]	1.05	1.0	0.95	1.12	1.05	0.8	0.8	0.8	0.8	1.09	1.33	1.03	1.0

Notes *[1] Thomson (ET_o assumed to equal pan evaporation). [2] ET_o calculated according to FAO-56 (Allen et al. 1998).*

Infiltration though soil cracks

Infiltration through soil cracks (I_c) has been widely reported for soils that shrink upon drying, with I_c accounting for between 50 and 80 % of the total infiltration under border check irrigation (Shaw and Yule 1978; Ross and Bridge 1984; Talsma 1972; Austin and Prendergast 1997). The majority of I_c is absorbed into the soil matrix within the pasture rootzone (Prendergast 1995) and is available for extraction by pasture roots. The magnitude of I_c bypassing the rootzone is inversely related to soil wetness. I_c accounted for 15 % of annual deep percolation when irrigation is scheduled on an evaporative deficit (pan evaporation minus rainfall or **E-R**) of 5 cm (Prendergast 1995). Clearly, the application of simulation models to the water balance of border-check irrigated pasture on cracking soils need to account for infiltration through cracks.

A number of approaches have been adopted to account for I_c in simulation models. I_c can be accounted by increasing soil hydraulic properties to compensate for the high initial infiltration rates through cracks. This can be achieved by superposing two soil moisture retention functions or hydraulic conductivity functions (Zurmuhl and Durner, 1996, Ross and Smettem, 1993). One set of composite hydraulic properties representing both the macro- and micropore domains is produced using this approach. This approach does not model water movement in the macropore domain, but accounts for macropore flow by increasing fluxes in the micropore domain. The result is that flow through cracks would be greatest when the soil matrix is near saturation. This does not accurately reflect I_c where cracking and water fluxes are greatest when the soil matrix is dry and large shrinkage cracks are present (Prendergast 1995). Therefore, models that account for I_c by adjusting soil hydraulic properties should be applied with caution when used predictively to assess the impact of management on the water balance. A preferable method would be to capture I_c using a physically based approach.

The magnitude of I_c during an irrigation event is a function of E-R since the last irrigation (Ross and Bridge 1984; Robertson and Wood 2002). This agrees with theory describing crack formation, where crack volume is a function of soil moisture status (Yule 1984; Bronswijk 1988; Prendergast 1995). Theory describing crack formation and the process of infiltration through soil cracks is included in some soil water balance models (van Dam *et al.* 1997; Ross and Bridge 1984; Bronswijk 1988). Application of such models to rain fed pastures improved the prediction of water and solute movement in a cracking soil, when compared to a model that does not account for I_c (Bronswijk 1988; van Dam 2000b). Border-check irrigated pasture differs from rain fed pasture. Water is applied rapidly by surface flooding, ponded on the surface for extended periods of time (in the order of hours), and then drained from the end of the field following the cessation of the irrigation event. This creates considerable opportunity for I_c. Models of the soil water balance that include I_c have not been applied to a border check irrigated pasture. The importance of describing the process of water infiltrating through cracks under border irrigated pastures requires appraisal.

Materials and methods

The 'SWAP' (van Dam *et al.* 1997) model was used to simulate the water balance of an irrigated pasture. Outputs from model simulations were compared to lysimeter measured water balance data (Bethune and Cook 2002).

Lysimeter study

An undisturbed soil core (0.75 m in diameter and 2.0 m deep) was housed in an underground lysimeter facility. The lysimeter core had an established mixture of white clover, perennial ryegrass and paspalum. Rain (P), irrigation (I), runoff (Ru), recharge (R), evapotranspiration (ET) and soil water storage (SWS) define the lysimeter water balance (Fig 1, eq 2).

$$\Delta SWS = P + I - Ru - R - ET \qquad 2$$

Irrigation was applied when cumulated pan evaporation minus rainfall (E-R) exceeded 5 cm. Irrigation consisted of maintaining a pond of water on the lysimeter surface for 6 hrs. After this time, remaining surface water was drained and measured as runoff. The ponding of water for 6 hours was adopted to represent border check irrigation practices found on district farms in northern Victoria. Rainfall was measured at a Bureau of Meteorology Weather Station, located 100 m from the lysimeter facility. Rainfall runoff was also measured.

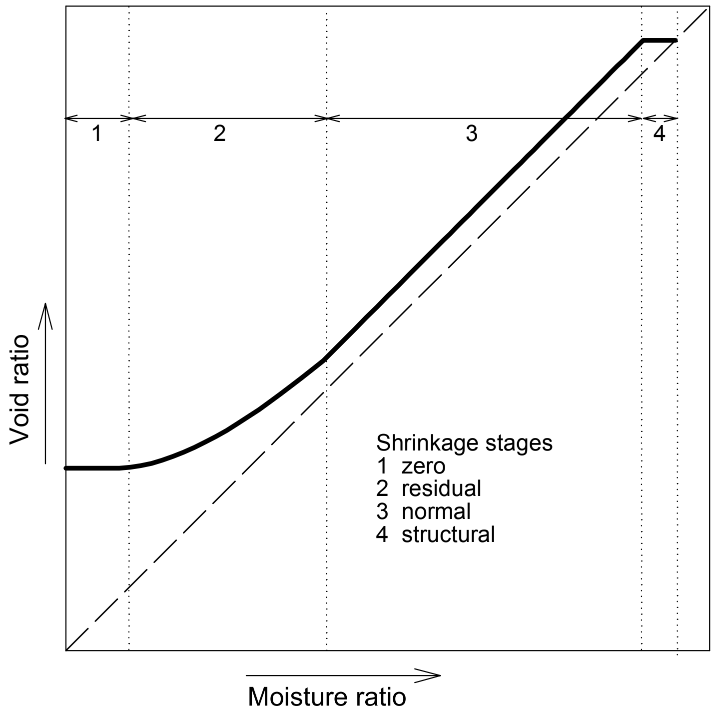
A marriotte bottle was used to apply a fixed pressure, equivalent to a watertable depth of 0.6 m, to the base of the lysimeter core. Recharge was defined as the difference between water leaving and entering the base of the lysimeter, with net water leaving the lysimeter measured as positive recharge. Soil moisture was monitored hourly at depths 0.1, 0.2, 0.3, 0.4, 0.6 and 0.9 m using Time Domain Reflectometry (TDR). The average volumetric moisture content (W) of the rootzone (0-0.3m) was calculated from this TDR data. An impermeable sub-soil and shallow watertable limited changes in soil moisture storage below this depth.

ET was measured using weighing scales, which recorded changes in core weight to a resolution of 0.01 cm of water every 20 minutes. These ET measurements derived from changes in weight were in good agreement with volume balance estimates of ET (eq 2).

The SWAP model

The SWAP model (van Dam *et al.* 1997) was adopted in this study as it simulates infiltration through soil cracks and allows for seasonally changing crop factors. Soil water movement is solved using Richards' equation, subject to pre-defined initial and boundary conditions, relationships between soil moisture (θ), soil water potential (h) and hydraulic conductivity (K). The Richards' equation is solved using an implicit finite difference scheme. The time step is adjusted automatically within the model, with short time steps (< 1 second) during infiltration events. The soil hydraulic properties are defined using the mathematical functions of Van Genuchten (1980) and Mualem (1976).

Figure 1. Shrinkage characteristic



The volume of soil cracks is defined by the soil shrinkage characteristic, a dimensionless geometry factor and soil moisture (Bronswijk 1988). The shrinkage characteristic defines the relationship between water content and soil volume change (Fig 1), where water content is expressed as the moisture ratio and soil volume expressed as the void ratio. The geometry factor partitions soil volume changes between subsidence and shrinkage (Bronswijk 1988). This approach results in the volume of cracks being calculated as a function of soil moisture and will thus change temporally and with depth as a result of changing soil water conditions. van Dam (van Dam 2000a) found that simulated water fluxes were sensitive to the presence of cracks, but not to actual crack dimensions. This implies that it is only important to know when cracks are present, and not the actual size of cracks. The onset of crack formation occurs at the transition between structural and normal shrinkage (Fig 1) and is defined by one input parameter. Four additional parameters are required to describe the shape of the shrinkage characteristic, the width of soil peds and the depth at which horizontal crack area is calculated. Based on the work of van Dam (van Dam 2000a), accurate definition of these four parameters is not critical.

Infiltration into the soil matrix (I_m) is calculated using Richards' equation. Water ponds on the soil surface when the rate of water application exceeds I_m. This surface water pond contributes to runoff when cracks are not simulated. Alternatively, all surface water is added to I_c when cracks are simulated (eq 3). The current SWAP model assumes that no surface runoff occurs when I_c is simulated, even when cracks are saturated or the soil is wet and no shrinkage cracks are present. This assumption is not valid under border-check irrigation, where both I_c and runoff occur during an irrigation event (Austin and Prendergast 1997). A modification was made to SWAP to account for runoff when soil cracks were saturated or closed (due to the soil being wet). I_c only occurred when soil cracks were open and the cracks were not saturated. Water that could not infiltrate through the matrix or soil cracks contributed to runoff. An additional modification was made to simulate lysimeter irrigation. This change prevented runoff for a 6 hr period during irrigation, to match the 6 hr period that water ponded on the lysimeter surface during an irrigation event.

$$I_c = P - I_m \qquad P > I_m \qquad 3$$

SWAP has a number of options for simulating crop growth. The "simple" crop growth option in SWAP was adopted to describe ET, which assumes that ET_{pot} is described by K_c and ET_o (eq 1). Full soil cover was assumed and therefore soil evaporation was not simulated. The model accounts for the impact of soil water stress on ET through a reduction coefficient on root water uptake. ET occurs at ET_{pot} until a critical soil water suction is exceeded. ET then reduces linearly with increasing soil water suction. Default parameters values defining this relationship were adopted for this study.

Model input

A 2.0 m deep soil profile was specified, consisting of 3 soil layers. Nodal spacings of 1 cm were adopted near the soil surface. This spacing is based on the work of van Dam and Feddes (van Dam and Feddes 2000), who consider layer thickness of 1 cm to be appropriate for simulating both evaporation and infiltration. Nodal spacing increased with depth to a maximum of 10 cm. Soil hydraulic properties were available for a Lemnos Loam soil (Greenwood – unpublished data), which is texturally similar to the Goulburn Loam soil (Skene and Poutsma 1962) used in the lysimeter. The soil water retention function of Van Genuchten (Van Genuchten 1980) was fitted to these data (eqs 4 and 5) using RETC (Van Genuchten *et al.* 1991). RETC uses a nonlinear least-squares optimisation algorithm to estimate soil parameters from measured retention and conductivity data. The residual water content (θ_r, assumed to equal 0) and saturated soil water content (θ_s, measured) were not adjusted during the fitting of the functions. The retention equations (eq 4 and eq 5) provide a good description of the soil water retention data. The fitted parameters are summarised in Table 2. Saturated hydraulic conductivity (K_s) data was measured on the Lemnos Loam (Greenwood-unpublished data). There was insufficient data to fit λ, a parameter that describes the pore connectivity and affects the relationship between hydraulic conductivity and soil water content (eq 6). λ was found to average 0.5 for a range of soils (Van Genuchten *et al.* 1991). Therefore, λ was set to equal 0.5 for this study.

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{(1 + (\alpha h)^n)^m} \qquad 4$$

$$m = 1 - \frac{1}{n} \qquad 5$$

$$K = K_s S_e^{\lambda} (1 - (1 - S_e^{1/m})^m)^2 \qquad 6$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad 7$$

θ= volumetric water content ($cm^3 cm^{-3}$)
K = hydraulic conductivity (cm/d)
h = soil water pressure head (cm)
Se = relative saturation
α (cm^{-1}) n (-) and m() = empirical shape factors

Table 2. Summary of soil moisture and hydraulic properties, including the degree of fit (r^2 – correlation coefficient) of eq 4 to the retention data.

Depth (cm)	Bulk density g/cc	θ_s	θ_r	$K_{sat\ c}$m/d	α	λ	n	r^2
0-30	1.52	0.35	0	1.5	0.025	0.5	1.33	0.98
30-70	1.6	0.41	0	0.1	0.0031	0.5	1.02	0.98
> 70	1.6	0.45	0	0.33	0.06	0.5	1.07	0.97

As discussed above, the presence of cracks, and thus structural shrinkage was the most important parameter describing crack formation. Structural shrinkage was assumed to equal 0.1. Default input values were assumed for other parameters describing crack formation.

ET_o was calculated using the Penman-Monteith equation (Allen *et al.* 1998) from daily climatic data measured at a weather station within 100 m of the lysimeter facility. Average annual crop factors and average monthly crop factors were calculated from ET measured by lysimeters and ET_o (Table 1).

Over 95 % of pasture roots are found within 0.3 m of the surface on the heavy soils subject to border-check irrigation in the MDB (Mehanni and Repsys 1986; Prendergast 1995). A triangular shaped root density distribution was adopted for the modelling, with maximum root concentration at the soil surface, and zero roots at 0.3 m depth.

The depth and timing of irrigation input to SWAP was the same as applied to the lysimeters. A surface water pond was maintained for 6 hours and then allowed to runoff. One critical factor affecting runoff is the residual depth of water (surface storage) remaining on the field surface after the cessation of runoff. A surface storage of 0.5 cm was used in this modelling study. This figure was based on a field study where surface storage of 0.5 cm was measured on a border-check field of slope 1:750 (Elliot 1984). Daily rainfall is input to the model. This rainfall is measured at the Bureau of Meteorology Weather Station, located 100 m from the lysimeter facility.

A fixed pressure was applied to the bottom of the soil profile in the model to represent a watertable depth of 0.6 m, as imposed on the lysimeter by the marriotte bottle.

SWAP simulations

Simulations were conducted under three model options, M-1, M-2 and M-3, to test model performance and to assess the need to account for crack flow processes and seasonal changes in K_c (Table 3). Simulation results were compared to lysimeter observations of the water balance made between 15/9/2000 to 1/7/2001. ET was cumulated between irrigation events while surface runoff (Ru) was compared on an event basis. As the majority of Ru events occurred following irrigation, the time scale for comparing ET and Ru was similar. W was compared on a daily basis. The subscript 'sim' (eg ET_{sim}) is used to indicate simulated components of the water balance, while the subscript 'lys' (eg ET_{lys}) indicates where components of the water balance were measured in the lysimeter.

Table 3. Summary of model simulations tested against lysimeter data.

	Crack flow process simulated	K_c
Model option 1 – (M-1)	yes	monthly crop factor
Model option 2 – (M-2)	yes	annual crop factor
Model option 3 – (M-3)	no	monthly crop factor

Results

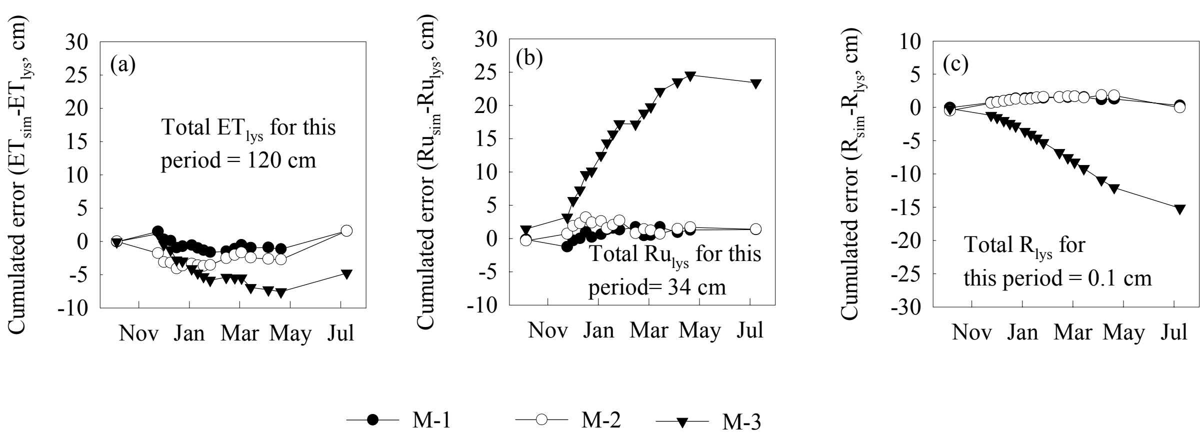
Seasonal variation in pasture crop factor

Total ET, Ru and R were well described under both M-1 and M-2 (Table 4). M-1 better predicted ET_{lys} than M-2 during the period October – December, as reflected in the cumulated error in ET_{sim} (Fig 2a). Low ET_{sim} in M-2 during this period led to over estimation of Ru_{sim} (Fig 2b). The difference between M-1 and M-2 in cumulated error in ET_{sim} (Fig 2a) and Ru_{sim} (Fig 2b) did not diverge further after December, since monthly K_c were comparable with the annual average K_c after this date. No major difference in the cumulated error in R_{sim} was evident between M-1 and M-2 over the simulation period (Fig 2c).

Table 4. Impact of crop factor and cracking on the prediction of annual ET, Ru and R.

		Ru (cm/y)	ET (cm/y)	R (cm/y)
Lysimeter	(observed)	34	121	0.1
M-1	(simulated)	34	123	0.7
M-2	(simulated)	367	122	-0.1
M-3	(simulated)	58	116	-15

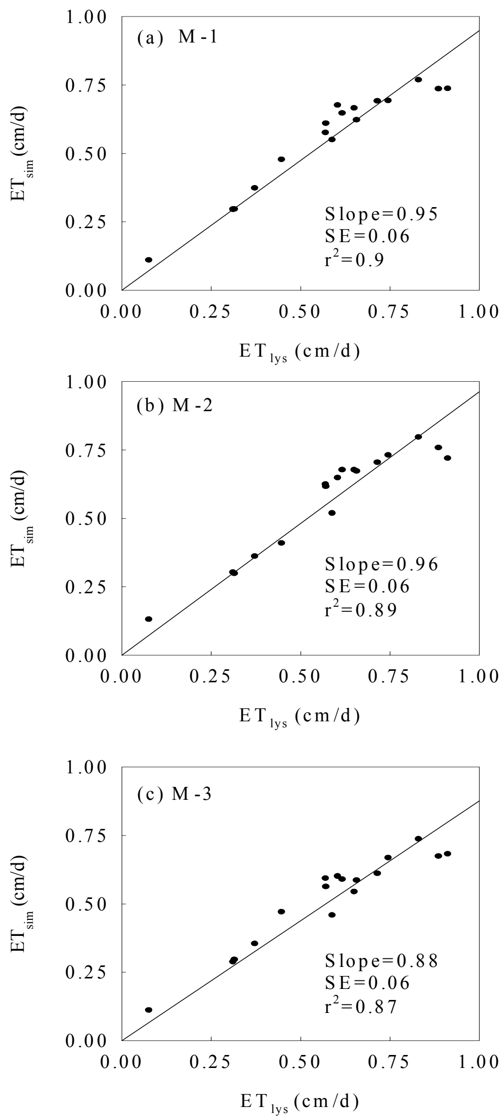
Figure 2. Cumulated error between simulated and predicted components of water balance.



The ET rate between irrigation events was well simulated in M-1 and M-2 (Fig 3a and 3b), with the slope of a linear model comparing ET_{lys} and ET_{sim} being close to unity. The standard error between ET_{lys} and ET_{sim} was less than 0.1 cm/d day for both M-1 and M-2. On average, the prediction of ET in individual periods between irrigation events was not improved by accounting for seasonal variation in K_c. However, cumulative ET over several consecutive irrigation periods was better predicted under M-1 (Fig 2a).

The slope of the linear model between Ru_{lys} and Ru_{sim} indicates that runoff was on average well predicted for M-1 and M-2 (Fig 4a and 4b). The prediction of Ru was marginally better under M-1 (Fig 4a) than M-2 (Fig 4c), although the improvement was not great. The standard error between Ru_{sim} and Ru_{lys} was relatively large for both M-1 and M-2, being approximately 30 % of the average runoff event. The depth of infiltrating irrigation water

Figure 3. Comparison between simulated and lysimeter ET. The slope, r^2 and the standard error of observations (SE) of the linear regression between simulated and observed are provided. The constant in the regression analysis was assumed to equal 0.



was well predicted under M-1 and M-2 (Fig 5a and 5b). The standard error between observed and predicted infiltration corresponded to 15 % of an average infiltration event (5.5 cm/irrigation) under M-1 and M-2.

W_{lys} was well predicted in both M-1 and M-2 (Fig 6a and 6b). The standard error between model and observed soil water was relatively small under M-1 and M-2 (0.02 cm^3cm^{-3}), being equivalent to 0.6 cm of water in the rootzone. This error is less than 1 days ET during the irrigation season. No improvement in the prediction of W was achieved by using monthly K_c.

Figure 4. Comparison between simulated and lysimeter Ru. The slope, r^2 and the standard error of observations (SE) of the linear regression between simulated and observed are provided. The constant in the regression model was set to 0 for comparison of ET and Ru.

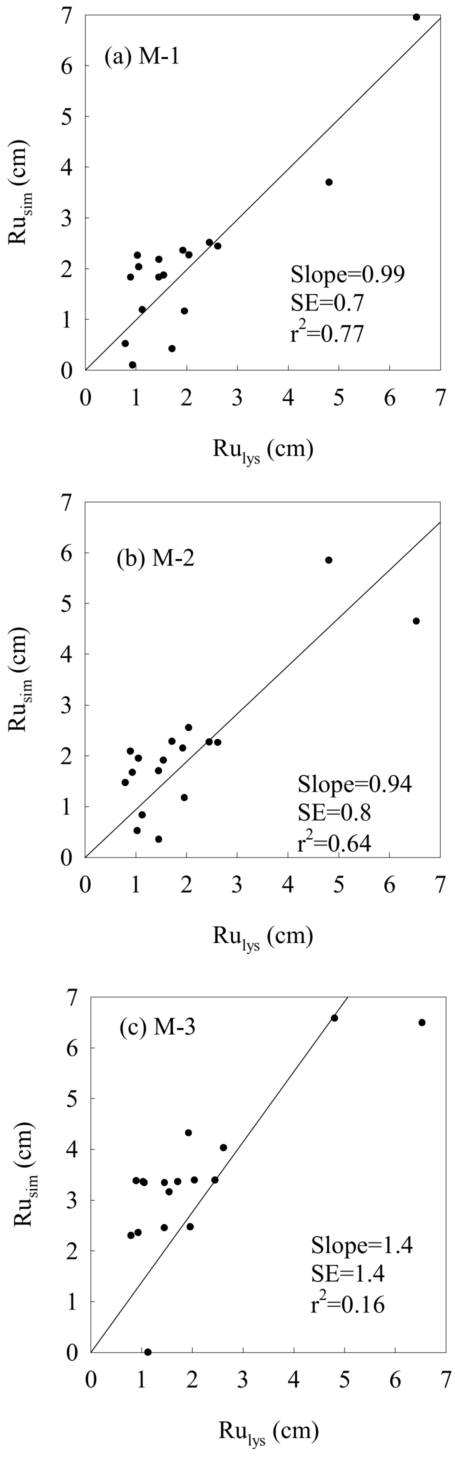


Figure 5. Comparison between simulated infiltration (I_{sim}) and lysimeter infiltration (I_{lys}) of irrigation water.

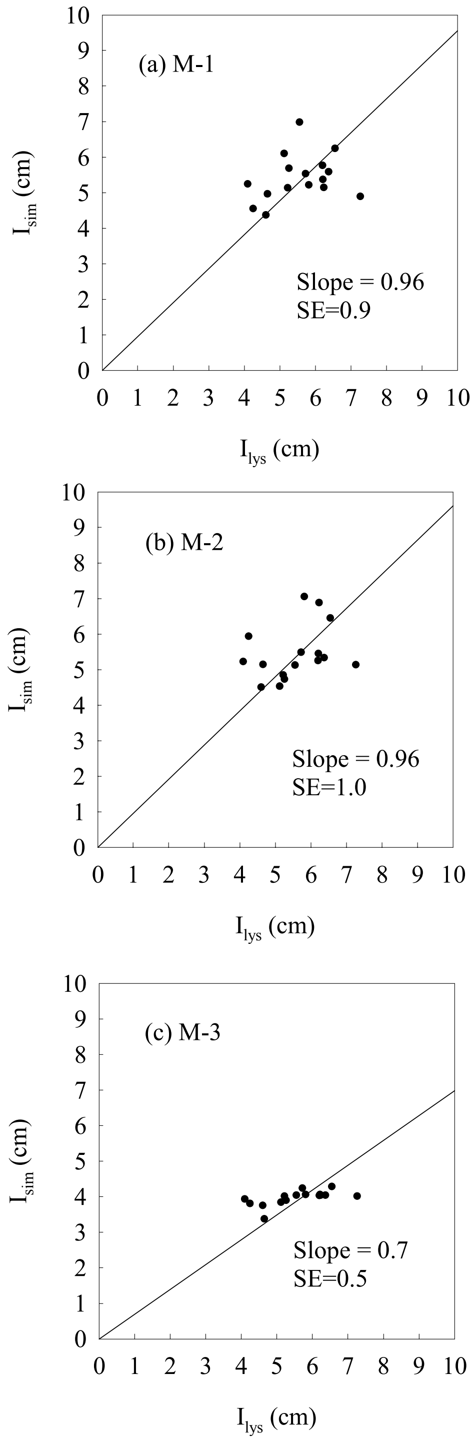
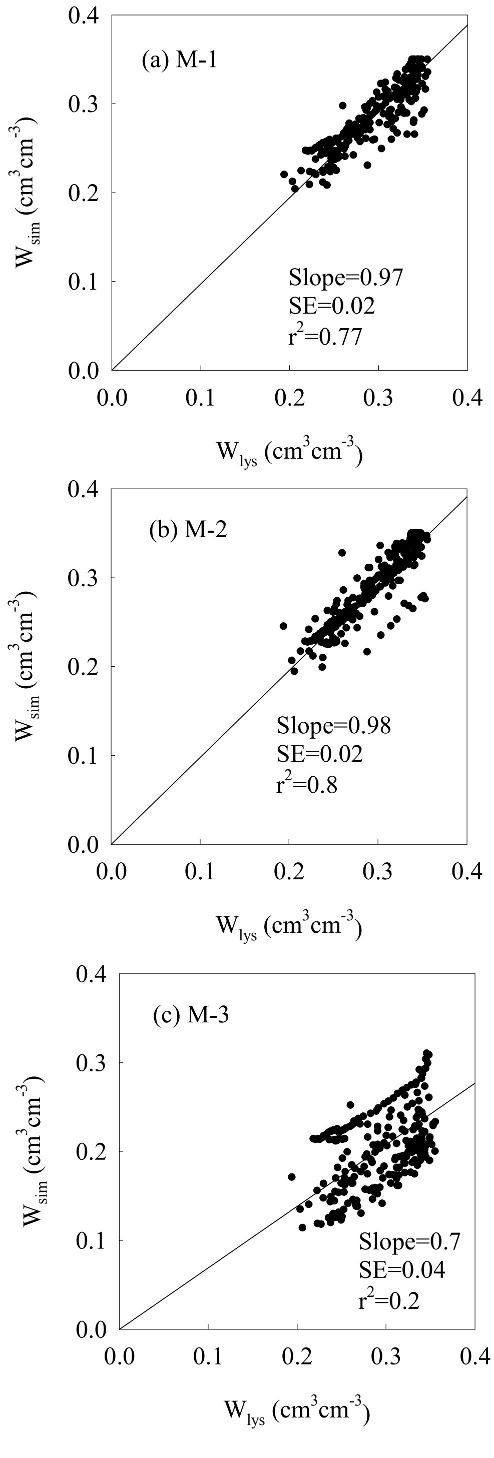


Figure 6. Comparison between simulated and lysimeter rootzone water content (W), including slope, r^2 and the standard error of observations (SE) of the linear regression between simulated and observed. The constant in the regression analysis was assumed to equal 0.



Infiltration through soil cracks

The error in the total predicted ET, Ru and R was considerably worse under M-3 than M-1 (Table 4). This was also evident in the cumulated errors in ET_{sim} (Fig 2a), Ru_{sim} (Fig 2b) and R_{sim} (Fig 2c). The larger errors in M-3 result from under predicting infiltration when cracks were not simulated, with low soil permeability (1.5 cm/d) restricting infiltration into the matrix. Infiltration was under predicted by 33 % on an event basis in M-3 (Fig 5c) and runoff over predicted by 40 % (Fig 4c). Consequently, insufficient water infiltrated the soil to refill the rootzone during the 6 hr irrigation event (Fig 6c) and rootzone water content was under predicted by 25 % in M-3 (Fig 6c). The under prediction in W induced plant water stress and resulted in under prediction of ET. The ET rate between irrigation events was under predicted by 13 % in M-3 (Fig 3c), as compared to a 5 % under prediction in M-1 (Fig 3a). The largest errors in ET_{sim} occurred after December in M-3, when there was high evaporative demand (Fig 2a). Large amounts of capillary rise were predicted under M-3 to compensate for reduced infiltration. This led to large errors in R_{sim} under M-3 (Fig 2c). The simulated high rates of capillary rise supplemented soil water available for plant uptake, reducing pasture water stress and the absolute error in ET_{sim} (Table 4).

Discussion

Infiltration studies on flood irrigated pastures suggest that typically between 50 and 80 % of water infiltrates through cracks into cracking soils (Ross and Bridge 1984; Austin and Prendergast 1997). SWAP predicted that on average 50 % of water infiltrating the soil entered through soil cracks in M-1. This gives some confidence that the lysimeter results and model predictions are similar to observations made under field conditions. However, further testing under field conditions is the only way to ensure that SWAP can describe the field infiltration behaviour under border irrigated pastures on cracking soils.

The accuracy in calculated soil water fluxes depend on a range of factors, including the vertical discretization of the soil profile (van Dam and Feddes 2000). Numerical problems in solving Richards equation are typically encountered where there are large gradients in soil water content, such as at the surface during an infiltration event (Ross 1990). Close nodal spacings near the surface are recommended to overcome these problems (van Dam and Feddes 2000). Convergence of the Richards equation did not always occur when using the recommended nodal spacings. This was attributed to large gradients in soil water potential being created at depth as a result of water flow through soil cracks. This problem was overcome by adopting fine nodal spacing (1 cm) over the depth of soil cracking.

Lysimeters may not always be representative of field conditions due to their limited surface area and the disturbance to the surrounding environment. This is likely to affect the relationship between ET_o and ET_{lys} in the current study. In addition, Ru_{lys} is also likely to be different to runoff occurring under field conditions. Further testing of the model against observations made under field conditions would increase confidence in the use of the model as a practical management tool. This testing should be based on field measured water balance data. Accurate measurement of ET using tools such as Bowen Ratio would be beneficial, as it represents the major component of the water balance. Accurate definition of the lower boundary condition will also give greater confidence in recharge predictions.

Water fluxes predicted by SWAP are sensitive to the presence of cracks, but not actual crack dimensions {van Dam 2000 59 /id}. The soil moisture conditions at the onset of crack formation is therefore of vital importance in applying this approach to describing the water balance of border irrigated pasture. Good experimental programs that quantify soil moisture conditions at the initiation of crack formation are required.

Conclusions

Minor modifications to SWAP were required to allow simulation of the water balance of a border check irrigated pasture. Input parameters necessary to run the model were obtained through literature or prior measurement. Good agreement between lysimeter and model predicted R, ET and Ru occurred when infiltration through cracks was simulated. Large errors in the predicted R, ET and Ru resulted when infiltration through cracks was ignored. An additional 6 parameters are required to implement the description in I_c used in SWAP. Only one of these 6 parameters, which defines the soil moisture conditions at the onset of cracking, appears critical. Experimental programs will be required to quantify this parameter under soils used for border irrigated pasture.

Prediction of total ET and R over the simulation period was not improved by using monthly K_c, as opposed to a constant annual K_c. Studies looking to investigate options for reducing recharge do not need to account for seasonal variation in K_c. Small improvements in the temporal prediction of ET occurred as a result of using monthly K_c. Allowance for seasonal variations in K_c may be warranted when the model is used for scheduling irrigation or pasture growth studies.

References

Allen RG, Smith M, Perrier A, Pereira LS (1998) 'Crop evapotranspiration, Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56.' (United Nations: New York)

Austin N (1998) Sustainable use of water and fertiliser in the irrigated dairy industry of Australia. 'PhD University of Melbourne.

Austin N, Prendergast JB (1997) Use of Kinematic wave theory to model irrigation on cracking soil. *Irrigation Science* **18,** 1-10.

Bethune M, Cook A (2002) Quantification of components of the water balance of irrigated pastures using lysimetry. *In preparation*.

Bronswijk JJB (1988) Modelling of water balance, cracking and subsidence of clay soils. *Journal of Hydrology* **97,** 199-212.

Crabb P (1997) 'Murray-Darling Basin Resources.' (Murray Darling Basin Commission: Canberra, Australia)

Dingman SL (1994) 'Physical hydrology.' (Macmillan College Publishing Company: New York)

Doorenbos J, Kassam AH (1977) 'Yield response to water. FAO irrigation and drainage paper 33.' (United Nations: Rome)

Elliot, P. J. Effect of bay slope on perennial pasture production. Notes from Kerang agriculture farm field day. 1984. Kerang, Department of Agriculture.
Ref Type: Unpublished Work

GHD (1970) 'Murray Valley Salinity Investigations.' (River Murray Commission, Canberra)

Mehanni AH, Repsys AP (1986) Perennial pasture production after irrigation with saline groundwater in the Goulburn Valley, Victoria. *Australian Journal of Experimental Agriculture* **26,** 1087-1093.

Mualem Y (1976) A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resources Research* **12,** 513-522.

Prendergast JB (1995) Soil water bypass and solute transport under irrigated pasture. *Soil Science Society of America Journal* **59,** 1531-1539.

Robertson D, Wood M (2002) Independent estimation of irrigation model parameters for cracking soils. *Australian Journal of Experimental Agriculture* **This issue**.

Ross PJ (1990) Efficient numerical methods for infiltration using Richards equation. *Water Resources Research* **26,** 279-290.

Ross PJ, Bridge BJ (1984) Ross P.J. and Bridge B.J., in Eds. McGarity J.W., Hoult E.H. and So H.B., 1984. MICCS: a model of infiltration into cracking clay soils. Rev. Rural Sci. 5, Univ of New England, Armidale 155-163. In 'The properties and utilization of cracking clay soils'. (Eds JW McGarity, EH Hoult, and HB So) pp. 155-163. (University of New England: Armidale, Australia)

Shaw RJ, Yule DF (1978) 'The assessment of soils for irrigation. Emerald, Queensland.' (Agricultural Chemistry Branch, Queensland Department of Primary Industries, Brisbane)

Skene JKM, Poutsma TJ (1962) 'Soils and land use in part of the Goulburn Valley, Victoria. Technical Bulletin No 14.' (Department of Agriculture, Victoria, Australia)

Szeicz G, Long IF (1969) Surface resistance of crop canopies. *Water Resources Research* **5,** 622-633.

Talsma T (1972) Physical aspects of swelling soils. In 'Physical aspects of swelling clay soils.'. (Ed. BJF James) pp. 33-37. (University of New England: Armidale)

van Dam JC (2000a) Field-scale water flow and solute transport. SWAP model concepts, parameter estimation and case studies. Doctorate,' Wageningen University.

van Dam JC (2000b) Simulation of field-scale water flow and bromide transport in a cracked clay soil. *Hydrological Processes* **14,** 1101-1117.

van Dam JC, Feddes RA (2000) Numerical simulation of infiltration, evaporation and shallow groundwater levels with the Richards equation. *Journal of Hydrology* **233,** 72-85.

van Dam JC, Huygen J, Wesseling JC, Feddes RA, Kabat P, van Walsum PEV, Groenendijk P, van Diepen CA (1997) 'SWAP version 2.0, Theory. Simulation of water flow, solute transport and plant growth in the Soil-Water-Atmosphere-Plant environment. Technical Document 45, DLO Winand Staring Centre, Report 71.' (Department Water Resources, Agriculture University, Wageningen, Netherlands)

Van Genuchten MTh (1980) A closed form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal* **44,** 892-898.

Van Genuchten MTh, Leij FJ, Yates SR (1991) 'The RETC code for quantifying the hydraulic functions of unsaturated soils.' (United States Environmental Authority, Ada, Oklahoma, America)

Yule DF (1984) Volumetric calculations in cracking clay soils. Reviews in Rural Science 5. (Eds JW McGarity, EH Hoult, and HB So) pp. 136-140. (University of New England: Armidale, New South Wales, Australia)

Model Testing Against NSW Field Sites

Attachment 6

Introduction

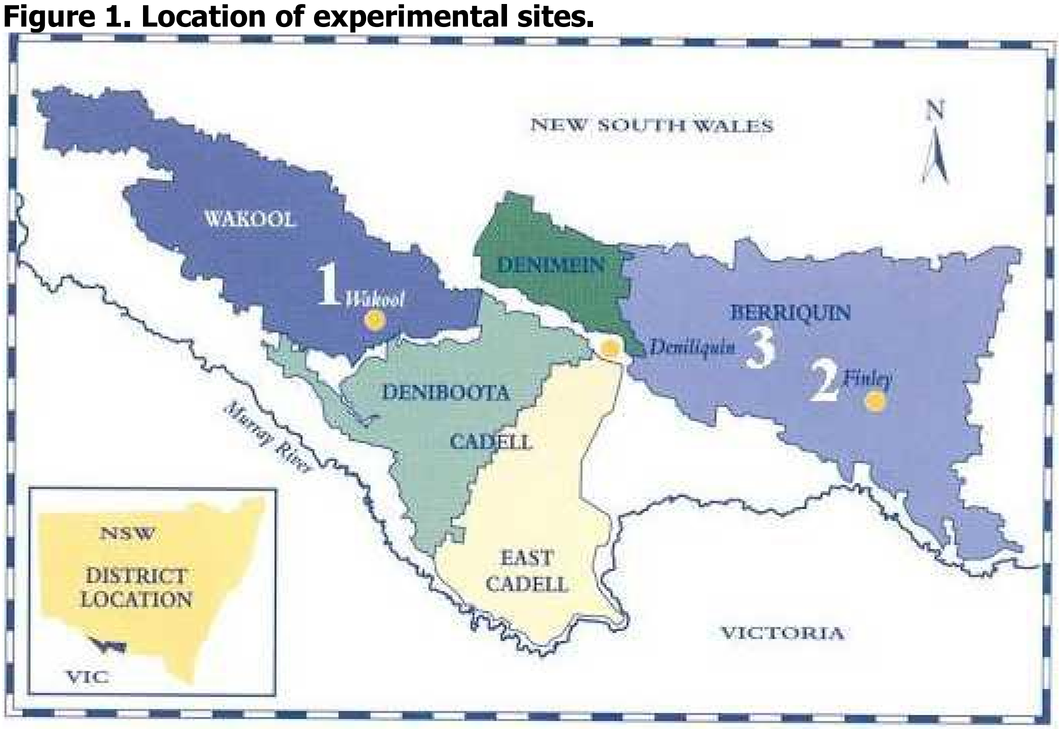
An extensive monitoring program was conducted between October 1996 and October 2000 to monitor soil moisture, groundwater levels and pasture production (attachment 1). This data was used to appraise the application of the SWAP model (van Dam *et al.* 1997) (Kroes *et al.* 1998)for describing the water balance of border-check irrigated pasture under field conditions. The model was previously shown (attachment 5) to provide a good description of the water balance of irrigated pasture in a controlled lysimeter environment (attachment 2).

Materials and Methods

Experimental location

Three farms were selected from the Wakool and Berriquin Irrigation Districts in southern New South Wales (Fig 1). These farms were selected on the basis that they had a whole farm plan, were landformed, had a surface water drainage and recycling system and had highly productive pastures with higher fertiliser and stocking rates than the district average.

Figure 1. Location of experimental sites.



Farm 1

Farm 1 is in the Wakool irrigation district. Long-term average pan evaporation is 1400 mm and rainfall 400 mm/yr. Approximately 900 mm of irrigation water is applied each year. The soils are typical of prior stream deposits, being highly variable and changing from almost pure sand through to a clay loam over the property.

Farm 2
Farm 2 is located in the Berriquin irrigation district near Finley. Long term pan evaporation is 1800mm/y and rainfall is 420 mm/y. The farm has three sources of irrigation water, low salinity channel supply water, a shallow groundwater bore (1500 EC) and a deep groundwater bore (2500 EC). The mixing of these water sources results in an average applied water salinity of 900 EC for the period 1998-2001. This salinity of irrigation water will impact substantially on recharge through reducing plant water use and increasing the soil hydraulic properties (Lyle *et al.* 1986; Prendergast 1995). This farm is located on an old flood plain of the Murray River and the predominant soil is Cobram Loam.

Farm 3
Farm 3 is located in the Berriquin irrigation district, also near Finley. Long term pan evaporation is 1800mm and rainfall is 420 mm/y. All irrigation water is sourced from the channel supply network, with an average annual irrigation intensity of 1000 mm/y. The site is located on a flood plain of the old Murray river and soil (Birganbigil loam) was reasonably uniform across the property.

Experimental measurements

Two sites were instrumented to measure soil moisture, dry matter production and watertable levels on each farm. These two sites corresponding to the lightest and heaviest soil on each property.

Soil moisture was monitored continuously using capacitance type soil moisture probes (EnviroSCAN^{TM} , Sentek, 1994) installed at depths 0.1,0.2,0.3,0.5,0.9 and 1.4 m. The capacitance probes were calibrated for Farm 1 and Farm 2. No calibration was made for Farm 3 as it was assumed to have similar soils to Farm 2 (attachment 1). The available calibrations of the soil moisture sensors were of varying quality. Good calibration relationships existed for Farm 2 and the heavy soil on Farm 1. The calibration of the light soils on Farm 1 was poor, with large standard errors in the relationship (5 % volumetric water content). No calibration was available for Farm 3, however the soils were texturally similar to Farm 2.

Piezometers were installed to 2m depth to measure the depth to the watertable. The piezometers were 50 mm diameter, and slotted over the bottom 0.25 m. The piezometers were installed into hand augered holes. The bottom 0.25 m of the hole was back filled with coarse sand, then a 10 cm sodium bentonite plug was inserted. The hole was then back filled with soil to within 0.1 m of the surface. A second sodium bentonite plug was inserted for over the last 0.1 m. Piezometer levels were recorded continuously using capacitance water levels. Manual water levels were measuring using a fox whistle to test instrument calibration.

Pasture growth was measured at each site. Steel cages (60 X 120 cm) were used to protect pasture from grazing stock. There were four cages at each location. Pasture dry matter (DM) was measured by cutting a 50 X 50 cm quadrant just after grazing. Pasture samples were taken from both inside and outside of the cages to calculate the amount of grass consumed by the cattle. It was assumed that grass growth in the steel cage was equivalent to pre grazing growth. The cut pasture was dried at 75 ^{o}C for 24 h to determine DM. Each pasture species were separated and DM was determined separately for the year 1998-99.

Soil salinity was measured at each site in both 1997 and 1999 at 30 cm increments to 0.9 m depth. No replication of these soil salinity measurements were made. Six cores were extracted at each site in May 2001, dried, crushed and analysis for soil salinity. The leaching fraction was calculated using the steady state leaching equations, given by the ratio of irrigation water salinity to drainage water salinity (US Salinity Laboratory 1954). This method has been shown to provide a good estimate of the leaching fraction under the conditions experienced in the study area (Prendergast 1995; Lyle and Mehanni 1984).The average annual depth of recharge (steady state) was calculated from the leaching fraction and annual depth of irrigation.

Model development

The numerical model SWAP (Soil-Water-Atmosphere-Plant) was used to model the water balance. Extensive testing of the model against lysimeter data identified that the model captured the key soil-water-plant processes affecting the water balance under flood irrigated pasture (attachment 5). Detailed description of the SWAP model is provided elsewhere (van Dam *et al.* 1997). In summary, the model solves Richards equation numerically using a implicit finite difference scheme. There is considerable flexibility in the model to represent a range of upper and lower boundary conditions and relationships between soil moisture content (θ), soil water potential (h) and hydraulic conductivity (K). The model allows simulation of grass growth, assuming a single pasture species. Parameters describing root depth, distribution and growth response to climate and soil drivers needs to be specified by the user.

The model input requires information describing soil hydraulic functions, climate, grass growth and root water extraction, soil shrinkage, irrigation and the lower boundary conditions. Soil hydraulic data were described using the Van Genuchten (Van Genuchten 1980) relationships.

No data describing soil hydraulic properties were available for the site. The soils at the experimental farms were developed through prior stream activity. Lighter sandier soils being found close to the prior stream and heavier clay soils found at distance from the prior stream (Skene and Poutsma 1962). All of the soils in the study have similar originals. The variability in soil hydraulic properties between geometrically similar media can be explained by one scaling factor (Miller and Miller 1956). Scaling theory was found to provide a good describing of the in-field spatial variability in soil-water retention data (Daamen *et al.* 1990). Therefore, it was proposed to describe soil hydraulic properties at the different sites using scaling theory. This requires knowledge of the $\theta(h)$ and $k(h)$ data for a reference soil, and appropriate scaling factor that relates the characteristic length of the soil at the experimental location to the reference soil. A good data set was available describing in-situ soil hydraulic properties (Table 1) for a Shepparton fine sandy loam soil (Olsson and Rose 1978). This soil is typical of the prior stream soils found on the three farms. Appropriate scaling factors were estimated through a calibration process, so that observed and predicted soil moisture and watertable response matched. Calibration of the model using scaling theory considerably simplifies the process, as there is only one unknown parameter per soil layer.

Crack formation was described by the shrinkage characteristic. The slope of the shrinkage characteristic for Sfsl was provided by Olsson and Rose (Olsson and Rose 1978). Parameters describing the geometry of cracks were found not to substantially affect the prediction of the water balance (van Dam 2000), providing the depth of the cracks was well specified. Therefore, no adjustment was made to parameters describing crack formation during the model calibration.

Table 1. Hydraulic properties of the reference soil, after (Olsson and Rose 1978)

Soil layer	α (cm^{-1})	n (-)	θ_{sat} ($cm^3\ cm^{-3}$)	θ_{res}($cm^3\ cm^{-3}$)	K_{sat} (cm/d)	λ (-)
Topsoil (0-0.3m)	0.05	1.13	0.4	0.03	3.6	0.5
Subsoil >0.3 m	0.015	1.37	0.5	0.34	0.7	5.8

Daily climatic data describing rainfall, minimum and maximum temperature, minimum and maximum humidity, radiation and daily wind run were recorded at an automatic weather station located close to the studied farms. Potential evapotranspiration (ET_o) was calculated using the Penmon-Monteith (Allen *et al.* 1998). Potential pasture water use was specified as a function of ET_o and a crop factor. Monthly crop factors were derived from lysimeter data for a flood-irrigated pasture (attachment 5). Pasture rooting depth was assumed to be 0.3 m deep and be uniformly distributed.

No record of irrigation depths or timing was recorded. Therefore, irrigation dates were identified by examining soil moisture storage and rainfall data. Irrigation was assumed to occur on dates when soil water storage increased and there was no rainfall A fixed depth of 70 mm per irrigation was applied at each irrigation. The applied water was ponded on the soil surface for 6 hours. The residual surface water after this 6 hour period was removed and assumed to equal runoff. The coding of the SWAP model was modified so that the model could describe this representation of border irrigation.

A prescribed head was adopted for the lower boundary condition. This head was set to equal the average monthly depth to watertable, as measured at the experimental site. The depth to the watertable was below the bottom of the observation well at the heavy soil site on Farm 1. Therefore, a unit gradient was specified as the bottom boundary condition at this site.

Calibration

Soil moisture in the rootzone (θ_{rz}) and watertable data were used to calibrate the model over the period 1/1/2000 to 1/7/2000. The model was then run over a 16 year period. Model predicted recharge was then compared with recharge estimated using salt balance approaches. Model predicted differences in pasture water use between the heavy and the light soil on individual properties was compared to observed differences in dry matter production. This assumes that dry matter production is a linear function of ET. Comparisons between farms was not possible due to differences in pasture composition and nutrient management, which will affect the relationship between DM and ET.

Results and discussion

Scaling factors were adjusted for each soil layer to minimise differences between observed and predicted θ_{rz} over the period 1/1/2000 to 1/7/2000 (Fig 2). Estimated scaling factors for each site are listed in Table 3. There was generally good agreement between modelled and observed soil water content and watertable depth at each of the sites. The crop factor needed to be reduced by 25 % for the heavy soil at Farm 1 to improve the fit between observed and predicted θ_{rz}. This adjustment was necessary to account for the impact of soil salinity on plant water use. Soil salinity at the site (3.8 dS/m) was high enough to restrict pasture water use. The threshold salinity at which pasture growth becomes limited is 1.6 dS/m, with an 9 % reduction in yield for every unit EC (dS/m) increase above this threshold (Mehanni and Repsys 1986). The soil salinity at the site was 2.2 dS/m above the threshold, which would result in a 20 % reduction in pasture growth. The reduction in pasture growth would be associated with reduced pasture water use, of a similar order of magnitude to that encountered by reducing the crop factor by 25 %.

Table 3. Estimated scaling factors for each experimental site.

Layer	Farm 1 Heavy	Farm 1 Light	Farm 2 Heavy	Farm 2 Light	Farm 3 Heavy	Farm 3 Light
0-0.3 m	0.70	0.4	0.85	0.9	0.5	0.4
0.3-0.6 m	0.35	1	0.3	0.3	0.15	0.6
> 0.6 m	0.35	1	0.3	0.8	0.2	0.6

Regression analysis was used to compare predicted and observed daily changes in θ_{rz} (Table 4). The standard error between observed and simulated rootzone water content varied between 0.5 and 1.5 %. These errors are within the accuracy of the soil moisture sensors. However, an error in θ_{rz} of 1% over a 300 mm rootzone results in water balance error of 3 mm, which is equivalent to half a days plant water use is the peak of the irrigation season. The slopes of the linear models between sites were generally close to unity, suggesting that the model provided a good prediction of the rate of change in θ_{rz}. The slope of this linear model was heavily influenced by irrigation events, which resulted in daily changes in θ_{rz} of an order of magnitude greater than changes in θ_{rz} resulting from plant water use. The predicted rate of change in θ_{rz} was less than observed at the light soil on Farm 1, even though a good correlation between observed and predicted was seen. There was a poor calibration of the soil moisture sensor at this site that could explain the difference in slope.

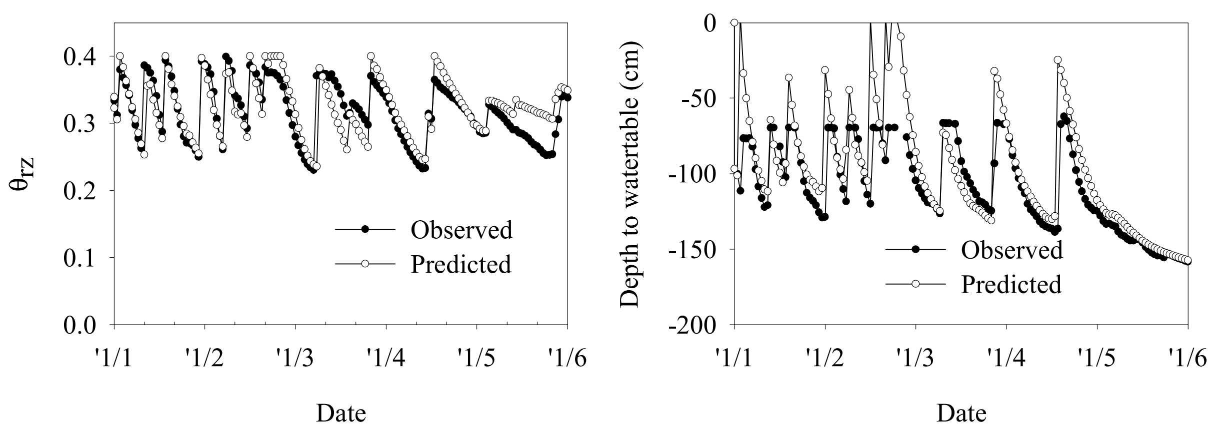
Table 4. Regression parameters defining the linear relationship between observed and simulated daily changes in soil water content in the rootzone,

including the standard error (σ) between observed and simulated rootzone water content.

Site	Slope	r^2	σ
Farm 1 Heavy	1.07	73	1.2
Farm 1 Light	0.77	88	0.6
Farm 2 Heavy	0.86	87	1.0
Farm 2 Light	0.96	87	1.5
Farm 3 Heavy	0.94	82	1.3
Farm 3 Light	1.06	80	1.0

There were larger differences between predicted and observed θ_{rz} and watertable level during the early months of winter (Fig 2 and 3). The reason for this is not understood. However, there are a number of possible reasons, all of which are equally feasible. The differences could result from an inadequate definition of the lower boundary condition or crop factors during this period. Another source of potential error may result from the impact of soil salinity on the soil moisture sensor.

Figure 2. Time series comparison of predicted and observed rootzone water content and watertable level at light soil on Farm 2.



Recharge estimated by salt balance varied between 0.1 and 0.3 ML/ha/yr (10 to 30 mm/yr) in 1999 and 2001 on Farms 1 and 2. Recharge rates were substantially higher at all sites in 1997. Model predictions of recharge were generally of the same order of magnitude as those estimated by salt balance (Table 3). The greatest difference occurred at Farm 2 where the farm used groundwater for irrigation. This results in higher applied water salinity. The impact of irrigation water salinity on the leaching fraction and thus recharge has been widely documented (Lyle *et al.* 1986; Prendergast and Noble 1990). No attempt was made to include the impact of irrigation water salinity into the model. The model could predict impact of irrigation water salinity on soil salinity and plant water use. However, irrigation water salinity also impacts on soil hydraulic properties (Lyle *et al.* 1986). The model does not currently describe the impact of water and soil chemistry on hydraulic properties.

Figure 3. Time series comparison of predicted and observed rootzone water content and watertable level at heavy soil on Farm 2.

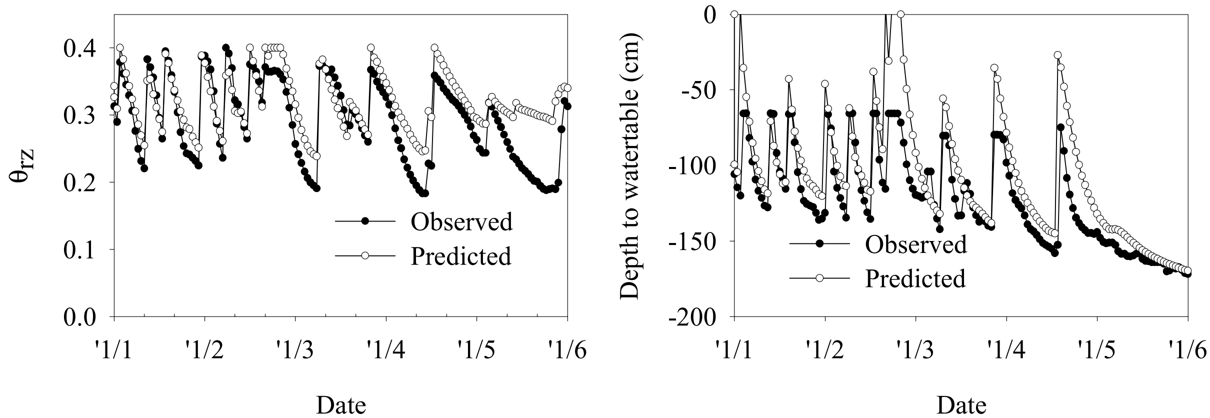


Table 2. Estimate recharge by salt balance, including the standard deviation (σ) of 2001 estimates.

	Farm 1 Heavy	Farm 1 Light	Farm 2 Heavy	Farm 2 Light	Farm 3 Heavy	Farm 3 Light
Recharge	ML/ha/yr	ML/ha/yr	ML/ha/yr	ML/ha/yr	ML/ha/yr	ML/ha/yr
1997	0.05	0.67	2.54	1.79	0.07	0.59
1999	0.04	0.21	1.12	1.11	0.15	0.18
2001	0.06	0.24	1.04	1.11	0.14	0.17
σ (2001)	0.04	0.01	0.16	0.22	0.08	0.01

Table 3. Model predicted recharge.

	Farm 1 Heavy	Farm 1 Light	Farm 2 Heavy	Farm 2 Light	Farm 3 Heavy	Farm 3 Light
Recharge	ML/ha/yr	ML/ha/yr	ML/ha/yr	ML/ha/yr	ML/ha/yr	ML/ha/yr
1997	0.69	0.96	0.33	0.44	0.35	0.42
1999	0.42	0.75	0.12	0.19	0.34	0.25
2001	0.33	0.69	-0.02	0.05	0.50	0.30

Conclusions

Results from a previously conducted field experiment were used to test the ability of the SWAP model to describe the water balance of border check irrigated pasture. The results available for testing the model were limited to soil moisture measurements and salt balance estimates of recharge. No other components of the water balance were measured. Soil hydraulic properties were defined for the experimental sites using the similar media scaling concept and hydraulic properties for a reference soil. This simplified the fitting of soil hydraulic properties to one parameter per soil layer. Confidence in the calibrated scaling factor was higher for the uppermost soil layer, where there were relatively large changes in soil water content over the study period. However, less confidence can be expressed in calibration of soil properties at greater depths, as soil water content did not change greatly over the study period.

The model provided a good qualitative and quantitative description of changes in soil moisture in the pasture rootzone. It was necessary to include the impact of soil salinity on pasture water use at one of the sites. Adjustment of the crop factor to reflect salinity stress resulted in an improved prediction of $\theta_{rz.}$ Irrigation water salinity had a large impact on recharge estimated using salt balance approaches. This occurs as a result of salinity impacts on plant water use and soil hydraulic properties. Plant water use response to salinity is well known for pastures. The impact of irrigation water salinity on soil properties is less well known. Experimentation is required that defines the impact of irrigation water salinity on soil hydraulic properties.

Recharge predicted by the model was of a similar order of magnitude to that estimated from salt balance techniques.

The SWAP model provided a reasonable description plant water use and the infiltration process, as affected by soil cracks. The limited nature of available data set does not allow conclusive testing of other components of the water balance. However, the theory describing water flow in the matrix is well defined and has been well tested. Therefore, the model should provide a good description of other components of the water balance, particularly deep drainage, if a suitable description of soil properties and the lower boundary condition are available. Good experimental programs are required that define these soil properties for the range of soils found under border irrigated pasture. Procedures are also required that allow soil properties to be transferred to sites with sparse information. The similar media scaling concept could be a simple way of achieving this end.

References

Allen RG, Smith M, Perrier A, Pereira LS (1998) 'Crop evapotranspiration, Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56.' (United Nations: FAO Rome)

Daamen CC, Xiao Z, Robinson JA (1990) Estimation of water retention function using scaling theory and soil physical properties. *Soil Science Society of America Journal* **54,** 8-13.

Kroes JG, van Dam JC, Huygen J, Vervoort RW (1998) 'Users's Guide of SWAP version 2.0; Simulation of water flow, solute transport and plant growth in the Soil-Water-Atmosphere-Plant environment.' (DLO-Staring Centre and Wageningen Agricultural University., Wagengingen, The Netherlands)

Lyle CW, Mehanni AH (1984) Leaching rates under perennial pastures grown on clay soil and irrigated with saline water in northern Victoria. p. -303. Brisbane)

Lyle CW, Mehanni AH, Repsys AP (1986) Leaching rates under a perennial pasture irrigation with saline water. *Irrigation Science* **7,** 277-286.

Mehanni AH, Repsys AP (1986) Perennial pasture production after irrigation with saline groundwater in the Goulburn Valley, Victoria. *Australian Journal of Experimental Agriculture* **26,** 1087-1093.

Miller EE, Miller RD (1956) Physical theory for capillary flow phenomena. *Journal of applied physics* **27,** 324-332.

Olsson KA, Rose CW (1978) Hydraulic properties of a red-brown earth determined from in-situ measurement. *Australian Journal of Soil Research* **16,** 169-180.

Prendergast BJ, Noble CL (1990) The effect of groundwater reuse on infiltration and groundwater recharge under an irrigation perennial pasture.

Prendergast JB (1995) Soil water bypass and solute transport under irrigated pasture. *Soil Science Society of America Journal* **59,** 1531-1539.

Skene JKM, Poutsma TJ (1962) 'Soils and land use in part of the Goulburn Valley, Victoria. Technical Bulletin No 14.' (Department of Agriculture, Victoria, Australia)

US Salinity Laboratory (1954) 'Diagnosis and improvement of saline and alkali soils.' (USDA: Washington, USA)

van Dam JC (2000) Field-scale water flow and solute transport. SWAP model concepts, parameter estimation and case studies. Doctorate,' Wageningen University.

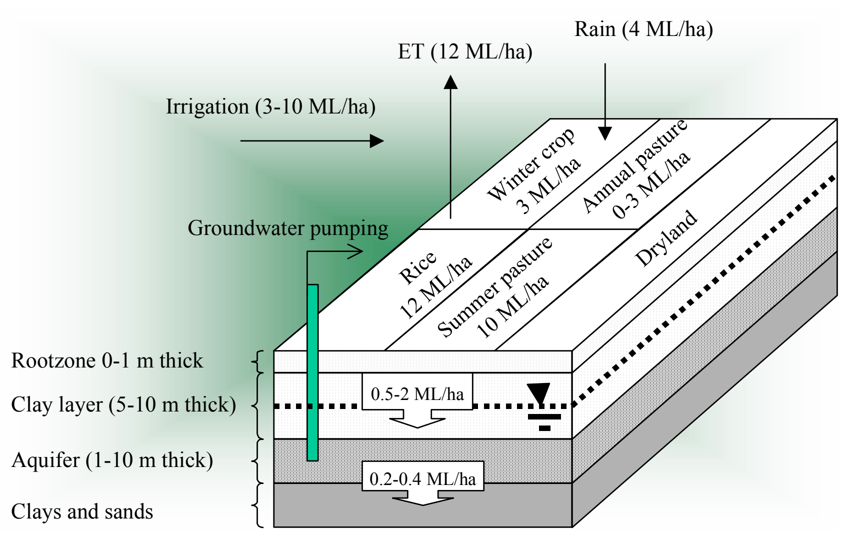
van Dam JC, Huygen J, Wesseling JC, Feddes RA, Kabat P, van Walsum PEV, Groenendijk P, van Diepen CA (1997) 'SWAP version 2.0, Theory. Simulation of water flow, solute transport and plant growth in the Soil-Water-Atmosphere-Plant environment. Technical Document 45, DLO Winand Staring Centre, Report 71.' (Department Water Resources, Agriculture University, Wageningen, Netherlands)

Van Genuchten MTh (1980) A closed form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal* **44,** 892-898.

Modelling water movement in cracking soils

Workshop 16-17 May 2001

Edited by Matthew Bethune and Mac Kirby



Melbourne Victoria
2001

Modelling water movement in cracking soils

Workshop 16-17 May 2001

For More Information Contact

Matthew Bethune

Institute of Sustainable Irrigated Agriculture (ISIA)
Agriculture Victoria (Tatura)
Department of Natural Resources and Environment
Ferguson Road, Tatura, Victoria, 3616
Phone: (03) 58 336 223
Fax: (03) 58 335 229
Email: matthew.bethune@nre.vic.gov.au

Summary

This report summarises a workshop that was conducted to review our current state of knowledge in modelling water movement in cracking soils. The workshop was held in Melbourne on the 16 – 17 of May 2001.

The need and motivation for a workshop on modelling water movement in cracking soils arose out of the National Program on Irrigation and Development (NPIRD) Project DAN11, '*Improving water use efficiency by reducing groundwater recharge under irrigated pastures*'. Considerable difficulty was encountered in this project in reconciling the differences between recharge estimated by lysimeters and by models, which was influenced by water movement in cracks and macropores. It has also been recognised that in the Northern Murray Darling Basin (NMDB) there is insufficient information about water balance in, and drainage from, swelling and cracking soils.

The objectives of the workshop were:

1. Identify management problems associated with water movement in cracking soils (including water balance issues);
2. Identify key technical and functional weaknesses in modelling approaches, in relation to Objective 1;
3. Assess the ability of existing models to underpin water policy and planning decisions; and,
4. Recommend steps (model development and testing) to improve model capabilities.

The workshop identified that there is a demand for appropriate models for many applications ranging from irrigation management to water policy and planning. Three issues were identified in the workshop that restrict the practical application of such models. The first issue relates to defining the correct conceptual model of the hydrology of cracking soils, with particular regard to infiltration though cracks. Secondly, there is insufficient information describing the water balance and drainage of cracking/swelling soils, thus limiting our ability to test/develop appropriate modelling frameworks. Finally, there is insufficient general awareness and knowledge amongst researchers and practitioners of the impact of soil cracking and swelling on water movement in water balance studies.

A clear message coming out of the workshop was that theoretical development had progressed further than the data sets available to test the theory. Therefore, studies that focus solely on model development were considered inappropriate at this stage. For this reason, no attempt was made to list models that have been, or might be, applied to water balance in swelling and cracking soils.

A key conclusion was that we lack information, in particular, well-documented case studies of the water balance in swelling and cracking soils. Existing case studies typically assume soils do not crack and swell, have limited documentation and do not contain the data necessary to apply models of water movement in cracking and swelling soils. Therefore, we cannot currently develop or verify models for water movement in cracking and swelling soils, nor apply them to practical problems with any confidence.

The workshop recommended that the next steps in the modelling of cracking and swelling soils should be:

- Conduction of good experimental case studies, in which measurements are made of all components of the water balance (including flow down cracks, if it occurs), and the consequences of drainage from the soil profile (this could be partially achieved by *'value adding'* to current experimental programs);
- Using those case studies to test and improve models, or develop them where necessary;
- An investigation to identify when, under what circumstances (of climate, soil type, and land management), and how to include cracks in water balance models; and,
- The development of guidelines to assist in the practical application of models to cracking and swelling soils, so that the modelling pays attention to:

  - Clearly defining the purpose and scope of the proposed modelling study;
  - The needs of and interactions with users, managers, advisers, and policymakers;
  - Data issues including standards and guidelines for datasets, and the use of common field sites;
  - Building multi-disciplinary teams, including economists; and,
  - Reviewing and building on current experience.

Acknowledgments

Participants of the workshop are especially acknowledged for their provision of time, knowledge and expertise, and contribution to this report. Funding for this workshop was provided by the National Program on Irrigation and Development, Land and Water Australia.

Facilitator
Dr Peter Box

Workshop Participants

Dr Nick Austin	NSW Agriculture
Mr Matthew Bethune	DNRE
Dr Keith Bristow	CSIRO Land & Water
Dr Peter Fisher	DNRE
Mr Kep Gouglin	QLD Department of NR
Dr John Hutson	Flinders University
Mr Hayden Kingston	NSW Agriculture
Mr Geoff McLeod	Murray Irrigation Limited
Prof. Wayne Meyer	CSIRO Land & Water
Mr Budiman Minasny	University of Sydney
Dr Mac Kirby	CSIRO Land & Water
Mr Mark Silburn	QLD Department of NRE

Mr Brett Tucker	Land & Water Australia
Dr Hugh Turral	University of Melbourne
Dr Willem Vervoort	University of Sydney
Dr Don Yule	QLD Department of NR

Table of contents

Background

The need and motivation for a workshop on modelling water movement in cracking soils arose out of National Program on Irrigation and Development (NPIRD) Project DAN11, '*Improving water use efficiency by reducing groundwater recharge under irrigated pastures*'. Project DAN11 is a collaborative project between NSW Agriculture and Agriculture Victoria, and is based in the southern Murray Darling Basin (SMDB). DAN11 objectives were to quantify recharge (deep drainage) through a combination of field data collection, lysimetry and modelling. Each of the three approaches yielded different estimates of recharge, and despite employing a range of models, considerable difficulty was encountered in reconciling the differences. It became increasingly apparent that infiltration and water movement was influenced to a great extent by cracks and macropores.

It has also been recognised that in the Northern Murray Darling Basin (NMDB) there is insufficient information about water balance in, and, drainage from swelling and cracking soils. A program of research and extension is being developed by several research partners including the Cotton CRC, Queensland Department of Natural Resources (QDNR), NSW Agriculture, University of Sydney and CSIRO Land and Water. The program will address irrigated and dryland agriculture as well as native vegetation. The main focus of the work being developed is experimental, although there is a modelling component.

Nationally, the problems associated with modelling water movement in cracking soils are increasingly being recognised. A diverse range of modelling approaches have been, and are currently being, employed to describe the impact of the cracking process on soil water movement. These approaches range from simple, empirical methods to complex, and physically based models, with each approach having advantages and limitations.

To obtain a clearer perspective, NPIRD requested a critical review of the approaches currently being employed to model water movement in cracking soils in Australia. This report summarises a workshop that was conducted to review our current state of knowledge in modelling water movement in cracking soils. The workshop was held in Melbourne on the 16 - 17 of May 2001.

Workshop structure

The workshop was structured to achieve the four objectives (outlined below). Discussion and findings from the workshop are summarised under these four objectives. The workshop agenda is included in Attachment 1.

Workshop participants

Participants were invited from several research organisations, Land and Water Australia (LWA) and client groups. A full list of participants can be found in Attachment 2.

Objectives of workshop

1. Identify management problems associated with water movement in cracking soils (including water balance issues).
2. Identify key technical and functional weaknesses in modelling approaches in relation to Objective 1.
3. Assess the ability of existing models to underpin water policy and planning decisions.
4. Recommend steps (model development and testing) to improve model capabilities.

1. Management problems associated with water movement in cracking soils

A regional perspective (for both SMDB and NMDB) was presented as a basis for identifying management problems associated with water movement in cracking soils. A summary of these two presentations is provided below (Refer Sections 1.1 and 1.2) and the overheads used by the presenters attached (Refer Attachment 3 - southern perspective and Attachment 4 - northern perspective). Following these presentations, the workshop divided into four groups and discussed the information requirements of land and water managers for the development of policy and planning activities (Refer Section 1.3). This was followed by discussion on how water movement in cracking soils is likely to impact on this information (Refer Section 1.4).

1.1 Southern Murray Darling Basin

Presented by Geoff McLeod - Environmental Manager, Murray Irrigation Limited (MIL).

Irrigation water use

Water use by crop within the SMDB is summarised in Fig 1. The farm gate value of production in this area is $2billion.

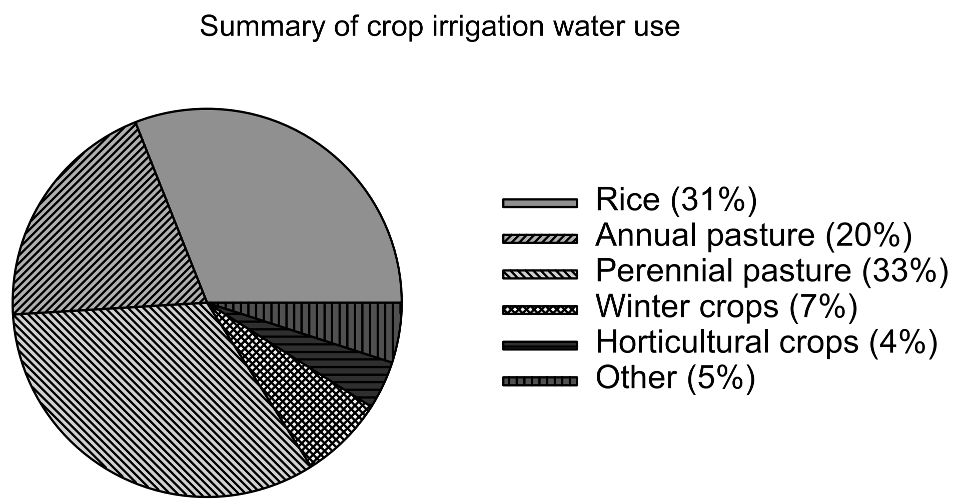


Fig 1. Break up of irrigation water use by enterprise in SMDB.

The threats

- Approximately 50 % of the irrigated area has watertables with 2m. Watertables are still rising in many of these areas.
- Groundwater salinity is often high and not suitable as a source of irrigation water.
- Salinity leads to losses in agriculture production in the dairy, rice and horticulture industries.
- Loss of natural vegetation, bio-diversity
  - Particularly a problem for vegetation in lower areas.

Managing Salinity

The following activities are ongoing in a bid to combat salinity problems:

- Development of Integrated Strategies
  - Land and Water Management Plans
- Management that minimise groundwater accessions
  - Irrigation induced
  - Rainfall related
- Manage areas of high watertable (groundwater pumping)
- Development of water use policies that limit irrigation intensity
  - Total Farm Water Balance Policy

– Rice Growing Policy

Research Focus

- Understand levels of groundwater accessions
  - Flood irrigated pastures
  - Rice
- Determine optimal level of water use on irrigation farms
  - SWAGMAN Farm

Water Use Models

- Develop models that assist interpretation of field results and with policy development
  - Describe water movement within common soil types
  - Evaluate alternative management/policy strategies

Current research Project – DAN 11

- Objective:
  - Quantify water movement below rootzone of flood irrigated pastures
  - Refine Total Farm Water Balance Limit Policy to achieve farm water balance
- Approach:
  - Quantify water movement through soil profile
  - Lysimeter work (Tatura)
  - Field work (Southern NSW)
  - Use information to refine soil water models
- Concern:
  - That existing models to not adequately describe field experience
  - Models don't describe the role of cracks in influencing water movement

1.2 Summary of Northern Perspective

Mac Kirby gave a brief outline of the issues in estimating the water balance, plant water use, and drainage in the swelling and cracking soils in the NMDB. Estimates of the water balance in the swelling soils of the region cannot be made with sufficient confidence to assess the environmental impact of farm (or other land) management, or for land use planning. In response to this, a program of work is currently being developed by several research partners, including the Cotton CRC, QDNR, NSW Agriculture, University of Sydney and CSIRO Land and Water. The program is sourcing funding from several funding agencies.

What are the water balance and drainage issues involving swelling and cracking clays?

Salinity

- Salinity audit – salinity increasing in many northern rivers
- Many will exceed 800 EC threshold in 20 – 50 years
- Irrigation areas will have to manage salt – by increasing leaching fractions?
- (Four NMDB catchments in National Action Plan)

Other reasons

- Improving water use efficiency – increased competition for limited water (irrigation)
  - greater uptake equals reduced drainage (dryland)
- Reducing other nutrient and pollutant exports to rivers and groundwater

What's different in the NMDB

- Extensive areas of swelling clays – 50 % of irrigated areas
- Summer rainfall
  - irrigated areas have more chance of rain landing on wet profile resulting in runoff / drainage
  - dryland areas have different rotation options / problems

Another difference?

- Problems are less serious than south? (Younger irrigation areas, no extensive areas with water tables close to surface.)
- Which presents an opportunity
  - to put in place systems **before** major problems emerge
- And a danger
  - of complacency, and doing nothing **until** major problems emerge

But swelling soils don't drain, do they?

- Recent evidence suggests that there might be more drainage than has been supposed

Some issues in swelling soils

- Swelling – must be measured to account for changes in storage (swelling accounted for ~ 120 mm of water in one year at Hudson).
- Corrections to water balance on account of swelling are of the same order as drainage estimates (Ringrose-Voase, Liverpool Plains).
- How to extrapolate to other soils? Pedo-transfer functions have been developed for rigid soils (e.g. Cresswell of CSIRO Land and Water), but not for swelling soils. Cracking and preferential flow - Not good at dealing with: new project with GRDC Extent of swelling

soils knowledge.

- Much theoretical knowledge about swelling soils, little field measurement.
- No study with fully closed measured water balance (cf CSU Wagga Wagga site with Smith/Dunin).
- No study that measures all components of a farm water balance in irrigation - where best to target measures to prevent drainage?
- Limited knowledge of hydraulic properties, what pedo-transfer functions to use: no properties database (cf non-swelling soils).
- Limited knowledge of influence of water quality on hydraulic and swelling properties.

Other issues

- Groundwater
  - Depth to groundwater and rates of change (falling in some aquifers)? What about shallow groundwaters? Fewer studies than in south? Frequent mismatch between surface drainage estimates and groundwater recharge estimates. Need to link surface water balance studies to groundwater studies.
- Spatial extrapolation
  - Which landscape/landuse contributes most to drainage/salinity? Change in drainage from native vegetation? Where to target action? Example of Liverpool Plains – no irrigation districts, mismatch of drainage and recharge estimates.

1.3 What information do land and water management plans require from models for policy formation and planning?

The general requirements are to determine the components of the water balance. It will often be necessary to link the water balance assessments to other considerations such as economics or groundwater and salinity trends. The main estimates of interest in practical land management are the:

1. Amount of irrigation water required for cropping;

2. Crop water use (from which relative yield might be estimated); and,

3. Movement of water and solutes out of the root zone, usually by downward drainage though sometimes by lateral movement.

This information was identified as being necessary for:

- Determining optimum level of water use on irrigation farms –
  - When and where to apply water;
  - Specify a reasonable crop water use for different enterprises
  - Maximise productivity and maintain soil resource.
- Quantifying water losses
  - Regional level / hazard mapping.
- Identifying impacts of management and enterprise on groundwater / river water quality.
  - What is water carrying with it?
  - Whether cracks hit permeable / impermeable layers
  - Design of irrigation systems / management systems.

The main advantages of models over field experimentation identified include:

- Predict future impacts of current management.
- Predict impacts of different management scenarios.
- To handle temporal / spatial scaling.
- Potential for reduced dollars /effort over time.
- Educational tool / process understanding.
- To determine / guide experimental work.
- Policy development.

1.4 Under what circumstances are cracks likely to be important?

Cracks are important, and should be included in the model when they significantly affect either the storage or movement of water. The importance of cracks will depend on:

- Connectivity and depth of cracks, which in turn is affected by wetting and drying cycles and rooting patterns;
- Numbers and size of cracks (also affected by wetting and drying cycles and rooting patterns);
- Whether cracks reach a permeable layer resulting in rapid lateral water movement
  - ➢ Can play different role / importance at paddock → catchment scale.
- Whether the rate of application of water exceeds soil infiltration. At low application rates the cracks will not contain any water. Identification of the conditions that result in this occurring (for both rainfed and irrigated agriculture) is necessary.

2. Key technical and functional weaknesses in modelling approaches

A review paper was prepared prior to the workshop. This review summarised published literature, identifying shortfalls in knowledge and conflicting information in the literature Attachment 5). The review paper was structured to address 5 key components in a dual porosity model after the work of Bevan and Germann (1982). These five components (or processes) are illustrated in Fig 2. It was assumed that root water extraction by plants is well described and therefore outside the scope of this workshop.

A summary of the key issues identified in the review paper was presented as an initial basis for discussion on the key technical and functional weaknesses in modelling approaches. The following group discussion examined and prioritised the current state of knowledge on these key issues. Results of discussions have been summarised into tabular form in sections 2.1 to 2.5. Limited time constraints meant that only some of the issues could be discussed in detail.

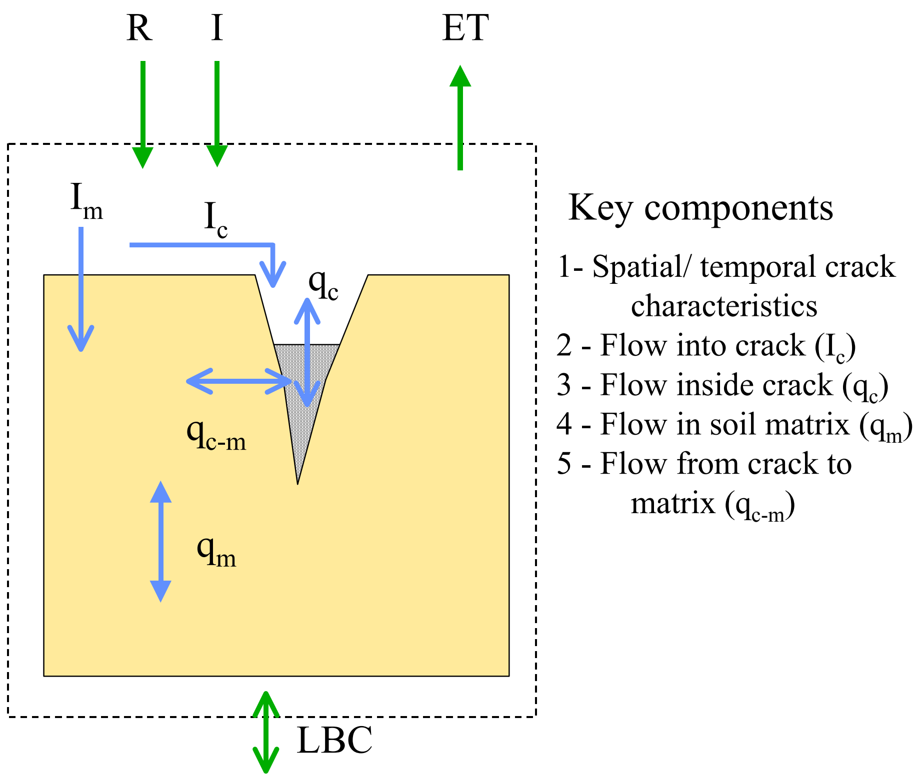


Fig 2. Key components in a dual porosity model.

2.1 Spatial and temporal characteristics of cracks

Cracks are important only where they exist in sufficient numbers and size to influence water storage and flow. The spatial and temporal characteristics of the cracks are clearly a key consideration.

2.1.1 Key issues

Key Issue	*Workshop comments*
The spatial and temporal characteristics of the cracks depend upon several factors including: • Is shrinkage 1D or 3D? - is shrinkage curve representative	Several studies on Australian Vertisols have clearly identified that shrinkage is 3-D. The work of Yule and Coughlan are good examples of this. Therefore, this was considered not to be an issue. How these findings apply to red brown earths, which are nominally non-shrinking soils

of what happens in the field?	is not known. Since shrinkage is 3-D, field measurement of vertical shrinkage can be used to determine crack volume. This can be done under field conditions and is a simpler way of developing the shrinkage characteristic.
• Hysteresis of shrinkage curve.	Little information exists on this topic, which is not covered in the literature. It was raised at the workshop as a possible source of uncertainty. No information is available on how this impacts on the water balance and is considered to be a gap in knowledge.
• Impact of plant roots on crack patterns.	It was recognised that plant rooting pattens will have a big impact on crack formation and location.
• Cropping and climate sequences.	No discussion on this topic.
How much does measurement technique impact on estimates of the shrinkage characteristic?	No discussion on this topic.
How important are the spatial and temporal characteristics (i.e. crack geometry) on water flow and water balance?	This topic was discussed in detail Refer 2.1.2 .

2.1.2 Crack geometry

Crack geometry is important if you want to look at management.

- Knowledge on crack geometry (including volume) was considered necessary for:
  - Water movement studies in cracking soils.
  - Small/paddock scale studies.
  - Assessing the impact on local watertables.

  Crack geometry was considered not important for:
  - Large scale water balance studies.
  - (But might be important for carrying solutes at larger scale).

- Some work done has been done in past describing crack geometry for Riverina soils.
- Crack volume can be predicted from the shrinkage characteristic.
- Have to work on how to characterise and parameterise shrinkage. Theory exists that describes shrinkage, but most models do not utilise this information.
- Relationship of crack geometry to pedology is important. This relationship would be useful in determining where cracking soils occur and may be useful in assisting in transferring results to similar soil types. Pedo-transfer functions are one way of trying to capture this relationship. Pedo-transfer functions for different properties have been developed for non-swelling soils, their application to cracking/swelling soils is unclear.
- Do not know conclusively if geometry has a major impact on solute movement.

2.2 Flow into cracks

Identifying the initiation of flow into cracks is a key step in determining the partitioning between crack flow and matrix flow through the soil. The workshop discussed the issues involved.

2.2.1 Key issues

Key issue	*Workshop comments*
Accurate description of surface infiltration and runoff.	Description of surface infiltration/runoff was seen as the major weakness in this area. This weakness also applied to non-swelling soils. (See detailed comments below).
Rate of closure of cracks (= rate of wetting of surface layer).	No discussion on this topic. Described by rate of infiltration from crack into matrix. Also relates to comment

	on hysteresis of shrinkage characteristic under component 1.
Tillage and its impact on crack connectivity.	Several studies have been conducted which measure the impact of tillage on surface roughness. Limited information is available on how tillage affects crack connectivity, particularly to depth.

2.2.2 Description of infiltration and runoff

Accurate description of infiltration/runoff was seen to have the greatest impact on the water balance. It was considered to be very difficult to capture this in models and is still one of the largest sources of uncertainty (in both swelling and non-swelling soils).

It was questioned whether we are able to accurately describe infiltration given the spatial variability in soil properties. This has a large impact on ponding and initiation of flow into the macropore. The spatial variability in hydraulic properties and how this impacts on infiltration was considered a major issue.

Two areas identified that require further work include:

- methods for accurate measurement of soil hydraulic properties; and
- characterising spatial variability.

2.3 Flow inside cracks

The nature of flows within a soil crack will define the redistribution of water within the soil profile.

2.3.1 Key issues

Key issue	*Workshop comments*
Nature of flows within cracks.	Under flood irrigation the crack becomes saturated very rapidly and crack infiltration occurs over the full depth of the crack. Under rain-fed conditions, crack closure will most likely occur prior to significant crack infiltration. Under rain-fed situations, crack water infiltration will occur from the top down. Unlikely under rainfall to get wetting from the bottom.
Do we want to describe water movement inside the macropore?	Not an issue / weakness.
Can we ever parameterise explicit models of crack flow?	Probably never be able to parameterise flows through cracks – but would be useful to simulate – 4 scenarios (small / large crack x small / large peds).
Will we ever be able to test / verify this?	Probably not.

The general conclusion was that there is no need to simulate water movement in the crack.

2.4 Flow in the soil matrix

Flow in the soil matrix is important for three reasons. Firstly, water flowing in the matrix is not flowing in the cracks, so estimating the matrix flow is an important step in estimating crack flow. Secondly, water that enters the soil matrix causes swelling, which in turn, causes crack closure and thus determines the amount of water that flows in cracks. Thirdly, drainage losses often occur during winter periods (high rainfall and low plant water use) when cracks are likely to be closed. During these periods matrix flow will be the dominant process for water transport to depth. The workshop discussed the following issues.

2.4.1 Key issues

Key issue	*Workshop comments*
How important is the over-burden potential?	Well described by existing theory. The key issue is when do we need to apply it?
When is it important to include the impact of soil movement on water movement?	Well described by existing theory. The key issue is when do we need to apply it?
Impact of water quality on soil hydraulic properties?	Poor understanding of impact of water and soil quality on hydraulic properties and crack geometry. See further comments below.

2.4.2 General comments

There is limited information available that gives the relative impacts of water quality on soil types. The response is known to happen, however, has probably not been well defined for most soils in Australia. No modelling studies include the impact of soil water quality on hydraulic properties into their description. Some work is required to characterise this response, and then it can be included into models.

2.5 Flow from crack into matrix

The capacity of a crack to transport water (and hence solutes) to depth will be influenced by the flow from the crack wall into the soil matrix. This will impact on water redistribution and thus the rate of swelling and crack closure. The workshop discussed the following issues.

2.5.1 Key issues

Key issue	*Workshop comments*
Is it important for models to adjust crack surface area with changing soil moisture?	See general comments below.
Description of infiltration from crack into matrix.	See general comments below.
Flow out of / evaporation from / salt movement out of cracks.	See general comments below.
Preferential flow / crack linkage to different layers / beneath crack zone.	An important factor. While models can describe this process, in practice it would be very difficult to parameterise such a model or even identify where such transmissive layers exist without detailed soil sampling.

2.5.2 General comments

There was mixed opinion as to significance of this process. It was thought that there was little evidence to suggest that infiltration through crack walls had an impact on the infiltration and redistribution process under rain-fed situations. This results from soil swelling and crack closure prior to ponding and water flow in cracks. In contrast some results from the Liverpool Plains indicates that crack flow may be occurring under rain-fed conditions.

Under flood irrigation, a large amount of water is applied very quickly. There is experimental evidence indicating the importance of redistribution via cracks under flood irrigated conditions.

In general, it was thought that there was insufficient experimental/empirical evidence to fully understand how this process occurs, and how important it is on the water movement and the water balance. Empirical knowledge of water flow between the crack and matrix is required to understand the rate and nature of water interaction between the two domains.

3. Assessment of the ability of models to underpin water policy and planning decisions

This discussion was based around two case studies, the NSW Murray Valley and the Liverpool Plains. Group discussion of these case studies followed, focussing on issues/weaknesses, data and model development required. Following this there was general discussion about data requirements.

3.1 Scenario 1 - NSW Murray Valley

Water use policy has been implemented to limit irrigation intensity on a farm basis to reduce groundwater accessions. Typical components of the water budget are summarised in Fig 3. There is a need for data describing accessions under summer pasture for input into this policy. A project was established to estimate accessions using a combination of lysimeter, field and modelling studies. Soil hydraulic properties were measured, and soil moisture profiles, pasture production and watertable depth were intensively monitored at six sites on 3 different farms. The soils at these farms are classified as non-cracking soils.

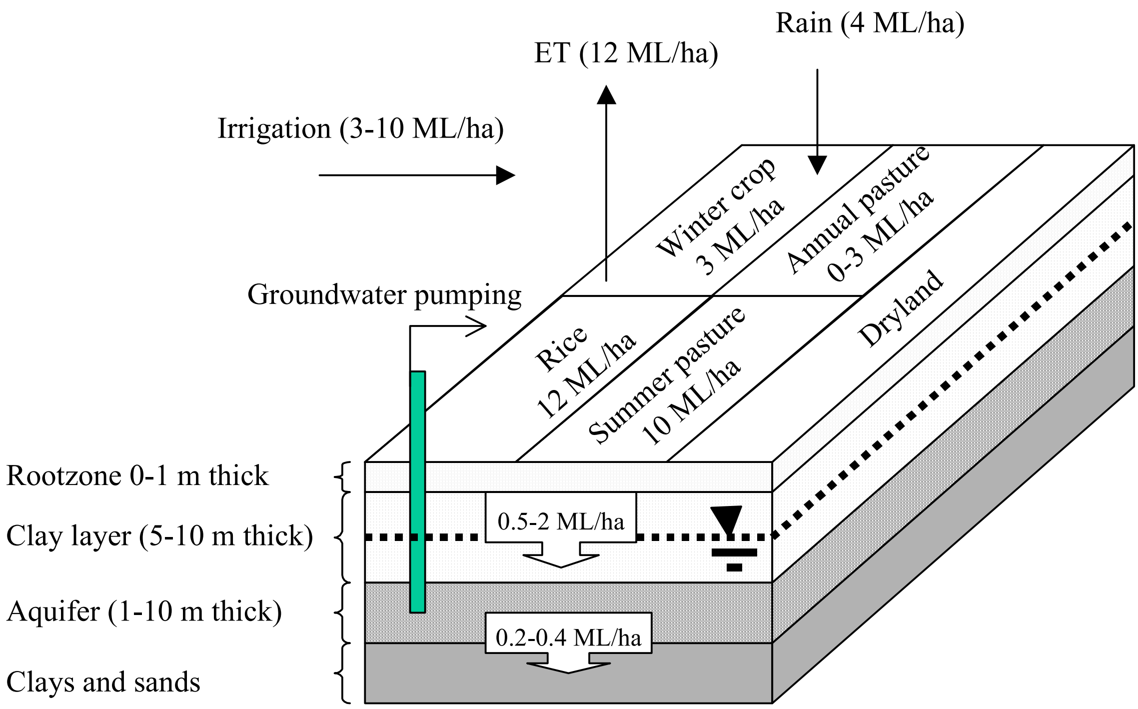


Fig 3. Typical components of the water balance for a farm in the Murray Valley.

Original modelling

The modelling study originally assumed that the soil was rigid and did not allow for water movement through cracks. Using field measured soil properties, insufficient water would infiltrate the soil during an irrigation event. Increasing soil hydraulic properties above the measured values was the only way to get realistic amounts of infiltration. This resulted in over prediction of recharge. From this it was concluded that the original conceptual model was incorrect and that it was necessary to include the impact of infiltration through cracks. Preliminary testing of a model that describes infiltration through both the soil matrix and soil cracks shows promise. However, additional data requirements are necessary for this model, which were not measured as part of the experimental program. Some of this missing data (shrinkage characteristic) may be available for similar soils.

3.1.1 Issues

- How much of applied irrigation water contributes to groundwater accessions?
- What options are available for reducing groundwater accessions?
- What is contributing most to the accessions?
- In autumn – should we be discouraging irrigation so we go into winter with a dry profile?

Key questions
- How do we describe movement / redistribution of water via cracks?
- What is the contribution of cracks in moving water below root zone and when is this occurring?
- How do we separate surface infiltration from crack infiltration? (Do we need to?)
- Are cracks acting as internal reservoirs, allowing further wetting over longer time period? → rate / distribution of water.
- Are the cracks connected to more transmissive layers at depth?
- Are there more appropriate models?

3.1.2 Data Requirements

- Crack – presence/absence, connectivity – understand how cracks are operating (shrinkage characteristic).
- Information on lateral infiltration.
- Rigid bio-pores – role / presence?
- Profile behaviours / soil spatial variability.
- Need to be able to distinguish contribution from –
  - Winter / wet profile – accessions
  - Irrigation → crack → accessions

  Which is the dominant process and how does this vary as watertables rise close to surface?

3.1.3 Model Development / Use Required

- Experience in using / choosing "right" models.
- Require experimental evidence to support / refute importance of cracks.
- Build conceptual model of what is happening –
  - Require empirical data
  - May vary across different areas / parts of Murray Valley.
- Accommodate variability between sites.
- May require the use of "distributed parameter" models.
- Management discrimination between areas that have cracks/macropore and those that do not.
- Discriminate rainfall /irrigation influences on ground water.

3.2 Scenario 2 - Liverpool Plains

The Liverpool Plains is a large catchment in the north of New South Wales. Salinity is of increasing concern, and is probably associated with the changed hydrology resulting from clearing for agriculture. The catchment has been the subject of a large study including assessment of the surface water balance and groundwater hydrology. Estimates of drainage made from the surface water balances have been difficult to reconcile with recharge estimates from groundwater modelling. Some of the catchment has swelling soils, and various issues have arisen in the assessment of their water balance.

3.2.1 Issues / Weaknesses

Key questions
- One field study found about 90 mm of water under lucerne could not be attributed to anything other than drainage, and yet appeared not to have wet the soil profile. In other words it appeared to have drained out of the soil without going through the matrix. Is there a "by-pass" mechanism operating?
- How do we resolve the discrepancy between surface drainage estimates and groundwater recharge estimates?

- Laboratory estimates of the field capacity and wilting point differ from those estimated in the field from wettest and driest profiles.
- How much does the system respond to sub-surface soil conductivities?
- Issue of spatial variability. (Different process under natural / native tree system).
- Do cracks go beyond root zone or connect to other permeable layers?

3.2.2 Data Requirements

- A much better feel for actual drainage is needed –
  - But there is not a simple sensor to measure drainage
  - Via lysimeters?
- Drainage – specify time period and reference depth.
- Role of cracks – geometry / connectivity.
- Sub-soil conductivities.

3.2.3 Model Development / Use Required

- Have we got our conceptual model correct?
- Attempt to explain / account for 90mm drainage under lucerne.
- Assess drainage (more) directly.
- Spatial and episodic events – understanding of these.
- How to measure preferential flow paths / rates?
- Do we have a model that considers cracks and could account for / cope with 90mm loss under lucerne? SWAP or HYDRUS-ET potentially, however do not account for movement inside cracks, impact of swelling on water movement and assumes that crack water goes straight to bottom of crack.

3.3 Discussion on data requirements and utility of models

It was the general opinion of the participants at the workshop that the ability of existing models to underpin water policy and planning is currently restricted by the lack of data on water balance in cracking clay soils. Without good data to identify the processes and verify the models, we are not currently in a position to use models in cracking soils with confidence. No field study in Australia to date, on a swelling soil, has measured all the components of the water balance or permitted unequivocal estimation of the drainage or the quantity of water flowing through cracks. Lysimeter studies (in Tatura and Griffith) have measured all components of the water balance. However, it is widely recognised that lysimeters are not always typical of field conditions. Therefore, a model is typically used to translate lysimeter results to field conditions. Models used for this translation in Australia do not consider the impact of cracking or swelling on the water budget.

A number of studies have been conducted which supply some of the information necessary to characterise and model cracking soils. This information is often difficult to find and only available in ‘grey literature’. This information needs to be collated so that knowledge/data gaps can be clearly identified.

Future studies can then target data and knowledge gaps. These studies should have direct measurement of all components of the water balance, including assessment of crack water flow or (perhaps more usefully) the impact of crack water flow such as the response of shallow groundwater tables.

4. Recommendations on necessary steps to improve model capabilities

The workshop participants identified that the principal limitations in modelling are not the models themselves, but water balance data to identify the processes and verify the models (Section 3.3) and soil physical information that characterises a cracking soil. As discussed in Section 3.3, a preliminary step to be undertaken prior to improving models and model capabilities is to obtain better data describing the behaviour of swelling and cracking soils.

Nevertheless, the workshop participants felt that there were some aspects of modelling that could be improved now. Broadly, these were:

- To improve the conceptual understanding of the processes;
- Quantification of the consequences of drainage; and
- Gain experience in using models for predicting behaviour of cracking soils.

Additional notes from the discussion sessions are included as Attachment 7. The main threads emerging from the discussions are described below.

4.1 Conceptual understanding of flow in cracking soils

Clearly, models used predictively to evaluate management options should describe the main processes and subsequent consequences on water movement. The discussion clarified that we are not currently well informed about when, under what circumstances (of climate, soil type, and land management), or how to include cracks in water balance models. Some current investigations (such as the DAN11 project) have made less progress than they might have done because of inadequate knowledge of these issues.

The workshop participants recommended that there be an investigation to identify when to include cracks in water balance models. This will lead to more targeted field experiments and correct conceptualisation of modelling studies.

4.2 Consequences of drainage in cracking soils

It was emphasised that there is no experimental study that has unequivocally determined the amount of drainage in a cracking or swelling soil (excluding lysimeter studies). The principal requirement is therefore, for experimental studies that measure all components of the water balance in dryland and irrigated agriculture.

The workshop participants noted that there is a proposal for a program of work in the NMDB that fulfils these requirements. It is recommended that this program of work be linked to other studies (such as the DAN11 project, or whatever follows it) in cracking and swelling soils in other parts of eastern Australia.

4.3 Practical application – experience in using and choosing models

The workshop participants noted that, in contrast to rigid soils, there is little experience in Australia in the use of models on swelling and cracking soils. There is a need for improved integration and collaboration between the few people working on this topic. In addition, greater attention needs to be given to the interaction with water and environmental managers involved in policy, planning and irrigation scheduling.

Education of model users is required to raise awareness of the impact of cracking and swelling on soil water movement and the water balance. This education could be achieved through the development of standards and guidelines for data sets. This will assist in the development of correct conceptual models that target the problem at hand.

5. Conclusions and next steps

The workshop was organised to review models of cracking and swelling soils, their applicability to management problems, and their usefulness in water policy and planning. The workshop was to recommend steps to improve the application of models to environmental management.

Demand for appropriate models was identified at the workshop for many applications, ranging from irrigation management to water policy and planning.

The participants collectively have much experience in water balance modeling of rigid soils, and some experience of water balance modeling of swelling and cracking soils. The main conclusion drawn from this experience was that we lack information, in particular, well-documented case studies of the water balance in swelling and cracking soils. At present we are unable to develop models, verify them, nor apply them to practical problems with any confidence. Thus no attempt was made to list models that have been, or might be, applied to water balance in swelling and cracking soils.

Cracks can significantly affect the storage and movement of water where they are large and numerous, connected to permeable horizons at depth, and where the rate of application of water exceeds the infiltration rate of the soil. More experimental information is required about the processes that contribute to crack flow, as shown in the table below.

Process	*Importance*
The distribution and connectivity of cracks, and the potential impact of flow down cracks on the underlying water tables.	Key step, requires experimental data.
Infiltration capacity when exceeded leads to run-off and flow into cracks.	Must be properly described by any crack flow model.
Flow inside cracks.	Need not be considered in detail.
Flow into and swelling of the soil matrix, including crack closure.	Important consideration, but few if any models incorporate the effect of water quality on soil hydraulic properties.
Flow from crack into matrix.	Possibly important but more experimental studies required.

Thus, rather than focusing on the models themselves, it was concluded that we should first gather experimental evidence of water balance and drainage from swelling and cracking soils. However, it is important that measurements be made with a view to developing and verifying models, and that models be tested using the experimental information. Otherwise there is the danger of failing to measure key processes or parameters.

The workshop recommended that the next steps in the modelling of cracking and swelling soils should be:

- Conduction of good experimental case studies, in which measurements are made of all components of the water balance (including flow down cracks, if it occurs), and the consequences of drainage from the soil profile;
- Using those case studies to test and improve models, or develop them where necessary;
- An investigation to identify when, under what circumstances (of climate, soil type, and land management), and how to include cracks in water balance models; and,
- The application of guidelines to the development and practical application of models in cracking and swelling soils, so that the modelling pays attention to:
    - The needs of, and interactions with users, managers, advisers, and policy makers;
    - Data issues including standards and guidelines for datasets, and the use of common field sites;
    - Building multi-disciplinary teams, including economists; and,
    - Reviewing and building on current experience.

Attachments

Attachment 1 - Workshop agenda

Introduction and welcome (Brett Tucker)

Structure and process of the workshop (Peter Box)

Setting the scene

'Why do we want models that describe water movement in cracking soils?'

- Northern perspective (Mac Kirby)
- Southern perspective (Geoff McLeod)

Group discussion to identify:

- what are the key uses of models with regards to policy and planning? (and at what scale/s and timeframe/s?)
- under what circumstances are cracks likely to impact on water movement models?

Key weaknesses in modelling approaches

Presentation of weakness as identified in literature review (Matthew Bethune)

Group discussion – prioritise identified **key weaknesses** as a basis for discussion in the technical review.

Technical review

For each key weakness / question:

- do we need to resolve this question to account for water movement in cracking soils?
- relate the weakness or question to use and scale / timeframe.
- provide a rationale for pursuing or not pursuing this weakness / question.

Assessment of the ability of existing models to underpin water policy and planning decisions (case studies)

Southern perspective Presented by Geoff McLeod

Group discussion to identify each of the following for the two case studies:

Issues / Weaknesses

Data Requirements

– Model Development / Use Required

Northern perspective Presented by Mac Kirby/Mark Silburn

Group discussion to identify each of the following for the two case studies.

Issues / Weaknesses

Data Requirements

Model Development / Use Require

Attachment 2 - Workshop participants

Dr Nick Austin
Technical Specialist WUE
Water Use Efficiency Plant Industries
NSW Agriculture
PO Box 865 DUBBO NSW 2830
Nick.austin@agric.nsw.gov.au
Tel: 02 68811280

Mr Matthew Bethune
Hydrologist
ISIA, DNRE
PB1 Ferguson Rd TATURA VIC 3616
Matthew.bethune@nre.vic.gov.au
Tel: 0358 335243

Dr Peter Box
Facilitator
Boxy@netc.net.au
Tel: 0357626309

Dr Keith Bristow
Scientist
Soil & Environmental Physics
CSIRO Land & Water
PMB PO
AITENVALE QLD 4818
Keith.bristow@tvl.ciw.csiro.au
Tel: 074758500

Dr Peter Fisher
Senior Scientist
ISIA, DNRE
PB1 Ferguson Rd TATURA VIC 3616
Peter.fisher@nre.vic.gov.au
Tel: 0358 335342

Mr Hayden Kingston
Officer
Finely Advisory Office
NSW Agriculture
PO Box 108
FINLEY NSW 2713
Hayden.kingston@agric.nsw.gov.au

Mr Budiman Minasny
Department of Ag Chemistry & Soil Science
University of Sydney
Ross St, Bldg A03
SYDNEY NSW 2006
Budiman@acss.usyd.edu.au

Mr Mac Kirby
Scientist
Soil Mechanics, Soil Physics
CSIRO Land & Water
GPO Box 1666
CANBERRA ACT 2601
mac.kirby@cbr.clw.csiro.au
Tel: 02 62465921

Mr Geoff McLeod
Manager
Murray Irrigation Limited
PO Box 528
DENILIQUIN NSW 2710
Geoffm@murrayirrigation.com.au
Tel: 0358819331

Prof. Wayne Meyer
Program Leader
Sustainable Agriculture
CSIRO Land & Water
PMB 2
GELN OSMOND SA 5064
Wayne.meyer@adi.clw.csiro.au
Tel: 08 83038683

Mr Mark Silburn
Hydrologist
APSRU
Resources
PO Box 318
TOOWOMBA QLD 4350
Mark.silbur@dnr.qld.gov.au
Tel:07 4688 1281

Mr Brett Tucker
Irrigation
National Program for Irrigation R&D
Land & water Australia
12 Belmore Gardens
BARTON ACT 2600
Btucker@bigpond.com
Tel: 0262730125

Dr Hugh Turral
Research Fellow
International Development Technologies Centre
University of Melbourne
PARKVILLE VIC 3010
Hnt@devtech.unimelb.edu.au
Tel: 03 93446876

Dr Willem Vervoot
Hydrology and R&D Co-ordinator
Department of Ag. Chem. & Soil Science
University of Sydney
Ross St
BLDG A03 SYDNEY NSW 2006
w.vervoort@acss.usyd.edu.au
Tel: 0293518744

Dr Don Yule
Rural Water Use Efficiency Initiative
Resources
80 Meiers Rd
INDOOROOPILLY QLD 4068
Don.yule@dnr.qld.gov.au
Tel: 0733629388

Dr John Hutson
Senior Lecturer
School of Chemistry, Physics & Earth Science
Flinders University
John.hutson@flinders.edu.gov.au
Tel: 0882012616

Mr Kep Goughlan
Catchment Processes
Resources
15 Dempsey St
ANNERLEY QLD
Keppel.coughlan@dnr.qld.gov.au

Attachment 3 - Overheads from talk on southern perspective

(Geoff McLeod)

Attachment 4 – Overheads from talk on northern perspective (Mac Kirby)

Attachment 5 - Review paper

Modelling Water movement in cracking soils: A review

Matthew Bethune[1] and Hugh Turral[2]

[1] Department of Natural Resources and Environment
[2] University of Melbourne

Introduction

Drainage losses below agricultural crops (deep percolation) are the key factor in water table rises and the genesis of dryland and irrigated salinity. Adequate data and realistic modelling are required to develop effective management strategies in land and water management plans, and, inform policy development. Deep percolation cannot be directly measured under field conditions and, therefore, models of the water balance are often used to quantify deep percolation and predict the impacts of land management on deep percolation and water table movement. Typically, these models have been developed to describe water movement in rigid soils without cracks. Cracking significantly modifies the dominant processes of soil water movement and redistribution, particularly under conditions of surface ponding, as in irrigation. Most soil water models rely on descriptions of porous media flow, leading to inaccuracies in the rate and destination of water movement in cracking soils.

The importance of swelling and cracking on soil water movement is increasingly being recognised as a major process contributing to drainage below the plant root zone. Talsma (1972) found on average 70 % of water infiltrated within the first 10 minutes in three cracking soils in the Riverina. Armstrong and Arrowsmith (1984) found substantial differences in the volumes of preferential crack flow compared to capillary water movement. Prendergast (1995) measured bypass fluxes under pasture flood irrigated with different irrigation water salinities. He measured lower bypass volume under wetter soil conditions, which he attributed to the more limited development of shrinkage cracks compared to dry soils. He also found that bypass fluxes contributed to leaching which indicates water movement from the crack into the matrix domain. Thorburn and Rose (1990) conducted a study of bypass fluxes using tracer techniques on 35 soils, 28 of which were cracking clays. They estimated the flux of water bypassing the root zone varied between 0 and 415 mm/y. These and other studies highlight the impact of cracking on water movement in soils, particularly on the depth and rate of infiltration.

Conventional infiltration theory assumes laminar flow and small voids and is not applicable to cracking soils (Ross and Bridge, 1984). Smiles (1984) summarises the problems and philosophical approaches to modelling water relations in swelling soils and is worthy of quoting from his conclusions:

> *'The study of water flow in swelling clay soils remains an area of soil physics that is most intriguing in its difficulty because it appears to bring together the most difficult features of water flow in non-swelling soils and superimposes them on the additional problem of volume change.'*

The difficulties associated with water movement in cracking soils have led to a diverse range of modelling approaches. The early 1980's saw the development of dual porosity models (German and Beven, 1981; Jarvis, 1994; and Gerke and Van Genuchten, 1993). Another approach is to superimpose the soil hydraulic functions of the macropore and matrix domain (Ross, 1990; Zuruhl and Durner, 1996). Bronswijk (1988) concludes that cracking clay soil should be considered as a two-domain system: soil and shrinkage cracks. Van Genuchten *et al.* (2000) state that process-based descriptions of preferential flow invoke dual porosity models. In more recent times, models have been developed that attempt to describe the physics of shrinking and swelling soils and the impact of this on the water balance (Bronswijk, 1988; Van Dam, 2000).

Beven and Germann (1982) identify 5 components of a complete two-domain macropore / matrix model. This review is focused on macropores formed through soil shrinkage and cracking, ignoring stable macropores. The review is limited to published literature describing approaches to modelling water movement in cracking soils and is grouped into the 5 components identified by Beven and Germann (1982).

The five components are discussed in order as follows:
1) Spatial and temporal characteristics of the macropore network
2) Initiation of flows in the macropores
3) The nature of flows in the macropore system
4) The nature of flows in the matrix domain
5) Interaction between the domains.

1) Spatial and temporal characteristics of the macropore network

Spatial distribution, connectivity and geometry with depth of cracks are important parameters affecting the spatial and temporal movement of water in cracking soils. These descriptive parameters change with different soil chemistry, mineralogy, soil moisture status and management, which make their physical description very difficult. Therefore, these processes are typically conceptualised prior to building models. Bronswijk (1990) divides the shrinkage process in clay soils into two parts. Firstly, the relationship between the change in soil water content and the soil matrix volume change. Secondly, the conversion of soil matrix volume change into cracking and surface subsidence.

Relationship between water content changes and soil volume change (shrinkage characteristic)

Stirk (1954) credits Tempany (1917) and Haines (1923) with the first investigations of swelling behaviour of remoulded clay blocks and the definition of three phases of swelling. He added a fourth component, structural shrinkage, and summarised the definitions of each stage as follows:

- Structural shrinkage - water loss from macropores with no discernible change in soil volume: typically this is water held at less than 100 mm matrix suction.
- Normal shrinkage - the change in soil volume equals the loss of water and usually occurs over a suction range from -0.3 bar to -15 bar. The slope of the normal shrinkage line is denoted as α and termed the compressibility factor.
- Residual shrinkage - volume change of the soil is less than the loss of water. The start of this phase is reported to be dependent on clay content and commences at -20 to -40 bars at 40% clay content (Stirk, 1954) and at -1000 bars at 80% clay content (Coughlan, 1984). The work of Bronswijk (1990) indicates that on average this stage would commence at suctions greater that -15 bar, however, in some instances it commenced at suctions of -0.1 bar.
- Zero shrinkage - there is no further change in soil volume for further loss of water.

It has become convention to express the shrinkage characteristic in terms of void ratio and moisture ratio, as in **Figure 1**, where:

$$\text{Void ratio} = e = \frac{\text{volume of voids}}{\text{volume of solids}} \quad (1)$$

$$\text{Moisture ratio} = \vartheta = \frac{\text{weight of soil water}}{\text{volume of solids}} = \theta_g . \gamma_s \quad (2)$$

where: θ_g = gravimetric moisture content
γ_s = particle density

A common alternative way of expressing the shrinkage characteristic is by plotting moisture content versus bulk density (McIntyre, 1984), or as gravimetric water loss against vertical shrinkage (Yule,

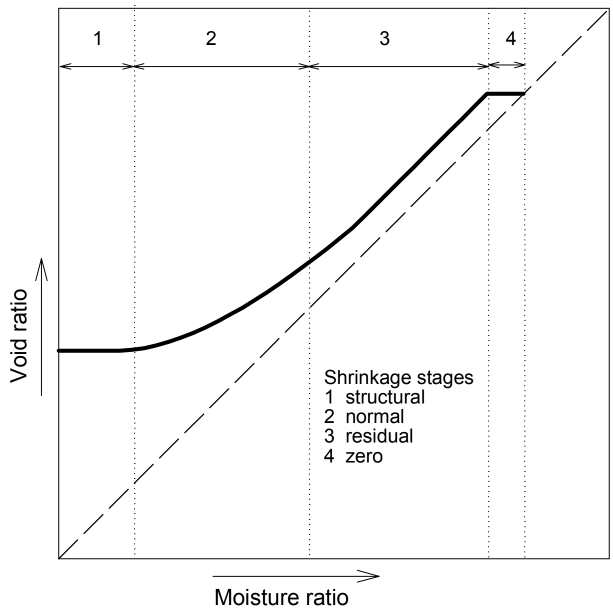


Figure 1 Graphic representation of a classical shrinkage curve.

This touches on a long running debate concerning the dimensional nature of shrinkage: Fox (1964) held that, at high moisture contents, shrinkage was 1-dimensional (1-D) and vertical and that, at low moisture contents, it was 3-dimensional (3-D), resulting in cracks. McIntyre (1984) showed that 1-dimensional (1-D) shrinkage did not need to be invoked to explain the behaviour and that even though peds were contracting in three dimensions (3-D) at low moisture content, the bulk soil was settling in only one dimension (1-D). Smiles (2000) states that field volume change is largely constrained to the vertical. In contrast, Yule (1984) and Berndt and Coughlan (1976) observed isotropic (3-D) shrinkage. Berndt and Coughlan (1976) induced one dimensional swelling was by confining dry soil cores to restrict the void ratio during wetting. However, shrinkage was isotropic on the drying of the same cores. Bronswijk (1989) felt that the 1-dimensional (1-D) shrinkage at high water contents was an artifact of supersaturated clay pastes, and, concluded that shrinkage was essentially three dimensional (3-D) over a range of depths to 0.65 m under field stresses. The method of measuring the shrinkage clearly has a large impact on both the magnitude and nature observed swelling and shrinkage. Field measured shrinkage would provide the most realistic estimate of the shrinkage characteristic. However, there are difficulties associated with measurement of bulk density in swelling soils (Kirby and Ringrose-Voase, 2000, Berndt and Coughlan, 1976, Olsson and Rose, 1978).

Conversion of soil matrix volume changes into cracking and surface subsidence.

Bronswijk stresses that, in (agricultural) field soils, we need to know actual volume change and that this cannot be done without determining actual water loss. He also found that if confining stresses were relieved in the field, the α coefficient reduced and became more variable, indicating horizontal shrinkage was dominating vertical shrinkage. Surface layer values of α were also lower than expected and Bronswijk attributed this to greater crack variability, although other authors attribute this to zero shrinkage in the uppermost layer of the soil. Bronswijk (1990b) determined shrinkage characteristics for seven different clay profiles and found that many deviated strongly from the theoretical relationship of **Figure 1**, and it is fair to say that the last word on this subject has still to be written. Other similar treatments of volume change are given by Giraldez *et al.* (1983) and incorporate the effect of applied loads on shrinkage.

Bronswijk (1988) presents relationships that allow the user to specify the nature of shrinkage through the introduction of a dimensionless geometry factor (eq 3). The geometry factor is equal to three for three-dimensional isotropic shrinkage and equal to one for one-dimensional vertical subsidence. The crack volume is then calculated from the change in the volume of the soil matrix and amount of subsidence (eq 3). This approach results in the volume of cracks being calculated as a function of depth and soil moisture. However, they provide little insight into the understanding of spatial pattern of cracking and connectivity of soil cracks. The FLOCR, HYDRUS-ET and SWAP models follow a similar approach to eq 3.

$$\Delta z = z - z\left(\frac{V - \Delta V}{V}\right)^{\frac{1}{r_s}} \qquad \textbf{(3)}$$

$V_c = \Delta V - \Delta z$

z = layer thickness (cm)

Δz = change in layer thickness (cm)

V = volume of soil matrix (cm^3)

ΔV = change in volume of soil matrix (cm^3)

V_c = volume of cracks (cm^3/cm^3)

r_s = geometry factor

Spatial distribution and connectivity

The topology of cracks has only been investigated by one team of researchers who quantified the numerical density and connectivity of crack networks (Scott *et al.* 1988). They found that loops can occur in horizontal, and also in vertical planes, if small peds are wedged between two larger crack faces. Connectivity measurements were made over micro-scales and no work has yet been done on the continuity of cracks over field distances, which would say more about the preferential flow paths available to water. It has been fairly well established that soils crack to ultimately form pillars or columns which may typically posses six faces (Raats, 1984). Crack faces tend to be stabilised by humins and other products of biological activity, so that cracks tend to reform in the same place and planes across sequential wetting and drying cycles.

Fox (1964) and Swartz (1966) found that crack geometry and distribution was affected by the rate of soil drying and plant distribution. O'Callaghan and Loveday (1973) found that the geometry of cracks may be modified by the exchangeable cation composition. The cracking pattern in clay soils is dependent on soil properties, tillage operations and the spatial pattern of plant water extraction (Bronswijk, 1991). He suggested that the surface crack pattern is solely a function of soil type in areas with no tillage and under spatially uniform plant water extraction (such as pasture). This argument was supported by findings of Virgo (1981) who observed that the cracking pattern repeated itself yearly.

The exact position of cracks varied but the average distance between cracks and polygonal crack pattern were similar.

Crack surface area

The surface area of crack walls is difficult to measure and has been the focus of relatively few studies. The area of the crack wall is usually expressed in models as a ratio of the surface area. The specific crack area is a predetermined value in the Hydrus-ET model. The SWAP model conceptualised the soil peds in the soil matrix as hexagons (Fig 2). The crack surface area per unit depth is calculated from the diameter of these hexagons, which is specified by the user and assumed constant over the model run. This assumption implies that the spatial distribution of cracks is constant over time and that crack surface area does not change with time or soil depth.

None of the reviewed models allows for change in crack surface area with depth as a result of change in soil moisture and crack volume. This has implications for the calculation of horizontal infiltration from the crack to the matrix. The importance of this process is difficult to assess as quantitative data describing crack surface area are scarce.

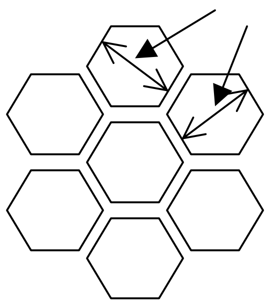


Figure 2 Conceptualised soil peds.

2) Initiation of flows in the macropores

The process of inflow to cracks has been treated in a similar manner in most models (eq 4). Rain or irrigation falling on a cracked soil infiltrates into the ped, without ponding, until a maximum infiltration rate (I_{max}) is achieved. Rainfall rates exceeding I_{max} result in surface ponding of water and consequently surface run off. This surface runoff flows into the cracks (I_c) surrounding the soil ped. Some modifications to this approach include the inclusion of a surface roughness factor. This requires the surface water to pond to a preset depth prior to the commencement of runoff. When this preset depth is exceeded, runoff into cracks occurs (Hydrus-ET, Novak *et al.* 2000). SWIMv2.1 takes this approach a step further and allows for a surface roughness factor that can change over time as a result of rainfall impact (Verburg *et al.* 1996).

Most models assume that the impact on crack inflow of direct precipitation and irrigation into the cracks is negligible. Two exceptions to this are the FLOCR and SWAP models. They account for direct precipitation and irrigation into cracks by calculating the percentage of the surface area containing cracks. Rain and irrigation is divided into matrix and crack infiltration based on this percentage. However, both of these models assume that no runoff can occur when simulating water movement in cracking soils. This means that water can pond to artificially high levels and may consequently over-predict infiltration.

The main differences between current models are in how I_{max} is defined. Models where the micropore domain is solved by solution of Darcy-Richard's equation calculate I_{max} as a function of soil hydraulic properties and current hydraulic gradient at the soil surface. Other approaches may use a Green-Ampt or Phillip's type infiltration equation to set I_{max}.

$$
\begin{aligned}
P + I < I_{max} \quad & I_m = P + I \\
P + I > I_{max} \quad & I_m = I_{max} \\
& I_c = P + I - I_{max}
\end{aligned}
\qquad (4)
$$

P = rainfall
I = irrigation
I_m = infiltration into matrix
I_{max} = maximum infiltration rate into matrix
I_c = inflow to cracks

Another source of I_c occurs through lateral flow of water in cracks. This is possible on hillslopes and from flood irrigation where significant lateral hydraulic gradients of water may be generated in cracks. Increasing the size of the representative elemental volume being modelled to the field scale should remove this source of I_c under flood irrigation.

3) Nature of Flows in the macropore system

Water movement within macropores determines the redistribution of I_c within the soil profile. Attempts to model water movement inside the macropore domain appear to be limited to studies of stable macropores and hillslope runoff/drainage studies. The reason for this is likely to be the scale of the studies and different processes operating at agricultural field scale to a catchment runoff study. In addition, the spatial and vertical description of crack geometry is very difficult to quantify.

In soil cracks, water flows down the crack face where it will either be adsorbed into the soil matrix or collect at the crack base. The crack water will then infiltrate into the matrix or cause ponding, depending on the local infiltration condition. Under intense rain, it is possible that the cracks will fill with water even to the point of surface ponding.

Beven and Germann (1981) model water movement inside the macropore, distinguishing between saturated and unsaturated zones. Water movement in the unsaturated zone is represented by a kinematic wave equation, solved numerically. A water balance procedure is used at each time step to work out the change in water level within the macropore after the bottom of the macropore becomes saturated. This water balance includes rate of inflow from unsaturated soil above, rate of loss to the micropore system, and storage capacity of the macropores above the crack water level. This modelling approach was developed for stable macropores and does not allow for changing crack morphology over time.

The MACRO model (Jarvis, 1994) simulates water movement in both the macropore and micropore domains. Flow within the macropore is calculated assuming a unit hydraulic gradient. SWIMv2.1 (Verburg *et al.* 1996) calculates a maximum bypass flow from user specified inputs of conductance and depth to bypass node. Bypass inflow is calculated as the water applied in excess of maximum infiltration rate. The bypass flux is added to the source term at the depth specified for the bypass flow. The MICCS model (Ross and Bridge,1984) uses a tipping bucket approach. The crack is discretinised into segments and layers. Free surface water runs down the face of the crack wall, infiltrating as it goes. A maximum infiltration rate is set for each layer. If the surface water running into a layer exceeds the maximum infiltration rate within a time step, the additional surface water runs further down the crack wall into the next layer. CRACK (Jarvis *et al.*1990) calculates the flow rate as a function of crack dimensions (width and porosity), degree of saturation, and an empirical ‘tortuosity factor’ which reflects flow path and geometry. However, these parameters would be very difficult to quantify under field conditions. Hoogmoed and Bouma (1980) argue that water flow in cracks is mainly film flow along crack walls when runoff occurs from rainfall. Therefore, the width of cracks is unlikely to impact on water movement within cracks (Bronswijk, 1991). Bronswijk recognises crack width may become more of a problem under near saturated conditions or following large irrigation or precipitation events.

Jarvis *et al*. (1990) argue that providing that rewetting of the profile occurs virtually simultaneously at all depths, an explicit model of water movement within the macropores is not important. Using similar arguments, a number of models simplify water flow within soil cracks to a water balance. Crack inflow is instantaneously transmitted to the bottom of the crack or added to the crack pond. A water balance is maintained in the crack, I_c leads to increase in crack water level, and q_c leading to a decrease in crack level. Examples of this approach include the FLOCR (Bronswijk, 1988), SWAP (Van Dam, 2000), Hydrus-ET (Novak *et al*. 2000). These models account for crack swelling and shrinkage, water level within the crack, but not the movement of water within these cracks.

Another approach to account for macropore flow is to modify the hydraulic properties of the soil matrix in the wet end to account for the highly non linear behaviour of macropore flow. This can be achieved by the superposition of two soil moisture retention functions (Zurmuhl and Durner, 1996). The SWIM model (Ross and Bridge, 1990) adjusts its hydraulic conductivity function by adding a term that increases hydraulic conductivity near saturation. This approach produces an average hydraulic property for both the macro- and micropore domains. These approaches do not model water movement in the macropore domain, but account for macropore flow by increasing fluxes in the micropore domain. The result is that macropore flow will be greatest when the soil is near saturation. This does not accurately reflect water movement in soil cracks where greatest macropore flow (and the greatest fluxes) will occur when the soil matrix is dry and large shrinkage cracks are present. Therefore such an approach has distinct limitations in considering accessions to groundwater and solute movement.

Theory has been developed that allows water flow within macropores to be explicitly modelled. However, these models are typically difficult to parameterise and equally difficult to calibrate/validate. Much of the literature supports the assumption that simple water balance procedures will be sufficient to characterise the impact of soil cracks on the soil water balance. This is likely to be true in relatively flat environments where water movement in cracks is largely 1-dimensional in the vertical direction. Explicit modelling of water movement in cracks may be more important in hillslopes where lateral water movement in cracks may be more significant.

4) Flow in the matrix domain

The HYDRUS-ET and SWAP models apply the Darcy-Richards equation to model water movement in the matrix. This approach has been widely accepted for non-swelling soils (Smiles, 2000). However, the continuity of the matrix space cannot necessarily be assumed in soils containing macropores. This questions the validity of Darcy-Richards equation (Beven and German, 1982). Talsma (1972) identified three basic differences between water movement in the matrix of rigid and swelling soils:

1) water moves in swelling soils in response to a potential gradient, which includes the overburden potential,
2) Darcy's law applies to flow relative to the soil particles which, in general, are in motion,
3) hydrodynamic characterisation of the soil requires, in addition to K-H relationships, a knowledge of the dependence of the void ratio, e, on moisture content.

The overburden potential (Philip, 1971) represents the work done in displacing soil when a unit quantity of water is added at the point that it is defined. Talsma (1977) notes that a tensiometer measures combined overburden and matric potential in the field. Bronswijk (1991) reports on a study conducted by van Vessem (1989) which found that including the impact of overburden potential had no significant impact on the water balance. This argument is supported by findings of Talsma (1977) who found the overburden potential to be small in field soils.

$$\Phi = \psi + \Omega - \Sigma \qquad (6)$$

where: Φ = total potential
ψ = matric potential
Ω = overburden potential due to the normal stress applied.
Σ = gravitational component, position potential

In 1968, both Smiles and Rosenthal and Philip separately evolved a similar philosophical approach to the description of saturated and unsaturated flow in swelling soils. The flux is calculated relative to the particles in the soil matrix, rather than to a fixed coordinate system. This approach is summarised in detail by Smiles (1997). The moisture ratio (ϑ) (weight water divided by weight of soil) replaces the volumetric moisture content in the continuity equation. They include the impact of overburden potential on soil water movement.

$$\frac{dm}{d\Sigma} = (1+e)^{-1} \qquad (7)$$

where: m = material coordinate

e = void ratio.

In the combined approach of Philip and Smiles (1969), the co-ordinate system is used and the continuity equation is written:

$$\left[\frac{\partial \vartheta}{\partial t}\right]_m = \left[\frac{\partial v}{\partial m}\right]_t = \frac{\partial}{\partial m}\left[K_m(\vartheta)\frac{\partial \Phi}{\partial m}\right] \quad \textbf{(8)}$$

The $K(\theta)$ and $\psi(\theta)$ properties must be redescribed relative to the material coordinates and become $K_m(\vartheta)$ and $\psi_m(\vartheta)$: $e(\vartheta, \Omega)$ must also be defined where Ω is the applied overburden.

There is little experimental evidence to fully validate the theory (Smiles, 1984). The approach is defended as establishing a flow theory from first principles and would therefore provide a rigorous framework for further experimental and theoretical development. Richards and Smettem (1992) have recently generalised the approach to a three dimensional Darcy-Richard's equation and incorporated it into a model solved by finite elements over space, and by finite differences over time. However, they have reverted to rigid soil descriptions of conductivity and moisture content as a function of total potential.

The impact of the coordinate system used (physical or material) on water balance errors was assessed by Smiles (1997) by integrating the areas under the infiltration/filtration curve. The error of the physical coordinate system relative to the material coordinate is summarised in eq 9. For a saturated bentonite (θ_{si}≈0.05) the volume of water escaping was incorrect by a factor of 20. In an unsaturated natural soil system (θ_{si}≈0.56, α≈1/3) this error was found to be a factor of 1.2 (Smiles, 1997).

θ_{si} = Initial volume fraction of solid

$$\text{Error} = \frac{1}{\theta_{si}} \text{ (saturated)} \qquad \text{Error} \geq \frac{\alpha}{\theta_{si}} \text{(unsaturated)} \quad \textbf{(9)}$$

Such a systematic analysis has not been applied to transient models based on the Richard-Darcy equation. The water balance errors associated with cycles of wetting and drying in swelling soils found in agricultural systems has not been quantified.

Garnier *et al.* (1997) used a new coordinate transformation that describes 3-dimensionsal deformation as affected by soil water. They utilised the geometry factor proposed by Bronswijk (1990) to describe the nature of soil swelling. Sensitivity analysis showed that vertical displacement of soil surface, infiltrating water and cumulative outflow were sensitive to this parameter. Increasing r_s from 1(vertical swelling only) to 3 (3-dimensional isotropic swelling) resulted in a 35% increase in infiltration and a 25 % decrease in drainage from a core. Model testing was limited to a repacked soil consisting of a mix of loam and bentonite. They compared the impact of the coordinate system on the water balance and found that the impact of swelling on the coordinate system has a minimal impact on the water budget. They concluded that it was not necessary to take into account soil deformation providing hydraulic characteristics were expressed in terms of the moisture ratio (weight of water/weight of soil). The hydraulic characteristics could then be converted to functions of volumetric moisture using knowledge of the shrinkage characteristic.

Kirby *et al.* (2000) replaced the rigid space coordinate system with a material coordinate system to model the drying of rice soils. They comment that the use of the moisture ratios offers advantages in the data collection on soft, swelling soils where measurement of soil volume is often difficult. No assessment of the impact of the coordinate system change on water movement is made in the paper.

More pragmatic approaches have recently been developed which consider matrix water movement as flow in a rigid soil, and determine volume change from the shrinkage characteristic (e.g. FLOCR by Bronswijk, 1988 and 1991). Distances between nodal points are held constant at one time step, but adapted for swelling prior to the next time step.

5) Interaction between the macropore and matrix domains

Representation of horizontal movement of water from the crack to the soil matrix in the peds is the least well modelled component of the system. The rate of horizontal infiltration of water entering the matrix from the crack (q_c) is often calculated using Darcy's-Richards' law. The total infiltration flux is then calculated from q_c and the specific crack area. This approach has been applied to both saturated and unsaturated parts of the soil macropores (Beven and German, 1981) and they assume the hydraulic head in the crack to be zero in unsaturated parts of macropores. Van Dam (2000) uses the hydraulic potential and conductivity calculated within the soil matrix for the calculation of K(h). The distance ∂x is constant over the simulation, calculated from the diameter of polygons used to represent a soil ped.

SWIMv2.1 (Verburg *et al.* 1996) defines a bypass node where runoff is transmitted by a Darcy-Richard type equation. The bypass flow is added to the source term at the bypass node and an instantaneous redistribution is assumed but additional water storage at a node is allowed when bypass flux exceeds redistribution flux.

Novak *et al.* (2000) calculated q_c using a Green-Ampt approach. They also introduced a reduction factor to represent hydraulic resistance across the crack-matrix interface. Bronswijk (1988) does not explicitly model q_c, rather assumes that crack water was added to soil moisture at depths below the crack water level. Jarvis and Leeds-Harrison (1990) note that this model does not allow lateral infiltration or exchange through the crack faces, and does not model crack flow or fully ponded conditions. Jarvis *et al.* (1990) adopt the Phillips' infiltration equation to model q_c with sorptivity being a linear function of soil water deficit. However, in this approach water movement is not modelled in the matrix. The approach of Ross and Bridge (1984) can use any infiltration function to describe q_c but the matrix domain is not modelled and the impact of soil moisture on q_c is not described.

A special form of q_c can occur through evaporation from the surface of crack walls. Evaporation from cracks makes a significant contribution to the deficit in the water balance of cracking soil as the surface area of crack faces may be 2.9 to 4.6 times the exposed surface area of soil (Adams and Hanks, 1964). In field measurements, evaporation rates were determined to range from 35-91% of the comparable rate per unit area of surface soil, and evaporation from crack faces 50 mm below soil surface was noted to be extremely sensitive to wind velocity. Ritchie and Adams (1974) found that for bare soils, 0.6 mm/d of evaporation occurred from cracks out of a total evaporation of 0.74 mm/d. However, this is only a small component of potential reference ET. Bronswijk (1988) argues that for cropped soils at high moisture contents, transpiration dominates evaporation. HYDRUS-ET and SWAP also ignore evaporation from cracks in their water balance models.

None of the models describing horizontal infiltration in the unsaturated zone account for the impact of swelling on crack size. No model allows the relative crack surface area to change over an infiltration event, even though crack volume is a function of depth and moisture content. This assumption results in the crack surface area being independent of crack volume. This assumption could potentially result in more horizontal infiltration at depths where crack volume and crack surface areas are very small. The importance of the limitations on the water balance has not been assessed or properly understood.

Discussion

It is clear that water movement in cracks has a large impact on water movement in swelling/shrinking agricultural soils, thus impact on the soil water balance. The level of complexity at which water movement in macropores needs to be described is not known. Jarvis *et al.* (1990) argue that water movement in shrinking clay soils is dominated by infiltration through cracks and extraction by plants. We agree with Jarvis *et al.*, and consider that the impact of cracks on the infiltration and redistribution process and plant water use to be the dominant process affecting water movement in cracking soils. The major impact of cracking, and our present inability to adequately model soil water movement occurs at infiltration and redistribution immediately following infiltration in macro-porous soils. For a long time, it has been argued that empirical descriptions of infiltration are unsatisfactory, even unnecessary, but until we can describe the preferential flows in terms of acceptable soil physics, we are no closer to simulating reality with the so-called physically derived expressions of soil water movement.

The importance of correctly characterising crack geometry and volume on modelling water movement and the water balance is unknown. It is clear that it is important to be able to describe the depth of cracks in a soil profile as affected by soil moisture (i.e. growing and shrinking cracks as a function of soil water content). Current literature indicates that water movement within the crack is not so important, providing the inflow of water into the crack and "its" depth are well described. Therefore, research quantifying these two parameters is of importance. No existing models include the impact of soil swelling and crack closure on water transport in the crack. Models describing crack formation and closure do not model water movement inside the crack.

The main considerations governing the level of detail to which preferential flow needs to be modelled include:

- scale at which preferential flow is considered - both in terms of representative elementary volume (REV) and the larger domain occupied by those REVs; and
- the purpose of modelling.

Our principle interests lie in the management of irrigated and dryland agricultural soils, and in the control of water table rise and waterlogging, and management of salinity and agricultural chemicals. Distinction between lateral movement within cracks and a more static volume balance approach to the fate of crack water becomes important at the sub-field scale. In particular the consideration of water movement at the wetting front in surface irrigation and on sloping hillsides, where lateral preferential flow may have considerable influence on the movement of agricultural chemicals and applied nutrients. The occurrence of significant lateral flow in hillsides is largely limited to heavy rainfall events following prolonged dry periods that result in extensive and contiguous sub-soil cracking.

At greater than field scale - farm, sub-catchment and catchment, the spatial occurrence of preferential flow and deep percolation is of over-riding interest and more localised lateral movement of water becomes less important, except perhaps again on sloping hillsides.

The practical importance of cracking cannot be separated from other factors governing infiltration and redistribution of water - notably the presence or absence of high water table, restricting or transmissive sub-surface layers, and the rooting depth of vegetation. The mapping of surface and sub-surface soil properties and topography must therefore be considered in conjunction with other modelling requirements in specifying the degree to which it is relevant, and, worthwhile to fully describe the cracking process.

At larger than field scales, we require models that simulate the development and closure of cracks and calculate redistribution vertically (from the base of the crack) and horizontally through crack faces into the ped matrix. Redistribution within peds and the development of cracks can be adequately handled using Darcy-Richard's equation approaches for layered soils, coupled to swelling and shrinkage relationships, such as those developed by Bronswijk. Accurate model partitioning of redistribution of preferential flow is important in the consideration of solute transport, leaching and water table accession, particularly in helping to define recharge areas at sub-catchment and catchment scales. Management options will logically focus on recharge areas in the landscape.

Models that develop co-ordinate transformation and consider overburden potential offer theoretical improvements in our understanding of water movement in cracking/swelling soils. There is conflicting evidence in the literature of the need for co-ordinate transformation and overburden potential when modelling water movement in cracking soils in agricultural environments. The practical implications on the water budget have not been clearly defined under soil conditions encountered in agricultural areas. No model including co-ordinate transformation and overburden potential has been developed that also include the larger fluxes and fundamentally different processes of preferential flow. There are no theoretical constraints to the inclusion of such processes into a model. However, we consider after reviewing the available literature that there are limited benefits in inclusion of overburden potential and co-ordinate transforms for water balance in cracking soils. This argument is further supported by the uncertainty in measured input parameters, such as encountered by Kirby *et al*. (hydraulic properties etc.). Until the necessary input parameters can be more accurately measured it will be difficult to identify the practical implications on water movement in agricultural soils resulting from the use of material coordinates.

There has been very little research conducted into modelling water movement in cracking soils in Australia. There has been a reasonable amount of research into plant water extraction in rigid soils. How this applies to swelling soils has not been studied or tested. A number of infiltration studies have been conducted on swelling cracking soils, which have typically focussed on irrigation management and have not collected sufficient information to model the soil water balance. Soil shrinkage curves have been developed for a number of soils across Australia but the methods used to derive these curves varies, and insufficient data has been collected for modelling studies. Errors in data collection and technique make it difficult to test and validate complicated hydrological models. Accurate data describing soil hydraulic and shrinkage characteristics is rare. Techniques that allow such data to be transferred between irrigation regions need to be developed. Until such a time that both these data can be accurately measured, including the in-soil variability, the value in further model development is questionable.

There is a considerable difference in approaches to modelling water movement in crack soils, the level of complexity varying considerably. The detailed, complex physically based models usually have not been validated due to difficulties with measurement, and the heterogeneity of soil hydraulic properties and shrinkage characteristics. The development of 2-D or 3-D models can only be justified if the extensive data input required is sufficiently accurate (Bronswijk, 1991). Model verification is largely restricted to small lab cores, in which swelling and deformation can be expected to behave differently from field conditions.

The conceptual modelling approaches adopted in HYDRUS-ET, SWAP and FLOCR would appear to go along way towards describing this infiltration and redistribution process in cracking soils. Limited testing of the SWAP model against lysimeter data on cracking soils shows considerable promise.

Modelling studies are usually poorly documented, and insufficient data is often collected to fully test models. This means that experiments need to be repeated because data is not accessible, of a complete nature and of known accuracy, to be reused to test models. This testing is made more difficult by a lack of a systematic approach to classifying soils on the basis of their physical characteristics. A consistent nation-wide approach would allow more data sharing, and more efficient use of investment, in the past and in the future.

We need to consider a robust modelling framework to account for the spatial and quantitative impacts of preferential flow on soil and catchment water balances. There is also a need to accumulate sufficient data to allow these approaches to work in practice, so that we can have faith in the output of models in evolving management strategies. We can approach the data problem through aggregation of existing data, with adequate metadata and use of databases on a national scale. Inevitably we will also require well-coordinated field work to complete data sets, and this should concentrate on the most important soils, where significant components of the data set already exist.

References

Adams J.E. and Hanks R.J., 1964. Evaporation from Soil Shrinkage Cracks. Soil Science Society American Proceedings. 28: 281-284

Armstrong A.C. an Arrowsmith R., in Eds. Bouma J. and Raats P.A.C., 1984. Field evidence for a two-phase soil water regime in clay soils. **In** Proceedings ISSS symposium water and solute movement in heavy clay soil, IILRI Pub. 37:142-147.

Beven K. and Germann P.F., 1982. Macropores and water flow in soils Water Resources Research, 18(5): 1311-1325

Beven K. and Germann P. 1981. Water Flow in soil macropores 11. A combine flow model. J. Soil Science 32,15-29.

Berndt R.D. and Coughlan K.J. 1976. The nature of changes in bulk density with water content in cracking clay. Australia J. Soil Research. 15:27-37.

Bronswijk J.J.B 1988. Modelling of water balance, cracking and subsidence of clay soils. J. Hydrol. 97:199-212

Bronswijk J.J.B., 1989. Prediction of actual cracking and subsidence in clay soils. Soil Science 148(2):87-93.

Bronswijk J.J.B., 1990. Drying, Cracking, and Subsidence of a Clay Soil in a Lysimeter. Soil Science 152(2): 92-99

Bronswijk J.J.B., 1991. Relation between Vertical Soil Movements and Water-Content Changes in Cracking Clays. Soil Science Society. America. J. 55: 1220-1226

Bronswijk, J.J. 1991. Magnitude, modelling and significance of swelling and shrinkage processes in clay soils. Doctoral thesis. Wageningen Agricultural University, Wageningen, The Netherlands, (IX) +145 pp.

Coughlan K.J., in Eds. McGarity J.W., Hoult E.H. and So H.B., 1984. The structure of vertisols. Review Rural Science 5, University of New England, Armidale: 87-96

Fox W.E., 1964. A study of bulk density and water in a swelling soil. Soil Science 98:307-316.

Garnier P., Perrier E., Angulo Jaramillo R. and Baveye P. 1997. Numerical model of 3-dimensional anisotropic deformation and 1-dimensional water flow in swelling soils. Soil Science 162(6):410-419

Germann P.F and Beven K., 1981. Water Flow in Soil Macropores: I. An Experimental Approach. J. of Soil Science 32: 1-13

Germann P.F. and Beven K., 1981. Water flow in soil macropores II. A statistical approach. J. Soil Science 32: 31-39

Gerke,.H.H., and van Genuchten, M. Th. 1993. A dual porosity model for simulating the preferential movement of water and solutes in structured media. Water Resources Research, 29(2),305-319

Giraldez J.V., Sposito G. and Delgado C., 1983. A General soil volume change equation: I. The two parameter model. Soil Scientist America J. 47: 419-422

Haines W.B., 1923. The volume changes associated with variations of water content in soil. J. Agricultural Scientist 13: 296-310

Hoogmoed W.B, and Bouma J, 1980. A simulation model for predicting infiltration into cracked clay soil. Soil Scientist Society America J. 44:458-461

Jarvis N.J and Leeds-Harrison P.B., 1990. Field test of a water balance model of cracking clay soils. J.Hydrol. 112: 203-218

Jarvis, N.J. 1994. MACRO Version 3.1 – Technical description and sample simulations. Reports and Dissertations 19, Department Soil Sciences, Swedish University of Agricultural Sciences, Uppsala, Sweden, 51 pp.

Kirby J.M. and Ringrose-Voase A.J., 2000. Drying of some Philippine and Indonesian puddled rice soils following surface drainage: Numerical analysis using a swelling soil flow model. Soil & Tillage Research 57 13-30.

McIntyre D.S., in Eds. McGarity J.W., Hoult E.H. and So H.B., 1984. The physics of volume change in cracking clay soils and the one-dimensional misconception. Review Rural Scientist 5, University of New England, Armidale: 116-122

Novak V., Simunek J. and van Genuchten M.Th. 2000. Infiltration of water into soil with cracks. J of Irrigation and drainage engineering. 126, Vo1,:41-47

Olsson K.A. and Rose C.W. 1978. Hydraulic properties of a red-brown earth determined from in situ measurements. Aust J. Soil Res., 1978. 16:169-180.

O'Callaghan, J.F., and Loveday, J. 1973. Quantitative measurement of soil cracking patterns. Pattern Recognition 5, 83-98.

Philip J.R., 1971.Hydrology of swelling soils. **In** Salinity and Water Use' Eds. Talsma T. and Philip J.R., Macmillan, London.:95-107.

Philip J.R., 1968. Kinetics of sorption and volume change in clay colloid pastes. Aust J. Soil Research 6:249-267.

Philip J.R. and Smiles D.E. 1969. Kinetics of sorption and volume change in three-component systems. Aust. J. Soil Research 7:1-19

Prendergast 1995. Soil water bypass and solute transport under irrigated pasture. Soil Scientist Society America J. 59:1531-1539.

Raats P.A.C., in Eds. Bouma J. and Raats P.A.C., 1984. Mechanics of cracking soils. **In** Proceedings ISSS symposium. Water and solute movement in heavy clay soil, IILRI Pub 37:23-44.

Richards BG and Smettem KRJ (1992). Modelling water flow in two and three dimensional applications: I. General theory for non-swelling and swelling soils. Trans. Amer. Soc. Agric. Engrs. 35(5):1497-1504.

Ritchie, J.T. and Adams, J.E., 1974. Field measurement of evaporation from soil shrinkage cracks. Soil Scientist Society America, Proceedings., 38131-134.

Ross P.J. and Bridge B.J., in Eds. McGarity J.W., Hoult E.H. and So H.B., 1984. MICCS: A model of infiltration into cracking clay soils. Review Rural Scientist. 5, University of New England, Armidale 155-163.

Ross P.J., 1990. Efficient numerical methods for infiltration using Richards' equation. Water Resources Research 26(2):279-290.

Scott G.J.T, Webster R. and Nortcliff S., 1988. The Topology of Pore Structure in Cracking Clay Soil: I. The Estimation of Numerical Density J. of Soil Scientist 39: 303-314

Smiles D.E., in Eds. McGarity J.W., Hoult E.H. and So H.B., 1984. Water relations of cracking clay soils. Rev. Rural Scientist 5, University of New England,. Armidale 143-149.

Smiles D. E. 2000. Hydrology of swelling soils. Australia J. Soil Research., 38,501-21.

Smiles D. E. 1997. Water balance in swelling materials: some comments. Australia J. Soil Research.35:1143-1152.

Smiles D. E., and Rosenthal M.J. 1968. The movement of water in swelling materials Australia J. Soil Research. 6:237-248.

Stirk G.B., 1954. Some aspects of soil shrinkage and the effect of cracking upon water entry into the soil. Australia J. Agriculture Research. 5: 279-290

Swartz, G.L. 1996. Modification of the cracking pattern on a black earth of the Darling Downs, Queensland. Queensland J. Agriculture Animal Science 23,279-285.

Talsma T., 1977. A note on the shrinkage behaviour of a clay paste under various loads. Australia. J. Soil Research. 15: 275-277

Talsma, T. 1977. Measurement of the overburden component of total potential in swelling field soils. Australia. J. Soil Research. 15:95-102

Talsma T., In Eds. James B. J. F., 1972. Physical aspects of swelling soils. Physical aspects of swelling clay soils. University of New England, Armidale:33-37.

Tempany H.A., 1917. The shrinkage of soils. J. Agricultural Science. 8: 312-333

Thorburn P.J. and Rose, C.W. 1990. Interpretation of solute profile dynamics in irrigated soils, III. A simple model of bypass flows in soils. Irrigation Science. 11:219-225

Van Dam, J.C., 2000. Simulation of field-scale water flow and bromide transport in a cracked clay soil. Hydrol Proces., 14:1101-1117.

Van Genuchten M.Th., Schaap M.G., Mohanty B.P., Simunek J. and Lelf F.J. in Eds 2000. Modelling flow and transport processes at the local scale. Modelling of transport processes in soils at various scales in time and space. International Workshop of EurAgEng's Field of Interest on Soil and Water, Leuven, Belgium, 24-26 November 1999. 1999, 23-45

Van Vessem A.D. 1989. MSc Thesis. Agricultural University Wageningen.

Verburg, K., Ross, P.J., Bristow, K.L., 1996. SWIMv2.1 User Manual. Divisional Report No. 130. Division of soils, CSIRO.

Virgo , K.J. 1981Observations of cracking in Somali. Soil Science. 131:60-61

Yule D.F., in Eds. McGarity J.W., Hoult E.H. and So H.B., 1984. Volumetric calculations in cracking clay soils. Rev. Rural Science. 5, University of New England, Armidale: 136-140

Zurmuhl, Tl, and Durner, W 1996. Modelling transient water and solute transport in a biporous soil. Water Resources Research, 32:819-829

Attachment 6 – Overheads from talk summarising review paper *(Matthew Bethune)*

Attachment 7 – Record of session on necessary to improve model capabilities

Record of session on necessary to improve model capabilities

The technical and functional issues were grouped under three headings, relating to processes, consequences and practical application (Refer Table 1). These issues affect our ability to determine appropriate management practices to control accessions and groundwater pollution.

The workshop divided into three groups to scope recommendations in terms of –

- The issue/s this addresses
- Outputs
- Broad methodology
- Benefits to industry
- Potential collaborators / links
- Indicative resources / timeframe

Table 1. Key issues in modelling of water movement in cracking soils.

Conceptual understanding (processes)	Spatial distribution of drainage characteristics (consequences)	Experiences in using and choosing models (practical application)
Impact on water movement and water balance of crack geometry and connectivity. Is crack geometry equally important for summer/winter rainfall and irrigation systems? How does depth to watertable impact Infiltration from crack into matrix?	Quantify - parameters required to describe drainage flux and for use in models depth of drainage flux and time scale.	Development of recommendations on minimum data set requirements. Recommendations on when certain processes need to be considered for different soil types, irrigation, climate, management, etc.

7.1 Processes

Implications of soil cracking processes on deep drainage losses

7.1.1 Issues this address

- correct conceptual models cannot be made until key processes affecting deep drainage losses are clearly described and defined. The requirement for including these processes into models is unknown.
- models not capturing key processes cannot be used for predictive modelling and assessing the impact of management on model outputs.

7.1.2 Outputs

- Ability to construct correct conceptual models of water movement for cracking soils.
- Table clearly identifying key processes that require inclusion into a conceptual model of water in cracking soils – under which climatic, management soil types and when.
- Clear description of the key soil properties that require measurement to measure drainage in cracking soils.

7.1.3 Broad methodology

- Numerical analysis of impacts of processes.
- Identify key parameters requiring characterisation.
- Match soils to key parameters.

7.1.4 Benefits to industry

Appropriate modelling framework for modelling studies in cracking soils. This will lead to more targeted field experimentation and correct conceptualisation of modelling studies.

7.1.5 Potential collaborators

CSIRO, DNR, QLD, NRE-Vic, Universities

7.1.6 Indicative resources

Ideal PhD or Masters project. Alternatively 12 months time for someone with well developed modelling/programming skills and an understanding of industry implications.

7.2 Consequences

Scoping consequences of drainage – drainage characteristics of vertisols / cracking soils across Eastern Australia

7.2.1 Discussion

- Vertisols – broadened to "cracking soils".
- Under irrigation.
- Continuous monitoring.
- Response of shallow wells – significance / implications / use.

7.2.2 Issue

Drainage under cracking soils –

- Limited data (hasn't been adequately measured).
- Unresolved "differences".
- Water Use Efficiency / productivity.
- Drainage – rising water table and salinity; accessions to deep aquifer – off site effects.
- Need to advise on management options – pollution.

7.2.3 Output

- Ability to advise on management options.
- Policy for landuse distribution – local or regional?
- Scale – farm level / scale – potential interaction with / and implications for catchment.
  Scale (in order of magnitude) 1/ Process. 2/ Model issues. 3/ Drivers.
  Also issue of correlation.
- Defining magnitude of drainage.
- Confirming / developing methodologies.
- Consequences – (not focus of project) – local ground water situation.

7.2.4 Broad Methods

(Further develops on the specifics of proposal already drafted to L&WA in addition, southern component.

- Continuous piezometer monitoring.
- Irrigated agricultural system – on farm – classic cracking; minimal cracking. eg Myall Vale (potentially 6).
- Closing water-balance (more general). Equal level of sophistication (by choice) however more effort on deep drainage.
- Site location choice – reviewing existing / recent past activities, water table level, climate (rainfall), extent of cracking.
- One El Nino cycle – duration. Need to demonstrate desirability of this to industry (combination of "extremes"), and consequences of not.

7.2.5 What's New

1. Direct measurements.
2. Groundwater responses (locally) quantified.
3. Direct observation of crack storage volumes.
4. Tracer measurements – times of transit.
5. Links to components a.& c. – conceptual & experience in using/choosing modelling.

7.2.6 Potential Collaborators / Links

- Existing projects.
- Logical geographical links to organisations.
- Team –
- ➢ Groundwater modeller.
- ➢ Soil Physicist / Applied Hydrologist.
- ➢ Regionally based expertise – Agronomists, Hydrologists.
- ➢ Coordinating role for components and coordinating role for other elements.
- ➢ State Water Use Efficiency initiatives.
- ➢ Cotton CRC adoption mechanisms.

7.2.7 Indicative Resources / Timeframes

- Need to stress investment – outcome relationships – e.g. Wagga site (Chris Smith, Frank Dunin), options and trade-offs.
- Offer different degrees of resolution – 2 sites well at $250K per site per year; other (4) sites far less sophisticated.

7.3 Practical applications

Experience in using /choosing models

7.3.1 Background

- Data sets standards and skills.
- This is about capability building – for this to be successful it needs to have a long term view, i.e. get people exposed during their formative education.
- Don't oversell model capability – it will not make the decision.
- Two areas of need –

1. *aggregations* (both networking and some co-location) of model developers are very few – this is a high cost, long duration investment (support for exchange needs to have clarity of purpose).
2. *model users* – those who appreciate the value and applicability of models – critical to appreciate the interface between data that is available, the models and the management needs – using models to examine and develop options critical to building this capacity.
    - Need examples and advocacy from those who have used models to guide policy development or management responses. Building trust and relationships between management / policy needs, model users and model developers. This takes time. There is absolute need for multi-disciplining interaction.
    - Need strong interaction between managers, developers, and users at the outset to understand and articulate questions.
    - Common field sites – avoid the scattering of efforts.
    - Look for links into ACLEP and interstate.
    - Avoid the" frenzy of activity" mentality, i.e. spend more time to review ("learn from history"), identify what has been done and who has done it.

- Advisers need to exposure to models early – issues, outputs, method, benefits, collaborators, and resources.
- Science.
- Cooperation between research groups and model developers.
- Model users (advocacy of users, e.g. MIL) –
- ➢ Value and limitation of models.
- ➢ Fool to assist in decision making process.
- ➢ Applicability of models.
- ➢ Using models to examine and develop options.

7.3.2 Issues

- Build capability, develop critical mass / cooperation (clarity of purpose) / collaboration.
- Build interface between developers / users.
- Standards and guidelines for data set and links with what was done before.

7.3.3 Outputs

- Develop capable skilled people – Human Resource.
- Using models in a more informed way and getting more benefit.

7.3.4 Methods

- Workshops between science / users – communication (user let modellers know what the questions are). Feedback on process.
- Common field sites – different groups using the sites.
- Use of networks / web – information available.
- Having guidelines / recipes available to people multi-disciplinary teams – relationship with industry.

7.3.5 Benefits

- Better informed.
- Skilled.
- Confidence in using models.

7.3.6 Collaborators

- Economists

7.3.7 Resources

Timeframe – 10 years

Assessment of scheduling options to reduce recharge under border-check irrigated pasture

Attachment 8

Objective

Appraise the potential for improved irrigation scheduling to reduce recharge under border-check irrigated pasture.

Methods

The SWAP model (van Dam *et al.* 1997; Kroes *et al.* 1998) was used to assess the potential for different irrigation scheduling options to reduce recharge under border-check irrigated pasture. The SWAP model was tested against lysimeter data and shown to capture the key processes affecting the water balance of a border-check irrigated pasture (Attachment 4). The model also performed acceptably under field conditions when compared to hydrologic data collected from district farms (attachment 6).

Irrigation scheduling options investigated

Four different options for scheduling border-check irrigation were appraised over a 15-year period (Table 1). The period between 1986-2000 was chosen as it includes relatively wet and dry periods and thus allows the effectiveness of the scheduling options to be compared under a range of climatic conditions.

Table 1. Comparison of irrigation scheduling options

Option	Description	Irrigation season		Irrigation trigger
		Start date	End date	
I_{50}	Irrigating on an E-R of 50 mm	15/8	15/5	∑E-R >50 mm
I_{day}	fixed interval	15/8	15/5	Time based (Table 4)
I_{early}	early end to irrigation season	15/8	15/4	∑E-R >50 mm
I_{late}	late start to irrigation season	15/9	15/5	∑E-R >50 mm

I_{day} represents typical irrigation scheduling practices used by farmers. Irrigation is scheduling on a time basis, usually every 7 days in the peak of summer. The number of days between irrigation events was increased at the start and end of the irrigation season to reflect common irrigation intervals adopted by farmers (Table 2). The irrigation season runs between the August 15th and May 15th. I_{50} is the current recommended best practice for scheduling border irrigation. Irrigation is scheduled under I_{50} when cumulated pan evaporation minus rainfall (∑E-R) since the last irrigation exceeds 50 mm. The irrigation season closes early (15th April) in the I_{early} irrigation scheduling option, while the I_{late} option has a late start (15th September) to the irrigation season. The trigger for irrigation in I_{early} and I_{late} is the same as for I_{50}.

Table 2. Scheduled number of days between irrigation events over the irrigation season.

Month	Oct	Nov	Dec	Jan	Feb	Mar	April	May
Days between irrigation	11	9	7	7	7	9	12	12

Model input

The impact of the scheduling options on recharge was compared for two soil types. These soils are typical of the heavier floodplain soils and lighter levee soils where border irrigated pasture are concentrated in southeastern Australia. The hydraulic properties of the floodplain soil (Lemnos loam or Ll) and levee soil (Shepparton fine sandy loam or Sfsl) are listed in table 3 and 4. A 2.5 m deep soil profile was specified, consisting of 2 soil layers. Nodal spacings of 1 cm were adopted near the soil surface. This spacing is based on the work of van Dam and Feddes (van Dam and Feddes 2000), who consider layer thickness of 1 cm to be appropriate for simulating both evaporation and infiltration. Nodal spacing increased with depth to a maximum of 10 cm.

Table 3. Summary of soil hydraulic data for Lemnos Loam (Greenwood-unpublished data)

Soil layer	α (cm^{-1})	n (-)	θ_{sat} ($cm^3\ cm^{-3}$)	θ_{res}($cm^3\ cm^{-3}$)	K_{sat} (cm/d)	λ (-)
0-0.3 m	0.04	1.17	0.41	0.0	0.2	-5
0.4-2.5m	0.02	1.05	0.4	0.0	0.01	-5

Table 4. Summary of soil hydraulic data for Shepparton Fine Sandy Loam (Olsson and Rose 1978)

Soil layer	α (cm^{-1})	n (-)	θ_{sat} ($cm^3\ cm^{-3}$)	θ_{res}($cm^3\ cm^{-3}$)	K_{sat} (cm/d)	λ (-)
0-0.4 m	0.27	1.09	0.42	0	10.8	0.5
0.4-2.5m	0.13	1.05	0.4	0	3	0.5

Potential pasture water use (ET_{pot}) was defined by reference crop evapotranspiration (ET_o) and a crop factor (K_c) (eq 1). ET_o was calculated using the Penman Monteith equation (Allen *et al.* 1998) from daily climatic data measured at Tatura. An annual K_c (K_c=1) for pasture was found to be acceptable for studies of recharge under border check irrigation (Attachment 5). The model accounts for the impact of soil water stress on actual pasture evapotranspiration (ET) through a reduction coefficient on root water uptake. ET occurs at ET_{pot} until a critical soil water suction is exceeded. ET then reduces linearly with increasing soil water suction. Default parameters values defining this relationship were adopted for this study.

Full ground cover was assumed in all simulations. Historical records of daily rainfall data measured at Tatura were input to the model.

$$ET_{pot} = K_c ET_o \qquad \text{eq 1}$$

Over 95 % of pasture roots are found within 0.3 m of the surface on the heavy soils subject to border-check irrigation in the MDB (Mehanni and Repsys 1986; Prendergast 1995). A triangular shaped root density distribution was adopted for the modelling, with maximum root concentration at the soil surface, and zero roots at 0.3 m depth. No data is available describing root distribution under Sfsl. The root distribution measured under Ll was assumed for the Sfsl soil.

Watertable levels under a Sfsl and Ll soil were recorded on a monthly basis since 1982 at the Tongala area in northern Victoria, which is an intensively irrigated dairying area near Tatura. These watertable levels were used to define a fixed pressure lower boundary condition, which was applied to the bottom layer in the soil profile. The fixed pressure boundary condition was updated monthly over the simulation period.

A fixed depth of water was applied during each irrigation event. This water was ponded on the soil surface for 6 hours during irrigation and then allowed to runoff. This means that there was a 6-hr opportunity time for infiltration during an irrigation event. One critical factor affecting runoff is the residual depth of water (surface storage) remaining on the field surface after the cessation of runoff. A surface storage of 0.5 cm was used in this modelling study. This figure was based on a field study where surface storage of 0.5 cm was measured on a border-check field of slope 1:750 (Elliot 1984).

Results

Average annual water balance figures for the simulations are summarised in Table 5. These water balance figures represent an average annual figure from the total 15-year simulation period. Recharge under the light levee soil (Sfsl) was considerably higher than under the floodplain soil (Ll). There was also considerable seasonal variation in recharge, with recharge varying between 0 –1 ML/ha/yr on Ll (Fig 1a) and between 0.5 and 2.5 ML/ha/yr on the Sfsl (Fig 1b). This seasonal variation in recharge was associated with, amongst other with things, winter rainfall (Fig 1).

None of the scheduling options resulted in reduced ET relative to I_{days} (Table 5). This means that none of the scheduling options should have detrimental impacts on pasture growth (assuming a linear relationship between ET and pasture growth). I_{days} had the highest recharge for both the Ll and Sfsl. Adoption of any of the other scheduling techniques resulted in approximately a 30 % reduction in recharge. I_{late} was the most effective scheduling option in reducing recharge on the Sfsl. The late start to the irrigation season allowing surplus winter rainfall stored in the soil profile to be utilised by the pasture. However, recharge under Sfsl was still high under this scheduling option. This indicates that alternative management options to improved irrigation scheduling may be required to reduce recharge on this soil type.

Figure 1. Time trend in recharge for the different management options and soils types.

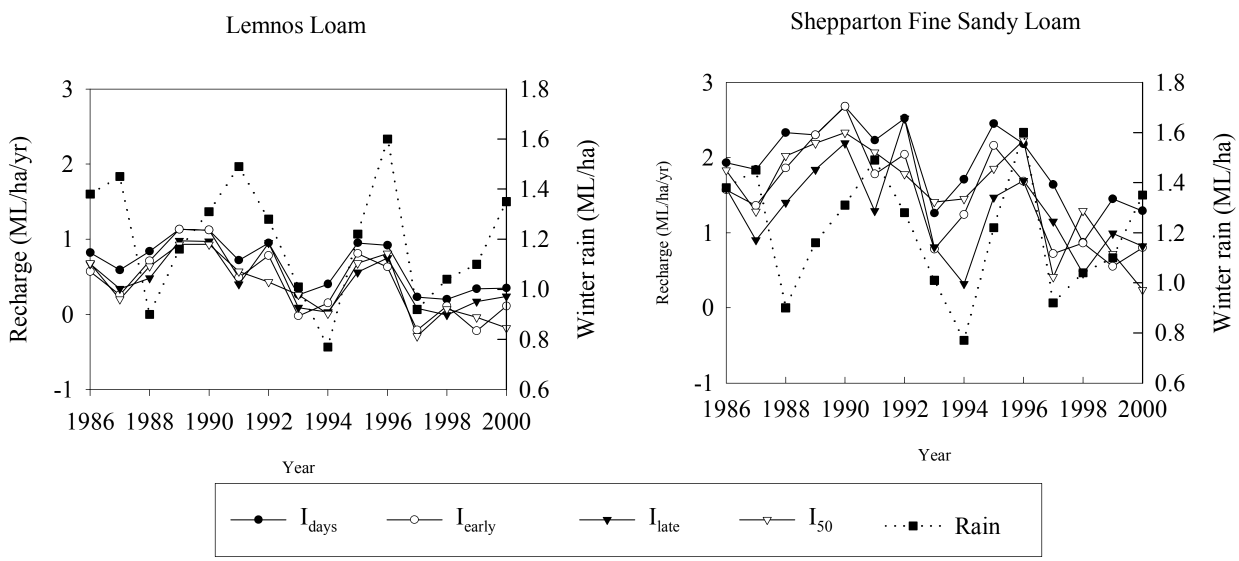


Table 5. Impact of irrigation schedule on the water balance for two soils. The values represent the average of the water balance component over the 15-yr simulation period. The range in recharge is given in brackets following the average.

	Lemnos Loam				Shepparton Fine Sandy Loam			
ML/ha/yr	I	Ru	ET	R	I	Ru	ET	R
I_{days}	9.7	2.0	10.5	0.65 (0.2 - 1.1)	9.6	0.4	10.5	1.91 (0.9 - 2.7)
I_{early}	9.1	1.6	10.5	0.43 (-0.2 - 1.1)	9.1	0.4	10.5	1.49 (0.5 - 2.7)
I_{late}	8.9	1.6	10.5	0.44 (0 - 1)	8.9	0.4	10.5	1.30 (0.3 - 2.5)
I_{50}	9.4	2.2	10.4	0.38 (-0.3 - 0.9)	9.3	0.8	10.4	1.54 (0.2 - 2.3)

Notes I = volume of irrigation, Ru= volume of runoff, R = volume of recharge

Summary

- Scheduling irrigation on the basis of ∑E-R resulted in relatively little recharge (0.4 ML/ha/yr) under the floodplain soil (Ll). The scheduling option typically employed by farmers had a higher level of recharge. Recharge was reduced by 30 % on average when irrigation was scheduled using climatic data. Water savings realised by reducing recharge through improved scheduling were small on the floodplain soil. This highlights that saving water will not be an effective mechanism for encouraging farmers to adopt improved irrigation scheduling techniques on heavy floodplain soils. The environmental benefit of reducing recharge needs to be quantified. These environmental benefits would form the basis for developing education and incentive schemes to encourage farmers to adopt improved scheduling options to reduce recharge.

- Recharge on the levee soil (Sfsl) was considerably higher (1.5 - 2 ML/ha/yr) than on the floodplain soil. Scheduling irrigation on a fixed time interval led to the highest annual recharge. As for the floodplain soil, the irrigation scheduling options based on climatic data reduced recharge by on average 30 %. This reduction in recharge corresponds to saving approximately 5 % of total irrigation water applied. Again, this water saving is unlikely to be sufficient to encourage farmers to implement more time consuming options for scheduling irrigation. As for the Ll, the environmental benefits in reducing recharge need to be quantified.

- The variation in recharge caused by the different scheduling options was less than introduced by climatic variation for both the levee and floodplain soil.

- Recharge under the levee soil was excessive under all of the scheduling techniques investigated. Reducing recharge under these soils may not be obtainable using border-check irrigation. Substantial reductions in recharge may require the use of pressurised irrigation systems on such soils.

References

Allen RG, Smith M, Perrier A, Pereira LS (1998) 'Crop evapotranspiration, Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56.' (United Nations: FAO Rome)

Elliot, P. J. Effect of bay slope on perennial pasture production. Notes from Kerang agriculture farm field day. 1984. Kerang, Department of Agriculture.
Ref Type: Unpublished Work

Kroes JG, van Dam JC, Huygen J, Vervoort RW (1998) 'Users's Guide of SWAP version 2.0; Simulation of water flow, solute transport and plant growth in the Soil-Water-Atmosphere-Plant environment.' (DLO-Staring Centre and Wageningen Agricultural University., Wagengingen, The Netherlands)

Mehanni AH, Repsys AP (1986) Perennial pasture production after irrigation with saline groundwater in the Goulburn Valley, Victoria. *Australian Journal of Experimental Agriculture* **26,** 1087-1093.

Olsson KA, Rose CW (1978) Hydraulic properties of a red-brown earth determined from in-situ measurement. *Australian Journal of Soil Research* **16,** 169-180.

Prendergast JB (1995) Soil water bypass and solute transport under irrigated pasture. *Soil Science Society of America Journal* **59,** 1531-1539.

van Dam JC, Feddes RA (2000) Numerical simulation of infiltration, evaporation and shallow groundwater levels with the Richards equation. *Journal of Hydrology* **233,** 72-85.

van Dam JC, Huygen J, Wesseling JC, Feddes RA, Kabat P, van Walsum PEV, Groenendijk P, van Diepen CA (1997) 'SWAP version 2.0, Theory. Simulation of water flow, solute transport and plant growth in the Soil-Water-Atmosphere-Plant environment. Technical Document 45, DLO Winand Staring Centre, Report 71.' (Department Water Resources, Agriculture University, Wageningen, Netherlands)

Improving Water Use Efficiency by Reducing Groundwater Recharge under Irrigated Pastures

Communication Activities

Attachment 9

Presentations by project team to L&WMP and farmer groups

Feb 2002, Deniliquin, Meeting, Presented project results and recommendations to the Land & Water Management Plans R&D Committee for their comment and consideration of future directions.

Tatura, Reference Group, Final reference group meeting for the project.

Oct 2001, Deniliquin/ Blighty, Barkool Discussion Group, Presentation on the project results

Aug 2001, Deniliquin, Seminar, Presentation on the project results to the Murray L&WMP Research Update meeting for farmers, researchers and managers.

July 2001, Chesworth Dairy, Finley. Lunch, Landcare Award judges.

May 2001, Melbourne, Workshop, Modelling Water Flow in Cracking Soils.

Echuca, Reference Group , Water Use Efficiency Project Reference Group Update on project to group.

April 2001, Blighty, DFA Meeting, Blighty branch meeting, update on project

Feb 2001, Wakool, Present data and results, Presented data and results from the project to the Wakool Land & Water Management Plan Working Group.

Jan 2001, MIL, Finley, Meeting, Murray Dairy Riverina Regional Group meeting to discuss regional issues and priorities, presented update.

Oct 2000, Barkool Discussion Group, Barham

July 2000, Presented a summary of the project to the Research and Development Update meeting at Deniliquin

June 2000, Barham/Wakool Discussion Group inspected trial site at Finley

Water Use Efficiency Team – Update on project progress

May 2000 - 20 South Australian dairy farmers and policy advisers on a tour of 3 local dairy farms inspected site and update on progress.

March 2000 - Milking Your Megalitres seminar at Blighty, presentation on results and trends

Feb 2000 - Met with the farmer co-operators and prominent local farmers to discuss results from the project to date.

Jan 2000 - Meeting on the development of management guidelines for undulating sandy soils in the region.

Dec 1999 – Reference Group meeting

Sept 1999 – 3 Water Use efficiency farmer seminars

August 1999 – Dairy Farmers Association meeting, results update

June 1999 - Best Management Practices for Water use on Irrigated Dairy Farms. Project reference group

Murray Dairy Industry Steering Group meeting - highlight was a presentation and inspection of research projects and facilities in the Improved Irrigation Practices Project at Tatura.

Mar 1999 - Wakool Discussion Group, water use efficiency - 20 farmers attended.

Journal papers currently in preparation, arising from DAN11 project work

Kingston (in prep) Relationship between dry matter and leaf area index for perennial ryegrass, white clover and paspalum

Bethune M (in prep). Quantification of the water balance of border check irrigated perennial pasture.

Bethune M (in prep) A review of groundwater recharge studies below flood irrigated pasture

Bethune M (in prep) Factors affecting recharge under border check irrigation of pasture

Bethune M (in prep) Simulating the water balance of flood irrigated pasture on a cracking soil

Bethune M (in prep) Testing a model of water movement in cracking soils against field data

Bethune M (in prep) Assessment of management options to reduce recharge under border irrigated pasture

Bethune M, Heuperman, A, Callinan, L. (in prep) Relationship between recharge, watertable levels and prior stream activity in Northern Victoria, Australia.

Bethune M, Kirby M, Turral H, Vervoort W (in prep) Measurement and simulation of water movement in cracking clay soils in Australia- A review

DAN11 was linked to the Improved Irrigation Practices (IIP) for Forage Production project. IIP integrates social, economic and research issues relevant to the dairy industry. Results from DAN11 were incorporated into communication activities of the IIP project and have been widely disseminated to a broad audience through this forum.

Communication Activities in IIP project 1998 – 31 December 2001

Publications / Conference Papers

'An approach to better border irrigation management', Irrigation Association of Australia's Water is Gold Conference, Brisbane, May 1998.

Armstrong, D., J. Knee, Doyle P., Pritchard, K., and Gyles, O. (2000). Water Use Efficiency on Irrigated Dairy Farms in Northern Victoria and Southern New South Wales. Australian Journal of Experimental Agriculture 40: 643-653pp.

Armstrong, D., Doyle P., Knee, J., Gyles, O., Johnson, F., Linehan, C., and Bowman, K., (2000). Efficient Water Use for Irrigated Dairying. Irrigation Australia 2000 Conference. 207-216pp.

Bethune, M., Q.J. Wang, (2000). Evapotranspiration from an irrigated rice crop in Northern Victoria. Irrigation Australia 2000 Conference. 301-305pp.

Bewsell, D., Bowman, K., Deren, B., Johnson, F., Kaine, G., Linehan, C. (2000). How Can Market Research Be Used in the Design of Extension Material? Australasia-Pacific Extension Network Conference.

Bush, B., Finger, L., and Bethune, M., (2000). Irrigation Scheduling Techniques for Border Irrigated Perennial Pastures. Irrigation Australia 2000 Conference. 423-429pp.

Doyle, P., Armstrong, D., Knee, J., Pritchard, K., and Gyles, O. (2000). Feeding Systems and Water Use Efficiency in Irrigated Dairying in Northern Victoria and Southern New South Wales. Australian Society of Animal Production Conference.

Robertson, D., Bethune, M., and Q.J. Wang (2000). Impact of Changing Weather Station Characteristics on Estimates of Crop Water Requirements. Irrigation Australia 2000 Conference. 319-326pp.

Wood, M. and Martin, M., (2000). Evaluating Alternative Irrigation Technologies for Forage Production. Irrigation Australia 2000 Conference. 412-422pp.

Wood, M. and Martin, M., (2000). Alternative Irrigation Technologies. Challenge, Change, Commitment. Target 10 Conference, 2000.

Armstrong, D., (2001). 'Water Use Efficiency and Profitability on Irrigated Dairy Farms in Northern Victoria and Southern New South Wales'. Masters thesis by Dan Armstrong, submitted to Melbourne University for examination.

Armstrong, D. A farm management economics approach to extension – water use

efficiency on irrigated dairy farms in northern Victoria and southern New South Wales2001 Australasian Pacific Extension Network Conference (October 2001).

Bowman, K. (2001). Best Management Practices for Water Use on Irrigated Dairy Farms – Adoption Packages (incorporating "Development of Adoption Packages Using Program Logic" and "Evaluation Strategy for Adoption Packages").

Johnson, F., Linehan, C. A Different Approach to Achieving the Adoption of Water Use Efficiency Improvements in the Dairy Industry. Paper submitted for the 2001 Australasian Pacific Extension Network Conference (October 2001).

Johnson, F., (2001). Adoption of Water Use Efficiency Improvements in the Dairy Industry. Proceedings from Murray Darling Basin Forum, 2001

Johnson, F., (2001). Improving Water Use Efficiency in the Dairy Industry. Murray Darling Basin Forum, 2001.

Keeble, B., Armstrong, D,. Johnson, F. Maintaining a Successful Dairy Industry with Better Water Use Efficiency. ANCID Conference, 2001

Keeble, B., Armstrong, D., Johnson, F., (2001). Irrigated Dairying in Northern Victoria – Maintaining a Successful Industry and Better Water Use Efficiency. ANCID Conference, 2001.

Bethune, M., Kirby, M. (2001). Modelling Water Movement in Cracking Soils, Workshop Proceedings, Melbourne, 2001.

Bethune, M. (2001). Recharge Under Flood Irrigated Pasture. In Proceedings of the Murray Darling Basin Groundwater Workshop, 2001.

Reports

Armstrong, D. (2000) Development of a Decision Support Framework for Improving Water Use Efficiency and Profitability – Case Studies on Two Irrigated Dairy Farms in Northern Victoria.

Finger, L., Bethune, M., and Bush, B., (2000). Irrigation Scheduling Techniques for Border Irrigated Perennial Pastures: Final Report, Module 3 of the Improved Irrigation Practices for Forage Production Project.

Nexhip, K. and Bethune, M., (2000). Hardware for Irrigation Audit: Final Report, Module 4 of the Improved Irrigation Practices for Forage Production Project.

Robertson, D., McDonald, P., Austin, N., Bethune, M., and Wood, M., (2000).

Development of a Decision Support Timer for Flood Irrigation Management, Final Report, Module 7 of the Improved Irrigation Practices for Forage Production Project (Technical Components).

Wood, M., (2000). Site Establishment Report for Module 6: Sprinkler, Subsurface Drip and Surge Irrigation Experiment.

Wood, M. and Martin, M. (2000). Alternative Irrigation Technology Desktop Analysis: Final Report for Module 2 of the Improved Irrigation Practices for Forage Production.
Nexhip, K. (2000). On-Farm Irrigation Audits: Progress Report for Module 8 of the Improved Irrigation Practices for Forage Production.

Deren, B. and Johnson, F., (2000). Report on Development of a Decision Support Timer to Improve Flood Irrigation Management of Module 7.

Johnson, F., Keeble, B., Kaine, G., Bewsell, D., Brown, S., (2001). Development of a Decision Support Timer for Flood Irrigation Management: Improved Irrigation Practices for Forage Prduction: Module 7. Final Report.

Robertson, D., Wood, M., (2000). Desktop Study on Sprinkler versus Surface Irrigation on the Lower Murray (Dairy) Swamps, South Australia. Final Report.

Improved Irrigation Practices for Forage Production: Milestone Report No. 1, 2, and 3 (1999, 2000 and 2001).

Wood, M., (2000). Site Establishment Report for Module 6: Sprinkler, Subsurface Drip and Surge Irrigation Experiment.

Bowman, K., (2001). Evaluation Report on the Improved Irrigation Practices for Forage Production Alternative Irrigation Field Day, DNRE (April 2001).

Improved Irrigation Practices for Forage Production: Final Report (2001)

Finger, L., Wood, M., (2001). Improved Irrigation Practices for Forage Production: Module 6: Sprinkler, Subsurface Drip and Surge Irrigation Experiment, Milestone Report Number 2.

Whitfield, D., Nexhip, K. (2001). Improved Irrigation Practices for Forage Production: Module 8: On-Farm Irrigation Audit. Final Report.

Wood, M. (2001). Improved Irrigation Practices for Forage Production: Module 1: Flood Irrigation Research Review. Final Report.

Electronic Media

BC radio news item (Shepparton), June 1999
WIN TV news item (audience 30,000), July 1999
ABC Regional Radio news item (audience 35,000), July 1999
ABC radio item on 'Country Roundup', September 1999
ABC radio (Bega) item, September 1999
ABC radio (Sale) item, September 1999
Classic Rock (Echuca) radio item, September 1999

WIN TV new item (Shepparton and Bendigo), December 1999
Local community broadcast on ABC radio, March 2000
Interview on 'Country Roundup', broadcast to 12 regional radio stations across Victoria and 2 in New South Wales, March 2000
ABC radio interview, November 2000
3WM radio interview, November 2000
3SR radio interview, November 2000
98.5 1FM radio interview, January 2001
3SR radio interview, January 2001
ABC radio interview, March 2001
Interview on ABC radio regarding Modules 2, 6 and 8, March 2001
ABC radio interview (Mildura), April 2001
3SR radio interview, September 2001
3SR 'Country Roundup' radio interview, October 2001

Articles/Newsletters

Article for Irrigation Committee of the Goulburn-Broken and Northern-Central Catchment Management Authorities visit, April 1998

Article for Stock and Land, November 1998

"More milk from less water PIE", Newsletter of Australia's International and National Primary Industries Research and Development Organisations, Vol 16, April 1999

"Improving efficiency of water use", DRDC Research Note 69, May 1999

"Stress on proven practice", Weekly Times (Circulation 77,700), June 1999

"Water use: just for the record", Stock & Land, July 1999

"Dairy Centre opens doors", Country News (Circulation 45,000), July 1999

"The Green Machine", Shepparton Advisor, (Circulation 23,600), July 1999

"Probing for Efficiency" (Green Machine article), Weekly Times, August 1999

"Trial looks at saving water", The Milky Whey, Campaspe News, August 1999

"Efficiency urged", Country News, August 1999

Article in The Standard, Warrnambool, August 1999

"How to get more milk from irrigation water", Dairy R&D News (DRDC), September 1999

"Water the key", North West Farmer, September 1999

"How to get more milk from irrigation water", The Australian Dairyfarmer, September

1999
“Improving water use efficiency”, North East Farmer, October 1999

Target 10 Newsletter, October 1999

Target 10 Newsletter, November 1999

“Dairy farmers go with the grain”, Weekly Times, December 1999

Article in Country News, December 1999

Target 10 Newsletter, December 1999

Article in CMSA Annual Report, December 1999

Kondinin group article, January 2000

Target 10 newsletter, January 2000

Kyabram Free Press – Research Report, February 2000

Article in Country News, February 2000

Target 10 newsletter, March 2000

Target 10 newsletter, April 2000

“Dairy 2010”, The Weekly Times, April 2000

“Alternative Irrigation Systems, North East Goulburn Murray Farmer, April 2000

“Seminar to Explore Irrigation Options”, Campaspe News, April 2000

“Seminar to Explore Irrigation System Options”, Bendigo Advertiser, April 2000

Article in Country News, October 2000

Target 10 Communicator, October 2000

Country News, November 2000

Article in the Devondaler, December 2000

“Flood versus Spray – Irrigation’s great challenge”, Devondaler, January 2001

WET Rag newsletter (WUE newsletter) distributed to 250 service providers, February 2001

"Mags a Good Rag", Country News, February 2001

"Farmers gain valuable management information by calculating WUE", Target 10 Newsletter, March 2001

Reviewed media release on alternative irrigation technology work, March 2001

The Weekly Times, "Study to tap savings….", March 2001

Shepparton Advertiser, "Less water, less cost the future of irrigation", March 2001

Nestles Dairy News, "Is it too late in the irrigation season to be thinking about improvements to the way I use irrigation water – right?", March 2001

Landcare newsletter for Shepparton Irrigation Region, "Is it too late in the irrigation season to be thinking about improvements to the way I use irrigation water – right?", March 2001

Target 10 newsletter, March 2001

Article in

News@NRE, March 2001
Channels (NRE staff newsletter) article on 11 April 2001 IIP Field Day, May 2001

The Australian Dairy Farmer, "Spray Irrigation to Expand Production", May 2001

Campaspe News, "Day at Tat" (Alternative Irrigation Field Day), May 2001

Country News, "Irrigation Day Pools Expertise" (Alternative Irrigation Field Day), May 2001

Article in IBIS Flyer, June 2001

Australian Landcare, "Water review suggests carrot and sticks recipe.", June 2001

The Weekly Times, "No Longer High and Dry", July 2001

Stock and Land, "Irrigation Helps Boost Production", September 2001

Country News, "Its All in the Sums – Calculating Efficiency", September 2001

Country News, "Milk Produce Doubled", September 2001

Dairy R & D News (DRDC), "More Milk with Less Water", October 2001

Kyabram Free Press, "Research Report", October 2001

Riverine Herald Article, November 2001

The Country News Dairy & Livestock Farmer Magazine, "Be a Water-Wise Irrigator", November 2001

Seminars / Field Days / Training Activities / T10 Courses / Discussion Groups

Talk to Echuca dairy trainee TAFE students, April 1998

Talk to Turkish delegates, April 1998

Lectures at Melbourne University on Water Quality, May 1998

Talk to Tatura Rotary, May 1998

Talk to Agriculture Victoria, Maffra extension staff, June 1998

Talk to Irrigation Western Australia delegates and dairy farmers, July 1998

Talk to RMIT students, August 1998

Talk to Agriculture Victoria, Ellinbank research staff, August 1998

Presentation at Murray-Darling Basin Commission/s NRMS SI&E Irrigation Forum, Tatura 8-10 September 1998

LaTrobe University 4th year Agriculture Science student, April 1999

5 Seminars – Sponsored by 'Keep Australia Beautiful' and Kraft (audience 400), April 1999

Murray Dairy Board presentation and field site visit on IIP Project (audience 25) June 1999

Seminar for visiting NZ students, 10, (covered entire Project), July 1999

Goulburn Valley Stockfeeds Customer Day, July 1999

Kyabram Dairy Centre Open Day (audience 200), July 1999

Goulburn-Murray Water Irrigation Expo, August 1999

Jersey Target 10 Discussion Group (6 farmers), August 1999

Presentation to DNRE Chief Scientists, August 1999

Murray Dairy Kerang Field Day (audience 200), August 1999

Finley Discussion Group (15 farmers), September 1999

Blighty Discussion Group (6 farmers), September 1999

Wakool Discussion group (7 farmers), September 1999

Presentation to Farmers from Pyramid Hill and 2 DNRE staff from Bendigo, September 1999

Tour and on site presentation to 4 visitors from China looking to import cattle from Australia, and their hosts, October 1999

Wyuna Landcare Group (audience 25), October 1999

CMA - Farm Group, November 1999

Lower Murray Irrigation Action Group Board Meeting, November 1999

Visit by Mike Shanon, US State Salinity Laboratory, November 1999

Farm Working Group of the Shepparton Land and Water Management Plan (audience 20), November 1999

Field site visit by students from the University of Ballarat (audience 15), November 1999

Golden Cow – Low Allocation Information Day (20 farmers), December 1999

Ardmona Target 10 discussion group (11 farmers), December 1999

Tatura Target 10 discussion group (10 farmers), December 1999

Kyabram Target 10 discussion group (30 farmers), December 1999

Nanneella-Timmering Target 10 discussion group (12 farmers), December 1999

Presentation to Irrigation Surveyors and Designers Group (audience 25), December 1999

Shepparton Irrigation Region Landcare Network Annual General Meeting, December 1999

Shepparton Irrigation Region Implementation Committee, December 1999

Tatura Target 10 discussion group (10 farmers), January 2000

Visit by Goulburn Valley TAFE Dairy Trainees, January 2000

Chinese Delegates study tour "Watershed Management for Technicians" (13 delegates), Participation in forum to develop Irrigation guidelines for new property developments, January 2000

Presentation to Steering Committee meeting (20 people), February 2000

La Trobe University 4th year Agriculture Science students, February 2000

Large Herds Conference (Workshop), February 2000

Gipps Dairy Innovation Day- Monash University, Churchill (300 farmers), February 2000

Presentation on recharge processes to PISC, Shepparton Land and Water Management Plan (15 people), February 2000

Chinese Delegates visit, February 2000

Presentation to Farm Program Working Group (15 people), February 2000

Agriculture & Horticultural Science secondary school students from Kyabram, March 2000

Katunga Target 10 discussion groups (20 people), March 2000

NSW Agriculture Spray and Drip Irrigation Information Day - Finley (25 people), March 2000

Four WUE seminars (' Milking your Megalitre') held at Numurkah, Barham, Kyabram, and Blighty (128 people), March 2000

Presentation to the National Board of National Program for Irrigation Research Development, March 2000

Visit from Indonesian delegates, March 2000

On-site field demonstration of Centre Pivot audit experiment to Maffra NRE staff, local agricultural service representatives and farmers, March 2000

Craig Beverly & Cassie Schefe, NRE Rutherglen, April 2000

Presentation at Kyabram Seminar Series Program (30 people), April 2000

Presentation to Lower Murray Irrigation Action Group (SA) tour (20 people), April 2000

Presentation to WUE Best Management Practices Reference Group, April 2000

Presentation to Agriculture Victoria Institute Directors visits, April 2000

Tour of lysimeter for Prof Wayne Lepori, Agriculture & Biological Engineering and Systems, A & M University, Texas, April 2000

Presentation to CAW visits (25 people), May 2000

Presentation to Farm Working Group of Goulburn-Broken Catchment Management Authority, May 2000

Presentation to Murray Dairy Board, May 2000

Presentation of Lysimeter facility and irrigation trial site to NRE Cadet, and staff from NRE Gippsland, July 2000

Bendigo TAFE students - Lysimeter and general discussion of Project (5 people), July 2000
Presentation to Murray Dairy, July 2000

Presentation to the Department of Natural Resources, Department of Primary Industry and Queensland University, Toowoomba, July 2000

Presentation to IIP Steering Committee members, August 2000

Presentation of lysimeter experiment (Module 5) and field site for the irrigation system comparison experiment (Module 6) to the Chinese Professor Jie-sheng Huang, Deputy Head of Irrigation and Drainage Engineering, Wuhan University of Engineering, September 2000

Field site visit – DNE Ellinbank and Rutherglen staff, September 2000

Netafim representatives visited Module 6 site, October 2000

Presentation to the French scientists from CIRAD, October 2000

Field site visit - Bill Heslop, Irrigation officer, Goulburn Murray Water, October 2000

Presentation to a public seminar at Kyabram Dairy Centre, October 2000

Presentation/field site visit to the IIP mid-term Project Review consultants, October 2000

Presentation to DRDC including site visits, November 2000

Presentation to Minister's representative, November 2000

Presentation to Farm Working Group, November 2000

Presentation to SWaN project reviewers, including site visits, December 2000

Presentation to a number of visitors, December 2000

Field tour of lysimeter/Module 6 field site for NRE Cadet Program, January 2001

Presentation to 20 DNRE Kyabram staff on pasture water requirements, January 2001

Victorian Irrigated Cropping Council Strategic Plan Launch, Echuca Worker's and Sports Club, February 2001

Wellington Salinity Group discussion on project design scenarios, February 2001

Water for Growth Discussion Group, Kyabram Dairy Centre (14 members), February 2001

Presentation to Shepparton Irrigation Region Land and Water Salinity Management Program Farm Plan Working Group (30 members), February 2001

Tour of lysimeter/Module 6 field site by Chinese Delegation from Shaanxi Guanzhong Irrigation Improvement Project Management Office, February 2001

Field tour by 4th year agricultural science students, LaTrobe University, February 2001

Light Soils Adoption Package meeting with Goulburn-Murray Water, February 2001

IIP Field Day meeting involving irrigation scientists, Target 10 and Project staff, February 2001

Field tour and presentation to members of Shepparton Irrigation Region Implementation Committee (30 members), March 2001

Seminar – "Getting research to make a difference on farm", NRE Tatura (50 attendees), March 2001

Gongupna Discussion Group (10 members), March 2001

Lysimeter site visit by ORICA, March 2001

Adoption Processes – WUE Case Study presentation to Goulburn-Broken and North-Central Catchment Management Authorities, March 2001

WUE survey results reported to IIP Steering Committee meeting, March 2001

Irrigation Benchmarking and Information System (IBIS) Trial Launch, Maffra, March 2001

IIP Field Day meeting involving irrigation scientists, Target 10 and Project staff, March 2001

IIP Field Day, presentation to 70 local irrigation industry service providers and NRE staff, April 2001

Field site visit of lysimeter/Module 6 site by 3 staff members of the Sunraysia Horticultural Centre, April 2001

Field visit of lysimeter/Module 6 site by 120 students of Dawes Road Primary School, Kyabram, May 2001

2-day visit to ISIA Tatura by 16 members of CSIRO Land & Water Griffith, May 2001

DNRE Rutherglen staff visit to IIP field sites (4 people)

Field visit by Bruce Kefford, Executive Director of Agriculture, DNRE Corporate, May 2001

National workshop presentation on water movement in cracking soils, University of Melbourne, May 2001

Field visit by 35 members of Wyuna Landcare Group, June 2001

Melbourne University Seminar (20 attendees), June 2001

Presentations to SWaN Science Meeting, June 2001

Field site visit by 20 Mooroopna Secondary College students, June 2001

Information session for Dairy Extension Workers, Kyabram Dairy Centre, July 2001

IIP Module presentations to IIP Steering Committee Members, August 2001

Visit to ISIA Tatura by Professor Rod Smith, University of Southern Queensland, August 2001

Visit to ISIA Tatura by Dr XiuboYu, Institute of Geographic Science and Natural Resources Institute, Chinese Academy of Science, Beijing, August 2001

Module 6 and 8 results presentation at NRE Kyabram Dairy Seminar to NRE Kyabram, Echuca and Tatura staff and dairy farmers, September 2001

Module 6 results presentation at NRE Tatura Staff Meeting (40 participants), September 2001

Modules 9 and 11 results presentation to MDBC Irrigation Issues Working Group, Canberra, (20 participants) September 2001

Presentation on Adoption of Water Use Efficiency Research, NPIRD Workshop, Melbourne, (40 participants) October 2001

Presentations on WUE extension work issues at NRE/Goulburn-Murray Water Rochester Field Day (30 participants), November 2001

Presentation on WUE Best Management Practices to DRDC representatives and regional groups (40 participants), December 2001

Presentation on WUE to NRE Sustainable Farming Systems Program Leader (4 persons), December 2001

Presentation on WUE Decision Support Framework, NRE Kyabram seminar (40 people), December 2001

WUE Best Management Practices Reference Group Meeting (15 people), December 2001

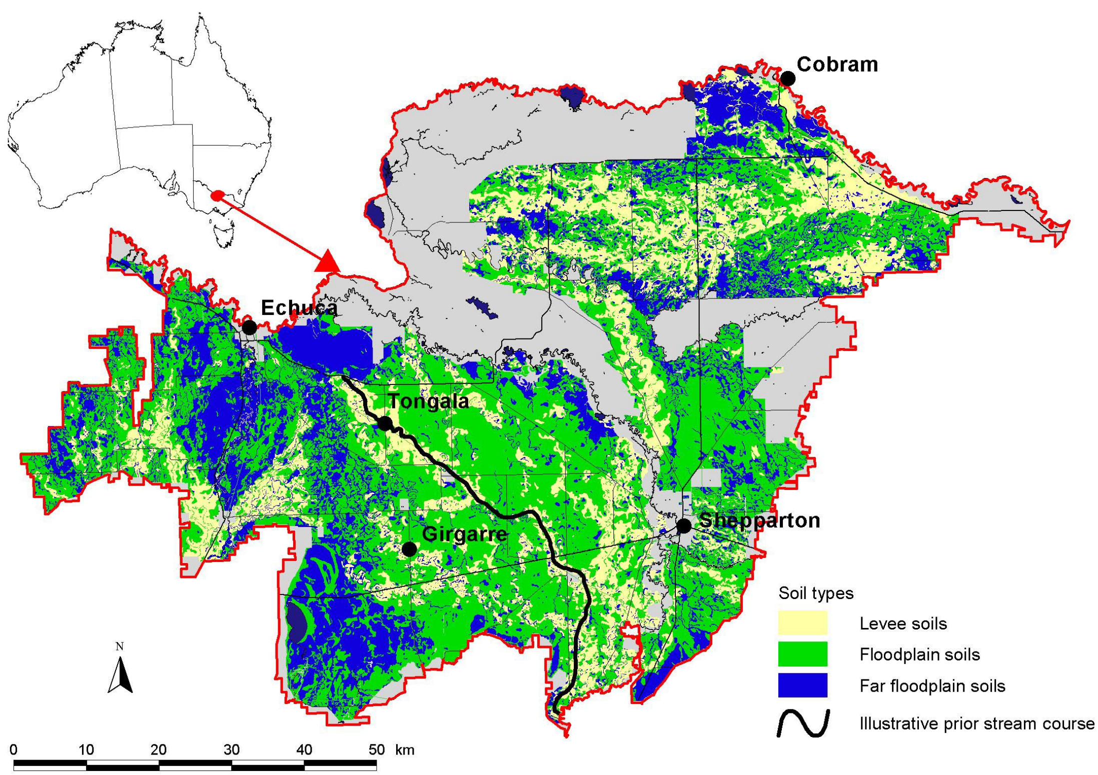
Relationship between recharge, watertable levels and prior stream formations in Northern Victoria, Australia

Attachment 10

Introduction

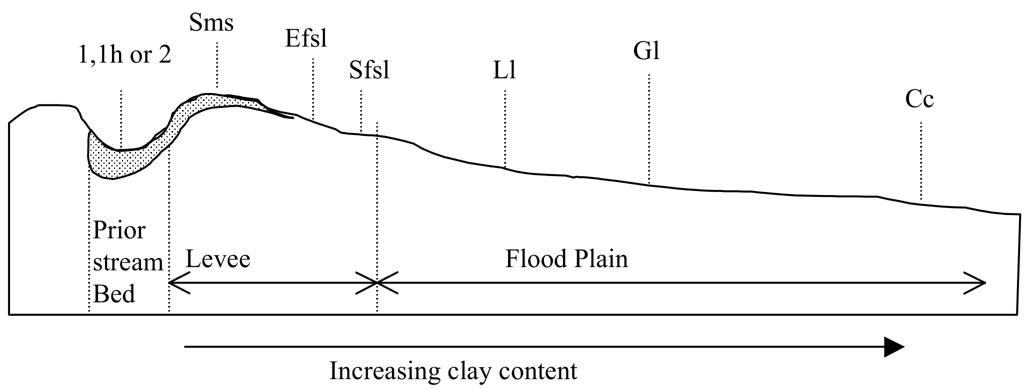
The Shepparton Irrigation Region (SIR) is located in northern Victoria and covers 0.5 Million hectares (Figure. 1). Rainfall is insufficient to meet crop water requirements during summer and irrigation is applied to supplement rainfall and increase crop production. High water tables (<2 m below the surface) have developed over much of the region, peaking at 55 % of the region in 1995. The development of high watertables results from the clearing of deep-rooted native vegetation and replacement with shallow rooted plant species (GHD, 1983). This led to greater drainage losses below the plant rootzone and concomitant groundwater recharge, which is exacerbated by irrigation and channel seepage (GHD 1983).

Figure. 1 Location of the Shepparton irrigation region, and soil distribution within the region.



The Shepparton Formation is the main geological unit that underlies the SIR, and is characteristic of the Riverine Plain of south-eastern Australia (Ife 1988). Associated with this formation are narrow "shoe string" aquifers, deposited in the channels of prior streams (Butler 1950). These deposits consist of medium to coarse sands and gravels. Soil type is also closely associated with prior stream activity, with lighter sandier soils (levee soils) being found close to the prior stream channel and heavier clay soils (floodplain soils) found at distance from the prior stream (Figures 1 and 2) (Skene and Poutsma 1962). Typically, these levees can be up to 3 m higher than the surrounding flood plain. The stream channel is in the highest part of the levee (where present) can be up to 3.5 m deep. The stream channel was remodelled and deepened to serve as a surface drain in the Tongala area. Sandmount sand (S^ms) is the lightest soil type found, consisting of sand to depths greater than 2 m. Small isolated pockets of S^ms formed on the edge of the prior stream channel by wind action moving sand from the prior stream channel (Skene and Poutsma 1962). East Shepparton fine sandy loam (Efsl), Shepparton fine sandy loam (Sfsl) and Lemnos loam (Ll) have red-brown clay subsoils and grade into each other texturally, Efsl being the lightest and Ll the heaviest. Texturally there is very little difference between Ll and Gl, the main difference being the colour of the subsoil which changes from red (Ll) to brown (Gl)(Skene and Poutsma 1962).

Figure 2. Cross section of idealised prior stream catena (after Skene and Poutsma, 1962).



Note
S^ms = Sandmount sand, Efsl = East Shepparton fine sandy loam, Sfsl = Shepparton fine sandy loam, Ll = Lemnos loam, Gl = Goulburn loam, Cc = Congupna clay. Soils in channel of prior stream; 1= light, 1h = medium, 2 = heavy textured

Prior stream activity has been recognised as being closely associated with the formation of the landscape. It is also accepted that groundwater hydrology is associated with prior stream activity. An 'intake' theory was developed that proposed that high drainage losses occur through the permeable levee soils close to the prior steam channel (Bakker and Cockcroft 1974). These drainage losses recharge underlying aquifers and move laterally out into the less permeable floodplain soil areas. In this paper we further analyse this intake theory by investigating the interaction between prior stream formations, watertable levels and groundwater salinity at two sites in northern Victoria. The potential implications for management are discussed.

Methods

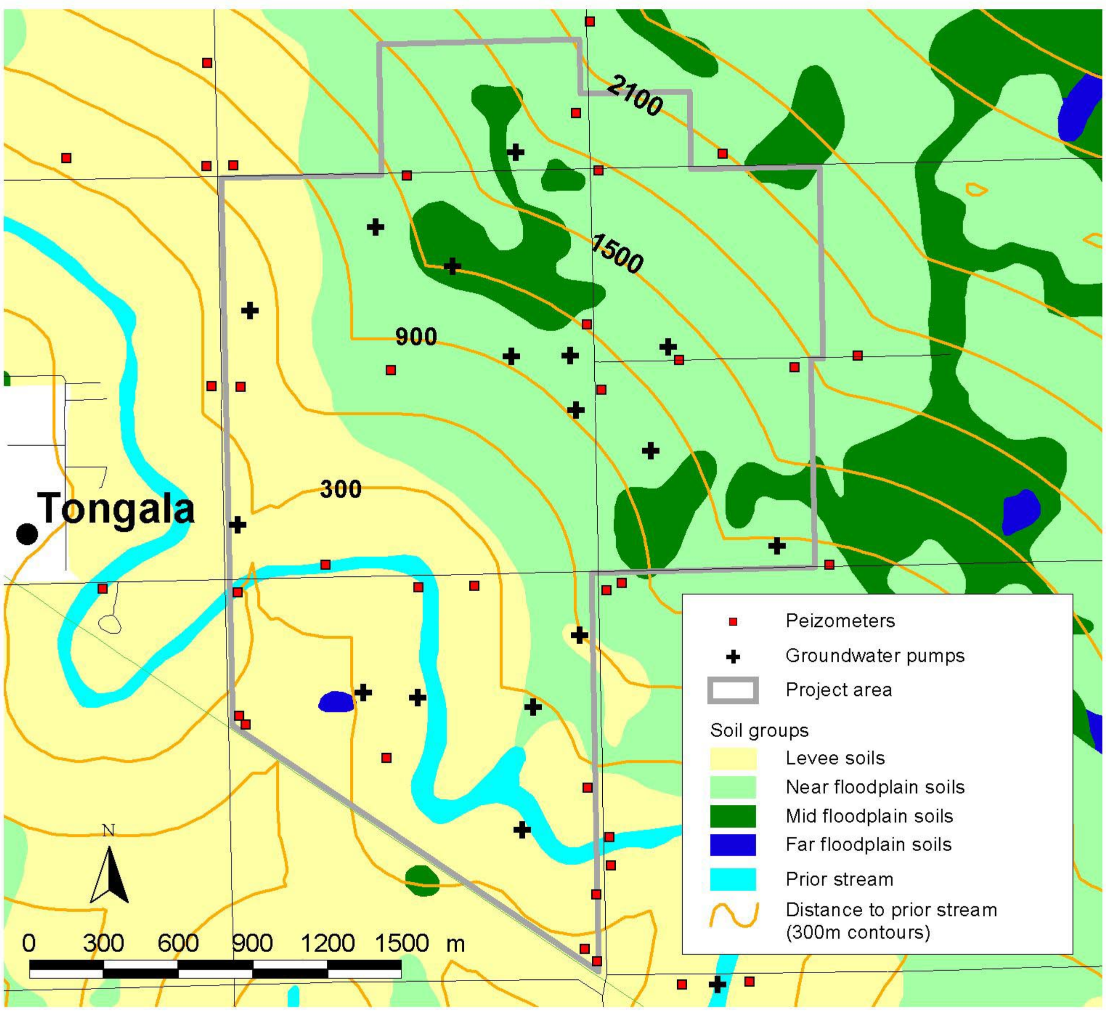
Tongala

The Tongala groundwater / reuse project was initiated in 1980 to combat salinity problems arising from shallow watertables. The project area is located in east of the township of Tongala in the SIR (Figure 1). The area covers 600 hectares and consists of thirteen dairy farms and one orchard property. The dairy farms in the area were developed for border check irrigation of perennial pastures around the 1930s. Intensive groundwater pumping has been practiced in the area since monitoring of watertables and piezometric pressures commenced in 1982.

The pedology in the Tongala area follows the scenario described above (Figure 2). The south-western part of the area is dominated by prior stream levee soils (Figure 3), covering the lighter soil types sandmount sand, East Shepparton fine sandy loam and Shepparton fine sandy loam. Moving away from the prior stream, soil texture becomes heavier, coinciding with the deposition of finer sediments during landscape formation.

Narrow shoestring aquifers (typically 2 to 4 m thick) are found at between 6 and 10 m below the soil surface (Heuperman 1988). A deeper aquifer (starting at around 13-15m depth) is also present under part of the area. Groundwater in this aquifer is typically more saline than found in the shallow aquifer, and pressure potential is generally 0.5 m lower than those found the shallow aquifer system.

Figure. 3 Soil types, observation bore network, groundwater pumps and surface drainage in the Tongala project area



A network of 26 piezometers was installed in 1982 into the shallow aquifer system across the study area (Figure 3). Piezometric pressure potential was measured on a monthly basis and groundwater salinity measured every six months since 1982. The long-term average piezometric head (ϕ, m above sea level) and groundwater salinity (GWS) were calculated for each piezometer that intersected the shallow aquifer system. Soil type and distance to the prior stream (DPS) were extracted from a GIS database for each piezometer. Groundwater in the shallow aquifer system under the area is generally considered to be unconfined and for this study ϕ was assumed to be equivalent to the watertable level.

Girgarre

The major landuse in the Girgarre area (Figure 1) is irrigated pasture for dairy production. In the early 1980s landholders at the site were suffering large production losses caused by salinity. Soil surveys were conducted in 1982 to assess the extent of the problem. The soil survey measured, amongst other things, the change in soil salinity with distance from a prior stream (Heuperman and Bourchier 1983). The soil salinity data (0-0.6 m profile) were used to estimate the steady state leaching fraction using the Rhoades equation (Rhoades 1974). This equation provides a good prediction of soil salinity from measured leaching fractions for a range of soils in northern Victoria (Lyle *et al.* 1986; Prendergast 1993). The depth of recharge was then calculated by multiplying the leaching fraction by the depth of applied water.

Results

Tongala

Soil type, natural surface level and DPS were correlated with ϕ ($p<0.01$). These variables are all interrelated, with light soil types found on prior stream deposits, typically located on high spots in the landscape (Figure 2).

There was a strong linearly correlation ϕ between the soil surface level (Figure 4). ϕ was also significantly higher ($p<0.001$) under the prior stream levee than under the floodplain soils (Figure. 5). These correlations are a reflection of two processes; firstly, the regional gradient of the groundwater system is approximately parallel to the soil surface and secondly, maintenance of the ϕ at a relatively constant depth below the surface is achieved through a balance of evaporation, recharge and groundwater discharge processes.

Analysis of ϕ highlights that a groundwater mound has formed under the light levee soils close to the prior stream (Figure 5). This mound indicates that recharge occurs faster through the levee soils than groundwater can dissipate through lateral movement and groundwater pumping. A study in the Tongala project area, based on chloride profiles, concluded that recharge under the levee soils was twice the recharge measured under the flood plain soils under irrigated pasture (Bethune 2001). This finding does not consider channel seepage, which is likely to be high on the permeable levee soils.

Figure. 4 Relationship between average groundwater level and soil surface level.

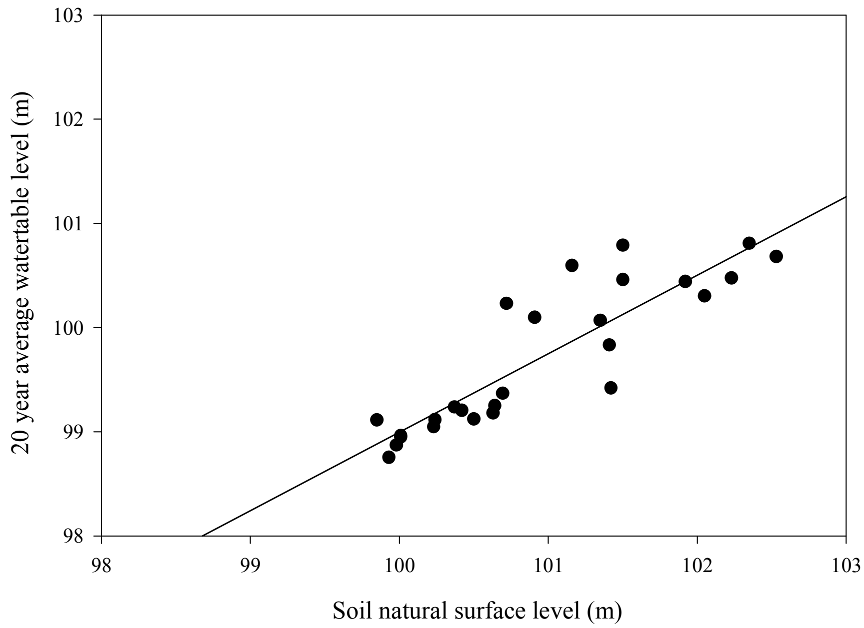
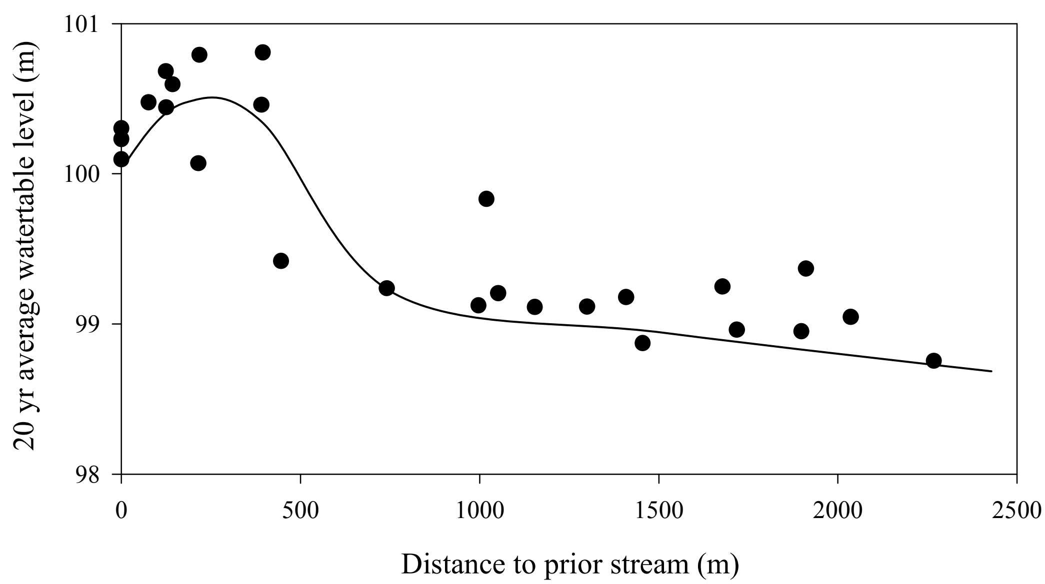
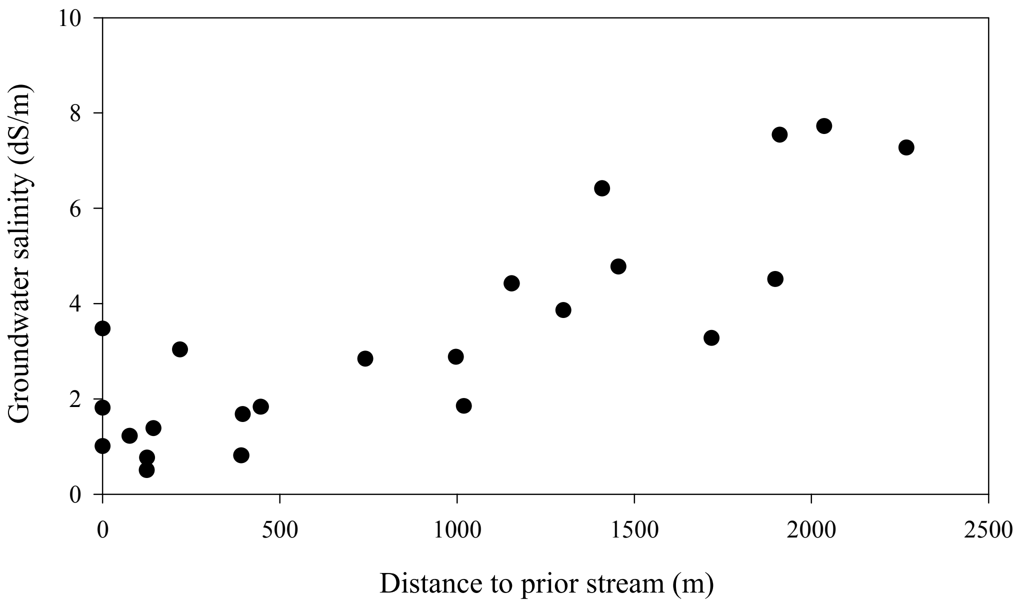


Figure 5. Impact of prior stream on watertable levels.



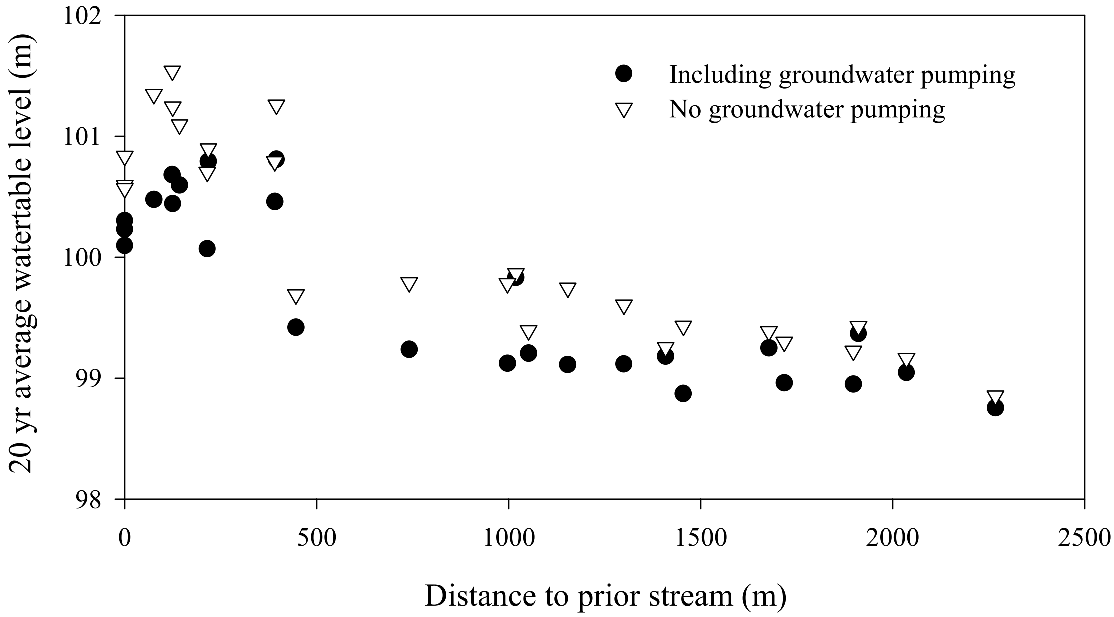
The formation of a mound supports the hypothesis that considerable accessions occur in relatively small areas of the prior stream landscape. These accessions dissipate laterally through shallow aquifers and result in upward pressure gradients further away from the prior stream. This leads to increased evaporation of groundwater and thus salt accumulation in the floodplain soils. The higher ϕ would also restrict leaching in these areas, leading to more saline drainage from below agricultural crops. These combined processes would be expected to result in increased groundwater salinity in the floodplain areas. This was observed in the Tongala data set, with a linear model of DPS against 20-year average groundwater salinity accounting for 63% of the variability in the data (Figure 6). It was also observed that some piezometers in the depression of the prior stream levee had high salinity levels. These piezometers correspond to local discharge spots, located lower in the landscape than the surrounding floodplain areas.

Figure 6. Impact of distance to prior stream on groundwater salinity



Groundwater pumping impacts on the response of watertables to DPS (Figure 7). The 'with pumping' data points present actual observations. The 'without pumping' data points were calculated from monthly groundwater pumping rates and typical aquifer properties. These aquifer properties were obtained from historical pump test results and averaged across the whole area. The calculation assumes that all pumped groundwater is used by plants and that re-use does not cause extra accessions. The calculated data 'without pumping' are thus higher than the actual outcome would be. Groundwater levels on average responded to pumping by a drop of about 1m close to the prior stream, the impact decreasing with distance from the prior streams. This reflects the high pumping rates under the levee soils where groundwater salinity is low (Figure. 6).

Figure. 7 Impact of prior stream on watertable levels, with and without groundwater pumping



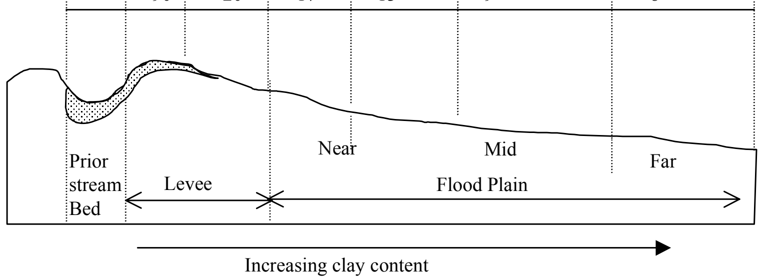
The pumping clearly reduced the groundwater gradient away from the prior stream and therefore should reduce the magnitude of groundwater discharge and concomitant salinity problems in the surrounding lower flood plain area. However, groundwater pumping was not sufficient to fully prevent lateral water losses from the prior stream levees to the surrounding flood plains (zero gradient); groundwater pumping in the Tongala area under current management, in spite of the very high density of pumps installed compared to other dairy areas in the SIR, is not sufficient to compensate for the impacts of high accessions on the light soil types. Higher volumes would need to be pumped to prevent discharge to the surrounding lower points in the landscape. As the incorporation of greater volumes of saline groundwater in the irrigation supplies could result in pasture production losses, the introduction of measures to reduce groundwater accessions on the light soils of the prior stream levees, such as pressurised overhead irrigation, should be considered.

Girgarre

Recharge increased with distance from the prior stream (Figure 8). This confirms the findings at Tongala where high recharge through the levee soils resulted in the formation of a groundwater mound. Similar to Tongala, shallow watertable levels in the heavier soils away from the prior stream restricted leaching of the root zone, causing the observed salinity problems reported under 'methods' above.

Figure. 8 Soil catena and related soil salinities and estimated recharge in a prior stream landscape at Girgarre (salinity data after Heuperman and Bourchier, 1983)

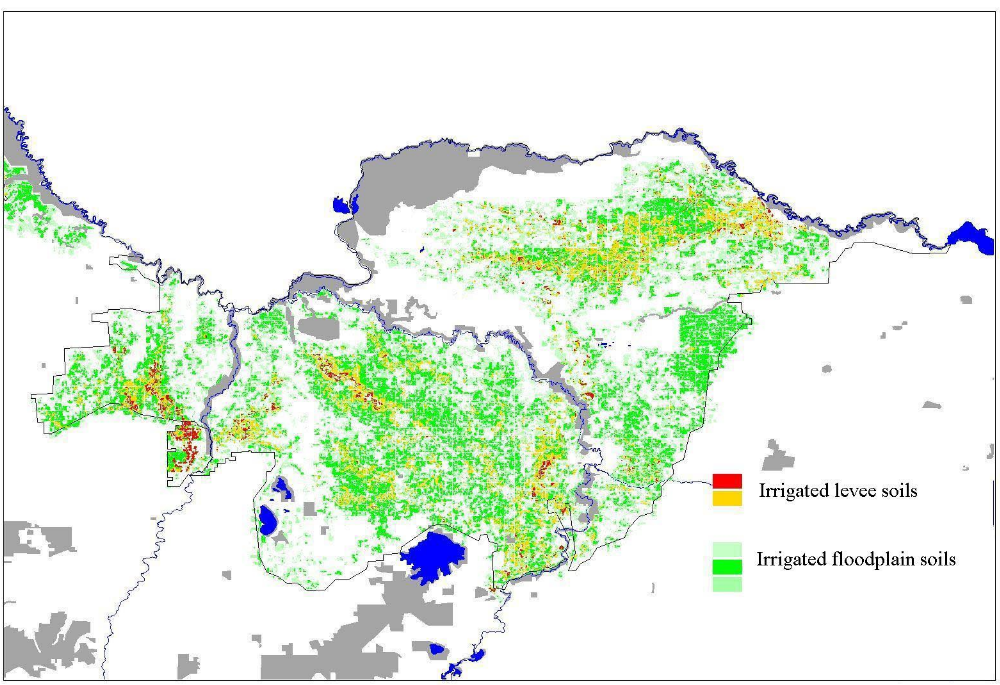
Average soil salinity 0-0.6(mg/l)		177	930	950	1304	1780	2110
Standard error		45	93	61	182	372	610
Recharge (mm/yr)		90	20	17	13	9	8



Discussion

The analysis indicates that high rates of recharge are occurring through levee soils in the Tongala and Girgarre areas. This impacts on watertable levels in the surrounding flood plains, potentially lead to land salinisation. There is a widespread distribution of irrigated levee soils in the SIR (Figure 9). Thirty percent of the irrigated area in the SIR is located on levee soils. Therefore, there is considerable potential for high recharge through the levee soils to impact on regional groundwater dynamics and salinisation processes.

Figure 9. Distribution of irrigated levee soils in the SIR.



Summary

Recharge, watertable behaviour and groundwater salinity was closely associated with prior stream activity. High rates of recharge occurred through the permeable levee soils found close to the channel of prior streams. This high recharge has led to the formation of a mound of groundwater under the levee soils, resulting in gradients in groundwater pressure towards the lower floodplain soils. This gradient potentially impacts on groundwater levels and salinisation processes in the surrounding, heavier floodplain soils. Intensive groundwater pumping in the Tongala area did not prevent the formation of the groundwater mound. This indicates that current groundwater pump management does not prevent the impacts of high recharge through levee soils. Options to reduce recharge on these levee soils are required.

This analysis in this study focussed on two relatively small areas within the SIR. The widespread irrigation of levee soils across the SIR indicates that the observed behaviour may occur at a regional scale. This requires further investigation. This analysis is of importance as it has the potential to change current policy and incentive schemes relating to controlling the impacts of irrigation through sub-surface drainage.

References

Bakker AC, Cockcroft B (1974) Salting in the Goulburn Valley. *Victorian Horticultural Digest* **62**.

Bethune M (2001) Recharge Under Flood Irrigated Pasture. (8th Murray Darling Basin Groundwater Workshop: Victor Harbour, South Australia)

Butler BE (1950) A theory of prior streams as a casual factor in the distribution of soils in the Riverine Plain of south eastern Australia. *Australian Journal of Agricultural Research* **1,** 231.

GHD (1983) 'The application of salinity control techniques in Victoria. A report prepared for the Salinity Committee of the Victorian Parliament.'

Heuperman AF (1988) The Tongala groundwater pumping/re-use project: A pilot study for groundwater table control in the Shepparton Region in Northern Victoria. *Agricultural Water Management* **14,** 513-523.

Heuperman AF, Bourchier J (1983) 'Girgarre Salinity Survey. Department of Agriculture Research Project Series No. 162, Agdex 524, ISSN 0313-4652.' (Department of Agriculture, Tatura, Victoria)

Ife D (1988) 'Geomorphic and hydrogeological mapping of the upper Shepparton formation, Shepparton Region.' (Rural Water Corporation, Melbourne, Australia)

Lyle CW, Mehanni AH, Repsys AP (1986) Leaching rates under a perennial pasture irrigation with saline water. *Irrigation Science* **7,** 277-286.

Prendergast JB (1993) A model of crop yield response to irrigation water salinity: theory, testing and application. *Irrigation Science* **13,** 157-164.

Rhoades JD (1974) Drainage for salinity control. In 'Drainage for agriculture, agronomy'. (Ed. Jv Schilfgaarde) pp. 433-461. (American Society Agronomy: Madison, WIS USA)

Skene JKM, Poutsma TJ (1962) 'Soils and land use in part of the Goulburn Valley, Victoria. Technical Bulletin No 14.' (Department of Agriculture, Victoria, Australia)