Estimating impacts of changed land use on recharge: review of modelling and other approaches appropriate for management of dryland salinity

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Abstract To manage dryland salinity, one needs to know how changed land use affects groundwater recharge. Few techniques are available for comparing 'deep drainage' under different land uses. Soil-tracer methods, although good for replication and remote field sites, are subject to spatial variability. Lysimeters are good for comparisons but are difficult for drier areas and sloping land. Agronomic water-balance studies, where appropriate soil-water measurements exist, may be used with a soil-vegetation model to estimate long-term deep drainage. Complex models are required to analyze specific land-use differences, such as perenniality and root and leaf area dynamics, but models require intensive and extensive data for calibration. This approach is time-consuming, labour-intensive, and difficult in remote locations. Because of the one-dimensionality of most soil-vegetation models and the small fraction of the total water balance that is deep drainage, little success has occurred in extrapolating beyond the research plot, or to spatially heterogeneous systems such as alley farming. Some 'top-down' modelling and landscape disaggregation approaches have been partially successful in making catchment or regional-scale predictions. The direction for further work depends on the level of recharge reduction that is required for most groundwater systems and difficulties that it imposes.

Résumé Pour contrôler la salinité des terres sèches, on a besoin de connaître comment le changement d'occupation du sol affecte la recharge de la nappe. Peu de techniques permettent de comparer le «drainage profond» sous des occupations des sols différentes. Bien qu'elles soient adaptées pour être reproduites et appliquées à des sites de terrain éloignés, des méthodes basées sur les traceurs des sols sont sujettes à une variabilité spatiale. Les lysimètres conviennent pour faire des comparaisons, mais sont difficiles à utiliser en régions sèches et sur les versants pentus. Les études agronomiques de bilan d'eau, lorsqu'il existe des mesures appropriées d'eau dans le sol, peuvent être utilisées avec un modèle de sol et de végétation pour estimer le drainage profond à long terme. Des modèles complexes sont nécessaires pour analyser les différences spécifiques d'occupation des sols, telles que la pérennité et la dynamique de la zone racinaire et foliaire, mais les modèles ont besoin de données intensives et extensives pour les calibrer. Cette approche prend du temps, demande un travail intensif et est difficile dans les régions éloignées. À cause de la dimension unique prise en compte dans la plupart des modèles de sol et de végétation et de la petite part du bilan hydrique total représenté par le drainage profond, il y a peu de chance d'extrapoler au-delà de ce point d'étude ou pour des systèmes hétérogènes tels que les cultures en alignement. Certaines approches de modélisation du haut vers le bas et de désagrégation de paysage ont donné des résultats en partie intéressants pour faire des prévisions à l'échelle régionale ou du bassin. L'orientation des futurs travaux dépend du niveau de réduction de la recharge qui est recherché pour la plupart des systèmes aquifères et des difficultés que cela impose.

Resumen Con objeto de gestionar la salinidad en terrenos áridos, se requiere conocer cómo la modificación de los usos del suelo afecta a la recarga de un acuífero, pero existen pocas técnicas que permitan comparar el 'drenaje en profundidad' en función de dichos usos. Los trazadores del suelo sirven para emplazamientos remotos y para

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reproducir datos, pero están sujetos a la variabilidad espacial. Los lisímetros son útiles para hacer este tipo de comparaciones, pero no se muestran tan eficaces en zonas más secas y agrestes. Los balances agronómicos de agua pueden ser aplicados con un modelo de vegetación del suelo para estimar el drenaje profundo a largo término, siempre y cuando se disponga de las medidas adecuadas de humedad en el suelo. Se necesita modelos complejos para analizar las diferencias específicas en los usos del suelo, tales como el carácter perenne y la dinámica de raíces y hojas, si bien estos requieren datos intensivos y extensivos para poder calibrarlos. Este enfoque exige más tiempo y trabajo, y resulta difícil de usar en zonas alejadas. Debido al comportamiento unidimensional de la mayoría de modelos de vegetación-suelo y a la pequeña fracción del balance de agua que se convierte en recarga, no se ha obtenido resultados satisfactorios a la hora de extrapolar los resultados de una investigación puntual, ni tampoco en sistemas espacialmente heterogéneos, como la plantación en hileras. Se ha logrado resultados aceptables por medio de modelos 'de arriba abajo' y de métodos de desagregación del paisaje a la hora de hacer predicciones a escala de cuenca o regional. Las líneas futuras de trabajo dependerán del nivel de reducción de la recarga que se necesite para la mayoría de los sistemas de aguas subterráneas, así como de las dificultades que esto suponga.

Keywords Groundwater recharge · Land use · Salinalization · Australia · Groundwater management

Introduction

Estimation of groundwater recharge is important for salinity studies and efficient groundwater-resource management. In regions where water supplies rely heavily on groundwater, knowledge of natural recharge is important for quantifying safe yields of aquifers to avoid unacceptable declines in water tables (Bouwer 1989; Sophocleous 1991). Understanding recharge under different land uses is generally not required to estimate the total recharge to the aquifer, except where different uses lead to substantial differences in recharge, e.g. irrigation and forests. The story is different in many areas of southern Australia, where dryland salinity occurs. Dryland salinity and the associated rising water tables have caused development of large areas of saline land, increased salinities in streams, and degradation of roads, urban infrastructure, and environment (NLWRA 2001). Because increased groundwater recharge has caused dryland salinity, it has generally been assumed that the reversal or control of dryland salinity can be effected by changes in agronomic practices that lead to sufficiently low recharge. Indeed, if the overall catchment recharge can be decreased to below the ability of the groundwater system to drain, eventually groundwater levels would lower. In the salinity context, it has become important to understand how changing land use affects groundwater recharge and then how groundwater levels respond to this change. This paper reviews the understanding of the first part (the relationship between land use and recharge) and the methods to investigate this relationship within a dryland-salinity context.

For the purposes of this paper, the following distinctions are made:

1. *Deep drainage* is the flux of water that moves past the root zone of vegetation. Deep drainage becomes recharge only when no impeding layers exist that would prevent water from moving down to the groundwater system.
2. *Recharge* is the amount of infiltrated water that reaches a specific groundwater system.
3. *Potential recharge* becomes future recharge. Where a change of land use occurs, a time delay occurs for the recharge associated with the new land use to reach the water table (e.g. Jolly et al. 1989).

This paper largely focuses on deep drainage, although the issue of impeding layers is raised throughout.

Land use and, in particular, vegetation, affect deep drainage in various ways:

Root distribution:
The root zone acts as a buffer in reducing recharge. A deeper root zone tends to retain more infiltrated rainfall, thereby allowing more time for plants to use the water and hence less deep drainage.

Perenniality:
In dryland agriculture, total plant water use depends primarily on the temporal distribution of both active green leaf area and rainfall. The period of evapotranspiration from annual plants is restricted to the growing season, and hence annual plants are unable to use rain that falls outside the growing season (Nulsen and Baxter 1982). Perennial plants generally use more water than annuals because they keep their leaves green and actively transpire for much longer. In addition, perennial plants have deeper roots and explore a much larger volume of soil than annual plants.

Rainfall interception:
Part of the rainfall intercepted by vegetation is evaporated directly to the atmosphere and is called interception loss. The intercepted rainfall may be retained on leaves, flow down the plant stems to become stem flow, or drop off the leaves to become part of the throughfall. Several studies show that interception losses range from 20–40% of annual gross rainfall in temperate coniferous forests (Zinke 1967), but the magnitude is much smaller for short crops and pasture on an annual basis.

Leaf area:
The amount of water that a plant transpires is related to its leaf area. Leaf area index (LAI) is commonly used to describe the total leaf area of a canopy. LAI affects the

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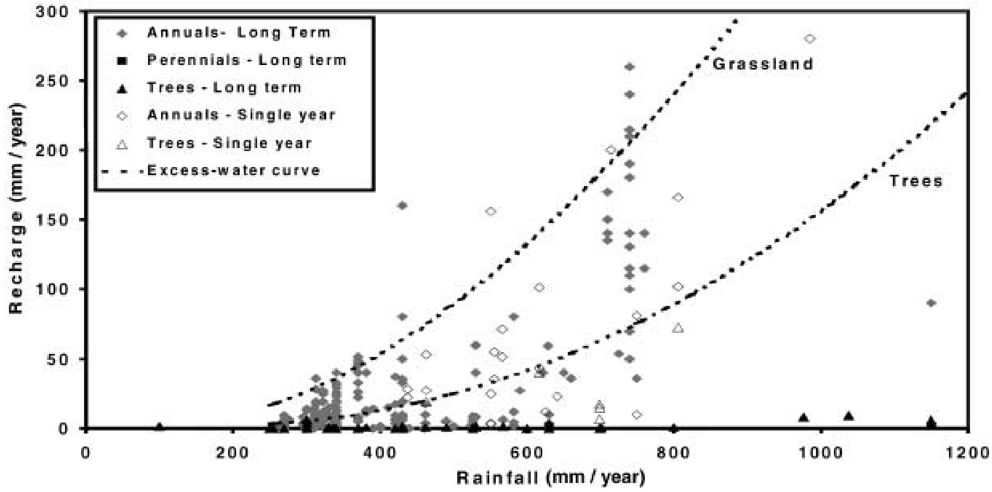

Fig. 1 Data from recharge studies compiled by Petheram et al. (2000). The *dashed lines* represent the rational functions for excess water for forests and grasses in Zhang et al. (2001) and hence a theoretical maximum for recharge measurements

interception of light and rainfall and defines the canopy area available for transpiration. When available water for plants is not limiting, transpiration increases with leaf area until canopy closure occurs. (e.g. Ritchie and Burnett 1971, for cotton and sorghum). Plants could develop smaller leaf area and hence transpire less water for various reasons, such as poor nutrition, plant disease, water stress, and salinity.

Microclimate effects:

Not only do plants respond to changes in their environment, they also modify the environment through microclimate effects. Plant canopies intercept radiation and rainfall and modify the wind profile, turbulent transport, and distribution of temperature and humidity in the canopy. These processes affect photosynthesis and plant growth and influence the hydrologic processes of the system by changing the partitioning of rainfall into runoff and evapotranspiration. When the vegetation structure is complex, as in the case of multistorey forest, interactions occur between overstorey and understorey in terms of radiation, soil water, and nutrients. Some studies report that evapotranspiration from an understorey is sometimes a substantial proportion of the total canopy water use (Tan and Black 1976). Studies also show that evapotranspiration from forested catchments is generally larger than that from cleared or pastured catchments (Dye 1996).

Access to groundwater:

In some areas, the natural vegetation has adapted to channel water more deeply into the soil profile or even into the groundwater; such vegetation uses the water at some time after the infiltration/recharge event. In areas with shallow water tables, this process occurs irrespective of the type of vegetation. The availability of shallow groundwater not only allows vegetation to survive during dry periods but also helps increase leaf area and water use. The extent to which groundwater is used is strongly influenced by salinity.

Plant rotations:

In many situations, a rotation of land use between annuals, perennials, and fallow sometimes occurs. A strategy for capturing more deep drainage under a predominantly annual rotation is to occasionally use a deep-rooted perennial to 'mine' deeper soil water.

Spatial patterns of land use:

Land use is obviously not always homogeneous across a catchment. A strategy for reducing recharge across the catchment is to target low-recharge land use at the high-recharge areas. Another is to use deeper-rooted vegetation to intercept water moving laterally across a low-permeable horizon or to have roots grow laterally under shallow-rooted vegetation to intercept vertically moving deep drainage.

Petheram et al. (2000) have collated the results of recharge studies from across Australia (Fig. 1). The results show that, as expected, recharge under trees is much less than under annual and perennial crops and grasses. Another finding is that so few measurements were made under perennials that determination of any clear differences between perennial crops and grasses and annuals is impossible. Certainly, the lack of measurements means that any sophisticated analysis based on theoretical understanding is beyond the dataset.

If biological options are to be successful in the management of salinity, a change in land use over a large area is needed in order to decrease the overall catchment recharge substantially. Thus, an understanding is needed of how land-use changes affect recharge over large areas. As is shown later, many of the techniques for comparing recharge under different land uses estimate recharge at points in the landscape, and results need to be interpolated between these points. The cost of these techniques often prohibits their use across broad areas. Hence, they need to be targeted where the agronomic option is most likely to have the required impact on recharge. Some benefit would result from an improved ability to provide

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Table 1 Techniques for measuring the impacts of land-use change on deep drainage and/or recharge

Method		Scale of measurement		Depth of measurement	Advantages	Disadvantages
		Spatial	Temporal			
Physical soil methods	1. Soil-flux meter	Point	~1–3 years	Root zone	– Understand processes in root zone	– Labor-intensive
	2. Zero-flux plane					– Difficult to compare different land uses
	3. Darcy's law					– Not good for remote sites
	4. Lysimeter				– Compares land uses	– Labor-intensive – Difficult for semi-arid areas – Difficult for remote sites
Soil Tracers	5. Chloride	Point	Historical average	Unsaturated zone (i.e. below root zone)	– Applicable to remote sites	– Requires long-term land use
	6. Tritium and ^{36}Cl				– Not as labor-intensive as other methods	– Does not give good understanding of processes
	7. Bromide					
8. Piezometeric rise		Catchment	Event	Water table	– Measures actual groundwater response – Applicable to remote areas – Not as labor-intensive	Difficult to distinguish effects of land use
9. Ratio of hydrograph amplitudes		Paddock	Event	Water table	– Distinguishes land-use effects – Advantages as above	Sometimes difficulty in isolating effects of land use

predictions, albeit crude, of the impacts of different land uses on recharge in different landscape elements, without substantial fieldwork. Such a predictive framework would enable a 'first guess' as to which options are likely to be viable and how best to target further efforts.

The achievement of such a predictive framework requires interpolation or interpretation of the results of previous field studies in some sensible fashion. Difficulties abound. For example, on the basis of theoretical understanding, one would expect deep drainage to be less under perennial crops and grasses than under annuals, but the Petheram et al. (2000) dataset shows that insufficient data exist to determine whether deep drainage is low enough to reverse groundwater trends over large areas of Australia. Also, even if further measurements were to be obtained, spatial variability of deep drainage (Cook et al. 1989) under both annuals and perennials is likely to mask differences. To better understand the difference in water use by the various plants, a better understanding is needed of the causes of the spatial variation and of the reasons for the variation.

Soil-vegetation-water models may be able to partially account for some of the variation by incorporating the impacts of different vegetation characteristics (e.g. rooting depth and perenniality), soil characteristics (e.g. water-holding capacity and permeability), and climate (e.g. rainfall patterns). Petheram et al. (2000) only considered studies in which either recharge or deep drainage was directly measured. In various studies, recharge is inferred indirectly from modelling, together with some field data. The results of modelling studies could add to the field dataset as well as explain some of the variation. Before doing so, however, an understanding is needed of the modelling outputs, the degree to which modelling explains the variation, and the practicality of using modelling as an interpolation or extrapolation tool outside of the research plot. For this paper, measurement approaches are reviewed (see Table 1) as they relate to land-use impacts and dryland salinity, and the potential for modelling to add value to these measurements is evaluated. To illustrate concepts, case examples are described from the Mallee region of southeastern Australia, using modelling in different ways.

The Mallee region (Fig. 2) is named after the multi-stemmed form of Eucalyptus that originally dominated the region. A brief description of the region is given here, but more details are in Allison et al. (1990). The region is characterized by aeolian, predominantly deep (>30 m) sandy soils and no surface-water drainage. The mean annual rainfall ranges from 250–400 mm and is

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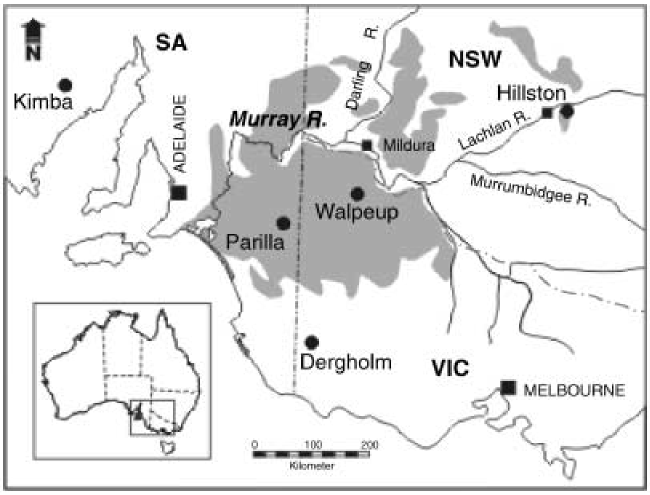

Fig. 2 Map of the Mallee region in the western Murray basin, Australia, showing field sites that are described in case examples

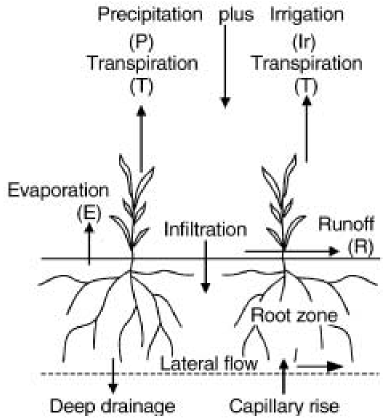

Fig. 3 Diagram of a soil-water balance

generally even in seasonal distribution. The underlying groundwater system forms the western portion of the Murray basin, is regional in extent, and mostly discharges into the Murray River. Studies (e.g. Allison and Hughes 1983) show that recharge under the mallee form of Eucalyptus was less than 1 mm/year. Extensive clearing in the early part of the 20th century increased this recharge by 10- to 100-fold (e.g. Walker et al. 1991). The deep water tables, combined with the low, deep, drainage fluxes, mean that significant time delays (>50 years) occur between the land-use change and recharge to the groundwater system. Currently, water tables are rising over a large fraction of the Mallee (Allison et al. 1990). Lateral pressure transmissions in the regional groundwater systems are much less than the spatial extent of the aquifer. Unless recharge is decreased to near that of native vegetation over a large fraction of the aquifer, water tables will continue to rise.

Issues for the region (Allison et al. 1990) include salinization of:

- the Murray River, the only river in the region and a major water supply;
- land on the lower areas, affecting agricultural production;
- Mallee groundwater resource, important due to the lack of surface streams in the area; and
- environmental values on the Murray River floodplain and lower areas

Objectives of past and current investigations and research are to understand the changes in recharge that have occurred, the timing of the groundwater response (and hence salinity impacts), and the feasibility of any biological recharge reduction. Groundwater-interception schemes have been and continue to be built to prevent salinization of the Murray River. Nonetheless, interest has been shown in longer-term biological recharge-reduction options, such as re-vegetation, inclusion of lucerne (alfalfa) in rotations, and low-rainfall perennial crops. The modelling examples described below help achieve some of these objectives.

Measurement Approaches

This section reviews the capability of different recharge techniques to estimate recharge under a changed land use. Although texts are available on different recharge techniques (e.g. Lerner et al. 1990), these tend to focus on absolute values rather than comparisons under different land uses. Deep drainage is generally a small component of the soil–water balance. For a given period of time, rainfall reaching the ground surface is partitioned into surface runoff, infiltration, and direct evapotranspiration (Fig. 3). Deep drainage occurs when the amount of water available over the time period exceeds the amount that can be used by the vegetation or stored in the root zone. The main difficulty in estimating deep drainage is that because it is often a small term in the water balance, errors in measuring or estimating rainfall and evapotranspiration are likely to be larger than the deep-drainage flux (Lerner et al. 1990). Several methods exist for estimating deep drainage, but all are problematic when used in low-rainfall zones, because of the small deep-drainage fluxes in these areas. Of these methods, only a few are capable of comparing fluxes under different land uses.

No routine direct technique for measuring deep-drainage flux in the field currently exists (Wagenet 1986). Soil-water flux meters exist (Wagenet 1986) but are subject to several problems, including disruption of soil during installation and interruption of flow patterns. Methods using flux meters require a high degree of training, sophisticated equipment, and are expensive in both time and money to install and monitor (Bond 1998). Recent improvements have allowed flux meters to be used under a limited range of conditions (van Grinsven et al. 1988; Hutchinson and Bond 2001), but these are not particularly suited to low-rainfall areas. The comparison under different land uses would require more than one and

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preferably several to be running simultaneously, making such methods problematic. However, anticipated development of more robust methods may radically change this for sub-humid areas.

Other physical soil methods indirectly measure deep-drainage flux. The best known of these is the zero-flux-plane (Bond 1998; Wellings 1984; Cooper et al. 1990; Hosty and Mulqueen 1996; Arya et al. 1975a; Roman et al. 1996). When it exists, the zero-flux plane is the plane that divides the soil into the zone with upward-moving soil moisture and that with downward-moving soil moisture. This downward-moving soil moisture leads to deep drainage. Because the zero-flux plane moves according to alternating wet and dry periods and in response to the growth of roots, the 'root-zone' below which deep drainage occurs is itself ill-defined. The zero-flux-plane method is one of the most direct and accurate techniques available for measuring drainage over short time intervals. However, the method is very labor-intensive, because it requires installation of multiple tensiometers and some means of measuring water content, both at frequent intervals. The method can only be applied when a zero-flux plane is observed within tensiometer depth and range. Even with potential developments, this method would continue to be problematic in comparing deep drainage under different land uses.

Some other physical soil methods are based on using Darcy's Law for the soil zone. Use of these methods requires measurements of hydraulic conductivity and potential gradient at the base of the root zone or deeper. One simplification is to assume that the hydraulic gradient is unity (Davidson et al. 1969; Black et al. 1970; Nielsen et al. 1973; Gee and Hillel 1988). However, for soils with any degree of layering, this assumption is likely to be violated (Bond 1998). Measurement of hydraulic gradient requires the use of two tensiometers (Cassell and Klute 1986). Hutchinson and Bond (2001) developed a method for the routine measurement of soil-water potential gradients for nearly saturated soils. The largest error is in the estimation of hydraulic conductivity at the moisture content or potential at the required depth. This very labor-intensive method is subject to large errors (Allison 1988), which makes measurements difficult to replicate and results in high uncertainty when comparing deep drainage under different treatments. Techniques based on Darcy's Law have been applied to crops (van Bavel et al. 1968; Davidson et al. 1969; Black et al. 1970; Stone et al. 1973; Arya et al. 1975b), grass (Rice 1975), forests (Scholl 1976; Nnyamah and Black 1977; Ahuja and El-Swaify 1979), and natural semi-arid vegetation (Stephens and Knowlton 1986). Enfield et al. (1973) measured water fluxes for conditions greater than 800 cm of water (the upper range of tensiometers) by using psychrometers.

Possibly the best-documented measurement technique for comparing deep drainage under different land uses involves lysimeters. Lysimeters are devices in which a volume of soil, generally planted to vegetation, is placed in a container to isolate it hydrologically from the surrounding soil (Tanner 1967). Lysimeters accurately estimate evapotranspiration and are designed to directly measure a drainage flux at the lysimeter base. When estimating deep drainage that leads to recharge, lysimeters need to be installed in field conditions, i.e., in such a way that they represent the surroundings as closely as possible (van Bavel 1961; Tanner 1967; Allen et al. 1991; Pakrou and Dillon 2000). Drainage under different land uses could be compared if some care were taken to minimize differences between lysimeters. However, some difficulties occur with lysimeters for deep-drainage studies. In dry areas, where the small fluxes lead to large relative errors (Allison et al. 1994), the boundary condition applied at the base of the lysimeter becomes more important. A time delay also exists for equilibrium to be attained throughout the whole soil volume (Kitching et al. 1980), and the drier conditions mean that thermal effects are often significant. In addition to these problems, lysimeters change external conditions on the soil column, e.g., on sloping land they may not allow runoff or sub-surface lateral flow, and in shallow water-table areas, replicating interactions with the water tables is difficult. For these reasons, and because of the substantial time and labor that are required to maintain them, the use of lysimeters in sub-humid to semi-arid conditions is not widespread. Applications of lysimeters include van Bavel et al. (1968; drainage under bare soil and sorghum), Black et al. (1969; drainage under bare soil), Holmes and Colville (1970a, 1970b; pastures and pine plantations), Aston and Dunin (1977; drainage under natural grassland), Kitching and Shearer (1982; deep drainage through chalk under grass), Prunty and Montgomery (1987; deep drainage and nitrate leaching under irrigated corn), Dunin et al. (1991; various), Klocke et al. (1991; drainage under corn), Timmons and Baker (1992; drainage under corn, nitrate leaching studies), Gee et al. (1992, 1994; potential recharge and recharge in a semi-arid climate), Jones and Serne (1995; potential recharge in a semi-arid climate), and Young et al. (1996; potential recharge under bare soil and turf grass).

Most physical soil methods are subject to problems of temporal variability. The nature of the measurements means that experiments take place over a few years. Given that the quantity of deep drainage is sensitive to wet periods and in some areas occurs episodically, measurements are not always significant for the longer period.

Because of the low fluxes in semi-arid and sub-humid conditions, natural tracer methods are more useful than physical methods for deep water-table situations (Walker 1998; Allison and Hughes 1983). In particular, the interpretation of chloride profiles has been one of the most useful techniques for estimating long-term mean annual recharge (Allison and Hughes 1978; Walker et al. 1991; Rose et al. 1979; Peck et al. 1981; Johnston 1987; Sukhija et al. 1988). However, the time for a chloride profile to develop is commonly of the order of decades (Thorburn and Rose 1990; Thorburn et al. 1991). Thus, using the chloride method for comparing land uses re-

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quires that the land use remains relatively constant for several decades. Comparing recharge under different land uses generally requires measurements to be made in different fields with similar soils and crop management (Walker 1998). Experience has shown that deep drainage usually varies over small distances (Kitching et al. 1977; Cook et al. 1989), so unless deep-drainage fluxes are markedly different, the variation due to differences in the fields is often greater than the difference in fluxes under different land uses. Despite the spatial variability of the factors controlling deep drainage, neighboring fields have been successfully used to compare deep drainage where significant differences have occurred in land use, e.g. under agronomic practices as opposed to land under natural vegetation (Allison and Hughes 1972). Natural-tracer methods have also been used to compare agronomic practices where long-term rotation studies have been made (O'Connell et al. 1995; O'Leary 1996). Unfortunately, not many of these long-term trials exist. For irrigation areas where drainage fluxes are higher and hence time scales are shorter, chloride methods have been used in the same field (Thorburn and Rose 1990).

For similar reasons, the use of artificial or historical tracers is often difficult in low-rainfall areas. Because the mean residence time within the root zone for non-volatile tracers is often decades, land use needs to remain constant for a long period of time for the technique to be used. Hence, artificial tracers are generally used in areas where deep-drainage rates are likely to be high (e.g. Jury et al. 1982; Rice et al. 1986; Sharma et al. 1987; Zimmermann et al. 1967). Historical 'bomb' tracers such as tritium and chlorine-36 have the advantage over artificial tracers in that they were deposited in the late 1950s–early 1960s, but in the Australian context they have little advantage over normal chloride as a tracer. Tracer methods for estimating changed deep drainage upon land use change are applicable to recharge rates as low as 10 mm/year (Walker 1998).

Inferring recharge from groundwater (hydrograph) response (Armstrong and Narayan 1998) has the main benefit that this record integrates all the processes occurring in the unsaturated zone. However, groundwater response generally reflects recharge from a large area, so it is difficult to infer the recharge contributed by a particular land use, unless most of the catchment is covered by that one land use. Using these techniques to compare recharge in catchments of different land uses is susceptible to errors due to spatial variability in catchment behavior. Comparing recharge under different land uses by inference from groundwater response (e.g. Colville and Holmes 1972; Loh and Stokes 1981; Brinkley et al. 1997) has only been done where the differences in recharge are high (e.g. resulting from trees versus annual vegetation).

The above provides a very brief overview of field methods that are applied to estimate the difference in deep drainage or recharge under different land uses. In summary, the following points are made:

1. Most of the methods provide point measurements of deep drainage. Results show that a high degree of variability of deep drainage occurs even within a field (Cook et al. 1989), let alone over a landscape unit or region.
2. Most methods are both labor-intensive and costly. Thus, conducting studies in remote regions or replicating studies to overcome the issues of spatial and temporal variability is difficult. The most accessible of the methods for remote areas or replication are the soil-tracer methods.
3. Most of the physical soil methods measure deep drainage or recharge for the period of the study, often two or three years. Given the likely inter-annual variability of deep drainage, a method to extrapolate these measurements to estimate long-term mean annual recharge is required.
4. For most of the physical soil or water-balance methods, it is difficult but necessary to focus on that small fraction of water that becomes deep drainage.
5. Most of the methods are more suited for obtaining a value for recharge rather than being able to distinguish recharge rates under different land uses. Of all the methods, the lysimeter is most suited for comparing the effects of different land uses.
6. Most soil-tracer methods do not provide information on the physical processes that explain the differences in recharge rates. An approach is required to correlate measurements with attributes that may be measured over a larger area.
7. For all of the methods, piezometric monitoring and groundwater analysis are required to provide a prediction of likely groundwater response and a better estimate of recharge at the scale of the groundwater system.

Bucket Models – Simple Modelling Approaches

Modelling of deep-drainage processes at the plot scale has been used as a way to overcome some of the difficulties mentioned in the previous section and increasingly to help determine the impacts of different land-use options. Modelling is useful in various ways:

- To objectively analyze climatic data in order to determine in which areas certain land-use options will always be ineffective. For example, if the contribution to recharge of summer storms is significant or if the continuous drainage in winter is dominant, these conditions have implications for the type of land use that would reduce recharge.
- To analyze which factors are important in determining recharge, so that results can be transferred from one field area to another with only limited additional field work.
- To estimate long-term impacts from short-term field trials by allowing for the natural climate variability.

Modelling also performs a goal-setting and educational role by forcing users to think through various 'what if'

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situations, helping them to set priorities, and defining questions that they should be asking.

In most cases, models have been developed for purposes other than estimating recharge. These include modelling components of the hydrological balance; fluxes of water, salt, nutrients, and contaminants in soils; crop growth; and transfer of water from the land surface to the atmosphere. Field experiments have been conducted for agronomic purposes that measure temporal patterns of soil water. These experiments have been designed in such a way to minimize spatial variability between plots for the purpose of investigating crop growth and water use, nitrate use and leaching, disease, etc. More recently, such plots have been commonly modelled using water balance as the basis. Given the small fraction of the water balance that is deep drainage, modelling does not necessarily produce sensible estimates for deep drainage without measurements of parameters directed toward that aim. In some instances, the estimates of the deep drainage were originally the component of the model that dealt with the accumulation of the residual water-balance errors from the other components (Holmes and Colville 1970a; Carbon et al. 1982).

To better understand the efficacy of modelling for recharge purposes, an understanding of the different types of models for recharge estimation is needed. The simplest mathematical representation of deep drainage and recharge is a bucket. Bucket models are generally used where a threshold exists above which the variable of interest increases. Empirical (statistical) relationships obtained from field data are relatively rare but do show such a threshold relationship. Field examples include localized catchments where groundwater discharge into streams is measured, or places where recharge is inferred from piezometric fluctuations (e.g. Houston 1990). The simplest regression developed from these is:

$$R = \alpha(P - P_{\mathrm{thr}}) \tag{1}$$

where α and P_{thr} are fitted parameters, P is the annual rainfall, and R the annual recharge. This relationship suggests that a threshold annual precipitation exists above which recharge increases. Numerous variations of this relationship are known. The difficulty with empirical relationships is that they do not provide any predictive framework should land use change, nor do they permit transfer of results to another catchment without going through another calibration exercise.

Bucket models partially overcome this limitation. Such a model is schematically represented in Fig. 4, where the bucket is conceptualized as the water capacity of the root zone across the catchment. The bucket fills with infiltration and empties through evapotranspiration. When the soil infiltration exceeds loss by evapotranspiration to the extent of filling the bucket, overflow (deep drainage or runoff) occurs. In the simplest form of bucket model, all excess water (deep drainage and runoff) is considered as deep drainage. The only input data required are daily rainfall and daily potential evapotranspiration, combined with a suitable method of calculating

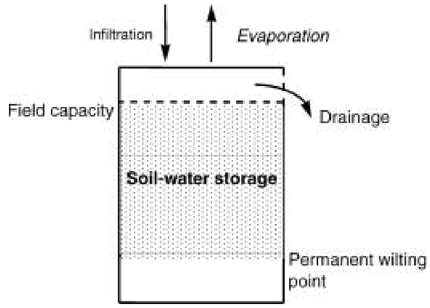

Fig. 4 Diagram of the bucket model

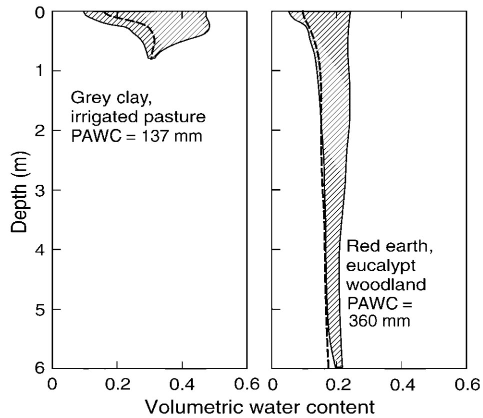

Fig. 5 Plant Available Water Capacity (PAWC) for two soil types under different plants (adapted from Greacen and Williams 1983). The *shaded area* represents the envelope of water contents between the wettest and driest times of year

actual evapotranspiration and the available water capacity of the soil within the root zone. The estimates of deep drainage are sensitive to this last parameter, illustrating the need to measure and understand this. Water capacity can be fitted as above to field data, but to be able to transfer the model outside of the experimental catchment, one must conceptualize and estimate this parameter a priori.

The most common assumption is that the bucket represents the Plant Available Water Capacity (PAWC), which in broad terms is the difference in the water held in the root zone between the wettest and driest times of the year. The PAWC is determined by the dynamic interaction between soil, plant, and its environment (Greacen and Williams 1983) and is mainly a combination of the rooting depth and soil water-holding capacity, i.e., the amount of water held by a soil between an upper limit (*field capacity*) and a lower limit (*permanent wilting point*). For example, for a *red earth* under eucalypt woodland with a deep profile, the PAWC is about 360 mm, although its water-holding capacity is relatively low (Fig. 5); for a *grey clay* under irrigated pasture, the profile is relatively shallow with high water-holding capacity, and the PAWC is only 137 mm. Often the soil water-holding capacity does not vary much between soils, and the PAWC is more sensitive to rooting depth.

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For example, Tennant (1976) shows that the PAWC of wheat in five different soils depends more on the rooting depth than it does on the soil hydraulic properties. The depth and distribution of plant roots are affected by factors such as physical barriers, chemical barriers, and fertilizer distribution (e.g. Taylor and Ratliff 1969; O'Connell et al. 1995). The amount and rate of water that plants extract from soils also depends on rooting density, the physiological ability of the plant to increase its water suction, and soil hydraulic properties.

In the bucket model, deep drainage occurs when, over a period of time, too much rain falls to be able to be transpired by vegetation or to be stored in the root zone for later evapotranspiration. The two extreme cases of this are as follows. The first is in situations where monthly rainfall exceeds potential evapotranspiration for several months, and hence more-or-less continuous drainage occurs over this time. The main plant water-use strategy used to reduce deep drainage is to increase the soil-water deficit at the start of this period (empty the bucket), or to use deep-rooted vegetation (increase the size of the bucket). The second is in an extreme episodic event, when enough water infiltrates to exceed the soil-water deficit irrespective of antecedent conditions. Zhang et al. (1999d) showed that deep drainage in the semi-arid Mallee region of southern Australia is episodic, and 10% of annual deep drainage events contribute over 85% of long-term totals. Episodic recharge (Lewis 1997) therefore has the potential to reduce the effectiveness of land-management options in controlling recharge. Only one water-use strategy is able to reduce recharge, i.e. to use deep-rooted perennial vegetation. The two extremes represent the wet Mediterranean climate and the semi-arid zone.

Between these two extremes are situations where climate variability means that on average potential evaporation exceeds rainfall during some months and during others rainfall for that month exceeds potential evaporation. Modelling offers a good opportunity to objectively analyze climatic data to identify the months in which most recharge occurs and which climatic patterns lead to this condition. This process enables better testing of how well plant-transpiration patterns match seasonality of rainfall.

Despite capturing the key processes in deep drainage, the simple bucket model does not include some important processes that would be necessary in order to be robust over a range of situations. These difficulties include the lack of distinction between surface runoff and deep drainage, and the exclusion of low-permeability sub-soil constraints. Additions to the bucket model to overcome these limitations lead to a more complex deep-drainage model, while still retaining the concept of the single bucket (see Fig. 6).

Table 2 shows the main complex water-balance models that are used in Australia for the purpose of water-balance modelling, contact details, references etc. These models all address many of the land-use interactions that lead to modified deep drainage.

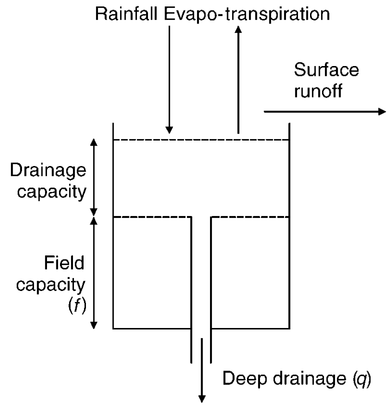

Fig. 6 Diagram of the bucket model with drainage constraints. In addition to the previous conceptual model, runoff is included (determined by a curve-number or equivalent technique), and deep drainage is constrained by subsoil hydraulic permeability

The simplest way to partition runoff and deep drainage is to use the curve-number technique developed by the USDA Soil and Conservation Service (SCS). Models such as PERFECT (Littleboy et al. 1989) and APSIM (McCown et al. 1996) use this technique. The curve-number method allows prediction of runoff from daily rainfall, and this approach is useful for some practical applications where sub-daily rainfall data are not available. Runoff can also be predicted using algebraic infiltration equations. Some of these equations are purely empirical, requiring parameters to be derived from measured infiltration. Others were developed by applying mechanistic flow equations using simplified boundary and initial conditions. The Richards equation is another alternative for deep drainage-runoff partitioning in water-balance models such as SWIM (Ross 1990b) and WAVES (Zhang and Dawes 1998), which are discussed later.

Whereas a bucket model does capture the key processes governing deep drainage, it does not necessarily provide enough detail to analyze the impacts of different land uses on deep drainage. The model largely treats the plant through its rooting depth but fails to capture the dynamics of growth or other plant factors, such as pereniality, interception of rainfall, leaf area, microclimate effects, and access to groundwater or plant rotations, all of which affect deep drainage in some way. To objectively analyze these factors, a more complex model must be used that incorporates these factors. However, it is often difficult to determine parameters even for the bucket model and its adaptations. Unless further data are available, little purpose is served by going to a more complex model to attempt to obtain a better estimate of recharge or deep drainage.

Bucket models commonly used in Australia include WATBAL (Keig and McAlpine 1974), AgET (http://www.agric.wa.gov.au/progserv/natural/AgET/), early versions of PERFECT (Littleboy et al. 1989), and APSIM (McCown et al. 1996).

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Table 2 Plot-scale models

Name	Purpose	Type	Target use	Contact and training	References
Single-layer bucket model	Analysis of climate data with the aim of identifying rainfall events that are likely to lead to deep drainage and the effects that different soils and plants may have on deep drainage, through modification of the bucket size and/or the magnitude of evapotranspiration	Empirical model	Educational and for initial analysis of data sets	A spreadsheet containing the simple bucket model is available free of charge by contacting CRC for Catchment Hydrology (crcch@cbr.clw.csiro.au). Training is not required. Also visit http://www.clw.csiro.au/products/bucket. For further information, contact Lu Zhang at lu.zhang@cbr.clw.csiro.au	Scotter et al. (1979)
PERFECT	To predict the effects of climate, soil type, crop sequence, and fallow management on the water balance, and erosion productivity of cereal-growing areas of the subtropics	The overall structure of the model is physically based, but individual processes are represented by empirical relationships	Developed as a research tool, but an educational version of the model is now available. Although designed for the subtropics, the model has also been successfully validated and applied in semi-arid areas	The model, including source code, is available free of charge. Training can be organized. For further information, contact Dr. Mark Littleboy, NSW Department of Land and Water Conservation, PO Box 189, NSW 2620. Tel.: (02) 6297 6477	Littleboy et al. (1992)
SWIM	To improve the management of soil water and nutrients in order to enhance environmentally sustainable production system	Physically based process model	Research scientists, university lecturers, and consultants	http://www.clw.csiro.au/products/swim. For further information, contact Dr. Keith Bristow, CSIRO Land and Water, PMB, PO Aitkenvale, Qld 4814; Tel.: (07) 4753 8596; Fax: (07) 4753 8650; keith.bristow@tvl.clw.csiro.au	Verburg et al. (1996)
APSIM	A comprehensive simulator of biophysical aspects of farming systems. Equal emphasis is placed on production activity in relation to management, the fate of the soil resource, and losses of water and nutrients beyond the farm. Focus of APSIMv1 is single-point simulation, whereas APSIMv2 provides a multi-point simulation capability	A modular framework that links a suite of biophysical modules of plant, soil, and environment processes with a suite of management and operations modules	Various interfaces provide access to APSIM simulation capability for a diverse range of users, including researchers, farm advisers, agribusiness, farmers, and policy analysts	APSIM is made available under license, which protects software integrity and manages legal liabilities. The license defines the purpose of application and outlines any relevant support and/or development plans. Details of APSIM and further contact information can be found at http://apsim-help.tag.csiro.au	McCown et al. (1996)
WAVES	To simulate energy, water, carbon, and solute balances of a one-dimensional soil-plant-atmosphere system. It can be used to predict plant-growth responses and recharge under different land/vegetation management options	Physically based process model with numerical bookkeeping approach	Research scientists, graduate students. Research with provision of model information to land managers, planners, and extension staff	The WAVES model and documentation can be found at http://www.clw.csiro.au/waves. Training can be organized. For further information, contact Warrick Dawes, CSIRO Land and Water, Christian Building, PO Box 1666, Canberra 2601; Tel.: (02) 6246 5751; Fax: (02) 6246 5800; warrick.dawes@cbr.clw.csiro.au	Zhang and Dawes (1998)

Example 1: Application of the Bucket Model – Correlating Recharge with Soil Texture in the Mallee Region

In the Mallee region, measurements of deep drainage using the soil-chloride method show that deep drainage is correlated with the clay content of the top 50 cm of the soil zone. The silt content of the Mallee soils is generally low (<5%), and the soil moisture at field capacity or drier is closely related to the clay content. Clay content of these aeolian soils is generally less than 5%. Also, subsurface alkalinity means that wheat roots often were only as deep as 50 cm (O'Leary 1996). Kennett-Smith et al.

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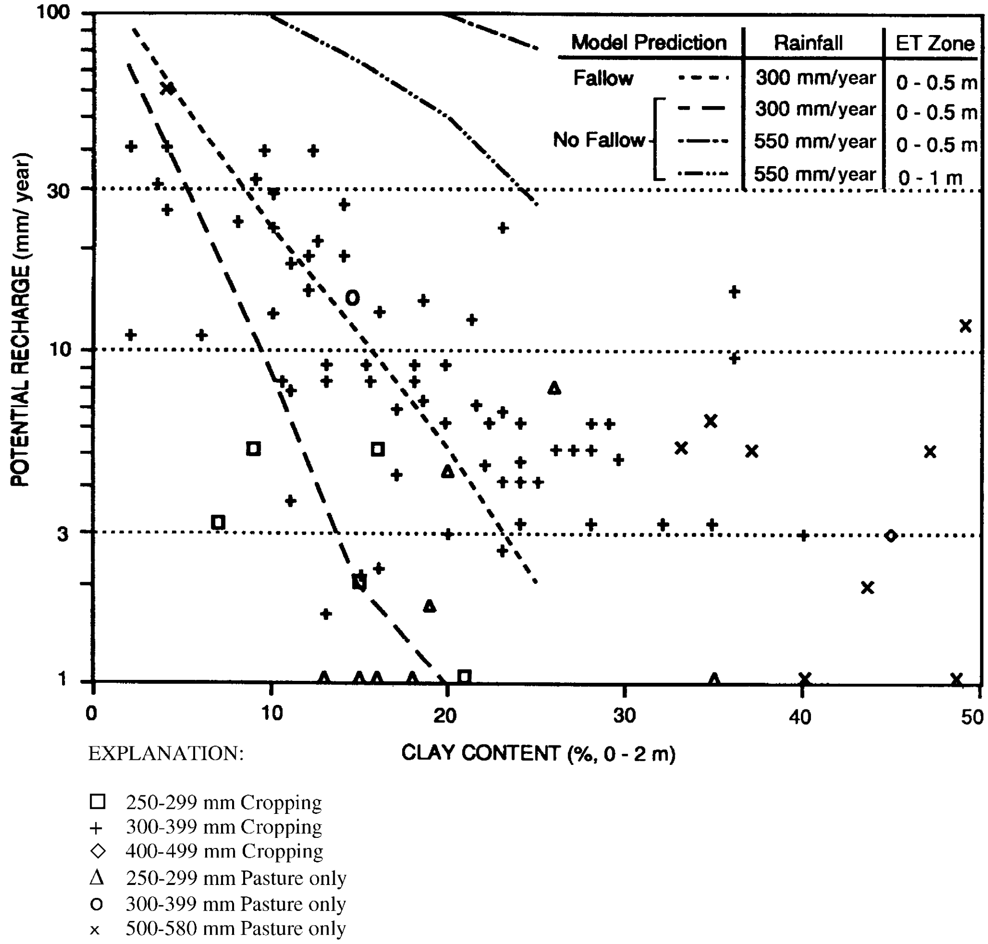

Fig. 7 Predictions of potential recharge from modelling compared to field results for the Mallee region. Measured results are derived from chloride-displacement method. Modelling results were obtained using WATBAL (*dashed lines*) for both fallow and non-fallow conditions for 300 mm/year rainfall and non-fallow conditions for 550 mm/year rainfall but different rooting depths

(1994) used a simple bucket model, WATBAL (Keig and McAlpine 1974), in order to test the hypothesis that the correlation of deep drainage with surface clay content was due to the variation in PAWC. Field measurements of water-retention curves for different clay contents were used to estimate the relationship between PAWC and clay content. A linear relation between Actual Evapotranspiration (AET) and Potential Evapotranspiration (PET) was assumed. Tests show that modelling results are not sensitive to this assumption. When compared to field results, modelling results show that the hypothesis is plausible (Fig. 7).

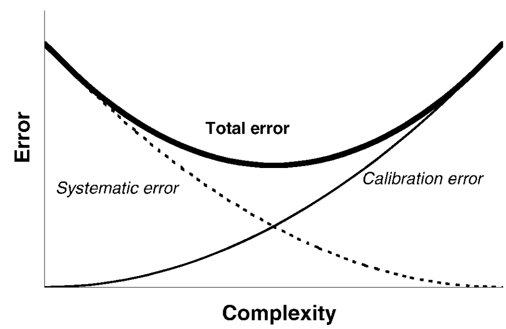

Fig. 8 Diagram showing the variation of systematic and calibration error with complexity

Complexity, Data and Errors

The inclusion of soil and vegetation processes in the deep drainage model allows an increase in the complexity of modelling. However, each new process requires additional parameters and much additional work in the interpretation of results. The aim of modelling is to add value to the field experiments described earlier. In doing so, a balance must exist between the need to simplify those processes with the desire to include the complexity that actually exists. Conceptually, this balance is achieved by starting at a simple level and moving to a more complex one. At each level, one tries to achieve a consistent level of process detail, whilst at the same time better targeting management options with greater confidence.

The aim at all levels is to reduce error and create greater confidence in the results. To do this, reduction must occur in both the 'systematic error' (i.e. the error that results from simplifying assumptions, (e.g. if runoff, macropore flow, etc., are not considered) and the 'calibration error' (i.e. the error resulting from incorrect parameters). Systematic error is reduced by the addition of more processes to the model (increased complexity; see Fig. 8). For a given dataset, calibration error is reduced by fitting fewer parameters (decreased complexity). Hence, conceptually added complexity results in a mini-

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mum of the total error, although in practice these errors are difficult to quantify (Fig. 8). To reduce the total error, more data are needed. Adding complexity does not necessarily increase model accuracy unless appropriate additional data are collected.

The data that are needed to properly calibrate complex models can only be obtained in research plots. Even the simple models should capture the processes that are most critical to recharge, and the data to do should be available. Even for a research plot, the issue of parameterization is difficult and is derived from a combination of the following categories:

1. The use of measured data (*direct estimation*) is ideal, but as the number of parameters increases, this approach becomes impractical or unwarranted. Detailed measurements of saturated hydraulic conductivity for each layer would be difficult enough, let alone measurements of unsaturated hydraulic conductivities.
2. *Model calibration* is the process of inferring model parameter values in order to match detailed measurements.
3. In *knowledge-based estimation*, information is transferred from other sites or surrogate information is used. One should distinguish between model variables that are well defined and measurable *(physical parameters*) and those that are artifacts of the model (*process parameters*). Examples of the former include water-content properties and saturated conductivity, whereas the latter include effective roughness and the leaf-mortality coefficient.

The choice of the objective function for calibration is important. Deep drainage is sensitive to various inputs, such as wet periods, and less sensitive to others. Thus, although a soil water-balance model may be able to replicate soil-water dynamics over a range of soil-moisture values, this capability does not matter unless it can satisfactorily replicate the wet end of the range. The objective function must emphasize these sensitive inputs and parameters.

For the bucket model, the key model inputs and/or parameters include:

1. Rainfall
2. Actual evapotranspiration
3. PAWC
4. Constraining hydraulic conductivity
5. Infiltration

These differ somewhat for the more complex models, but equivalent parameters and/or inputs exist.

1. For research plots, rainfall is usually measured directly, whereas outside of the research plot, rainfall data in Australia are usually only available on a daily basis (Clarkson and Owens 1991). Some developmental methods are available to disaggregate 'daily' rainfall data into sub-daily steps using probabilistic methods, but, realistically, deep drainage models need to only use daily rainfall data. In areas with elevation changes, transfer of rainfall distributions from nearby stations is not appropriate, although programs exist that provide correlations with elevation (e.g. ANUCLIM; Hutchinson et al. 1998).
2. The standard methods for estimating potential evapotranspiration (PET) using the Penman equation (Penman 1948), Priestley-Taylor method (Priestley and Taylor 1972), or pan evaporation rely on data from meteorological stations. Errors in interpolating PET or parameters from which it is calculated are usually less than rainfall. Actual evapotranspiration (AET) is often estimated from PET using a reduction coefficient. The simplest coefficient is one that decreases linearly with soil-water content in the root zone (Kowalczyk et al. 1991). Various relationships have been developed that relate AET to PET including power law and step function; see Mahfouf and Noilhan (1991) for a review.
3. PAWC is measured from soil-moisture profiles at wet and dry times of the year. In some cases, the field-capacity and wilting-point measurements are used with an estimate or observations of rooting depth. Water content is usually highly variable among soils, the difference between wilting point and field capacity is less so (Greacen and Williams 1983). 'Pedo-transfer' functions are used to extrapolate beyond the research plot (Bouma et al. 1986). Obtaining values of rooting depth is more complex, because it is affected by a numerous chemical and physical factors.
4. Hydraulic conductivity is highly spatially variable and sometimes temporally variable. Generally, saturated hydraulic conductivity is measured at a site, and unsaturated conductivity is estimated using functional approaches. Issues include scale of measurement and macropore flow.

Given the errors in measuring even the key processes, it is somewhat surprising that recharge models work at all. Deep drainage forms a relatively small component of the overall water balance and is frequently less than the error in any estimate of actual evapotranspiration. If actual evapotranspiration cannot be measured or modelled to within 5% of real value, what hope is there to model the deep drainage? To understand this, the two extreme cases of climatic conditions are considered.

In areas where episodic recharge dominates, the main rainfall events are so large that they fill the soil store irrespective of antecedent water. The reduction coefficient used to relate PET to AET has a functional form in which AET equals PET when the soil is wet and zero when soil approaches wilting-point. If AET is overestimated, the model predicts that the soil dries more quickly after a deep drainage event than it actually does. The reduction coefficient decreases because of the simulated drier conditions, and the difference between the modelled and real AET decreases. Hence a *self-correcting feedback* exists. Thus, the final estimates of deep drainage are not sensitive to the form of the reduction coefficient (e.g. Kennett-Smith et al. 1994). For areas where continuous drainage occurs, AET is equated to PET over

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the relevant periods (Ridley et al. 1997). Because drainage occurs over a long period of time, soil-storage changes can be feasibly monitored, and errors in PET and the time period for which deep drainage occurs can be minimized. In both these cases, the wet periods are the ones that matter, and over these periods deep drainage is a larger part of the water balance and hence relative model errors are less. Improving the model evaporation sub-components does not necessarily lead to a more accurate result without the appropriate monitoring.

Whether or not models, together with measurement data, produce accurate estimates of deep drainage or recharge is largely hypothetical. In most experiments, the water balance is not closed nor is the modelling. Where continuous soil monitoring and modelling both occur, more constraints are present on the soil-moisture profile and zone of extraction, and deep drainage gets treated less as a residual. Soil-tracer estimates of deep drainage have been used to calibrate models (Kennett-Smith et al. 1994) and compared with piezometric responses (Allison et al. 1990). Very few comparisons are known between independent model output and groundwater responses.

Modelling the Effects of Land Use on Recharge

This section describes how the modelling components of the more complex models simulate the specific land-use factors that affect deep drainage. By increasing the complexity of the plant model, consistency of complexity is needed within the model with other parts of the land use system, such as soils, groundwater, and evapotranspiration. For example, the analysis of root structure and dynamics only makes sense if the distribution of water within soils is handled well.

Root Distribution and Water Uptake

A deeper root zone tends to retain more infiltrated rainfall in the soil, thereby allowing more time for plants to use the water. As a result, deep-rooted plants are generally better at controlling drainage. The degree of control is also dependent on the root distribution, knowledge of which is usually required before water uptake of plants can be modelled. Some models (e.g. HYDRUS; Simunek et al. 1998) use root distribution as an input to model water uptake by assuming negative exponential functions (Ehlers et al. 1991). Most of these models are based on the original ideas of Philip (1957) and Gardner (1960). However, in practice, it is not easy to obtain information on root distribution, because root distribution is affected by factors such as soil properties (both physical and chemical), nutrient availability, shallow water tables, and irrigation regimes. Not surprisingly, morphology of plant root systems is highly variable (Knight 1999). Also, the presence of root material in the soil does not necessarily translate into plant water use, because water uptake is related to root activity in a wet profile rather than root distribution (Hillel et al. 1976; Lafolie et al. 1991). Hence, the more complex models of plant water uptake simulate the root activity as well. Despite the complexity in root distribution, current models of root activity are reasonable at modelling water uptake but not necessarily at modelling actual root material. Plant water uptake in other models (e.g. WAVES; Zhang and Dawes 1998) is modelled by considering the interactions between root distribution and soil-water profile. This method requires no assumption about the distribution of the roots in the soil and is better suited for estimating the effect of salt on plant water uptake (Zhang and Dawes 1998).

Perenniality

In modelling the differences between various vegetation types, a model should be able to represent such changes. One of the disadvantages of the simple bucket model is its inability to simulate changing rooting depth or leaf area due to plant growth. The more complex models allow the plant transpiration and hence carbon assimilation to change through the seasons. This change can be accommodated in various ways, although most involve specifying the growing season as an input. Some production models (e.g. CERES; Ritchie 1985) require user-specified growing season, whereas others (e.g. WAVES; Zhang and Dawes 1998) determine the growing season based on temperature, rainfall, and sowing dates.

Leaf Area

The amount of water that a plant transpires is related to its leaf area. Leaf area can be modelled with various degrees of complexity (Farquhar et al. 1980; Charles-Edwards et al. 1986; Shugart 1984). For example, WAVES uses an integrated rate methodology (IRM) by considering availability of light, water, and nutrients (Zhang and Dawes 1998). In contrast, PERFECT simulates leaf-area development partially based on the functions from the EPIC model (Williams et al. 1983) and is determined from user-defined parameters describing potential leaf-area development and a range of growth-stress indices (Littleboy et al. 1989). Generally, models do not consider all of the factors that may affect plant growth, but if leaf area is incorrect, this error generally leads to errors in the modelled water balance.

Rainfall Interception

Rainfall interception by vegetation depends both on the characteristics of rainfall and on the vegetation cover. However, a well-defined storage capacity exists for a given vegetation type, and any water in excess of this storage capacity becomes stem flow and/or throughfall. The rainfall storage capacity is related directly to the leaf-area index of the vegetation, and generally forest canopies intercept more rainfall than pasture or crops (Dye 1996). Rainfall interception is generally modelled in two ways: statistical methods based on linear regression of interception and gross rainfall, which offer little insight into the process of rainfall interception; or physically based methods using rainfall storage capacity, which consider the key factors controlling rainfall interception.

Soil Layering and Water Movement

The adaptation to the bucket model, discussed in the previous section, allows a permeability constraint. However, soil layering is usually more complex. In cascading bucket models, more than one bucket is used, representing different layers in the soil; an example is CERES (Ritchie and Otter-Nacke 1985; Ritchie 1985; Jones and Kiniry 1986). Generally, four parameters are needed for each layer. Another approach, which treats the soil-water movement as continuous rather than a series of cascades, solves the Richards equation. With increased computer power and more efficient solutions, numerical (finite-difference and finite-element) procedures for solving the Richards equation for infiltration and redistribution have increasingly been used to model the water supply to crops. Models that utilize solutions of the Richards equation to predict drainage, redistribution, and evaporation include the plant-growth/soil-management models NTRM (Shaffer and Larson 1987) and SWATR (Feddes 1982). Recently, a new generation of models utilizes more efficient solutions of the Richards equation, as exemplified by models such as SWIM (Ross 1990a, 1990b) and WAVES (Zhang and Dawes 1998). Several soil parameters are required for each soil horizon, and a root-extraction pattern is required with depth. The solution of the Richards equation leads to calculation of infiltration, redistribution, soil evaporation, plant water extraction, and deep drainage and hence does not need to treat each of these processes separately, as is the case with cascading models. Nonetheless, the basic processes for deep drainage are treated in the same way by both cascading models and solvers of the Richards equation.

Solvers of the Richards equation do not necessarily replicate soil-moisture dynamics more accurately. Apart from issues of calibration for many soils, the pressure of cracking, poor weathering, and self-mulching means that the Richards equation does not simulate the soil-moisture dynamics well. The transport of water and solutes in large pores or cracks is almost instantaneous when compared with transport through the soil matrix. Macropore flow is an important process in some soils, such as cracking clay soils, poorly weathered fractured rocks, and lateritic profiles, as well as those with stem flow, animal macropores, and root macropores. Attempts have been made to incorporate macropore flow into some water-balance models. However, these have been generally empirical and limited by a lack of adequate information on the size, continuity, and geometry of macropores.

Lateral Water Movement

All of the above processes are simulated as vertical processes. However, in many circumstances, water moves laterally. Lateral movement occurs at the surface, where runoff often prevents a significant fraction of rainfall from infiltrating. Water also moves laterally above a subsurface layer. This phenomenon is important when modelling upland areas with high rainfall and soils with contrasting textures. Not all models can simulate this; an example of a plot-scale model that does is WAVES (Zhang and Dawes 1998; http://www.clw.csiro.au/waves/). Catchment models (e.g. TOPOG, Vertessy et al. 1993; http://www.clw.csiro.au/topog/) are needed to capture lateral movement more properly. These are discussed in a later section.

Example 2: Application of A Complex Water-Balance Model – Comparing Different Land Uses in the Mallee Region

Whereas Example 1 illustrates one of the main causes of the variation of deep drainage in the Mallee region, it does not help provide an analysis of different land uses. The studies of Zhang et al. (1999c, 1999d) describe modelling of field experiments designed to analyze such differences. Detailed field experiments were conducted in Australia at Hillston (New South Wales) and Walpeup (Victoria). Two treatments (fallow/oats/wheat/wheat and wheat/wheat/lucerne/lucerne) were grown continuously for five phases of the rotation, and for three years, two treatments (fallow/wheat/field pea and Indian mustard/wheat/pea) were made. Soil moisture, climate, and biomass were measured.

A simple bucket model is unable to fully analyze this suite of data. Therefore, a more complex soil-vegetation model, WAVES (Zhang and Dawes 1998; Zhang et al. 1999b), was used. Soil hydraulic properties were estimated using inverse modelling of the soil-moisture data. Apart from this, the vegetation parameters were obtained by calibration of growing-season length and leaf and root respiration coefficients. Other parameters were obtained by direct field measurement or from literature values.

Annual deep drainage just below the root zone (i.e. 1.0 m depth) was episodic and had significant temporal variations (Fig. 9). At Hillston, deep drainage at 1.0 m depth under the lucerne rotation (RT1) occurred less frequently, and the magnitude was also smaller compared to the medic rotation (RT2). About 10% of annual deep drainage events account for 50–75% of the total deep drainage (Fig. 10a). At Walpeup, rooting depth had significant impact on the episodicity of the deep drainage. When the rooting depth was small (i.e. 0.5 m), deep drainage occurred much more frequently under both the non-fallow (RT3) and fallow (RT4) rotations (Fig. 9b, c). As shown in Fig. 10b, 10% of annual deep drainage events contributed to 20% of the totals; this proportion was increased to 85% by changing the rooting depth from 0.5 to 1.0 m (Fig. 9c). The magnitude of these annual deep-drainage events was as high as 130 mm/year. However, the deep-drainage rates shown in Fig. 9 are annual values, and these values may obscure the episodic nature of the actual deep-drainage process.

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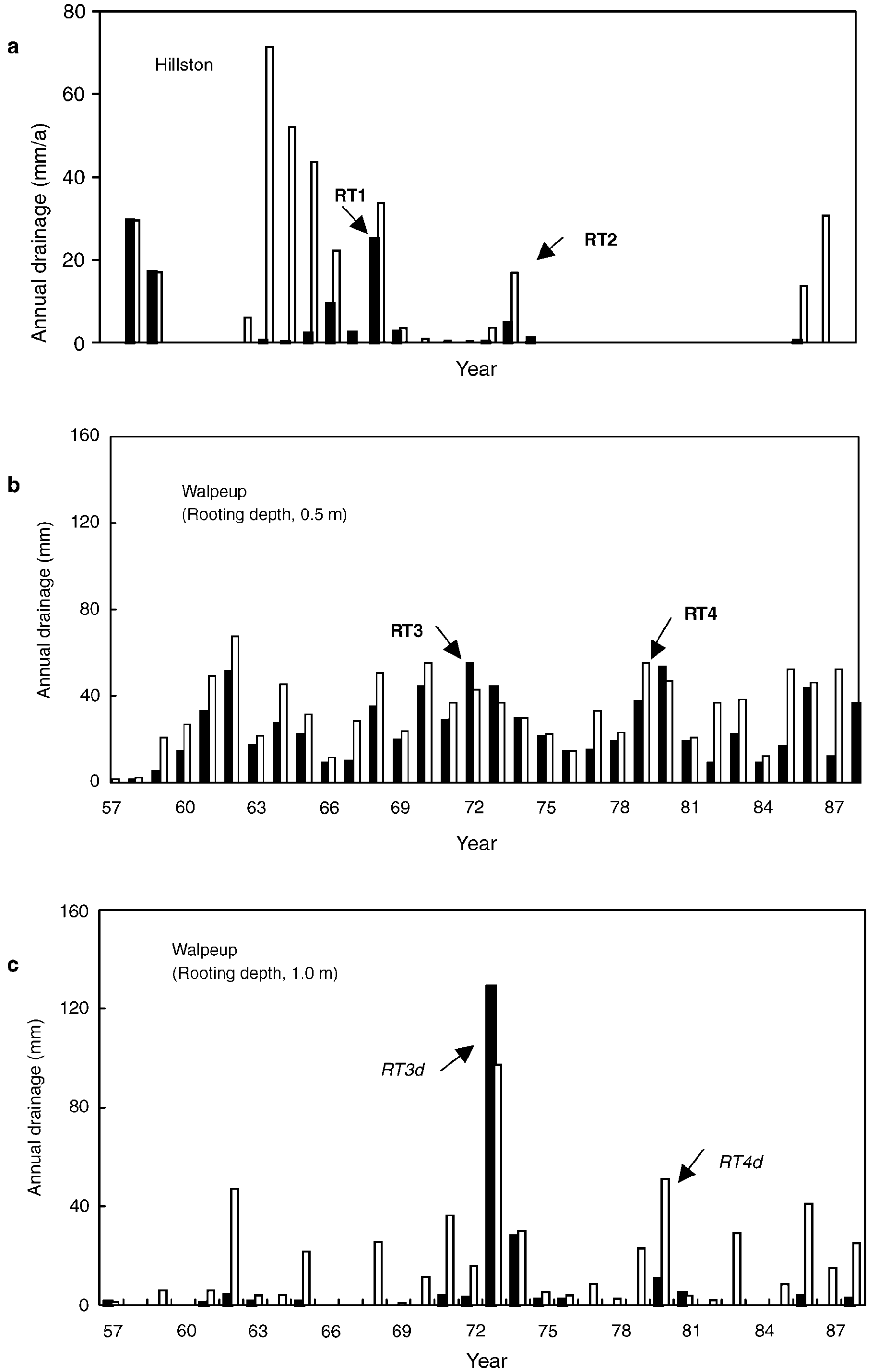
Fig. 9 Simulated deep drainage rates at 1.0 m depth for **a** Hillston under lucerne rotation (*RT1*) and medic rotation (*RT2*), **b** Walpeup under non-fallow (*RT3*) and fallow rotation (*RT4*) with rooting depth of 0.5 m, and **c** Walpeup under non-fallow (*RT3d*) and fallow rotation (*RT4d*) with rooting depth of 1.0 m



The episodic nature of the deep drainage is described by the frequency-distribution function shown in Fig. 10. The use of the lucerne and non-fallow rotations reduces average deep drainage, and these management options also make deep drainage more episodic – that is, deep drainage occurs much less frequently, although its magnitude is still sometimes significant (see Fig. 10). Therefore, agronomic practices are not likely to significantly control episodic deep drainage. For example, annual rainfall in 1973 was 538 mm (i.e. 58% higher than the long-term average), and the annual deep drainage at 1.0 m depth under the non-fallow rotation (RT3) even exceeds that under the fallow rotation (RT4). This difference is because the soil profile under the fallow rotation (RT4) was wetter than that under the non-fallow rotation (RT3), which led to substantially more surface runoff and hence less infiltration. However, this phenomenon only occurs during wet years, and the fallow rotations generally produced more deep drainage at 1.0 m depth. At Walpeup, both the fallow and non-fallow rotations produced similar

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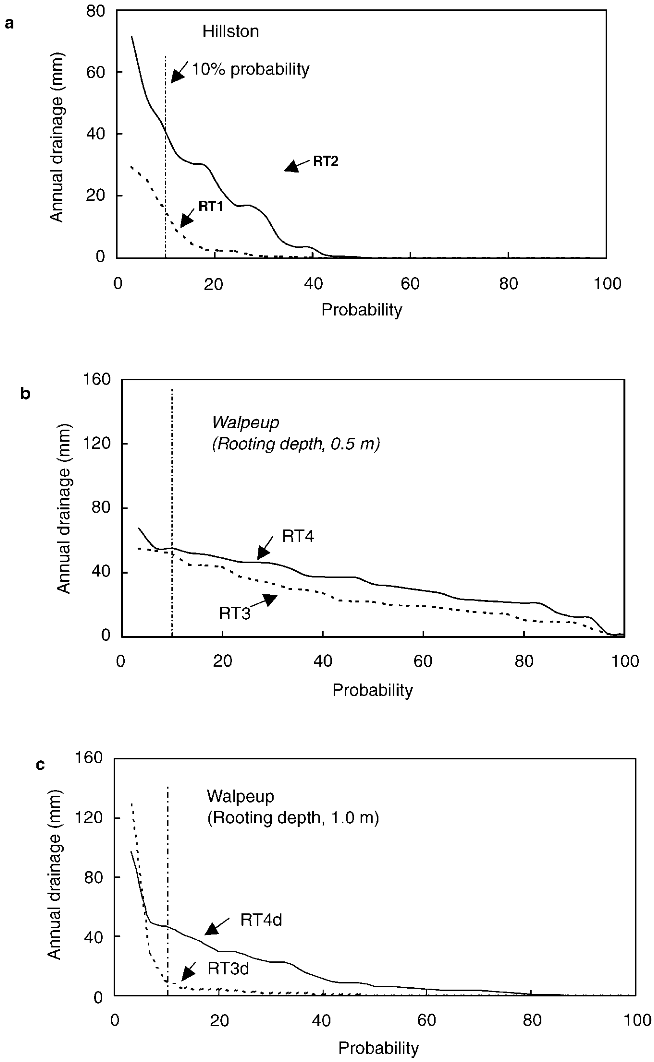

Fig. 10 Frequency distribution of annual deep drainage at 1.0 m depth for **a** Hillston under lucerne rotation (*RT1*) and medic rotation (*RT2*), **b** Walpeup under non-fallow (*RT3*) and fallow rotation (*RT4*) with rooting depth of 0.5 m, **c** Walpeup under non-fallow (*RT3d*) and fallow rotation (*RT4d*) with rooting depth of 1.0 m

annual deep drainage when the rooting depth was set to 0.5 m (Fig. 10b). This result is not surprising, because with such a shallow rooting depth most large rainfall events could penetrate the root zone and become deep drainage. Therefore, deep-rooted plants should be grown in the area for the purpose of recharge control.

Results show that:

- At Walpeup, the shallow rooting depth (30 cm) led to large deep-drainage rates.
- On average, the long fallow time led to an additional 22–37 mm of drainage water.
- 10% of the deep drainage events accounted for 25–85% of the total deep drainage. The magnitude of these annual events is as great as to 130 mm/year. Whereas changes in agronomic practices can reduce recharge, recharge is unlikely to be completely eliminated because of the size of these events.
- Average deep drainage under lucerne was about 30% of that under the medic pasture.
- Any reduction of deep drainage is likely to take decades to affect the position of the water table.

Catchment-Scale Modelling

The measurement and modelling techniques described above are largely appropriate for research plots and some surrounding area. If recharge reduction is to be used for salinity management, land use must be changed over large areas. In any given area, a need exists to predict the whole groundwater response to a change over a large area. At the catchment scale, the potential complexity and importance of the correct conceptual model increases greatly from the plot-scale model, because the model not only needs to include the processes relevant at the plot scale, but also the spatial distribution of properties, interaction between positions in the catchment, and the position and properties of aquitards and aquifers (Hatton 1998).

For those areas where it is feasible to ignore the lateral distribution of water, this complexity is simplified. Recharge is considered vertical and independent of other areas within the catchment. The Mallee region of south-eastern Australia is such an example with deep, permeable soils and a small topographic relief.

Example 3: Interpolating Point-Recharge Estimates to Obtain Regional-Recharge Estimates – A Stochastic Aggregation Approach

Example 1 shows how soil texture explains some of the variability of the point measurements. Cook et al. (1989) examined deep drainage in an area of 40 km^2 and observed that the distribution of deep drainage could be approximated by a log-normal function. This result is similar to results of studies of hydraulic conductivity and infiltration (e.g. Nielsen et al. 1973; Sisson and Wierenga 1981). Deep-drainage data collected from other areas of the Mallee are also consistent with a log-normal distribution. This consistency suggests that within a land unit, deep drainage over a substantial area could be represented as a log-normal distribution, but with the mean and variance changing for the different units. Allison et al. (1990) obtained the mean and variance for each land unit by fitting a log-normal function to the point data. Estimates across the Mallee were obtained by aggregating across land units.

A second important issue in converting point estimates of deep drainage into recharge estimates on an appropriate area-scale is the time lag between land-use change and changed recharge to the aquifer. If, over a given area, a distribution of deep drainage exists, a distribution of time lags also occurs. To overcome this problem, a simple formula for the advance of a ‘wetting front’ has been used that is consistent with data on this scale (Jolly et al. 1989). This use only required the aver-

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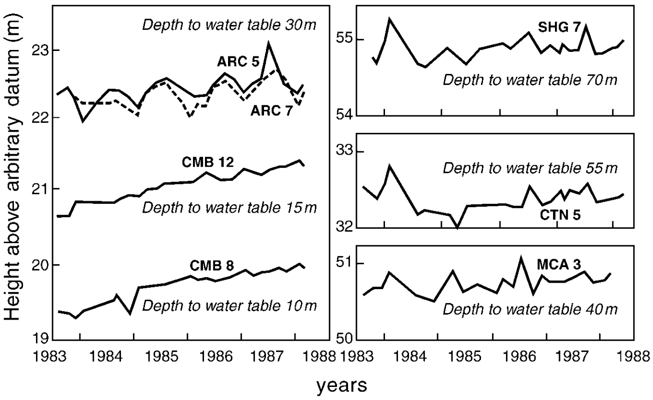

Fig. 11 Hydrographs from the Mallee region

age water contents for pre-clearing and post-clearing conditions and a deep-drainage estimate. A prediction was derived of recharge rate to the aquifer as a function of the time since clearing for agriculture. These time lags range from 40–100 years. Recharge estimates across the Mallee were compared with piezometric records, some of which are shown in Fig. 11. For areas of depth less than 30 m, water tables are rising, whereas those with a clay layer greater than 30 m show no obvious rise. Allison et al. (1990) used these recharge data within a groundwater model to predict future rises in stream salinity arising from past clearing.

Even with the simplification of vertical movement of water in the unsaturated zone, the heterogeneity of the catchment needs to be considered. In the case of the Mallee, many point estimates for deep drainage had already been obtained; this information simply does not exist widely outside of the Mallee. Hence, pressure exists for modelling to be used for other areas. Generally, the spatial distribution of those properties that are required for modelling deep drainage across a large area cannot be determined explicitly. In most cases, components of the catchment are divided into soil landscape units or geomorphic units, and information on these is stored within a GIS. This *disaggregation of the landscape* allows modelling to proceed by treating each unit as homogeneous with known properties. Under the one-dimensional assumption, the plot-scale models are used together with assumed properties of the homogeneous unit to estimate the change in total groundwater recharge due to any major change in land use in the catchment. Hatton (1998) and Salama et al. (1999) argue that this approach is only feasible for a region by applying an a priori leaf-area distribution rather than by spatially distributing properties such as sowing dates, fertility, etc. For their example of the Loddon-Campaspe, Australia, modelled recharge estimates matched independent groundwater estimates (Salama et al. 1999).

In areas of higher rainfall, greater slopes, and lower sub-soil conductivity, lateral redistribution of 'excess' water became more important. Various *distributed parameter* 'catchment' models exist that simulate the lateral redistribution of water. Of these, most do not have the capability to distinguish the impacts of different land use on groundwater recharge. An exception to this is TOPOG, which has the capability to model generic plant-growth and surface-energy balance. The model also efficiently solves for water flow and has groundwater modules. It has now been tested for cropping (Dawes et al. 1997), pasture (Zhang et al. 1999a), and forest (Vertessy et al. 1993, 1996). Such a model may be used to answer the questions of not only how a change of land use affects recharge at that point, but how the groundwater response varies with position of land-use change in the catchment (Hatton 1998).

The difficulties of 'calibration' error also affect these catchment models. It is even more difficult to obtain all the parameters for such a distributed-parameter model than it is for a plot-scale model. In most cases, such models are used in a hypothetical sense, by testing which parameters are sensitive in a given situation and how different processes may interact. This is an important role for both complex plot-scale models and catchment-scale models.

Given the likely variability of properties across the 'homogeneous' units, it is perhaps surprising that there are any sensible estimates at the regional scale. In some studies (e.g. Stauffacher et al. 2000), distributed parameters for one-dimensional models were obtained objectively and not calibrated according to measured groundwater parameters. These models produced deep-drainage estimates that are much greater than the recharge estimates from groundwater modelling. Possible causes for this discrepancy include: 1) The models fail to take into account lateral processes that may occur deeper in the profile, and 2) spatial variability of deep drainage and runoff processes within the catchment occurs, so that deep drainage upslope becomes runoff downslope (interactions between positions in catchment). Most likely, the number of variables in the soil-water models, even with tight constraints on known properties, leads to a large variation in predicted deep-drainage amounts.

Some simplifying patterns occur at the larger scale. An example is the simple relationship between mean annual AET for forested and non-forested catchments with mean rainfall (Zhang et al. 2001). The complement to this relationship is the 'excess water' that leads to overland flow, throughflow, and recharge and hence forms an upper limit to recharge (Petheram et al. 2000). Two associated relations are between leaf-area index (LAI) and transpiration (Hatton et al. 1998), and between LAI and wetness index (rainfall/PET) for native vegetation (Specht and Specht 1989). These relations are built upon experimental data and suggest that the LAI for woody perennial vegetation tends to come into a predictable dynamic relation with the amount of water available. These are examples of so-called 'top-down' approaches, or simple models and relations that are developed at the larger scale and related to a few parameters that are measurable at that scale. The examples given here are explicable by eco-hydrological optimality concepts (Eagleson

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1982; Eagleson and Tellers 1982). The complex models developed from processes at the small scale and related to several parameters are examples of ‘bottom-up’ approaches. At the minimum, the ‘bottom-up’ models should be able to replicate the ‘top-down’ relations, i.e. they should be able to replicate an underlying simplifying relation. Deviations from the simpler relations should be due to second-order effects.

The reduction of recharge to levels comparable to that of native vegetation requires the use of perennials (Stirzaker et al. 2000) and for the LAI to approach the Specht and Specht (1989) limit for native vegetation. If this condition were attained, then a new ‘landscape equilibrium’ would be reached. Evidence indicates that for many groundwater systems the recharge required to avoid land salinization is not much greater than that under native vegetation (M. Gilfedder, personal communication, CSIRO Land and Water, 1999; Clarke et al. 2002). If these low groundwater transmissivities are shown to be more widely applicable to aquifers associated with salinity, then the LAI for native vegetation becomes an obvious target for recharge reduction at the landscape level.

Modelling Spatially Heterogeneous Systems

Reducing recharge over large areas does not necessarily involve homogeneous land use over large areas. One tactic is the targeting of low-recharge options at higher-recharge areas, even at a fine scale. Another is to mix woody perennials with current vegetation types to intercept subsurface water or deep drainage movement beneath the shallow roots of annual crops. An example of the latter is the so-called ‘alley-farming’, which involves planting rows of trees amongst crops or pastures.

The application of process-based modelling approaches to spatially heterogeneous systems, such as alley farming (Lefroy and Scott 1994), requires more knowledge of the below-ground soil and root parameters. The representation of both tree belt and alley (crop/pasture) elements is needed as well as the ‘interface’ zones adjacent to the belts where tree and crop/pasture growth overlap. Where both the tree belts and alleys are very wide (e.g. 200 m; much wider than ‘interface’ zones), the tree belts and alleys can be thought of as separate, one-dimensional, ‘forest’ and ‘crop/pasture’ elements. Therefore, they can be modelled as one-dimensional systems, ignoring the interface zone and using any one of various process-based, empirical, or semi-empirical approaches (e.g. McJannet 1999 with TOPOG). In southern Australia, alley (crop/pasture) widths generally range from 100–200 m, whereas tree belts are typically about 10 m wide. These dimensions imply that the spread of lateral tree roots (20–50 m from the stems) and the associated interface zone is often larger than the belt width.

Theoretical models have been developed that describe water extraction by isolated trees (Landsberg and McMurtrie 1984) and the competition between trees and annual species (McMurtrie and Wolf 1983; Lawson et al. 1995) for water and nutrients. Thus, the theoretical models exist to simulate the interface zone, but they require knowledge of the horizontal and vertical distributions of roots and soil physical properties. The effort and destructive sampling required to obtain these parameters is severely limiting, even using the simplest methods (van Noorddwjik et al. 1995). Also important, but difficult to include in a process model, is information on the vertical and horizontal extraction of water by the trees, the perennial growth patterns of the trees, and the annual growth patterns of the crop/pasture. Lefroy et al. (2001) describe an extremely detailed water-balance experiment undertaken on tagastaste (*Chamaecytisus proliferus*) planted in an alley configuration on deep sands in Western Australia. The authors used the combined techniques of neutron moisture meter (NMM), time domain reflectometry (TDR), heat-pulse sap-flow sensors, and deuterium:hydrogen ratios of groundwater to obtain an estimate of the spatial and temporal distributions of deep drainage beneath belts and within the interface zone. The study illustrates the huge resources that are required to obtain an estimate of deep drainage from spatially heterogeneous systems, even in sandy soils where physical conditions are most conducive to subsurface instrumentation.

Example 4: Top-Down Approaches for Heterogeneous Systems – Deep Drainage Under Alley Farming

Stirzaker et al. (2000) provide some approximate solutions as to where to plant trees for controlling dryland salinity. They partition the soil into zones that are either ‘shared’ or ‘not-shared’ by trees and crops and also introduce the concept of a ‘capture zone’ up to a few meters wide, beyond the periphery of the tree-root zone. Lefroy and Stirzaker (1999a, 1999b) used these ideas to investigate the possibilities for gaining a recharge reduction that is proportionally larger than the land occupied by the trees and at the same time placing trees so that they use the water that is excess to the requirements of the crops.

Ellis et al. (1999, 2001a, 2001b) present and test another ‘top-down’ approach for estimating deep drainage under alley farming. The concept of Equivalent No Recharge (ENOR) is introduced to allow an abstract simplification of the root zone of tree belts so that alley farms can be represented as binary one-dimensional systems. This approach negates the need to consider a separate interface zone, by estimating an equivalent width of land (within which recharge is zero, i.e. an ENOR) that a tree belt would occupy. As mentioned in the previous section, the leaf-area index (LAI) of local native vegetation is predictable by a simple relationship with climatic factors. With this leaf area, the deep drainage under native vegetation is effectively zero, when compared to the crops and pastures normally grown in the area. Roots of tree belts often occupy a width of land larger than the

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belt crown width. This extended capture zone often supports a tree belt with a higher LAI than that of local native vegetation. The ratio of the ENOR to crown width of such tree belts is approximately the ratio of the LAI of the belt to the LAI of the native vegetation. The width of the ENOR (m) is therefore calculated by dividing Lineal Leaf Area (LLA – the leaf area of the tree belt per meter of belt) by the LAI of the native vegetation. For an alley farm comprising multiple, identical, evenly spaced tree belts, the relative recharge reduction imposed by the alley farm is therefore the ENOR width divided by the center-to-center tree-belt spacing.

The method of estimating ENOR from leaf areas was tested on two tree belts and four block edges in South Australia and Victoria. LAI of the native vegetation ranged from 0.56–1.21 m^2/m; LLA ranged from 6.5–71 m^2/m. Predicted ENOR widths in these cases ranged from 25–60 m. Deep drainage was determined along transects (Ellis et al. 2001a) using the chloride method (Allison and Hughes 1978; Walker et al. 1991) and ranged from <1 mm/year beneath the trees to about 7 mm/year outside the tree-root zone. The ENOR method was also tested at a single site using intense water-balance measurements on a belt of trees with an average LLA of 21 m^2/m over 11 months (Ellis et al. 2001b). The maximum error in predicting the ENOR for a tree belt from leaf areas was 20%. Techniques for estimating LLA and LAI for hypothetical alley farms were also developed. The approach requires four above-ground parameters, is scalable from plot to catchment, and can be quickly applied irrespective of soil and climatic conditions.

Discussion

The four examples from the Mallee region illustrate four different models being used for different objectives. The examples show the importance of a clear objective, an understanding of the key processes, and the data appropriate to these. To achieve the objectives, the models must adequately capture the key processes. One model is unlikely to suit all objectives and all situations. A model that is overly complex for the task, if nothing else, takes longer to calibrate and is more difficult to analyze. No added confidence to the conclusions is gained if data are not available to calibrate the more complex model.

The Mallee situation is simpler than most in that excess water moves approximately vertically to the water table. In most areas, surface-water drainage occurs and excess water occurs as overland flow, throughflow, and recharge. Obtaining data that are appropriate to partitioning the recharge and the lateral movements is often difficult. Little point exists in attempting to predict impacts of land use on recharge if the groundwater balance is not well understood. Land-use change is associated with diffuse recharge, and often the impact on localized recharge is not clear.

For the groundwater system underlying the Mallee region, water tables will continue to rise unless recharge is reduced to less than 1 mm/year. No current agronomic practice reduces recharge to a value near 1 mm/year, because of the episodicity of the recharge. Alley farming has the potential to reduce recharge by half, but this approach does not reduce recharge to nearly that of native vegetation without adversely affecting production. Reductions in recharge even slightly may have benefits for stream salinity, provided these occur in the vicinity of the Murray River. The Mallee groundwater system is likely to be similar to other regional and intermediate groundwater systems in that very low recharge rates are required to avoid salinity problems.

Thus, a need probably exists for deep-drainage fluxes that are much lower than current rates in order to control salinity. Of the techniques used to estimate the change in deep drainage under a changed land use described in this review, many would be adequate where a large contrast exists in deep drainage under the two land uses. Where the contrast is small, an experimental design is needed that deals with the spatial variability. This design means conducting experiments that are time-consuming, expensive, and difficult in remote areas. For example, agronomic water-balance or lysimeter studies may be required, together with complex water-balance modelling. These efforts need to be targeted where they can be most effective and as much as possible avoid duplication of field conditions.

On the other hand, where recharge needs to be close to that which occurs under conditions of native vegetation, simple ‘top-down’ targets of leaf-area index are available. These targets are more amenable for use in large areas.

Heterogeneity is an inherent component of land use and landscapes. No methods fully deal with heterogeneity, but some mixture of top-down, bottom-up, and bucket models can answer specific questions in regard to heterogeneity. This review does not discuss in any detail other heterogeneities, such as interactions between groundwater and surface water or modelling the effects of lateral flow over large areas. All of these difficulties affect the ability to sensibly extrapolate water-balance studies.

Conclusions

1. Several techniques are known for estimating deep drainage at a point. Few of them are suited for comparing deep drainage under different land uses. The best of these are the lysimeters and agronomic experiments with a focus on deep drainage, but these are labor-intensive and costly to use. Those more suited to replication and remote field sites (e.g. soil-tracer methods) are prone to errors due to variability in conditions.
2. Modelling has the potential to add value to these studies, and several models now exist for simulation of the soil-vegetation-atmosphere transfer of water. The

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simple bucket models simulate deep-drainage processes with as much confidence as more complex models, but bucket models do not have the capability of analyzing the effects due to different land use, e.g. seasonality and root growth.
3. Models are used not only to compare deep drainage under different land uses but to analyze factors such as soil type, time lags, and episodicity, and for purposes of extrapolation. For any modelling exercise, a clear objective should be identified, the model should incorporate the key processes, and the appropriate data should be available.
4. Use of modelling without any field data, although informative, usually introduces large errors. The deep-drainage term is often a small component of the overall water budget. Although the deep-drainage term is generally estimated with greater confidence than a simple error analysis would suggest, this advantage is negated without some field data.
5. A collation and analysis of water-balance studies is required. Further work in this area should be targeted (1) to avoid duplication with previous studies, (2) to groundwater systems that may respond to this decrease in recharge to avoid salinity, and (3) to areas where assets need to be protected.
6. More effort is required to better extrapolate from research plots. One approach is to better determine the limiting factors for recharge, such as root constraints, water-holding capacity, aquifer storage, etc., and to place the study in the context of the current total recharge to the underlying groundwater system.
7. The representation of spatially heterogeneous systems such as alley farming is challenging in that it requires extra effort to adequately describe the system in a manner that retains its salient characteristics; but it should not become crippled by the additional complexity of having to consider the extra horizontal dimension.
8. 'Top-down' approaches show some promise in giving suitable information at the regional scale on transpiration and target LAIs for a given rainfall zone, but more experience is required.

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