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Potential deep drainage under wheat crops in a Mediterranean climate. I. Temporal and spatial variability

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Abstract. High rates of deep drainage (water loss below the root-zone) in Western Australia are contributing to groundwater recharge and secondary salinity. However, quantifying potential drainage through measurements is hampered by the high degree of complexity of these systems as a result of diverse soil types, a range of crops, different rainfall regions, and in particular the inherent season-to-season variability. Simulation models can provide the appropriate means to extrapolate across time and space. The Agricultural Production Systems Simulator (APSIM) was used to analyse deep drainage under wheat crops in the Mediterranean climate of the central Western Australian wheatbelt. In addition to rigorous model testing elsewhere, comparisons between simulated and observed soil water loss, evapotranspiration, and deep drainage for different soil types and seasons confirmed the reasonable performance of the APSIM model.

The APSIM model was run with historical weather records (70–90 years) across 2 transects from the coast (high rainfall zone) to the eastern edge of the wheatbelt (low rainfall zone). Soils were classified as 5 major types: deep sand, deep loamy sand, acid loamy sand, shallow duplex (waterlogging), and clay soil (non-waterlogging). Simulations were carried out on these soil types with historical weather records, assuming current crop management and cultivars. Soil water profiles were reset each year to the lower limit of plant-available water, assuming maximum water use in the previous crop. Results stressed the high degree of seasonal variability of deep drainage ranging from 0 to 386 mm at Moora in the high rainfall region (461 mm/year average rainfall), from 0 to 296 mm at Wongan Hills in the medium rainfall region (386 mm/year average rainfall), and from 0 to 234 mm at Merredin in the low rainfall region (310 mm/year average rainfall). The largest amounts of drainage occurred in soils with lowest extractable water-holding capacities. Estimates of annual drainage varied with soil type and location. For example, average (±s.d.) annual drainage at Moora, Wongan Hills, and Merredin was 134 (±73), 90 (±61), and 36 (±43) mm on a sand, and 57 (±64), 26 (±43), and 4 (±18) mm on a clay soil, respectively. These values are an order of magnitude higher than drainage reported elsewhere under native vegetation. When not resetting the soil each year, carry-over of water left behind in the soil reduced the water storage capacity in the subsequent year, increasing long-term average deep drainage, depending on soil type and rainfall region. The analyses revealed the extent of the excess water problem that currently threatens the sustainability of the wheat-based farming systems in Western Australia.

Additional keywords: secondary salinity, evapotranspiration, crop water use, APSIM, simulation.

Introduction

The replacement of 19 Mha of native perennial vegetation (George *et al.* 1997) by annual crops (7.4 Mha; 4.7 Mha cropped to wheat; Anon. 2000) and pastures has been linked to watertable rise and salinisation in many areas of Western Australia. About 10% (1.8 Mha) of agricultural land is currently affected by salinity and it is suggested that this area may double over the next 25 years (George *et al.* 1997).

Several factors cause watertable rise and salinisation under annual cropping systems. Firstly, annual crops gener-

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Table 1. Measurements/estimates of deep drainage on agricultural land

Soil type	Region	Annual rainfall (mm)	Deep drainage (mm)	Reference
Sand	Western Australia	162–258[A]	44–154	Nulsen (1984)
Deep sand	Western Australia	438–703	114–214	Anderson *et al*. (1998)
Clay loam	South-eastern Australia	469–705	0–112	Smith *et al*. (1998); Dunin *et al*. (1999*a*)
Deep sand	Western Australia	243–496	25–111	Williamson (1973)
Clay loam	North-eastern Victoria	515–901	2–143	Ridley *et al*. (1997)
Sand, sandy loam, clay, duplex	South Australia	740	50–270	Allison and Hughes (1978)
Sand & sandy clay	South Australia	255–580	1–70	Kennett-Smith *et al*. (1994)
Fine & course textured	Western Australia	280–330	6–30	George (1992*a*)
n.a.	Western Australia	n.a.	24–73	Peck *et al*. (1973)
Duplex	Western Australia	386–392	4–28	Gregory *et al*. (1992)

n.a., not available.
[A] Growing season rainfall.

ally develop shallower root systems (<2 m) than perennial native vegetation, resulting in less water withdrawal from deeper soil profile layers and therefore lower water storage capacity before deep drainage commences (Williamson 1973). Secondly, perennial native vegetation can potentially utilise rainfall outside the growing seasons of annual crops (Williamson 1973). Thirdly, 10–37% less rainfall often reaches the soil surface under native vegetation due to canopy structure. This substantial interception can increase direct leaf evaporation during or shortly after rainfall events, causing rates of water loss that exceed potential evaporation (Dunin and Mackay 1982; Greenwood *et al.* 1985).

Deep drainage is often an order of magnitude less under native vegetation than annual crops (Peck *et al.* 1973; Smettem 1998). On agricultural land, drainage can vary substantially between rainfall regions, seasons, and soil types. A list of measured/estimated deep drainage amounts is given in Table 1. All of these measurements/estimates indicate a wide range, and potentially large amounts of excess water, in the annual cropping systems of Western Australia. These high rates of deep drainage are causing ground-watertables to rise, with widespread salinisation and degradation of agricultural land and adjacent native vegetation (George *et al.* 1997).

Drainage measurements/estimates are very specific to site and season, varying from year to year depending on the total amount of rainfall, but also on its seasonal distribution. Extrapolation of field measurements is further complicated by the diversity of soils and crops, and the lack of information on the interactions between crop, soil, and climate variability as they affect water use and water loss. Crop–soil models have been shown to be effective tools in the extrapolation of research findings over time, soil types, and climatic regions (e.g. Keating *et al.* 1995; Asseng *et al.* 1998*a*, 2000; Dunin *et al.* 1999*b*). However, acceptance of outcomes from simulation studies is dependent on the confidence in the models used to predict crop growth, water use, soil water dynamics, and deep drainage.

The Agricultural Production Systems Simulator (APSIM) (McCown *et al.* 1996) has been rigorously tested and subsequently used to estimate deep drainage under various rotations growing in a subtropical climate on the Liverpool Plains (Keating *et al.* 1995; Paydar *et al.* 1999; Ringrose-Voase *et al.* 1999), in a long-term fallow experiment (Probert *et al.* 1995; Turpin *et al.* 1996), and on a deep sandy soil in Western Australia (Asseng *et al.* 1998*a*). This paper aims to quantify likely deep drainage rates under wheat crops for major soil types across rainfall zones of the central Western Australian wheatbelt. Part II of this series (Asseng *et al.* 2001) examines the likely effect on deep drainage of different cropping management strategies.

Materials and methods

APSIM

APSIM (McCown *et al.* 1996) was configured with the Nwheat crop module (Keating *et al.* 1999), and SOILN2, SOILWAT2, and RESIDUE2 soil and residue modules (Probert *et al.* 1995, 1998). This configuration has been extensively tested against field studies on different soils in Western Australia (Asseng *et al.* 1998*a*, 1998*b*). The SOILWAT2 module simulates the various vertical water movements in a layered soil system using a multi-layer cascading approach. It is based on the water balance model by Ritchie *et al.* (1985) and Littleboy *et al.* (1992) as described in detail by Probert *et al.* (1995, 1998). Potential evapotranspiration (ET_{pot}) is calculated as in the CERES model (Ritchie *et al.* 1985) using the Priestley and Taylor (1972) approach as a function of solar radiation, soil and crop albedo, and air temperature. Unlike the CERES model, water uptake (or crop transpiration E_c) in Nwheat is linked to biomass production via transpiration efficiency and vapour pressure deficit (Monteith 1988). Simulated water uptake is a function of uptake demand, root length density distribution, and available soil water in the different soil layers based on an advancing rooting front. The advancing rooting front is a function of air temperature, crop water stress, and soil water content in the soil layer with the deepest roots. Rainfall is assumed to infiltrate uniformly as piston displacement flow through the soil profile, thus avoiding the complexity of modelling preferential soil water flow induced by water repellency in surface soil or cracking clays. Documented model source code in hypertext format is available (www.apsim-help.tag.csiro.au). Pests and diseases that can affect experimental crops are not considered in APSIM.

A modified version of SOILWAT2, which handles the dynamics of perched watertables (Asseng *et al.* 1997), was used for the simulations on waterlogging duplex soils. The modified version includes a new parameter that controls the flow rate of water through macropores, a process that is not controlled in the multi-layer cascading approach (Probert *et al.* 1998). The inclusion of the new parameter enabled soil layers to remain saturated over extended periods of time and a perched watertable in the profile is then calculated as the proportion of the water content between drained upper limit (DUL) and saturation (SAT) in a layer, when the next layer below is saturated. If a perched watertable rises into the rooting zone, crop and root growth is reduced. A more detailed description is given by Asseng *et al.* (1997).

Deep drainage is defined as water leaving the potential rooting depth of a wheat crop in a soil. The depth of water uptake in a year when soil water infiltration wet the whole profile is considered to be the potential root depth of a soil (potential root depth of a wheat crop is considered as a constant for a soil). The potential root depths are based on field measurements for a sandy soil reported by Anderson *et al.* (1998), for a duplex soil by Gregory and Eastham (1996), for a deep loamy sand by J. W. Bowden (pers. comm.), and for a clay soil by Rickert *et al.* (1987) and J. W. Bowden (pers. comm.).

Field measurements

Deep sand at Wongan Hills

Model outputs were compared with experimental data collected in 1983 from a wheat crop near Wongan Hills, WA (471 mm annual rainfall in 1983), by Hamblin and Tennant (1987). The soil was a deep yellow sand Uc5.22 (Northcote *et al.* 1975) with some soil compaction between 10 and 30 cm depth. Wheat (cv. Gamenya) was sown on DOY (day of year) 156 (5 June 1983) and 45 kg N/ha as ammonium nitrate was applied on DOY 186 (5 July). The previous crop was also a wheat crop. Weeds and disease occurrence were kept to a minimum with the appropriate use of herbicides, insecticides, and fungicides. Water loss to the atmosphere and drainage below the root-zone (actual ET plus drainage) were determined from fortnightly measurements of soil water contents to a depth of 220 cm using a neutron probe. Measured profile soil water contents from this experiment at the beginning of the growing season were used to initialise the model for the comparison with the field experiment. Hamblin and Tennant (1987) give a detailed description of the experimental design, including measurements undertaken.

Waterlogging duplex soil at Beverley

Model outputs were compared with data collected in experiments conducted from 1990 to 1992, at the East Beverley Research Annex, 21 km east of Beverley, WA, by Gregory and Eastham (1996) (annual rainfall at the experimental site in 1990, 386 mm; 1991, 392 mm; 1992, 448 mm). The soil was a shallow sand overlying some gravel and compacted clay at 30–50 cm depth (duplex soil), Dy2.82 (Northcote *et al.* 1975). Watertables frequently perched at about 40–50 cm depth, particularly in 1991 and 1992. The main treatments in these experiments were: (*i*) early and late sowing dates and (*ii*) normal and double plant density (only in 1992). The early wheat crops were sown in 1990 on DOY 145 (25 May, cv. Kulin), in 1991 on DOY 151 (31 May, cv. Kulin), and in 1992 on DOY 121 (1 May, cv. Spear). The late wheat crops were sown in 1990 on DOY 165 (14 June, cv. Kulin), in 1991 on DOY 179 (28 June, cv. Kulin), and in 1992 on DOY 161 (10 June, cv. Spear). All wheat crops were sown after a previous year's lupin crop and received 60, 90, and 90 kg N/ha in 1990, 1991, and 1992, respectively. Soil profile water contents to a depth of 150 cm were measured every 2 weeks using a neutron probe to calculate a combined value for water loss to the atmosphere and drainage below the root-zone (actual ET plus drainage). The wheat crops were kept free of weeds and diseases, except the early sown wheat crop in 1992, which was affected by *Septoria* after anthesis, a leaf disease which reduces assimilation and transpiration. Gregory and Eastham (1996) and Eastham and Gregory (2000) give a detailed description of the experimental design and measurements undertaken. Asseng *et al.* (1997) describe procedures used to simulate the dynamics of the perched watertable. The soil surface was parameterised with a ponding capacity of 10 mm, required to be filled before any runoff could occur. Measured profile soil water contents from this experiment at the beginning of the growing season were used to initialise the model for the comparison with field data.

Deep sand at Moora

Model outputs were compared with data collected in experiments conducted by Anderson *et al.* (1998) from 1995 to 1997, at a site 4 km west of Moora, WA (annual rainfall at the experimental site was 703 mm in 1995, 438 mm in 1996, and 405 mm in 1997). The soil was a deep yellow sand Uc5.22 (Northcote *et al.* 1975) with some non-wetting characteristics at the surface, soil compaction, and acidity between 10 and 30 cm depth. Wheat crops were sown after the previous year's lupin crops in 1995 on DOY 131 (11 May, cv. Dagger), in 1996 on DOY 169 (18 June, cv. Cascades), and in 1997 on DOY 143 (23 May, cv. Cascades). No fertiliser N was applied and wheat crops were kept free of weeds and diseases, except in 1995 when an infection of *Septoria* affected crop growth and transpiration after anthesis. The ET was measured in an adjacent wheat crop using a Bowen ratio technique (Dunin *et al.* 1989), except in 1997 when ET was estimated with 70% of Penman potential ET (Anderson *et al.* 1998) due to equipment malfunction. Soil profile water contents between the surface and 150 cm were measured every 30 min using time domain reflectrometry. Deep drainage was calculated from the change in measured soil water content and ET (Anderson *et al.* 1998). Measured profile soil water contents from this experiment at the beginning of the growing season were used to initialise the model for the comparison with the field experimental data.

The experimental plots were deep ripped (40 cm) before sowing in 1996 and 1997, which increased the depth of root growth but decreased the soil water holding capacity in the top 10 cm, compared with the non-ripped soil in 1995. Model simulation runs were adjusted accordingly. Anderson *et al.* (1998) give a detailed description of the experimental design and measurements undertaken.

All simulations were compared with the mean of replicated measurements and standard errors of the mean (if available) were used to show the variability of the measurements.

Simulation experiment

The soils of the wheatbelt of Western Australia, as described in the Atlas of Australian Soils by Northcote *et al.* (1975), were grouped into 5 major soil types: deep sand, deep loamy sand, acid loamy sand, shallow duplex (waterlogging), and clay soil (non-waterlogging) on the basis of extractable water-holding capacity and potential rooting depth, in order to produce a simplified soil map. The characteristics of the 5 major soil types were derived from field measurements (Table 2). The plant-available lower limits (LL) were derived from measured soil water contents at maturity of wheat crops in years of little or no rainfall during grain filling. The field DUL were derived from measured soil water contents after sufficient rainfall had wet the soil profile, and time was allowed for drainage. The difference between DUL and LL of the potential root-zone was defined as the extractable water-holding capacity of a soil (or plant-available water, PAW). Root hospitality factors (RHF, 0…1), a soil defined parameter which reduces the downwards elongation of the

Table 2. Plant available lower limit (LL, v/v), drained upper limit (DUL, v/v), and root hospitality factor (RHF, 0–1) for a deep sand (after Anderson *et al.* 1998), a deep loamy sand (after J. W. Bowden, pers. comm.), a shallow duplex (after Gregory and Eastham 1996), an acid loamy sand (based on the deep loamy sand but with restricted RHF), and a clay soil (after Rickert *et al.* 1987; J. W. Bowden, pers. comm.)

Layer	Deep sand			Loamy sand				Duplex			Clay		
(cm)	LL	DUL	RHF	LL	DUL	RHF	RHF[A]	LL	DUL	RHF	LL	DUL	RHF
0–5	0.030	0.180	0.1	0.050	0.130	0.1	0.1	0.05	0.16	0.1	0.08	0.17	0.3
5–10	0.030	0.130	0.1	0.050	0.130	0.05	0.05	0.05	0.16	0.1	0.08	0.18	0.3
10–20	0.060	0.120	0.1	0.080	0.140	0.2	0.2	0.04	0.21	0.1	0.10	0.22	0.3
20–30	0.060	0.110	0.2	0.085	0.144	0.5	0.3	0.06	0.21	0.2	0.13	0.24	0.3
30–40	0.060	0.110	0.5	0.085	0.144	0.5	0.3	0.06	0.22	0.2	0.17	0.28	0.3
40–50	0.060	0.095	0.5	0.095	0.147	0.7	0.4	0.13	0.22	0.2	0.18	0.29	0.3
50–60	0.070	0.095	0.5	0.095	0.147	0.7	0.4	0.14	0.22	0.1	0.19	0.29	0.3
60–70	0.070	0.095	0.5	0.100	0.151	0.7	0.4	0.17	0.22	0.1	0.21	0.29	0.3
70–90	0.080	0.100	0.5	0.100	0.155	0.7	0.4	0.17	0.22	0.1	0.22	0.29	0.2
90–110	0.085	0.110	0.5	0.100	0.160	0.7	0.4	0.17	0.21	0.1	0.23	0.29	0.2
110–130	0.085	0.110	0.5	0.110	0.175	0.7	0.4	0.17	0.195	0.001	0.24	0.29	0.2
130–150	0.100	0.120	0.3	0.110	0.175	0.7	0.4	0.17	0.195	0.001	0.25	0.29	0.2
150–170	0.100	0.120	0.2	0.120	0.175	0.5	0.4	0.17	0.195	0.001	0.26	0.29	0.2
170–190	0.100	0.120	0.2	0.120	0.175	0.5	0.4	0.17	0.195	0.001	0.26	0.29	0.2
190–210	0.100	0.120	0.2	0.130	0.175	0.5	0.4	0.17	0.195	0.001	0.26	0.29	0.2
210–230	0.100	0.120	0.2	0.130	0.175	0.5	0.4	0.17	0.195	0.001	0.26	0.29	0.2
230–250	0.100	0.120	0.2	0.130	0.175	0.5	0.4	0.17	0.195	0.001	0.26	0.29	0.2

[A] Acid loamy sand, LL and DUL are the same as for deep loamy sand.

Table 3. Weather stations with long-term weather records (70–90 years) of the central wheatbelt of the Mediterranean climate of Western Australia (30–32°S, 115–120°E) used for maps of potential drainage

No.	Transect 1 location	Average annual rainfall (mm)	No.	Transect 2 location	Average annual rainfall (mm)
1	Dandaragan	624	14	Lancelin	683
2	Moora	461	15	Gin Gin	739
3	New Norcia	458	16	Toodyay	531
4	Calingiri	439	17	Northam	528
5	Wongan Hills	386	18	Cunderdin	371
6	Goomalling	366	19	Tammin	344
7	Dowerin	366	20	Kellerberrin	337
8	Wyalkatchem	333	21	Merredin	310
9	Koorda	300	22	Burracoppin	326
10	Trayning	323	23	Westonia	325
11	Nungarin	309	24	Southern Cross	293
12	Mukinbudin	281	25[A]	Kalgoorlie	258
13	Bullfinch	292			

[A] 230 km east of eastern edge of central wheatbelt.

root system in each particular soil layer according to soil constraints, were derived from measured dynamics of root length densities (>0.1 cm cm^3) and measured soil water change due to crop uptake. Soil characteristics for the deep sandy soil were based on data from Anderson *et al.* (1998), for the duplex soil on data from Gregory and Eastham (1996), for the deep loamy sand on data from J. W. Bowden (pers. comm.), and for the clay soil on data from Rickert *et al.* (1987) and J. W. Bowden (pers. comm.). Soil characteristics for the acid deep loamy sand were derived by taking LL and DUL from the deep loamy sand and modifying RHF below 20 cm to take reduced root growth into account due to soil acidification (Table 2). For soil evaporation, parameters for the first stage (u, upper limit for energy-limited soil evaporation loss) and second stage [*cona*, upper limit of water flux to the surface for soil evaporation lost (source-limited)] (after Ritchie 1972) were u = 6 mm and *cona* = 2 mm for the deep sand, deep loamy sand, acid loam, and the shallow duplex. Parameter values of u = 7.5 mm and *cona* = 3.5 mm were used for the clay soil to take into account the finer texture of this soil type (D. Tennant, pers. comm.). Runoff was parameterised (Ritchie *et al.* 1985) for each soil type–site location assuming little runoff, reflecting the generally flat landscape (relative relief <300 m) of most of the agricultural region of Western Australia (George *et al.* 1997).

Simulation experiments were conducted using historical long-term daily weather records (70–90 years) from 25 locations along 2 transects from the west coast through the central wheatbelt to Kalgoorlie, 230 km east of the eastern edge of the wheatbelt (Table 3).

Each simulation run commenced on 1 January (DOY 1). Soil water profiles were initialised (reset) each year on 1 January to the lower limit of plant-available water, assuming maximum water use in the previous crop. In addition, to study the carry-over effect of water left behind in the soil after harvesting the crop on long-term deep drainage, simulations were also carried out without re-initialising the soil water each year. Previous crop residues were set each year on 1 January to 3 t/ha (2 t/ha of wheat stubble and straw with C : N ratio of 70, 1 t/ha of dead root biomass with C : N ratio of 40). Both total and mineral N in soil profiles were reset on 20 April each year with 40 kg mineral N/ha in 0–100 cm soil depth (mainly as NO_3-N) in each simulation.

Sowing time was controlled by a sowing rule in the model. Sowing date was set between 5 May (DOY 125) and 31 July (DOY 212), but did not occur before at least 25 mm of rainfall within 10 days before 5 June (DOY 156) or 10 mm thereafter. In addition, soil water in the 5–10 cm layer had to exceed 50% of extractable soil water-holding capacity to ensure that successful germination conditions prevailed. The variety Spear (late maturing) was used in the simulations where wheat was sown before 5 June. Otherwise the variety Amery (early maturing) was

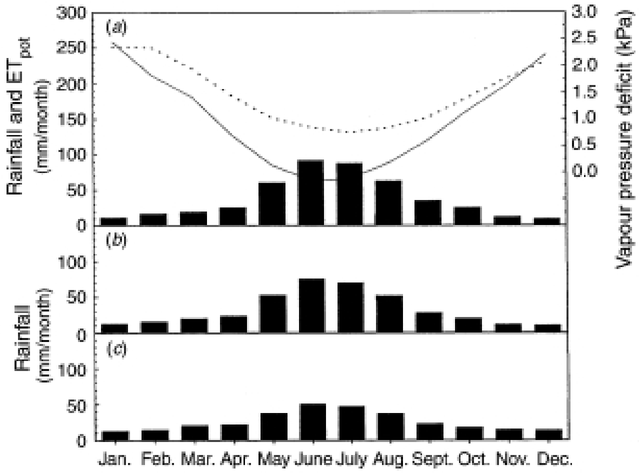

Fig. 1. (*a*) Long-term monthly average rainfall (bars), potential evapotranspiration (Et_{pot}) (——), and vapour pressure deficit (VPD) (············) at Moora (high rainfall zone, 461 mm/year average). Long-term monthly average rainfall (bars) at (*b*) Wongan Hills (medium rainfall zone, 386 mm/year average), and at (*c*) Merredin (low rainfall zone, 310 mm/year average). Long-term monthly average Et_{pot} and VPD at Wongan Hills and Merredin are almost identical to Moora and therefore not shown. Long-term averages are based on weather records from 1907 to 1993 for Moora and Wongan Hills and for 1912–1992 for Merredin.

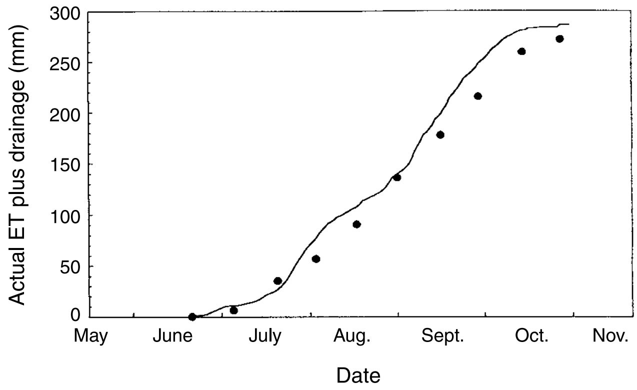

Fig. 2. Simulated (——) and observed (●) soil water loss (actual ET plus drainage) for a deep sandy soil at Wongan Hills, WA, in 1983. Observed data after Hamblin and Tennant (1987).

used in the simulations. Sowing depth was set to 3 cm and plant density to 120 plants/m^2. Nitrogen (30 kg/ha) was applied as urea at sowing. All planting rules represent current 'best farming practice'.

Accumulation of annual deep drainage below the potential rooting depth (deep sand, 150 cm; deep loamy sand, 230 cm; acid loamy sand, 150 cm; shallow duplex, 70 cm; clay soil, 130 cm) commenced on 1 January.

The results for selected percentiles (100%, 90%, 50%, 10%, and 0%) from cumulative probability distributions for the 5 major soil types for each of the 25 locations of the central wheatbelt of Western Australia (Table 3) were used to interpolate surface grids for drainage potential. The interpolated surfaces for each soil type were created using a geographic information system (ARC/INFO) with an ordinary kriging interpolative method. A circular model was used for kriging throughout the interpolation of the surfaces. To increase the resolution to a cell size of 500 m, the initial interpolated surfaces with a cell size of 9 km were re-interpolated. Surface grids for drainage potential of each of the soil types were combined according to the simplified soil map consisting of the 5 major soil types: deep sand, deep loamy sand, acid loamy sand, shallow duplex, and clay soil.

Source of long-term weather data

Long-term daily historical weather records used in the simulations comprised measured daily rainfall for over 70–90 years and up to 30 years of measured maximum and minimum temperatures for 25 locations in the central wheatbelt of Western Australia. Missing maximum and minimum temperatures and all radiation data were generated using WGEN (Richardson and Wright 1984). Details and the validity of this approach are given by Meinke *et al.* (1995). Weather records for Moora and Wongan Hills were from the years 1907–1993 and for Merredin for 1912–1992.

Results

In general, more than two-thirds of the total annual rain falls in winter, with total rainfall declining from the west coast towards the east in the central wheatbelt of Western Australia (Fig. 1). The highest rainfall months are June and July and these coincide with the lowest ET_{pot} due to low solar radiation and temperatures. Indeed, average monthly rainfall exceeds average monthly ET_{pot} during these months in the high rainfall zone at Moora. The lowest vapour pressure deficit occurs between June and August.

Comparison of simulations with observations

As previously noted, rigorous testing of the APSIM model has been conducted elsewhere (e.g. Probert *et al.* 1995; Turpin *et al.* 1996; Asseng *et al.* 1998*a*, 1998*b*, 2000; Paydar *et al.* 1999). However, additional model-measurements comparisons relating to soil water change, ET, and drainage were undertaken and are presented in Figs 2–4. Results for model-measurement comparisons for biomass growth, yield, and N dynamics of these experiments were reported by Asseng *et al.* (1998*a*, 1998*b*).

Figure 2 shows that in general, the model reproduced seasonal patterns and the final amount of soil water loss (actual ET plus drainage) on a sandy soil in the medium rainfall zone at Wongan Hills in 1983. The discrepancy between simulated and measured loss of soil water at crop maturity was less than 6%, well within the expected error of analysis for soil water in field experimentation.

Soil water loss on a shallow duplex soil at Beverley was also generally simulated well over 3 seasons (Fig. 3*a*,*b*), despite some discrepancies in 1991, where the model overestimated the measured soil water loss by 27 mm (10%) at the end of the growing season. Periods of waterlogging in 1991 and 1992 could have affected the measurements through lateral water flow or by underestimating soil water content measurements with the neutron probe meter in satu-

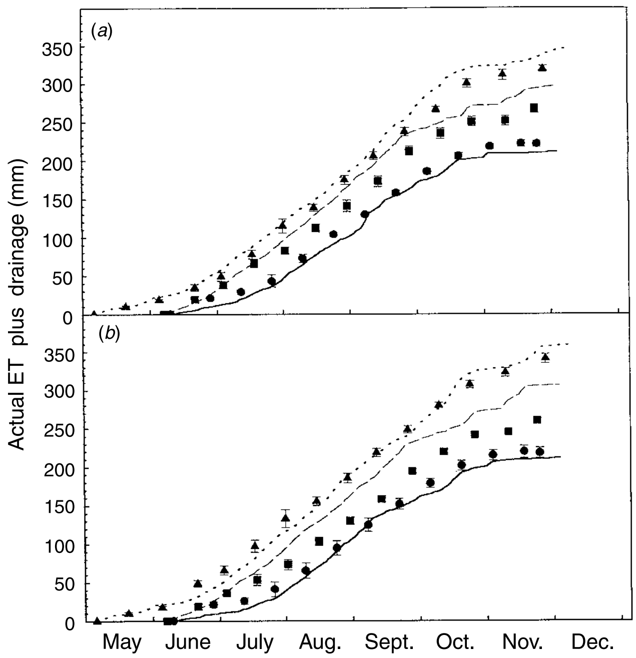

Fig. 3. Simulated (lines) and observed (symbols) soil water loss (actual ET plus drainage) for a shallow duplex soil (waterlogging) at Beverley, WA, in 1990 (● ——), 1991 (■ – – –), and 1992 (▲ ·········). (*a*) Early sown and (*b*) late sown crops. Observed data after Gregory *et al.* (1992) and Eastham and Gregory (2000). Vertical lines indicate standard error of the mean where these exceed the size of the symbol.

rated soil. Some of the small discrepancies in 1992 could be also related to a *Septoria* infection that started at anthesis, reducing growth and crop transpiration. Annual rainfall was 386 mm in 1990, 392 mm in 1991, and 448 mm in 1992, causing waterlogging particularly in 1991 and 1992. In 1990 there was hardly any waterlogging, hence the most reliable neutron probe measurements, and it was simulated with a very close fit to the measured data. Noteworthy are also the rather small differences in soil water loss between early and late sowing in the actual, as well as in the simulated data. Doubling the plant density for early and late sown wheat crops in 1992 had no effect on soil water loss in the field experiment and in the simulation (not shown).

Data from 3 seasons on a deep sandy soil at Moora partitioned soil water loss into actual ET and deep drainage (Fig. 4). The model underestimated actual ET in 1995 by 10% at the end of the season, but simulated the other 2 seasons reasonably well. Observed annual deep drainage was 214 mm in 1995, 114 mm in 1996, and 97 mm in 1997. In each of the 3 seasons the observed onset and pattern (or series of events) of deep drainage were different. The model reproduced well each of the drainage events, which ranged between 10 mm (e.g. in May 1997) and 130 mm (in July 1995) as well as the total annual amounts of deep drainage in each of the seasons.

Temporal variability

Large year-to-year variability in the seasonal pattern and annual amount of deep drainage was observed at Moora between 1995 and 1997 (Fig. 4*b*). The analysis of deep drainage at the Moora site was extended to the full length of the daily weather records, using the simulation model. Annual rainfall and simulated deep drainage are shown in Fig. 5 for the period 1907–1993. Variability in rainfall, ranging from 203 to 790 mm (s.d.%, 22), was amplified further in estimates of deep drainage, ranging from 0 to 386 mm (s.d.%, 54), with an average annual rainfall of 461 mm and an average annual drainage of 134 mm (Fig. 5*a*, *b*).

Spatial variability

Both soil type and rainfall region affected spatial variability in simulated deep drainage. The climate of the Western Australian wheatbelt has traditionally been divided into 3 rainfall regions with high (>450 mm), medium (350–450 mm), and low (<350 mm) annual rainfall. Simulated average long-term drainage (±s.d.) on deep sands ranged from 134 (±73) mm at Moora (high rainfall zone, 461 mm annual average) to 90 (±61) mm at Wongan Hills (medium rainfall zone, 386 mm annual average) to 36 (±43) mm at Merredin (low rainfall zone, 310 mm annual average) (Fig. 6*a*). The average amount of simulated drainage changed with the amount of rainfall but the difference in drainage was less than the difference in rainfall.

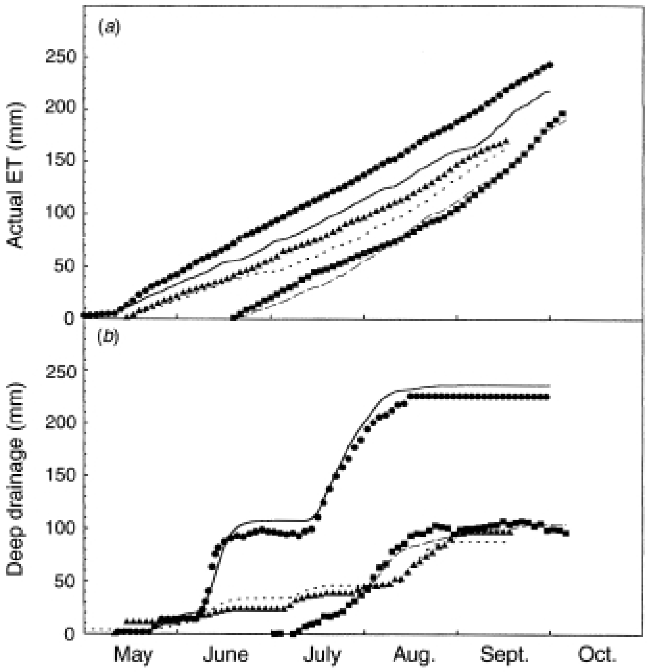

Fig. 4. Simulated (lines) and observed (symbols) for (*a*) actual ET and (*b*) deep drainage on a deep sand at Moora, WA, in 1995 (● ——), 1996 (■ – – –), and 1997 (▲ ·········). Simulated and observed data for 1995 after Asseng *et al.* (1998*a*), observed data for 1996 after Anderson *et al.* (1998), and observed data for 1997 after I. Fillery and F. X. Dunin (unpubl. data).

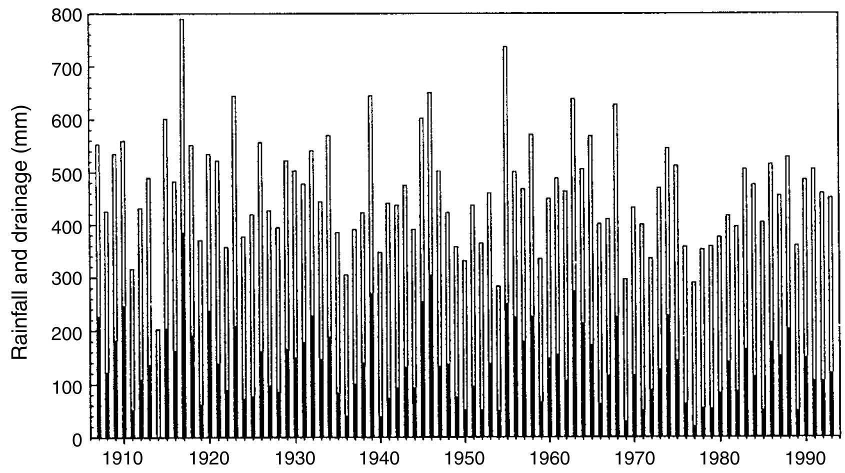

Fig. 5. Yearly rainfall (open bars) and simulated deep drainage below 150 cm (closed bars) on a deep sand at Moora, WA, from 1907 to 1993.

The extractable soil water-holding capacities also showed a large impact on simulated drainage rates. Average long-term simulated drainage (±s.d.) on clay soil ranged from 57 (±64) mm at Moora, to 26 (±43) mm at Wongan Hills, to 4 (±18) mm at Merredin. Hence, average drainage on a clay soil (109 mm PAW in potential root-zone) compared with a deep sand (55 mm PAW) was less by 77 mm at Moora, by 64 mm at Wongan Hills, and by 32 mm at Merredin (Fig. 6). This indicated that in the high rainfall region, long-term average drainage was more reduced in the better water-holding soil than the difference in PAW. The reduction in drainage was about equal to the difference in PAW in the medium, and less than the difference in the low rainfall region. That means the reduction in average deep drainage due to an additional PAW in better water-holding soils becomes less towards lower rainfall regions in absolute values.

The relationship between simulated drainage and annual rainfall was approximately linear (Fig. 7), with the slope of the functions decreasing from the high to the low rainfall region by about one-third, regardless of soil type. Extractable water-holding capacity of the soil had a significant effect on the *x*-intercept of these relationships, but locations (i.e. rainfall region) had only a minor effect (<7% difference in *x*-intercept between locations). The average onset of drainage for the high (Moora) and low (Merredin) rainfall location was at 248 mm annual rainfall on deep sand (55 mm PAW) (Fig. 7*a*). In contrast, on a clay soil (109 mm PAW) the average onset of drainage for the 2 locations was simulated when annual rainfall exceeded about 359 mm (Fig. 7*b*). Hence, increasing the extractable water-holding capacity of the soil by 54 mm increased the amount of rainfall required by 111 mm before drainage occurred, almost double the amount of PAW increase.

The spatial and probabilistic distribution of deep drainage of the central wheatbelt is shown in Fig. 8, with rainfall generally declining from the coast in the west towards east. The 100% percentile (or 100% probability of exceedence) of drainage indicates the minimum possible drainage in any year according to long-term simulation runs with APSIM. From the coast to about a longitude of 116.0°E (at about Moora), an area dominated by deep sands and shallow duplex soils, drainage was predicted in every year due to the high annual rainfall and low extractable water-holding capacity soils. Locations east of about a longitude of 116.0°E had at least 1% of all years without a drainage event, and further east of a longitude of about 116.5°E (at about Wongan Hills) had at least 10% of years without drainage. The median drainage potential (50% percentile) indicated that most of the central wheatbelt was likely to experience drainage once every second year, except for the deep loamy sand and clay soils in the low rainfall region. Deep drainage occurred in all locations in at least 10% of years across the wheatbelt. All locations regardless of soil types had at least 1 event of >95 mm of annual deep drainage over the simulated period of 70–90 years.

Maximum water use in the previous crop is assumed when soil water profiles are reset each year to the lower limit of plant-available water. Substantial amounts of soil water can remain at harvest, particularly in the case of N-deficient crops, and this carry-over of soil water can reduce the soil water storage in the subsequent year and increase long-term average deep drainage, especially in soils with a large capacity to hold plant-available water (Table 4). Therefore, the resetting of soil water profile at the start of each simulation run, as undertaken previously, can result in predicted deep drainage rates at the lower range of drainage for crops.

Runoff was generally a negligible part of the simulated water balance (on average <1% of annual rainfall). However, the waterlogging shallow duplex soils often have perched watertables (a second non-saline watertable, temporarily perching on the clay horizon of duplex soils, independent of the ground-watertable). When this perched watertable reaches the surface, any excess over a 10-mm ponding

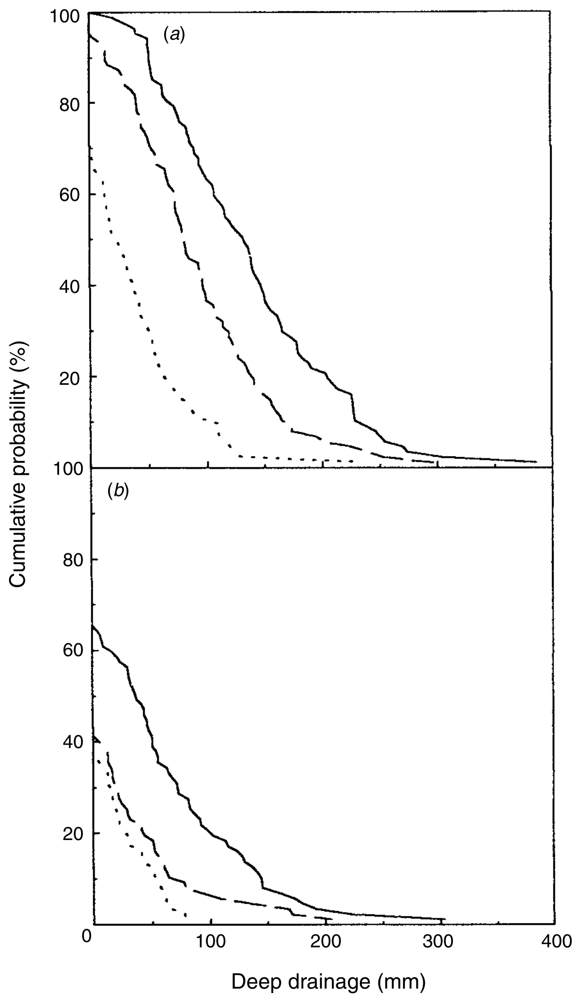

Fig. 6. Cumulative probability distribution (based on simulations with 81–87 years of weather records) for annual deep drainage on (*a*) deep sand and (*b*) clay soil at Moora (——, high rainfall zone, 461 mm/year average), Wongan Hills (— — —, medium rainfall zone, 386 mm/year average), and Merredin (··········, low rainfall zone, 310 mm/year average), WA.

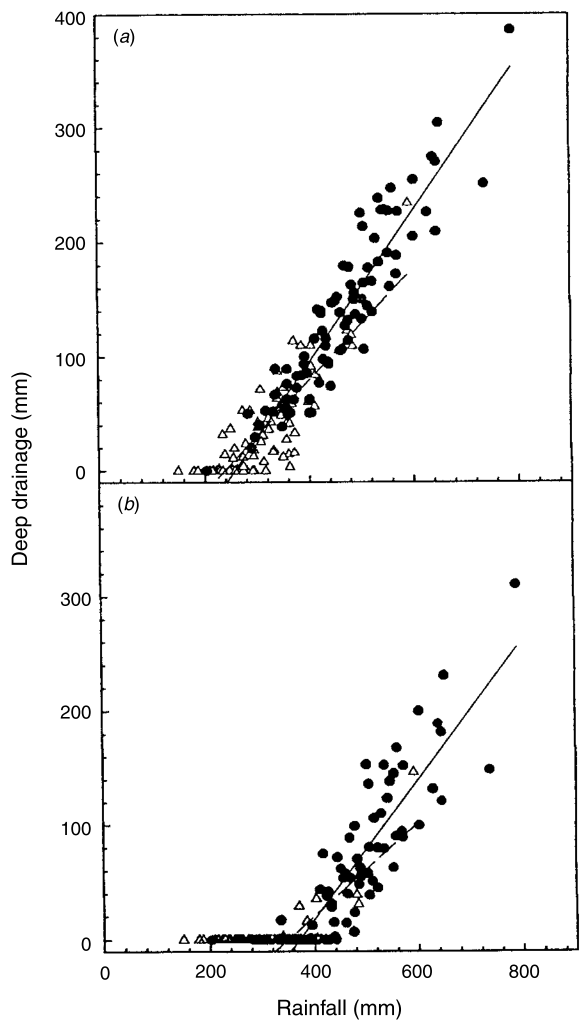

Fig. 7. Simulated annual deep drainage *v.* rainfall on (*a*) deep sand and (*b*) clay soil at Moora (●, high rainfall zone, 461 mm/year average) and Merredin (△, low rainfall zone, 310 mm/year average), WA (for the period 1907–1993 for Moora and 1912–1992 for Merredin). Linear regression lines for drainage values >0 are shown for Moora (——) (sand: $y = 0.66x - 171$, $r^2 = 0.85$; clay: $y = 0.61x - 226$, $r^2 = 0.70$) and Merredin (— — —) (sand: $y = 0.49x - 116$, $r^2 = 0.65$; clay: $y = 0.41x - 141$, $r^2 = 0.62$).

capacity is assumed to be runoff. In the higher rainfall regions, and years with above-average rainfall in the other regions, runoff became a larger component of the water balance on duplex soils. Figure 9 shows the simulated annual runoff for Wongan Hills (medium rainfall zone with 386 mm annual average). No runoff occurred on either soil in 28 of the 87 years, but runoff on the duplex soil exceeded the sandy soil by several times in years with high rainfall and watertables reaching to the surface. The average simulated runoff for the sandy soil at Wongan Hills was 4 mm/year, for the duplex soil 15 mm/year, with the difference due to perched watertables in the duplex soil. Depending on the ultimate destination of this runoff, it may need to be considered as another component of excess water on the duplex soils adding to deep drainage on a regional scale.

Discussion

Watertable rise is a function of the amount of deep drainage and the discharge capacity, which is the amount of water that can be transmitted by an aquifer without ground-watertable rise, a hydrogeological and topographic constant for a particular catchment (George 1992*b*). In our paper, only the probable rates of deep drainage are discussed for 5 major soil types under wheat in the Western Australian wheatbelt.

Use of the APSIM wheat model together with long-term historic weather data has highlighted that there is likely to be large season-to-season variability in deep drainage commensurate with large fluctuations in annual rainfall, which is a characteristic of the Mediterranean climate zone. Episodic

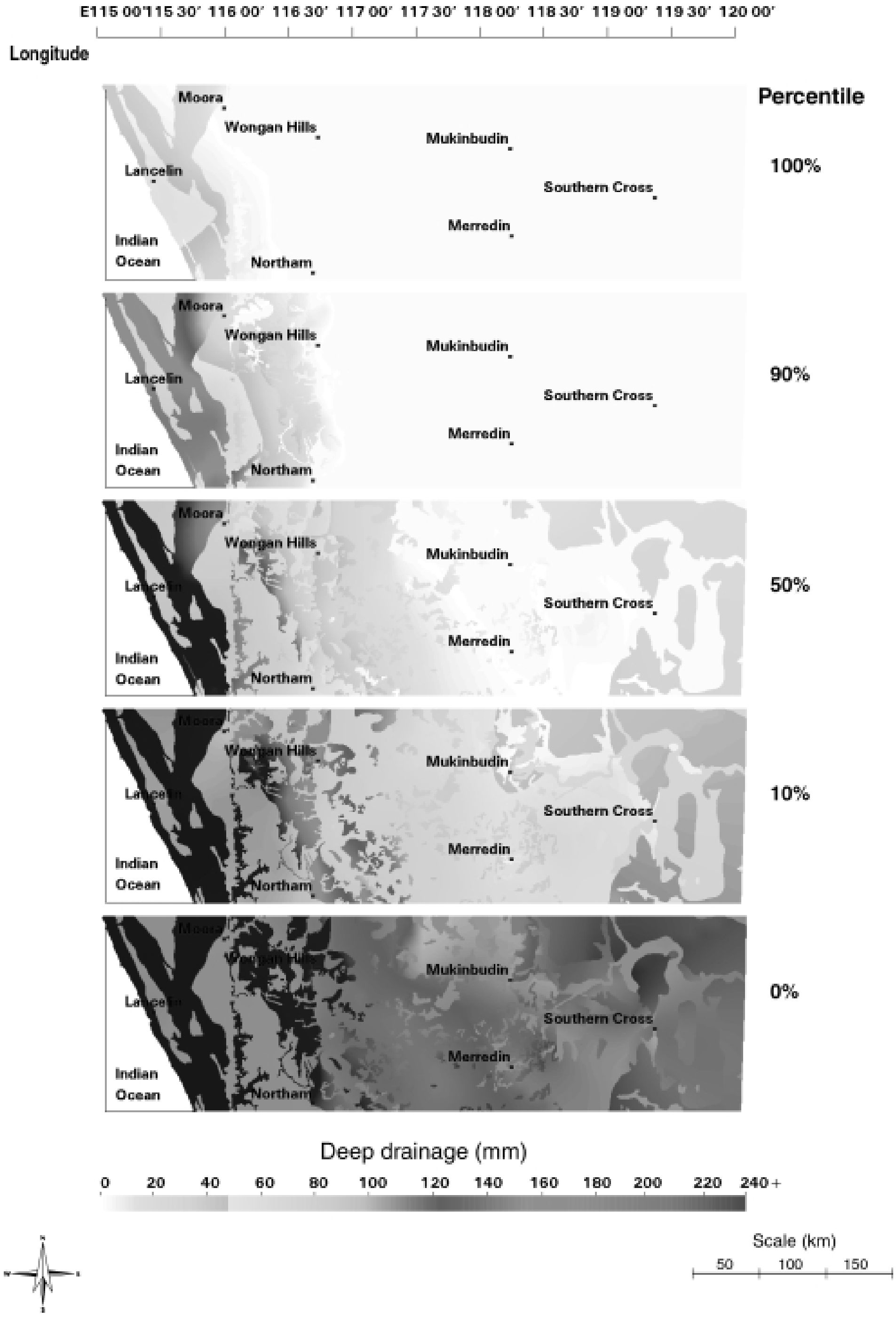

Fig. 8. Maps of simulated annual deep drainage below the potential root-zone for 100%, 90%, 50%, 10%, and 0% percentile (probability of exceedence) for wheat crops in the central wheatbelt of Western Australia. Soils were classified into 5 major soil types, and areas between the 25 locations used in the long-term simulations were linear interpolated with an ordinary kriging interpolative method.

large drainage events will therefore be important contributors to groundwater recharge in some situations (George *et al.* 1997). Nevertheless, the determination of long-term means of deep drainage rates can be a useful guide to the future rates of rise of ground-watertables.

Simulated average drainage in deep sands planted to wheat accounted for 29% of annual rainfall in a high rainfall zone (461 mm/year average rainfall), 23% in a medium (386 mm/year average rainfall), and 12% in a low rainfall location (310 mm/year average rainfall). In the case of clay soils with

Table 4. Simulated long-term average deep drainage (mm) below the root-zone with 30 kg N/ha for a deep sand, a clay, and a deep loamy sand at Moora (high rainfall region), Wongan Hills (medium rainfall), and Merredin (low rainfall), with resetting the soil water profile and without resetting

Soil type	PAW[A]	Deep drainage Rainfall region:		
		High	Medium	Low
	With resetting[B]			
Deep sand	55	134	90	36
Clay	109	57	26	4
Deep loamy sand	130	68	34	7
	Without resetting			
Deep sand	55	149	103	49
Clay	109	73	35	6
Deep loamy sand	130	139	97	39

[A] Plant available water in potential rooting depth.
[B] Resetting soil water profile to plant available lower limits at 1 January each year.

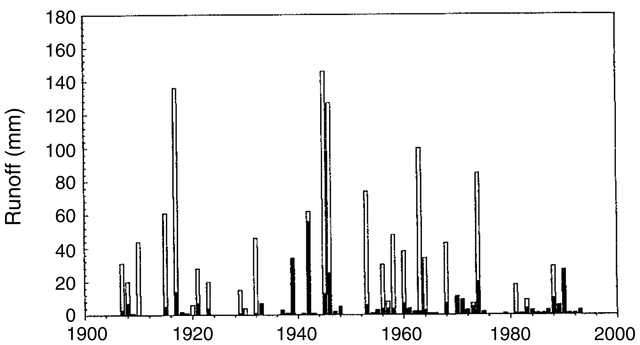

Fig. 9. Simulated annual runoff for a sandy soil (closed bars) and a shallow waterlogging duplex soil (open bars) at Wongan Hills, WA (medium rainfall zone, 386 mm/year average), from 1907 to 1993.

twice the extractable water-holding capacity, average deep drainage was much lower and accounted for only 12%, 7%, and 1% of rainfall for the high, medium, and low rainfall zones, respectively. In addition, the on set of deep drainage is dependent on the water-holding capacity of soil, e.g. is later for a clay than for a sandy soil for the same rainfall. Knowledge of the onset of drainage and the proportion of annual rainfall lost as drainage allows a simple estimate of drainage potential for any particular location in the Western Australian wheatbelt, based on only annual rainfall and extractable soil water-holding capacity. However, more accurate estimates will require a daily time-step consideration of the system, since inter-seasonal rainfall distribution can have a large effect on total deep drainage, as the amplified variability in deep drainage over the variability in annual rainfall has shown. Similar directional changes in deep drainage were estimated with changes in extractable water-holding capacity and rainfall region by Kennett-Smith *et al.* (1994) for south-eastern Australia.

The simulated drainage results are in good agreement with other reports from limited experimentation. Williamson (1973) reported that deep drainage accounted for 10–22% of annual rainfall under annual crops in the medium rainfall region, and Anderson *et al.* (1998) found 26–30% of annual rainfall drained below 1.5 m for wheat crops growing on deep sands in a high rainfall region in Western Australia. Dunin *et al.* (1999*a*) found 25% of growing season rainfall (404 mm) as deep drainage under a wheat crop on a clay soil and Ridley *et al.* (1997) reported drainage of 2–21% of annual rainfall under annual ryegrass on clay soils in eastern Australia.

In our analysis, which assumes that plant-available water is at the lower limit after the harvest of the previous crop, the absolute long-term average of deep drainage ranged from 4 to 57 mm on clay and from 36 to 134 mm on sandy soils in the low, medium, and high rainfall regions. Similar ranges in drainage under annual crops have been reported with respect to soil type and in relation to annual rainfall. A list of measured/estimated deep drainage amounts is given in Table 1. Whereas field-based studies on deep drainage are limited to a few locations and seasons, model simulations supply estimates of potential deep drainage both spatially (geographical location and soil type) and temporally. The temporal analysis enabled probabilistic estimates to be determined. The drainage map represents the equivalent of 3.6 million daily data points collected over 80 years, across 25 locations with 5 soil types, an information density that is difficult to obtain experimentally. For any location in the central wheatbelt of Western Australia, the probability and quantity of deep drainage under a wheat crop can be derived from the map. This information can assist in estimating ground-water recharge and possible ground-water rise [also depending on the discharge capacity of the catchment (George 1992*b*)], to identify the extent of future salinisation under wheat cropping systems.

The largest amounts and frequencies of deep drainage are likely to occur on the sandplains close to the coast, which are located in the highest rainfall regions. However, episodic events with extremes of >95 mm drainage are possible at least once in a century for any location and soil type in the Western Australian wheatbelt.

Resetting of soil water profiles to the LL each year assumed maximum water use in the previous crop and ignored any additional carryover effect of soil water left behind at crop harvest, which can substantially increase the following year's drainage. Actual drainage potential can therefore be even higher when water carryover occurs, particularly in a low N input cropping system and on high water storing soils.

In contrast to cropping land, measured deep drainage under native vegetation over 2 years was as low as 1.4–1.6% of annual rainfall on a sand/duplex soil in the high rainfall zone (George 1978) and on average <0.2% of annual rainfall on clay soil in the medium rainfall regions of Western Australia (Williamson 1973). The low drainage potential under native vegetation is mainly due to deeper soil water uptake (Williamson 1973), interception loss of rain before it enters the soil (Dunin and Mackay 1982; Greenwood *et al.* 1985), and ET occurring outside the main annual crop growing season (Williamson 1973). Actual measured/estimated values of deep drainage under native vegetation were with 0.05–3.7 mm/year in the 750–1250 mm/year rainfall region (Peck and Hurle 1973; Williamson *et al.* 1987), about 1 mm/year with rainfall between 490 and 730 mm/year (Peck *et al.* 1973), 6.5 mm/year with 470 mm/year rainfall (George 1978), and <1 mm/year for medium rainfall regions (Williamson 1973), substantially less than under annual cropping systems. The deep drainage estimates of native systems can be considered as a benchmark for a sustainable system in terms of water balance and deep drainage. A large excess of water under wheat crops is apparent when compared with native vegetation across the wheatbelt of Western Australia and indicates that the wheat-based agricultural systems are currently far from sustainable. Manipulating current agronomic practices has been suggested as a means to control deep drainage from cropping systems without incurring a loss in profitability (Miller *et al.* 1981; Nulsen 1984; George *et al.* 1997; Ridley *et al.* 1997). The long-term effects of some alternative practices have been analysed in the second part of this series (Asseng *et al.* 2001).

Conclusion

This study has highlighted the potential for properly tested and parameterised simulation models to add value to experimental research. The APSIM model has been shown to simulate the water balance of wheat-based farming systems in Western Australia. This model, when combined with long-term climate data and regional soil information is able to greatly extend the interpretation possible from limited experimental studies.

Deep drainage has been shown to be highly variable, depending on annual rainfall, rainfall distribution, and soil type. The analysis indicated the 'leakiness' of Western Australia's annual wheat cropping systems, which cover about one-quarter of the cleared land. Annual estimates from both the experimental studies and the modelling analysis can be an order of magnitude greater than the deep drainage from natural vegetation that agriculture has displaced. Shifts in the water balance of this magnitude have caused ground-water rise generally associated with the salinisation that threatens the viability of both the agricultural and remnant natural ecosystems.

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