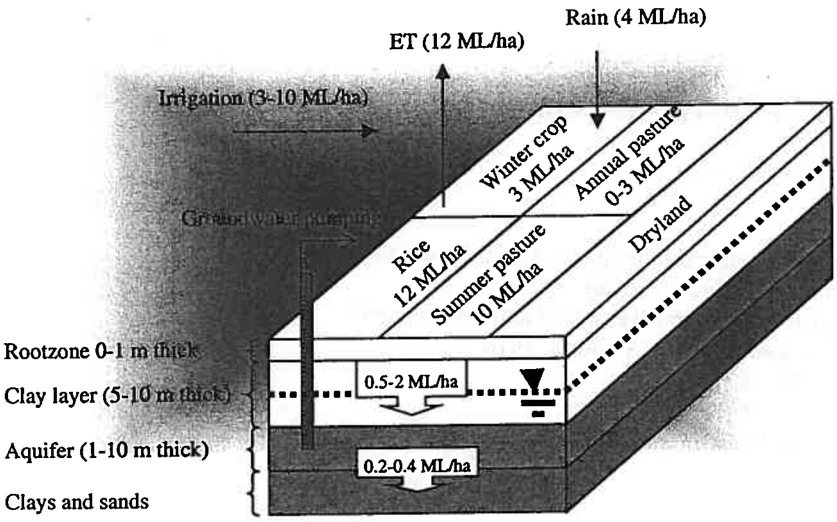
Modelling water movement in cracking soils

Workshop 16-17 May 2001

Edited by Matthew Bethune and Mac Kirby



Melbourne Victoria
2001

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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 estimates, which was influenced 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.

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. Firstly, the nature of the 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 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 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.

ACKNOWLEDGEMENTS

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.

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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.

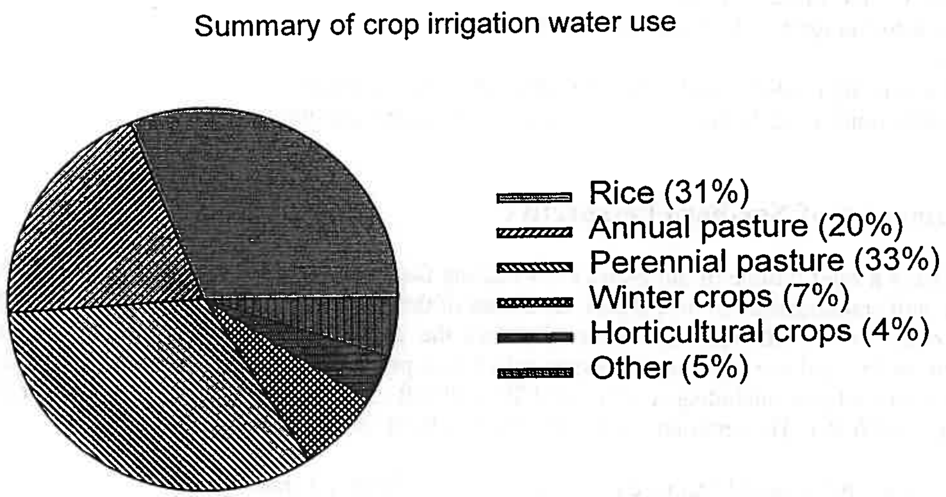

Fig 1. Break up of irrigation water use by enterprise in SMDB.

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.

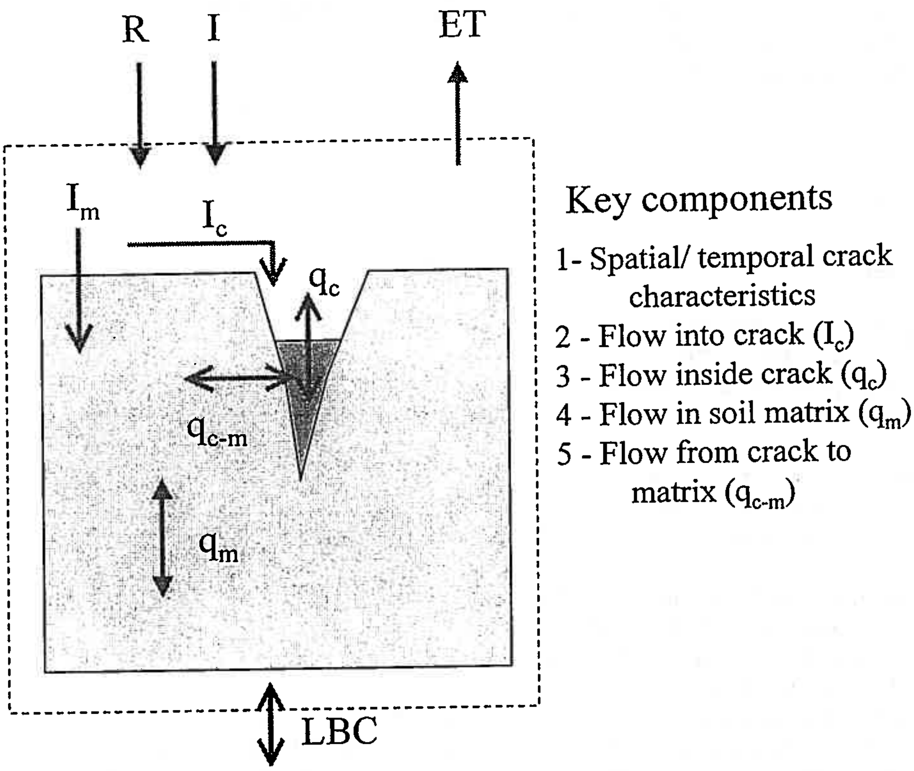

Fig 2. Key components in a dual porosity model.

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.

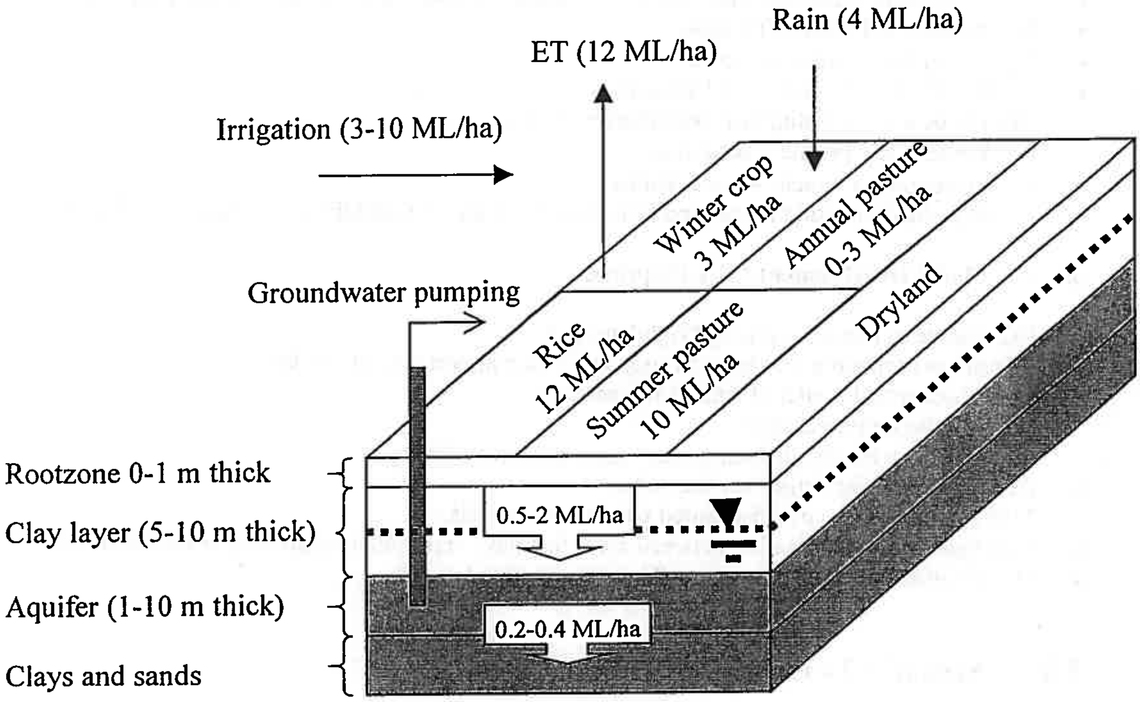

Fig 3. Typical components of the water balance for a farm in the Murray Valley.

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.

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 Required

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Attachment 3 - Overheads from talk on southern perspective (Geoff McLeod)

Southern Murray Darling Perspective

Geoff McLeod
Environmental Manager
Murray Irrigation Limited

Slide 1

Water Use within Southern MDB

Crop Type	Use (%)
Rice	31
Annual Pasture	20
Summer Pasture	33
Winter Crops	7
Horticulture Neg.	4
Other	5

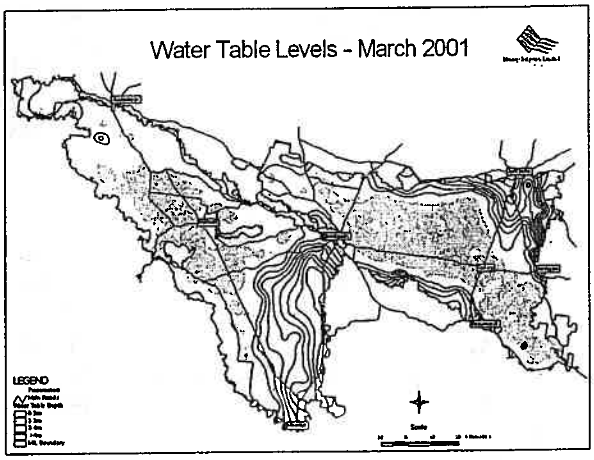
Value of Production: $2b farm gate

Slide 2

Threats

- Rising Watertables
  - Approx. 50% of region has watertables within 2m

Slide 3



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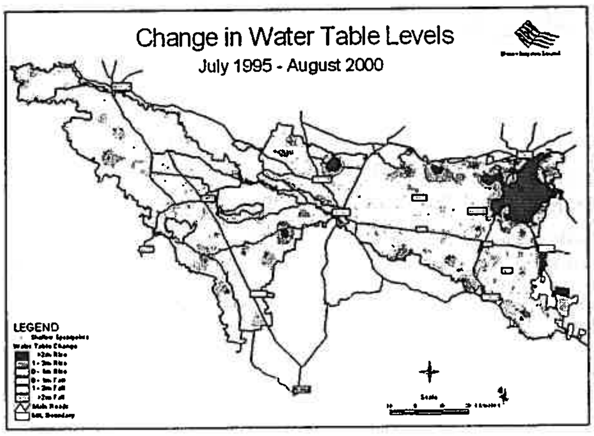


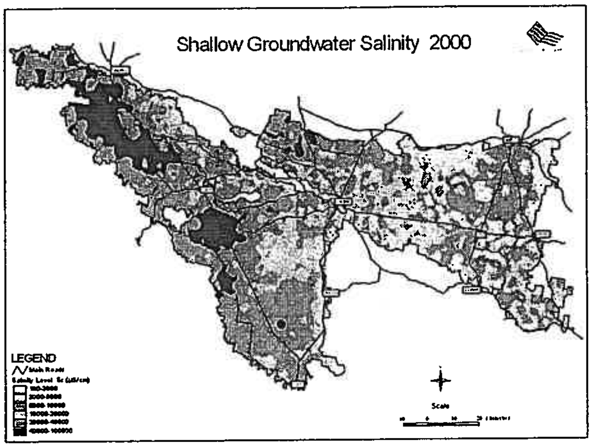
Slide 5

Threats

- Rising Watertables
- Groundwater Salinity
  - large proportion of region is underlain by saline groundwater

Slide 6

Attachment 3 - Overheads from talk on southern perspective (Geoff McLeod)



Slide 7

Threats

- Rising Watertables
- Groundwater Salinity
- Loss of Agriculture Production
  - Dairy, rice, horticulture
- Loss of natural vegetation, biodiversity
  - vegetation in lower areas

Slide 8

Managing Salinity

- Development of Integrated Strategies
  - Land and Water Management Plans
- Minimise groundwater accessions
  - Irrigation induced
  - Rainfall related
- Manage areas of high watertable
- Need for sound water use policies
  - Total Farm Water Balance Policy
  - Rice Growing Policy

Slide 9

Research Focus

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

Slide 10

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

Slide 11

Current 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
  - Don't describe well role of cracking in influencing water movement

Slide 12

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

Water Balance in the Northern Murray Darling Basin

Background to a Proposed Program – why do it?

Slide 1

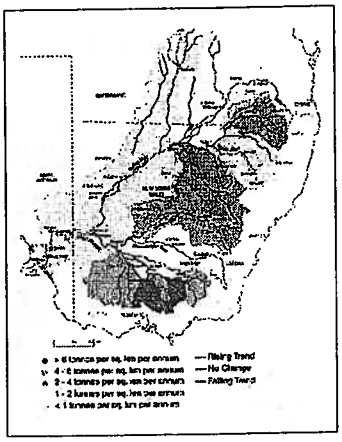
Salinity trends

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)



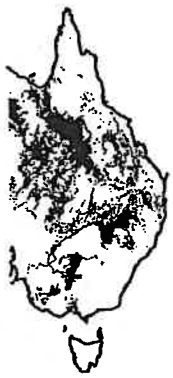
Slide 2

Slide 3

What's different in the Northern MDB?

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



Vertosols in eastern Australia

Slide 4

Slide 5

But swelling soils don't drain, do they?

Various estimates show significant drainage:
- Liverpool Plains (Hudson), dryland ~ 80 mm/yr, amount influenced by management
- lysimeter work QDNR, irrigated ~ 200 mm/yr
- ACRI / Vervoorts 12 mm per irrigation under cotton
- Calculations based on modelling (SSaLF, APSIM), estimation of hydraulic conductivity at measured moisture content, by difference from other measured components, salt balance, all yield estimates in the range 10's to 100's mm/yr.

(If they don't drain then cotton is in serious trouble!)

Slide 6

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

Salt loads.....

Based on the above drainage estimates and a typical soil water salinity of (say) 1 dS/m:
- irrigated area ~ 500 000 ha
- 1 dS/m ~ 0.6 g/l
- 100 mm/yr ~ 1 Ml/ha/yr

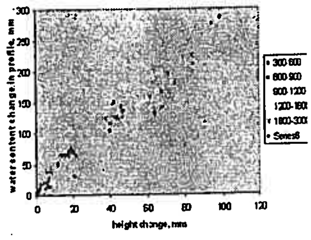
- Area x drainage x salt concentration = 500 000 T salt being mobilised by drainage (using range of soil water salinity, and range of drainage estimates, range is say 100 000 to 5 000 000 T salt / yr)

For comparison, the salt moved by the Gwydir, Namoi, Macintyre, Border and Balonne-Condamine is ~ 300 000 T/yr (Salinity Audit)

Slide 7

Other issues

- Swelling – must be measured to account for changes in storage (Hudson ~ 120 mm in one year)
- Corrections to water balance of same order as drainage estimates (Ringrose-Voase, Liverpool Plains)
- How to extrapolate to other soils? Pedo-transfer functions not studied

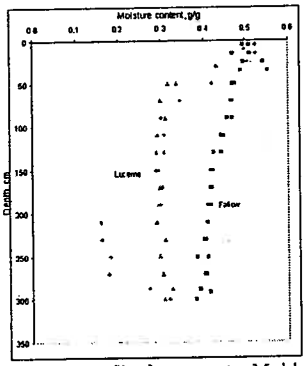


Swelling and moisture content change at Hudson

Slide 8

Other issues

- Cracking and preferential flow?
  - Atrazine at 80 m beneath Liverpool Plains
  - Lucerne plots at Hudson did not wet up in wet winter, but there was much drainage
- Not good at dealing with: NSWAg next project with GRDC



Moisture profile after wet winter. Model predicted 1.3 m of wetting under lucerne

Slide 9

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 pedotransfer functions to use: no properties database (cf non swelling soils).
- Limited knowledge of influence of water quality on hydraulic and swelling properties.
  - eg order gave 10 fold difference in sorptivity need field studies

Na bentonite → exchange → Ca bentonite
compress

Slide 10

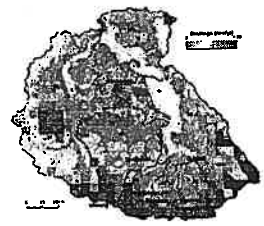
Other issues: groundwater

- 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 program to groundwater studies.

Slide 11

Other issues: 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



Liverpool Plains drainage

Slide 12

Attachment 5 - Review paper

Modelling Water movement in cracking soils: A review

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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:

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

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

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, 1984). Small departures from the normal shrinkage line are often found in practice and are attributed to air entering the voids or to cracks forming within aggregates (Ross and Bridge, 1984). Volume change had previously been categorised by COLE, the coefficient of linear extensibility and PVC, the potential volume change, both of which are civil engineering terms concerned primarily with vertical elevation changes on cracking soils.

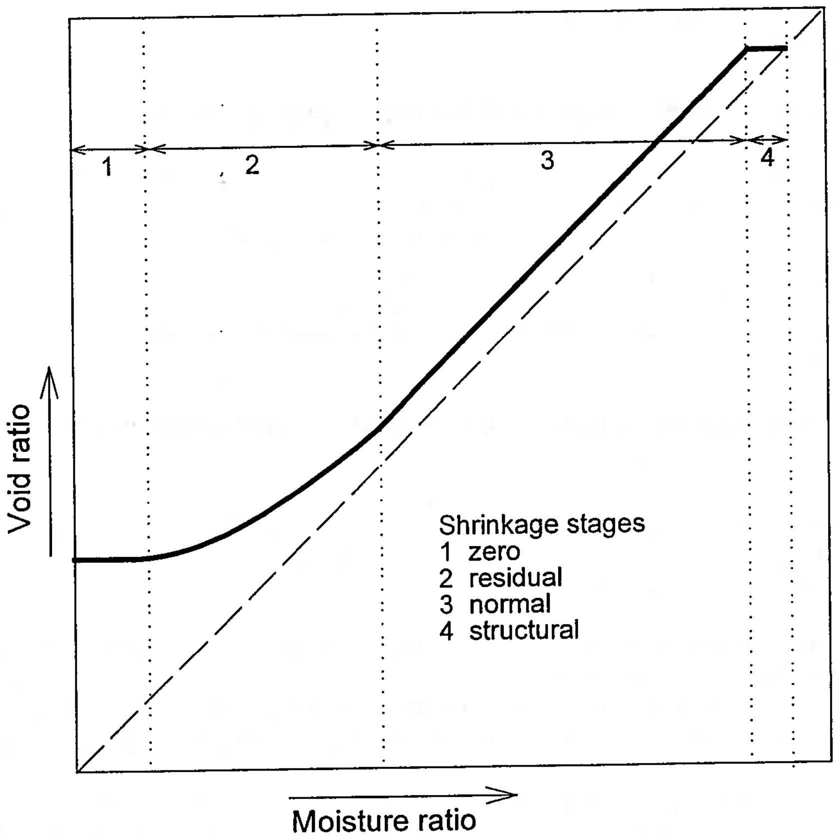

Figure 1 Graphic representation of a classical shrinkage curve.

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.

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

$Vc = \Delta V - \Delta z$
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)
Vc = 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.

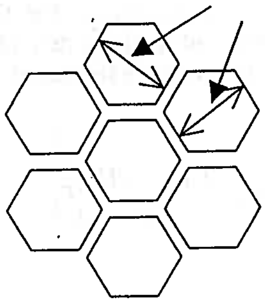

Figure 2 Conceptualised soil peds.

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}.

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

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:

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

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 ($\theta_{si}\approx 0.05$) the volume of water escaping was incorrect by a factor of 20. In an unsaturated natural soil system ($\theta_{si}\approx 0.56$, $\alpha\approx 1/3$) this error was found to be a factor of 1.2 (Smiles, 1997).

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

θ_{si} = Initial volume fraction of solid

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.

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Attachment 6 – Overheads from talk summarising review paper (Matthew Bethune)

Overview

A lot of work on characterising cracking soils (>20 yrs ago)

Theoretical model developments exceed our ability to paramertise these models

Limited data to run/test these models

Little published information in Aust on modelling water movement in cracking soils

Natural Resources and Environment
Agriculture · Resources · Conservation · Land Management
Victoria The Place To Be

Slide 1

To focus discussion

•Assume ET and plant root extraction are clearly defined

•Limit discussion to water movement (ignore solute)

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Slide 2

Technical weakness-component 2
Initiation of flows in the macropores

•Crack inflow results from runoff

•Initiation of runoff

- surface roughness
- accurate description of surface infiltration
- How do you measure?

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Slide 3

Spatial/temporal crack characteristics

Where do cracks occur?

How big are they ?

Are they inter-connected?

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Slide 4

Technical weakness-component 4
Soil matrix flow

•Is Richards equation valid (horizontal cracks)?

•Most models do not allow for overburden potential, how important is this?

•When is it important to include the impact of soil movement on water movement?

- use of material coordinates
- adjusting spatial coordinates

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Slide 5

Technical weakness-component 1
Spatial/temporal crack characteristics

What is the relationship between volume change and subsidence?

- 1-D vs 3-D shrinkage.
  - soil moisture impacts on geometry factor
- Impact of soil depth (greater loading)
- Measurement technique (field vs lab)

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

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Slide 6

Attachment 6 – Overheads from talk summarising review paper (Matthew Bethune)

Technical weakness-component 1
Spatial/temporal crack characteristics

Crack geometry

•Importance of crack volume, geometry and depth is unkown.

- limited data and models decribing
- difficult to measurement

Slide 7

Technical weakness-component 1
Spatial/temporal crack characteristics

•What is the spatial distribution and connectivity of cracks?

- *Few studies in this area*
- *Mostly stochastic modeling approaches*
- *When does the spatial distribution/connectivity become important (1-D vs 3-D water movement)*

Slide 8

Technical weakness-component 2
Initiation of flows in the macropores

•Crack inflow results from runoff

•Initiation of runoff

- surface roughness
- accurate description of surface infiltration
- How do you measure?

Slide 9

Technical weakness-component 3
The nature of flows in the macropore system

•Explicit models of water movement inside cracks

- very difficult to parameterise
- very difficiult to verify/test

•Simple water balance in crack adopted

•When is a simple water balance procedure sufficient?

•Can we parameterise explicit models of crack flow?

Slide 10

Technical weakness-component 4
Soil matrix flow

•Is Richards equation valid (horizontal cracks)?

•Most models do not allow for overburden potential, how important is this?

•When is it important to include the impact of soil movement on water movement?

- use of material coordinates
- adjusting spatial coordinates

Slide 11

Technical weakness-component 5
Interaction between the domains

How important is it to know crack surface area?

- > 10 times soil surface area
- no model adjusts crack surface area with changing soil moisture

Does a 1-D model capture the lateral infiltration process?

Slide 12

Attachment 6 – Overheads from talk summarising review paper (Matthew Bethune)

Summary

- Theory reasonably well developed
- Testing of theory largely limited to lab studies
- Limited testing under field conditions
- Difficult to obtain necessary data under field conditions

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Slide 13

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.

8.2 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