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Review

The Australian Cotton Industry and four decades of deep drainage research: a review

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Abstract. The Australian cotton industry and governments have funded research into the deep-drainage component of the soil–water balance for several decades. Cotton is dominantly grown in the northern Murray–Darling and Fitzroy Basins, using furrow irrigation on cracking clays. Previously, it was held that furrow irrigation on cracking clays was inherently efficient and there was little deep drainage. This has been shown to be simplistic and generally incorrect. This paper reviews global and northern Australian deep-drainage studies in irrigation, generally at point- or paddock-scale, and the consequences of deep drainage.

For furrow-irrigated fields in Australia, key findings are as follows. (i) Deep drainage varies considerably depending on soil properties and irrigation management, and is not necessarily 'very small'. Historically, values of 100–250 mm year^{-1} were typical, with 3–900 mm year^{-1} observed, until water shortage in the 2000s and continued research and extension focussed attention on water-use efficiency (WUE). (ii) More recently, values of 50–100 mm year^{-1} have been observed, with no deep drainage in drier years; these levels are lower than global values. (iii) Optimisation (flow rate, field length, cut-off time) of furrow irrigation can at least halve deep drainage. (iv) Cotton is grown on soils with a wide range in texture, sodicity and structure. (v) Deep drainage is moderately to strongly related to total rainfall plus irrigation, as it is globally. (vi) A leaching fraction, to avoid salt build-up in the soil profile, is only needed for irrigation where more saline water is used. Drainage from rainfall often provides an adequate leaching fraction. (vii) Near-saturated conditions occur for at least 2–6 m under irrigated fields, whereas profiles are dry under native vegetation in the same landscapes. (viii) Deep drainage leachate is typically saline and not a source of good quality groundwater recharge. Large losses of nitrate also occur in deep drainage.

The consequences of deep drainage for groundwater and salinity are different where underlying groundwater can be used for pumping (fresh water, high yield; e.g. Condamine alluvia) and where it cannot (saline water or low yield; e.g. Border Rivers alluvia). Continuing improvements in WUE are needed to ensure long-term sustainability of irrigated cropping industries. Globally there is great potential for increased production using existing water supplies, given deep drainage of 10–25% of water delivered to fields and WUE of <50%. Future research priorities are to further characterise water movement through the unsaturated zone and the consequences of deep drainage.

Additional keywords: cracking clay, deep percolation, Vertosol, water use efficiency, irrigation.

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Introduction

Of the 1554 Mha of arable land and permanent crops worldwide, irrigation occurs on some 290 Mha, 18% of global croplands (Scanlon *et al*. 2007*a*) or 18.7% (ICID 2009). Of the irrigated area, 44 Mha (15.2%) is sprinkler and micro-irrigated (ICID 2009). Most of the remaining area of 246 Mha (~85%) is surface-irrigated, whereby the water is spread over the field by gravity, including furrow and related irrigation methods. Globally, the area of irrigated land more than doubled between 1950 and 2000 (increase of 2.8 times) and global withdrawals of water increased 2.7 times between 1950 and 1995 (Scanlon *et al*. 2007*a*). Irrigated agriculture has significant impacts on water resources because it withdraws an average of 80% of global freshwater (Scanlon *et al*. 2007*a*). Irrigation is responsible for a large proportion of food production (~40%; Scanlon *et al*. 2007*a*) and fibre production, but most studies indicate low efficiencies as a proportion of extractions and of delivery to fields, both globally (Bos and Nugteren 1990) and in the Australian cotton industry (Tennakoon and Milroy 2003; Roth *et al*. 2013). The main losses are from evaporation from farm storages (where they are used), followed by in-field deep drainage (Roth *et al*. 2013). This is both a problem, as the losses cause the main degradation issues resulting from irrigation (Jensen *et al*. 1990; Duncan *et al*. 2008), and an opportunity, because the water is already owned by or allocated to the irrigation scheme or land owner/irrigator. Thus, it is a 'free' source of extra water if efficiency can be improved and the water reallocated to productive uses.

Deep drainage (or deep percolation) is water that infiltrates below the root-zone. Some may eventually reach the groundwater and is then called recharge (Walker *et al*. 2002). Deep drainage is a loss to the production of crops, reduces water-use efficiency (WUE), and may lead to rising groundwater and salinity where the regolith or groundwater contains excessive salts; it can also be a source of recharge for groundwater. Deep drainage has been studied for over four decades in the Australian cotton industry. However, for much of that time there was a lack of consensus on the extent and occurrence of deep drainage and on the methods for measuring it (Hearn 1998). The cotton industry occurs largely within the northern Murray–Darling Basin and the Fitzroy Basin, where cotton is mostly irrigated by surface application (furrow irrigation) on low sloping plains and is grown on a wide range of soils, but predominantly on cracking clays. Deep drainage was assumed to be minimal due to the low permeability of these clay soils, although some of the earliest field studies did not support this view.

The water balance of the crop root-zone can be represented as:

$$\mathrm{R} + \mathrm{I} = \mathrm{ET} + \mathrm{S} + \mathrm{Ro} + \mathrm{D}$$

or

$$\mathrm{D} = \mathrm{R} + \mathrm{I} - (\mathrm{ET} + \mathrm{S} + \mathrm{Ro})$$

where water inputs are rainfall (R) and irrigation (I); outputs are deep drainage (D), runoff (Ro), and evapotranspiration (ET); and S is the change in soil water storage in the root-zone. Thus, D is expected to increase with increasing I + R if not compensated by losses to ET and R, and storage S is exceeded. This is a simple conceptual framework, i.e. D plotted against R+I, which we use to compare various data.

Deep drainage and poor WUE are issues for irrigation globally. For millennia, irrigation has eventually led to the dual problems of salinisation and water logging (Jensen *et al.* 1990). These are directly related to excessive losses of water from distribution systems, storages and from fields, causing groundwater to rise and adding salts to the soil. Jensen *et al.* (1990) gave two examples: the world's largest contiguous irrigated area in the Indus Plain, Pakistan, where the groundwater table reached the surface in the early 1960s and ~10 Mha of cultivatable land was waterlogged (see also Smedema 2000); and the Central Valley of California, where problems occurred soon after irrigation began in the 1870s and extensive areas were abandoned because of salinity and alkalinity problems. The solutions implemented to remediate these problems also created new problems. In the Indus Plain, installation of many private tube wells to pump groundwater for irrigation increased the area cropped and lowered the watertable, but the groundwater is now at its maximum exploitable potential (Ahmad *et al*. 2002). Drainage works were used to control the watertable in the Californian Central Valley. However, this led to pollution problems in a wetland (Kesterson Reservoir) used for disposal of the drainage water, due to high levels of selenium, and farmers were required to greatly improve irrigation management. Thus, constructing drainage systems or pumping groundwater does not deal with the core problem, which is excessive input of water into the system and the need for WUE.

Catchment salt balances are an indicator of the state of hydrologic change in a catchment (Jolly *et al*. 2001; Silburn *et al*. 2008); e.g. after a change such as major land clearing or irrigation development. Catchment salt balances can indicate whether the excess deep drainage is returning to streams. The catchments draining four of the five largest irrigation developments in arid climates—the Aral Sea, the Colorado, Murray–Darling and the Nile—are net exporters of salt, whereas the Indus is storing salt (Smedema 2000). In catchments in the northern Murray–Darling Basin where cotton is grown, catchment salt balances are close to equilibrium, i.e. salt input = salt output (Jolly *et al*. 2001; Biggs *et al*. 2013). This may be due to the effect of large diversions of water and salt, which result in temporary storage of large amounts of salt that may have otherwise contributed to salt export, and a 'zero' tail-water release policy, rather than actively releasing water via drainage schemes. However, as natural catchments in this region are storing salt (output/input <1; Biggs *et al*. 2013), these current salt balances may indicate an increased export relative to the natural state. If and when any of these catchments start to significantly export salts, through groundwater discharge to streams or surface wash-off, the salt balances will start to show outputs greater than inputs.

In this paper, we review current knowledge of deep-drainage rates in irrigated cropping areas in northern Australia and globally, particularly where Vertosols (cracking clays; Isbell 2002) occur, and discuss the consequences with examples from southern inland Queensland. Deep drainage has been determined using most available methods, but assessments are generally at point- or paddock-scale. Some context is provided with deep-drainage rates under native vegetation and rain-fed cropping. We include studies published in technical and project reports that may not be widely available and provide some contextual details for each study. We do not review or compare the different methods for measuring or modelling deep drainage, although some comparisons are made in references cited and in the tabulation of data.

Characteristics of irrigated cotton growing areas in Australia

The major cotton-production areas in Australia span from inland central Queensland to southern New South Wales, ranging from 160 000 to 580 000 ha in the 5 years to 2012–13 (Roth *et al.* 2013). The cropped area declined in 2002–03 due to the 'Millennium drought' (2002–10) but was back >550 000 ha in 2010–11 (4–5 million bales), with major floods in 2011–13. Over the 10 years to 2012–13, 83% of the area was irrigated, predominantly by flood irrigation in furrows. The average irrigation application rate was 7 ML/ha.year in 1988–94 (Hearn 1998) and 5.2 ML/ha.year in 2010–11 (Australian Bureau of Statistics 2012). The Australian cotton industry contributes around AU$2.5 billion to the Australian economy, is vital for the prosperity of many regional communities, and contributes to viability of infrastructure (transport, agribusiness, services, etc.) used by them. The industry has the highest average cotton yields in the world (2.5 times world average), the highest water productivity, which increased by 40% from 2002 to 2012

(Trindall *et al*. 2012), and the lowest use of insecticides (Pyke 2007).

Approximately 70% of Australia's cotton is grown in New South Wales (NSW) and the remainder in Queensland (Roth 2006). In Queensland, cotton is grown mostly in the south in the Darling Downs (Condamine catchment), St George and Dirranbandi (Lower Balonne-Culgoa), and Macintyre Valley (Border and Weir Rivers) regions (Fig. 1). The rest is grown near Emerald, Theodore and Biloela in Central Queensland. In NSW, the growing area stretches south from the Macintyre River (Border Rivers) on the Queensland border and covers the Gwydir, Namoi and Macquarie Valleys. Cotton is also grown along the Barwon and Darling Rivers in the west and the Lachlan and Murrumbidgee Rivers in the south. Inland irrigation of grain and oilseed crops is also concentrated in these areas, with cotton growers also growing these crops.

The northern cotton-growing areas (Queensland) experience a subtropical to tropical, semi-arid climatic regime (550–700 mm average annual rainfall), whereas the southern growing areas are temperate and semi-arid to arid (350–550 mm average annual rainfall). Rainfall is highly variable. The proportion of summer rainfall decreases from ~70% in the north to 50% in the south, and cotton growing in southern areas is significantly limited by climatic factors such as temperature and length of growing season. Potential evaporation varies from 1500 mm/year in the east to >2500 mm/year in the west, and is in excess of rainfall in all months on average (Yee Yet and Silburn 2003).

The higher yielding production areas are all irrigated, but in favourable years, extensive rainfed plantings occur in Queensland. Availability of water is more limiting than availability of suitable land. Water use efficiency became important during the drought of the 2000s and after water extraction was capped. The majority of growing areas are dominated by Vertosols on alluvial plains, but in some areas, such the Macquarie Valley and Emerald area, crops are also grown on texture-contrast soils and lighter textured, non-cracking clays on either alluvia or low gradient hillslopes with *in-situ* derived (e.g. basalt) soils (Emerald). Original native vegetation was typically open woodland to woodland. In alluvial areas, the unsaturated zone is typically clay over 'fining up' sequences of sand at some meters depth. There are large accumulations of salt in most soils and in the unsaturated zone, similar to those in other semi-arid lands (Scanlon *et al*. 2007*b*; Kurtzman and Scanlon 2011).

Groundwater either tends to be of good quality and used as an irrigation water supply, e.g. Condamine alluvia (Dafny and Silburn 2013) and Namoi alluvia (Kelly *et al*. 2013), although upper aquifers can be more saline, or is saline (Border Rivers, Lower Balonne alluvia; Biggs *et al*. 2005, 2006). Some areas of salinised soils have occurred in areas using poorer quality water (i.e. groundwater; Brough *et al*. 2008). Salinity caused by rising groundwater within or surrounding irrigation areas is the most common irrigation salinity process in Queensland (Brough *et al*. 2008). Groundwater levels are typically rising or have risen to a shallow depth (<3 m) in and around many irrigated areas (not just irrigated cotton lands) throughout Queensland (e.g. Border Rivers, St. George and Emerald irrigation areas), except where groundwater is used as a source of irrigation supply. In these areas, groundwater levels tend to be steady or falling due to pumping at a rate greater then recharge, e.g. Condamine alluvia (Dafny and Silburn 2013) and Namoi alluvia (Kelly *et al*. 2013). However, in most cotton-growing areas, major salinity problems due to salt addition or rising groundwater have not occurred and shallow groundwater and seepage discharge is not yet an issue, although areas of concern are emerging.

Issue of deep drainage and 'clay soils don't drain'

The issues of deep drainage and water balances in irrigated cotton, and the anticipated effects, were discussed widely at a series of

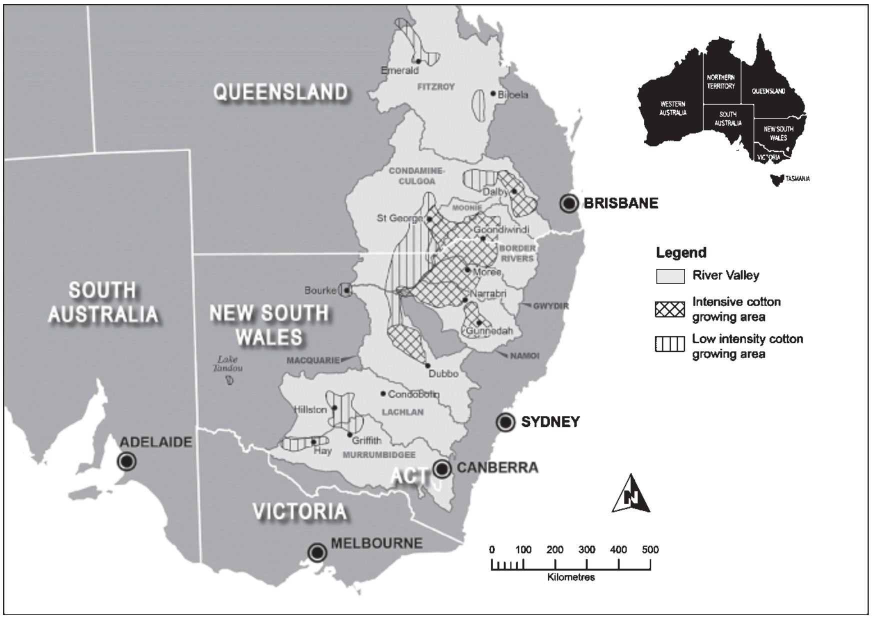

Fig. 1. Approximate location of cotton-growing areas in Australia.

workshops in Australia from 1999 to 2003 and at numerous conferences. Knowledge of the runoff component (and soil erosion) was reviewed by Silburn *et al*. (1997, 1998). The 1999 workshop revealed a lack of consensus on deep drainage (its measurement, modelling, existence or extent) and water balance for irrigated clay soils (CRDC and ACCRC 1999). Available, limited data (e.g. Shaw and Yule 1978; Thorburn *et al*. 1990; Willis and Black 1996; Willis *et al*. 1997; Connolly *et al*. 1998, 1999) appeared to conflict with the long-held view that 'clay soils don't drain' (e.g. Lane 1979; Hearn 1998) and that furrow irrigation on cracking clays is inherently efficient or self-regulating (Farbrother 1972, cited by Hearn 1998). Note that the deep-drainage studies indicated above were all from studies at Emerald, Biloela, the Lockyer and the Macquarie, i.e. not from the 'core' cotton-growing areas (Condamine, Border Rivers, Lower Balonne, Gwydir, Namoi), and, thus, may have been be perceived as unrepresentative of the wider industry.

In the next 5 years, a series of studies of deep drainage under irrigation on clay soils also found considerable deep drainage in 'core' cotton-growing areas (Hulugalle and Weaver 2000; Zischke and Gordon 2000; Dalton *et al*. 2001; Moss *et al*. 2001; Weaver *et al*. 2002; Dalton 2003; Montgomery 2003; McHugh 2003), and the cotton industry determined that WUE of irrigation was poor (Tennakoon and Milroy 2003). A 'Rural Water Use Efficiency' extension program (Goyne and McIntyre 2003) was also running in response to the Millennium drought, with the mantra 'you can't manage it if you aren't measuring it'. Simultaneously, deep-drainage understanding had advanced greatly in rain-fed land uses (cropping, pastures and native vegetation) on clay soils (Abbs and Littleboy 1998; Young and McLeod 2001; Keating *et al*. 2002; Tolmie and Silburn 2002, 2003; Tolmie *et al*. 2003; Ringrose-Voase *et al*. 2003; Yee Yet and Silburn 2003). Logically, if drainage was up to, say, 40 mm/year for rainfed cropping, it would be higher for irrigated cropping and much higher where rainfall plus irrigation was several hundred mm greater than potential crop water use (Tennakoon and Milroy 2003; Silburn and Montgomery 2004).

Indeed by 2000, Hearn (2000) had noted that: '*a mounting body of evidence is challenging the conventional wisdom on drainage. Are these observations from a few aberrant sites, or is deep drainage much more significant and prevalent than believed*?'

Raine and Foley (2001) explained the 'clay soils don't drain' story as follows: '*This major industry misconception arose from research during the 1980s which only looked at a limited number of soils in select areas using relatively short furrow lengths. The soils investigated may also have been structurally degraded due to compaction induced by the cultural practices of the period*', i.e. causing reduced infiltration, and by association, reduced deep drainage.

The issue culminated in the workshop entitled 'Deep Drainage—so what?' organised by the then Australian Cotton Cooperative Research Centre (more recently Cotton Catchment Communities CRC) in 2003 and reported by Silburn *et al*. (2004), and the release of WATERpak (Dugdale *et al*. 2004). This included a review of deep-drainage knowledge in Australian cotton-growing areas for the period up to ~2003 by Silburn and Montgomery (2004). They concluded that: '*deep drainage varies considerably depending on soil properties and irrigation management, and is not necessarily* '*very small*'. *Drainage of 100 to 200 mm/year* (*1–2 ML/ha*) *is typical, although 3 to 900 mm/year* (*0.03 to 9 ML/ha*) *has been observed.*'

This review updates knowledge advances since then, including deep drainage under irrigation globally, particularly, but not exclusively, where Vertosols occur. Given the large amount of publicity regarding deep drainage losses in the Australian cotton industry leading up to 2004, the release of WATERpak, cotton industry and Rural Water Use Efficiency efforts (Roth *et al*. 2013), and the water shortage during the extended Millennium drought, a comparison is made of the deep-drainage rates before and after ~2004.

Irrigation and farm water use efficiency

Bos and Nugteren (1990), in a global survey of data on irrigation efficiencies, reported field application efficiency values ranging from 17% to 88%. The higher values are for drip and sprinkler irrigation systems, whereas the application efficiencies of surface irrigation systems in developing countries are reported to be, on average, ≤40%. An example of these inefficiencies is provided in Uzbekistan, Central Asia (Reddy *et al*. 2013), where irrigation supply systems are reasonably unsophisticated, farms/fields are small, and management is less than optimal. Total irrigated area in Uzbekistan is close to 4 Mha (Reddy *et al*. 2013). By 1994, almost 50% of the total irrigated area was affected by waterlogging and salinity, as a result of excessive seepage and losses from the canal networks and fields and poor performance of drainage systems. Cotton and winter wheat are the main crops, all grown with furrow irrigation, theoretically using 4–7 ML/ha per cotton season.

In a study of 46 irrigation events at nine fields (loamy sands to sandy clay loams), average runoff volume was 39% of the total volume of water applied (whether this is reused is not clear), indicating problems with selection of appropriate furrow flow rates and durations (Reddy *et al*. 2013). There was often a large mismatch between the volume of water applied and the volume of water deficit within the crop root-zone. Measured application rates were 4–11.6 ML/ha, averaging 7.4 ML/ha. Average application efficiency was 49% (compared with the soil water deficit), ranging from 7 to 82%. Inefficiencies were, in part, related to unreliable (and unknown) magnitude and duration of flow rate delivered to the fields, slope >0.5% at seven of the nine sites, and light-textured but variable soils.

The Australian cotton industry—water use efficiency

In the Australian cotton industry, the improvement in WUE reported by Trindall *et al*. (2012) was driven by the Millennium drought, a national agenda for water reform, and enabled by large research, development and extension efforts. Average irrigation application was 5 ML/ha in 2009–10 (Harris 2012), although these were wetter years and the value may not apply in all years, down from ~7 ML/ha in previous years (e.g. ~1996–99; Tennakoon and Milroy 2003). Tennakoon and Milroy (2003) evaluated irrigation input (to the farm, i.e. greater than irrigation applied to fields), evapotranspiration (ET), and efficiency on 20 farms and including 200 fields for 1996–99. Irrigation efficiency was calculated as the proportion of irrigation water input to the farm for cotton production that was used by the crop as ET (after subtracting rainfall and change in soil water) over the growing season. Crop WUE was calculated as lint production per unit of ET. Average irrigation and total inputs were 7 and 12 ML/ha, with ET of 7.35 ML/ha; thus, on average there was an excess of 4.65 ML/ha (465 mm), which can be losses in storage and transmission or in-field (deep drainage and runoff). The average irrigation efficiency was 57%, with a large variation between farms, somewhat above the global average. The wide variation in efficiency was suggested to indicate significant scope for many producers to increase their efficiency.

When a similar survey was conducted in 2006–11 on 30 farms, Montgomery and Wigginton (2012) found the crop water use (ET) was 63% of total water input (water harvested + rainfall). Irrigation water use index or bales of cotton per ML (irrigation + rainfall + change in soil water) had improved from 0.79 to 1.10 (range 0.64–1.71), a 40% improvement, based on 108 farms. The losses of total input (38%) were also divided between on-farm storages (25%), in-field (11.4%), channels (0.5%) and drains (<0.7%), but there was large variability between farms. Raine and Foley (2002) found from farmer surveys that irrigation water use index was 0.6–1.6 bales/ML irrigation for furrow irrigation, 1.5–2.75 for subsurface drip irrigation, and 1.35–2.6 for centre-pivot–lateral move (CPLM) irrigation, with averages of 1.0, 2.4, and 1.9, respectively. The irrigation water use index reported for furrow irrigation is less than the 1.26 bales/ML obtained by Tennakoon and Milroy (2003). Many more studies of WUE in Australia and globally are reviewed by Payero and Harris (2007).

Wigginton (2012) led a program of measurement of evaporation and seepage from 136 on-farm storages. Losses were divided to show that the large loss from on-farm storages is dominated by evaporation. The minority of storages with seepage losses could be ameliorated with engineering solutions. The cost of saving water using either storage cell division or increased wall height strategies (i.e. increasing storage depth and reducing area) was reasonable, with an average cost ~AU$150/ML.year. The cost was as low as $15/ML.year for cell division and $59/ML.year for wall height increase. The cost of water saved was often reasonably attractive compared with the typical value of water available from temporary transfer markets, but the capital cost of increasing wall heights was high. However, not all cotton farms use storages or have other sources of water; thus, the conclusions here differ somewhat from those presented for a broader segment of the irrigation industry presented below.

Baillie *et al.* (2007) conducted a survey of crops grown and irrigation systems used, drivers for private investment in WUE, the economics of investments in irrigation improvements, and future research needs and knowledge gaps, in the Northern Murray–Darling Basin, which covers most of the cotton industry excluding areas south of the Macquarie and in the Fitzroy (Fig. 1). They identified significant opportunities for improved on-farm WUE. Whereas 90% of cotton was irrigated using surface (furrow) irrigation, the area converted to drip irrigation, and particularly CPLM, was increasing. This change has continued since this survey. A total of 1480 GL of potential WUE gains (100% adoption) was identified. However, a significant proportion of these gains cannot yet be realised and further research and development of commercially applicable technologies is required. Losses were split between 48% from storages (mainly evaporation), 45% in-field, and 7% from distribution systems. However, the largest WUE gains in most valleys would be achieved through addressing in-field application efficiency; whereas the Condamine–Balonne was dominated by losses from storages, due to their prevalence.

Review of deep drainage—deep drainage for native vegetation and rainfed (dryland) cropping

To understand the consequences of deep drainage from irrigation, an understanding of deep drainage under native vegetation and rainfed (dryland) agriculture, the 'baseline conditions', is useful. There is now a reasonably good understanding of deep drainage under native vegetation and rainfed agriculture in several areas of relevance to the Australian cotton industry: (*i*) the Northern Murray–Darling and Fitzroy Basins, from measurements (Radford *et al.* 2009; Silburn *et al.* 2009, 2011; Tolmie *et al.* 2011; Young *et al.* in press) and modelling (Abbs and Littleboy 1998; Ringrose-Voase *et al.* 2003; Yee Yet and Silburn 2003; Silburn *et al.* 2007; Robinson *et al.* 2010); (*ii*) the Texas High Plains (McMahon *et al.* 2003; Scanlon *et al.* 2005, 2007*b*, 2010*a*); and (*iii*) Vertisols in Israel (Kurtzman and Scanlon 2011). General conclusions from these studies, supported by measured or modelled deep drainage and unsaturated zone moisture and solute profiles, include:

1. Deep drainage is greatest in summer rainfall zones for cropping (winter > summer > opportunity cropping), less for perennial pastures, and least for native perennial, evergreen vegetation (all measurement and modelling papers cited address this issue).
2. Within each land use, deep drainage increases with increasing average annual rainfall and with decreasing soil water-holding capacity (Yee Yet and Silburn 2003; Radford *et al.* 2009; Tolmie *et al.* 2011).
3. Deep drainage is highly variable over time (all modelling papers).
4. The unsaturated zone under native vegetation is typically dry (e.g. at or below wilting point) to considerable depths (e.g. 6–10 m), which provides a large buffer for storage of deep drainage from more leaky land uses (Scanlon *et al.* 2005; Radford *et al.* 2009; Silburn *et al.* 2009, 2011; Foley *et al.* 2010; Kurtzman and Scanlon 2011).
5. Large amounts of chloride (and other salts) are stored in soil and unsaturated zone profiles under native vegetation in semi-arid to arid landscapes, and this is leached downwards after a change to land uses with higher deep drainage rates (all measurement and modelling papers addressing this issue).
6. The salinity of this leachate is typically high and generally much higher than underlying groundwaters, unless they are already saline (all measurement papers addressing this issue).

Deep drainage under irrigation

Global studies

China, India, Israel, Pakistan and Uzbekistan

Ahmad *et al.* (2002) determined deep drainage of 294 mm/year (22% of rainfall plus irrigation, R + I) for border irrigation, wheat–rice double cropping in the Indus Basin Irrigation System, Pakistan, and 197 mm/year (17% of R + I) for cotton–wheat double cropping (Table 1, Fig. 2) (using a calibrated water balance model). Somewhat larger values were reported for annual simulations (389 and 233 mm/year). Reddy *et al.* (2013) did not report deep drainage for irrigation (mainly cotton and winter wheat) in the Fergana Valley of Uzbekistan. However, as average irrigation efficiency was 48% and average runoff was 38% of volume applied (average 744 mm/year), it is likely that deep drainage was up to 14% of water applied, i.e. 104 mm/year. Some deep drainage is consistent with the depth to watertable being 0.37–3.5 m for the fields studied.

Deep drainage was estimated in the North China Plain (or Hebei Plain) by calibrated water balance modelling of irrigated wheat–maize rotations (Kendy *et al.* 2003, 2004) and by applied tritium and bromide tracers (Wang *et al.* 2008) (Table 1, Fig. 2). Kendy *et al.* (2003) gave deep-drainage rates (loam soils, for 3 years) of 36–209 mm/year, averaging 117 ± 46 mm/year. This is 8–25% of R + I (420–850 mm/year), averaging 17% ± 4.5%. Kendy *et al.* (2004) modelled a longer period and derived the relationship: $D = (R + I) - 660$. Deep drainage varied annually from 50 to 1090 mm/year. However, this analysis does not seem to make physical sense, as ET was ~660 mm/year whether R + I was 800 or 2000 mm/year, due to assumptions made, and the equation given is much steeper (not shown) than other data in Fig. 2. Wang *et al.* (2008) measured deep drainage over specific time periods of ~2 years in mm per day using the aforementioned tracers. Assuming these apply for 365 days per year, annual values are 80–117 mm/year for non-irrigated, non-crop land, 62–84 for sprinkler irrigation, and 153–212 for furrow irrigation. Deep drainage was higher for non-irrigated, non-crop land than for sprinkler irrigation, because the former was poorly vegetated. They found deep drainage of $D = 0.21\ (P + I) - 47.75$, where D is groundwater recharge (deep drainage) (mm), P is precipitation (mm), and I is irrigation (mm) over the time interval considered ($r = 0.74$), which is reproduced in Fig. 2. Such relationships were also found by Kendy *et al.* (2003) in China and in India (table 7 in Wang *et al.* 2008; Table 1, Fig. 2) and the USA (Scanlon *et al.* 2005). Lu *et al.* (2011) found deep drainage of 133–175 for five sites on the Hebei Plain (15–25% of R + I) (Table 1), similar to other estimates. Lin *et al.* (2013) measured deep drainage for four irrigated sites in the western North China Plain, using chloride (Cl) steady-state mass balance, of 66–127 mm/year, or 11–17% of R + I (Table 1, Fig. 2). Lin *et al.* (2013) refer to other published deep-drainage/recharge estimates in China, which are not reviewed here. Figure 2 shows that the various deep-drainage estimates from Asia cover a reasonably consistent range, and that total water input explains some of the deep drainage.

Kurtzman and Scanlon (2011) modelled deep drainage under irrigated cropland on Vertisols in Israel at 90–230 mm/year, compared with 1–3 mm/year for natural ecosystems, and consistent with steady-state, mass-balance estimates of 90–190 mm/year and groundwater-balance estimates of average recharge of 110–160 mm/year. This is also consistent with Fig. 2 for R + I of a little under 1000 mm/year. The travel time for Cl to move down 9 m in the unsaturated zone averaged 11 years. Soil profiles under irrigated cropland were often wetter than those under rainfed or natural lands with similar soil texture, as also seen in the USA High Plains (Scanlon *et al.* 2005, 2010*b*; McMahon *et al.* 2006; Gurdak *et al.* 2009) and Australian cotton-growing areas (Shaw and Yule 1978; Foley *et al.* 2010, 2012; Kelly *et al.* 2011). The Kurtzman and Scanlon (2011) study, on Vertisols, illustrates that heavy clay soils and lower rainfall (although Mediterranean rather than semi-arid climate) are no impediment to deep drainage occurring under irrigation.

USA deep drainage rates

Roack and Healy (1998), in two fields in one year in New Mexico, measured deep drainage by three methods and obtained reasonably consistently high deep drainage for border flood irrigation of lucerne (alfalfa) of 164–816 mm/year, 223–316 mm/year, and 150–380 mm/year, all 13–43% of the water input (Table 2). Higher deep drainage is again associated with the higher water inputs (i.e. site 2 with ~1700 mm of irrigation). Although this study is not on heavy clay soils, it is in a semi-arid environment, and shows that irrigation, and especially over-irrigation, causes large deep drainage losses. This conclusion also applies to the study by Scanlon *et al.* (2005), in semi-arid Nevada, using sprinkler irrigation and lucerne, both considered more efficient (e.g. than furrow irrigation and less perennial cropping), low deep-drainage systems, where deep drainage of 10–14% of water input was determined.

Dugan and Zelt (2000), as reported by Sophocleous (2005), estimated deep drainage for irrigated cropping of 75–119 mm/year in higher rainfall Nebraska and 21–45 mm/year in drier Colorado, and much lower rates for lucerne (Table 2). McMahon *et al.* (2003) estimated deep drainage of ~55 mm/year or more (depending on assumptions, using two methods) for a period of ~30+ years of furrow irrigation in the central High Plains, and 4–12 times drainage rates under rangelands (Table 2).

Deep drainage rates measured in the south-western USA range from 19 to 485 mm/year or 2–19% of rainfall plus irrigation applied (Scanlon *et al.* 2005) (Table 2). Scanlon *et al.* (2005) found a strong linearly increasing relationship between total R + I and average deep drainage rates ($R^2 = 0.94$) using data from four studies in the south-western USA (Fig. 3; labelled 'USA arid/semi'). The intercept approached zero deep drainage at just under 850 mm of R + I and increased to 500 mm of deep drainage at just under 3000 mm of R + I. This contrasts with the relationships from China and India (Fig. 3), due to the lower rainfall inputs and higher evaporation. The USA deep-drainage–total input line is displaced to the right, so that more irrigation is needed to instigate deep drainage but the slope is similar to the 25% of input line.

McMahon *et al.* (2006) measured deep drainage increasing from north to south in the High Plains, apparently due to increasing irrigation inputs (Table 2). Average deep drainage was 59 mm/year and the highest values were ~105 mm/year in the southern High Plains. These deep drainage rates were considerably higher than under rangeland.

In the Texas (southern) High Plains (Scanlon *et al.* 2010*a*), the ranges in R + I and deep-drainage rates were limited, with no relationship (Table 2, Fig. 3). There was a general similarity in the range of deep-drainage rates beneath rainfed and irrigated agroecosystems, despite the additional water inputs in irrigated areas. This was attributed partly to (*i*) deficit irrigation practices, (*ii*) higher crop yields and (*iii*) higher ET rates with irrigation, and

Table 1. Deep drainage estimates for global irrigated sites

R + I, Rainfall + irrigation; SS, steady-state; CMB, chloride mass balance, Cl front displacement (Walker *et al.* 1991)

Study	Av. ann. rainfall	Av. ann. irrigation (mm/year)	Deep drainage Av. ann.	Deep drainage % of R + I	Method	Source
Indus Basin irrigation system, Pakistan, Rechna, Doab						
1) Border irrigation wheat/rice double crop loam	360	993	294[A], 389[B]	22	Calibrated water balance SWAP model	Ahmad *et al.* 2002: 1, tables IV, V; 2, tables VIII and IX
2) Cotton/wheat double crop, sandy loam	290	844	197[A], 233[B]	17		
China, North China Plain:						
Hebei Province, loam, 16 sites, wheat/maize, 3 years	R + I 420–850		36–209	8–25	Calibrated soil water model	Kendy *et al.* 2003
Luancheng County, loam, wheat/maize/cotton, 1970–2000	R + I 800–2000 yearly		117 ± 47 50–1090	17 ± 4.5 DD = 10[(R + I)/10–66]		Kendy *et al.* 2004
Hebei Plain, China, silt, clay, silt/clay, ~2 years, *n* = 39:			(mm/day)			
Luancheng site, sprinkler irrigation	702, 1135	158, 458	0.23, 0.17	10.8, 8.2	Applied tritium and Br tracers	Wang *et al.* 2008
Furrow irrigation	702, 1135	300, 675	0.58, 0.42	23.5, 17.7		
No irrigation	702, 934	0, 0	0.32, 0.22	18.5, 16.1		
India (table 7 in Wang *et al.* 2008)			(mm)			
4 published tracer studies		R + I		11.0[A]	Applied tritium and Br tracers	Wang *et al.* 2008 (from Goel *et al.* 1975; Athavale *et al.* 1983; Sukhija *et al.* 1996; Chand *et al.* 2004)
Rain, irrigation and deep drainage are for the periods of sampling (e.g. <1 year)		219–1067	17–215	6–22		
China, Hebei Plain, ~1 year, 5 sites, silt and silty clay soils	435–535	375–255	133–175	15–25	Hydrus 1D, calibrated	Lu *et al.* 2011
China, North China Plain, long-term, deep cores					Cl, F, SO_4 tracers, SS mass balance	Lin *et al.* (2013), tables 5 and 6
1 rainfed	526	0	19	3.6		
4 irrigated (Shijiazhuang, near Hutuo River)	526	387	66–127	7.2–14		
Israel, Vertisols, Mediterranean climate	480	487	90–190	9–20	SS CMB	Kurtzman and Scanlon 2011
Brown to grey alluvial soils, Chromic Haploxererts (Soil Survey Staff 1999); irrigated summer crops (maize, sunflower, cotton) and rainfed winter wheat.			90–230	9–24	Calibrated unsaturated flow and transport model	
			110–160	11–17	Groundwater balance	

[A] Mean. [B] Median.

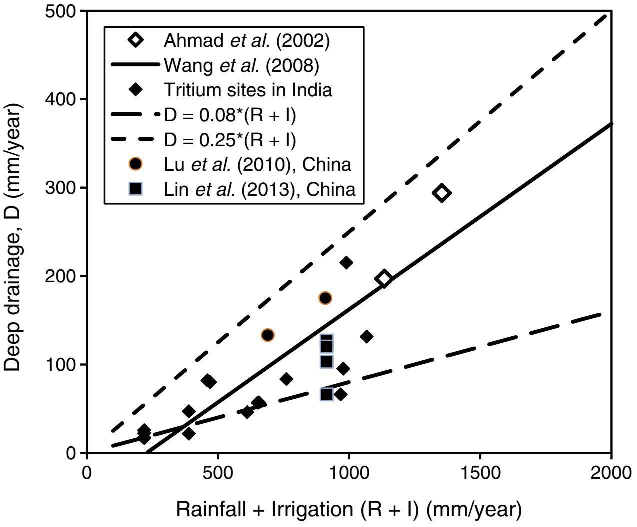

Fig. 2. Annual deep drainage as a function of water input (rainfall plus irrigation, R + I) from Pakistan (Ahmad *et al.* 2002); North China Plain (solid line, D = 0.21*(R + I) – 47.75; *r* = 0.74) from Wang *et al.* (2008) tritium tracer sites and the 8–25% deep drainage range of Kendy *et al.* (2003) (dashed lines), modelling of Lu *et al.* (2011) and Cl mass balance of Lin *et al.* (2013); and India, tritium tracer sites (table 7 in Wang *et al.* 2008).

(*iv*) irrigation applications (300 mm/year) well below that required for optimal crop yield (580 mm/year), for irrigated relative to rainfed agroecosystems. By contrast, where much higher application rates were used in Nevada (Scanlon *et al.* 2005) and New Mexico (Roack and Healy 1998), deep drainage rates were also much higher. In summary, (*a*) deep drainage in the USA is considerably greater for irrigated sites than rangeland or rainfed agriculture; (*b*) considerable salt has been leached downward in irrigated profiles (Scanlon *et al.* 2010*b*); and (*c*) total water additions (R + I) (Fig. 3) and climatic factors are important in determining deep drainage in irrigated farming systems.

Consequences of deep drainage

The Indus basin irrigation system of Pakistan is one of the largest contiguous surface irrigation systems in the world (Ahmad *et al.* 2002). Losses from earthen channels and irrigated fields resulted in rising groundwater in some areas, leading to waterlogging and salinisation in parts of the Indus Plain (Smedema 2000). According to Ahmad *et al.* (2002): '*The first symptoms of the problem appeared in the first half of the twentieth century, but the problem reached alarming proportions in the period between 1950 and 1960. To combat this menace, the government of Pakistan took several measures and encouraged the farming community, through tax reduction and other subsidies, to install private tubewells to pump groundwater for irrigation.*' However, the resulting development of groundwater has reached a point where over-extraction of groundwater is occurring. This highlights a common theme seen in Pakistan, China and the US High Plains—groundwater extraction for irrigation can sometimes be used to manage the rising groundwater associated with irrigation, but focusing on better quality aquifers leads to their depletion.

In the USA, higher recharge (deep drainage arriving at the watertable) was generally associated with increased salinity in groundwater, due to flushing of salts from the unsaturated zone, or accumulation of salts in the unsaturated zone in areas where irrigation is more efficient (Scanlon *et al.* 2010*b*). Estimated travel times to the watertable ranged from 9 to 46 years at the arid Nevada sites, to 132–373 years at the Texas High Plain site (watertables ~35+ m deep). In the Southern High Plains, median total dissolved salts in groundwater increased by 34% and 31% under irrigated and rainfed areas, respectively (Scanlon *et al.* 2005). Median groundwater nitrate-N concentrations increased by 221% beneath irrigated areas and 163% beneath rainfed areas, reflecting land-use change induced contamination of groundwater. Scanlon *et al.* (2005) found increases in soil and groundwater salinisation with increased irrigation efficiency: '*Degradation of groundwater quality caused by irrigation will not be readily reversed by changes from irrigated to dryland or rangeland settings.*' Thus, there is much more to be done to manage both the water and salt balances of large-scale irrigation developments.

Australian deep drainage studies relevant to the cotton industry

Emerald Irrigation Area (1973–1974) (Shaw and Yule 1978)

Shaw and Yule (1978) used two indicators of deep drainage in their study of soil water-holding capacity, ponded infiltration rates and irrigation water requirements during development of the Emerald Irrigation Area (EIA). These were change in soil moisture content below the root-zone and changes in soil Cl profiles, which indicate that leaching had occurred. Soils were Vertosols of basaltic, alluvial and Tertiary sedimentary origin and Sodosols of alluvial origin, and had clay content ranging from 30 to 70%. Cation exchange capacity (CEC) ranged from low (12 cmol(+)/kg) to high (75 cmol(+)/kg) and exchangeable sodium percentage (ESP) from 1 to 26. Infiltration rates (during 36–72 h ponding) were 2–21 mm/day. Shaw and Yule (1978) noted: '*All soils showed water movement below the root zone and in some sites, quite high water movement occurred*', and '*Significant drainage and substantial leaching of chloride occurred under prolonged ponding*'.

Subsequently, the EIA suffered from localised water logging and salinity, due to groundwater rise into the root-zone in areas of poor lateral discharge (Yule 1997). This was managed successfully using tile and surface drainage, but at a cost greater than the land was worth (Yule 1997). The EIA is small enough and the flow in the Nogoa River (where the drainage water is discharged) is large enough that the export of the drained salt is not problematic for river salinity. Gardner and Coughlan (1982) conducted similar studies in the Burdekin Irrigation Area in North Queensland, with generally similar results. This area also has shallow watertables under extensive areas, due to excessive deep drainage, and also zones of seawater intrusion due to excessive groundwater extraction (Brough *et al.* 2008).

Final infiltration rates for soils used for irrigation

Shaw (1995) synthesised the results from Shaw and Yule (1978) and Gardner and Coughlan (1982). Final infiltration rate

Table 2. Deep drainage estimates for USA irrigated sites

R + I, Rainfall + irrigation; SS, steady-state; CMB, chloride mass balance; T, transient, either SODICS (Thorburn *et al.* 1987, 1990) or Cl front displacement (Walker *et al.* 1991); n.a., not available

Study	Av. ann. rainfall	Av. ann. irrigation (mm/year)	Deep drainage Av. ann.	Deep drainage % of R + I	Method	Source
Roswell, New Mexico. Loams over clay loam.	219	958, 1698	164, 816	14, 43	Water-budget	Roack and Healy 1998
Two adjacent fields, alfalfa, flood ‘border’			223, 316	19, 16	Volumetric-moisture	
irrigation, estimated by three methods in one year (1996)			150, 380	13, 20	CMB	
Amargosa Desert, Nevada, sands and gravels						Scanlon *et al.* (2005)
Alfalfa (lucerne) and turf grass, sprinkler irrigation	113		130		SS CMB	
Field 1 and 2 ($n = 6$)		2000	202^{A}, 150–280	10, 7–13	TCMB—solute front displacement	
Field 3 and 4 ($n = 6$)		2700	385^{A}, 130–640	14, 6–30		
Kansas USA High Plains				n.a.	Modelled soil water balance	Dugan and Zelt 2000 reported by Sophocleous 2005
Kearney, NE, maize/sorghum/soybeans	623	n.a.	75–119			
Alfalfa (lucerne)			25			
Holyoke CO, maize/sorghum/soybeans	448	n.a.	21–45	n.a.		
Alfalfa (lucerne)			2			
South-western Kansas, central High Plains	452	n.a.	53	n.a.	Cl displacement	McMahon *et al.* 2003; deep drainage rates were 4–12 times those of rangeland
Furrow irrigation 1955–56 to 1989,			54	n.a.	Tritium	
loamy, fine sand soil			39–54 or 106–116	n.a.	Various assumptions about tritium	
High Plains, irrigated sites ($n = 6$), coarse textured soils	420–500		59^{A}		Tritium movement and Cl displacement	McMahon *et al.* 2006; irrigated fluxes 1.5, 9.3, and 122 times larger than for rangelands
Northern		140–700	17, 32	n.a.		
Central		425–850	39, 52	n.a.		
Southern		255–915	102, 111	n.a.		
Southern High Plains, Texas	~450	0	24^{B}	5	SS CMB	Scanlon *et al.* (2007*b*)
Rain-fed cultivation ($n = 19$)			5–92			
Southern High Plains, Texas, flood and sprinkler	430–480	~300	18–97		SS CMB and soil water displacement	Scanlon *et al.* 2010*a*; authors selected between methods for each site
Irrigated—finer grained soils ($n = 2$)		440, 380	36, 22	2–3		
Irrigated—coarser grained soils ($n = 11$)		200–380	48^{B}	6		

^{A}Mean. ^{B}Median.

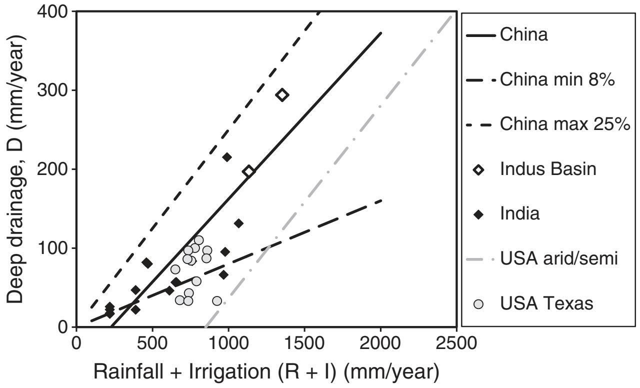

Fig. 3. Deep drainage as a function of total water input (rainfall plus irrigation) for USA irrigation arid/semi-arid sites (approximated from Scanlon *et al*. 2005) and Texas (Scanlon *et al*. 2010*a*), in contrast with those in China (solid line Wang *et al*. 2008; dashed lines Kendy *et al*. 2003), Pakistan (Ahmad *et al*. 2002) and India (table 7 in Wang *et al*. 2008) (see Fig. 2).

(FIR; at 3–7 days' ponding) had a good relationship with ESP at 0.9 m depth (Fig. 4). The range in FIR is from 1 to 23 mm/day (ignoring high and low outliers). The value of 1 mm/day at high ESP is consistent with the value of 1 mm/day measured by Mason *et al*. (1980). (While these also seem to be low rates of infiltration, an interpretation of what they mean for annual deep drainage rates is given below.) For Black Vertosol soils in Queensland, Foley *et al*. (2006) reported near-saturated hydraulic conductivity (Ksat) of 0.3–2 mm/h (7–48 mm/day) for shallow plough pans (annual cropping and lucerne leys, controlled traffic, minimum tillage), and 8–25 mm/h (192–600 mm/day) under grass pasture. The cropping and ley values span a similar range to the Shaw (1995) FIR values. (The lower permeability of the cropped site compared with pasture sites is probably indicative of structural degradation in the cropped soils.)

Interpretation of soil infiltration or hydraulic conductivity rates for determining deep drainage has apparently been problematic. For example, see discussion in Smith (2008) of early ideas that clays in the Ord River Irrigation Area were suitable for rice production (i.e. would not lead to excessive deep drainage): '*Chapman* (1984) *also pointed out the contradiction that the infiltration rates measured in the previous studies were still significant at the conclusion of the infiltration tests, even though there was no evidence of moisture change below a depth of around 1.5 m*' Smith (2008).

When estimating deep drainage rates, the final infiltration rate is only one part of the answer. The number of days that the profile is draining at this rate must also be estimated. Although a small soil core may equilibrate to drained upper limit in 2 or 3 days, a soil profile will continue to drain for many days after saturation (e.g. 16 and 30 days after irrigation, Gardner 1988; 16 days, Moss *et al*. 2001). Infiltration rates or hydraulic conductivities by themselves are insufficient for estimating deep drainage without understanding the duration of drainage and the hydraulic gradient operating after a wetting event (See below: *Understanding flow processes in clay soils*).

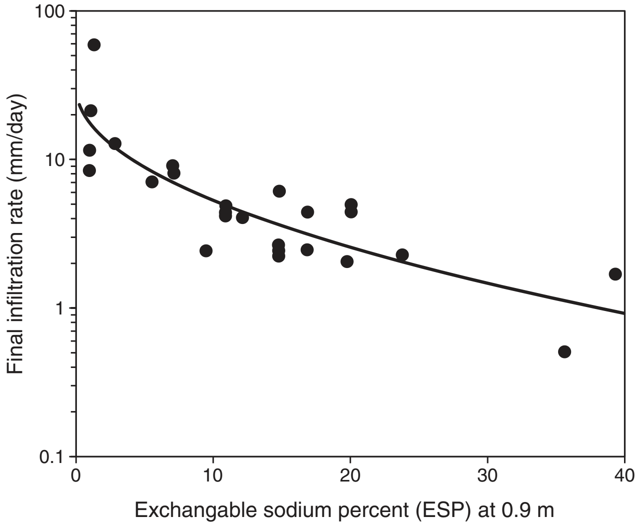

Fig. 4. Final infiltration rate (FIR) after 3–7 days of ponding in 'mini-bays' at Emerald (Shaw and Yule 1978) and the Burdekin (Gardner and Coughlan 1982), Australia. The fitted line is FIR = 30.69*(10^(–0.241*ESP$^{0.5}$)) (R^2 = 0.73). Source: Redrawn from Shaw (1995).

Condamine alluvia (Lane 1979)

Lane (1979) investigated the sources of recharge for the Condamine alluvial aquifers—a large plain in southern Queensland dominated by Vertosols (Dafny and Silburn 2013)—including diffuse recharge by rainfall and irrigation (deep drainage) and various means of artificial recharge. This included measurements of the depth to drier soil after 756 mm of rainfall over ~3 months (the wettest 3 months on record), and surface inundation for much of this time (13 sites) and infiltration measurements in seven natural depressions inundated for ~3 months. It was found that the water penetrated only to shallow depths (~1–2.5 m) and it was concluded that infiltration of rainfall would not reach the aquifer. Diffuse recharge on the clay soils was excluded as a source of recharge for the aquifers ≥20 m below the surface. That is, deep drainage from rainfall and irrigation were considered negligible. Lane (1979) also determined that the final infiltration rate was ~6 mm/day in the natural depressions, which was used for calculating recharge from the Condamine River, but not deep drainage.

More recent investigations, e.g. rainfed cropping and pasture (Silburn *et al*. 2011; Tolmie *et al*. 2011) and irrigated cropping (Zischke and Gordon 2000; Foley *et al*. 2010; Gunawardena *et al*. 2011; described below), have shown that Lane's conclusions were incorrect—soil and unsaturated zone profiles in the same area have wet to large depths. While Lane's reasoning may suit investigations on rigid soils, it cannot be applied to cracking clays. Prolonged rainfall and flooding resulted in poor infiltration depths because the surface soil swelled, pore spaces closed and soil conductivity declined to very low rates (Foley *et al*. 2006), whereas periodic rainfall and furrow irrigation events result in deep wetting of clay profiles and in deep drainage.

Australian Cotton Research Institute irrigation trials—Narrabri and related sites

Mason *et al*. (1980) irrigated two soybean varieties with two irrigation frequencies (90 and 135 mm deficits) for 3 years, on a sodic grey cracking clay at the Australian Cotton Research Institute (ACRI). Soil water loss (deep drainage below 1.5 m) was measured from bare soil under plastic for 12 days after irrigation. The average rate of water loss was 1.3 mm/day or ~1.0 mm/day after accounting for lateral losses or ~10 mm per irrigation. The frequently irrigated crops received ~four or five irrigations plus a pre-irrigation. Thus, a rough estimate of total deep drainage is 50 mm (5 irrigations × 10 mm) or ~6% of total water supplied (ET plus runoff). This estimate is similar to the Darcian flux measurements on another block on the same research station at Narrabri by Montgomery (2003) and estimates by Weaver *et al*. (2005) and Hulugalle *et al*. (2010).

Both Chan and Hodgson (1981) in the Namoi Valley and Hulme *et al*. (1991) in the Macquarie Valley found that furrow irrigation water did not infiltrate into sodic soils beyond 0.8 m, even in soil at permanent wilting point to a depth of 1.5 m before irrigation. This has been used as evidence for a lack of deep drainage. However, Chan and Hodgson (1981) also show full soil water profiles 3 weeks after a pre-irrigation and following a winter fallow, and Hulme *et al*. (1991) show a reasonably full profile after a cultivated fallow. This indicates that deep infiltration and drainage are possible, but that the method or rate of wetting is important in determining the outcome. In the Macquarie case, ESP was ~20%, electrical conductivity (EC) 0.76 dS/m and bulk density ~1500 kg/m^3 below 0.8 m, and the soil was structurally degraded. That is, infiltration is expected to be poor.

Soil chloride profiles and transient chloride mass balance

Chloride concentrations in the soil profile provide an insight into past drainage through a soil, particularly when it is compared with a Cl profile from native vegetation, which does not change at time-scales of decades (Silburn *et al*. 2009), or with other profiles through time. This is because Cl, which occurs naturally in rain and soil, is conservative, soluble and mobile, and in the long-term moves where the water moves (subject to various caveats; see Walker 1998). Under native vegetation in semi-arid and sub-humid regions, Cl concentrations typically increase with soil depth to a maximum and are then variable but similar in deeper layers (Silburn *et al*. 2011; Tolmie *et al*. 2011), due to storage of historic Cl from rainfall (see e.g. Fig. 5). Observations of significantly lower EC or Cl levels in irrigated soils compared with paired native vegetation or rainfed sites are common (Shaw and Yule 1978; Gardner and Coughlan 1982; McKenzie *et al*. 1991; Willis and Black 1996; Scanlon *et al*. 2010*a*), indicating an increase in deep drainage.

Changes in Cl profiles can be analysed to determine deep drainage rates using steady-state (USSL 1954) or transient Cl mass balance (CMB). Transient CMB uses change in the Cl mass either in the soil profile (e.g. SODICS, Thorburn *et al*. 1987, 1990) or in the unsaturated zone (Cl front displacement, Walker *et al*. 1991). Transient CMB assumes complete mixing and does not include deep drainage by bypass flow, and therefore may underestimate deep drainage, although Prendergast (1995) has shown that bypass flow can have the same Cl concentrations as the soil matrix pore water and CMB would include this form of leaching. Chloride profiles often attain a new steady-state reasonably rapidly under irrigation (Thorburn *et al*. 1990; Weaver *et al*. 2005), and the simpler steady-state analysis is then valid. Several studies have found reasonable agreement between transient CMB and water balance modelling (Yee Yet and Silburn 2003; Huth *et al*. 2010). Transient CMB does have some advantages: it indicates whether the Cl is in steady-state; it can consider long periods and thus give results approaching a long-term average; it is inexpensive enough to use for many sites, replicates or composited samples; it can detect low rates of deep drainage (e.g. 1 mm/year) if the change in mass of soil Cl is sufficient (i.e. given enough drainage or time); and it provides clear and compelling evidence of deep drainage (Silburn *et al*. 2009).

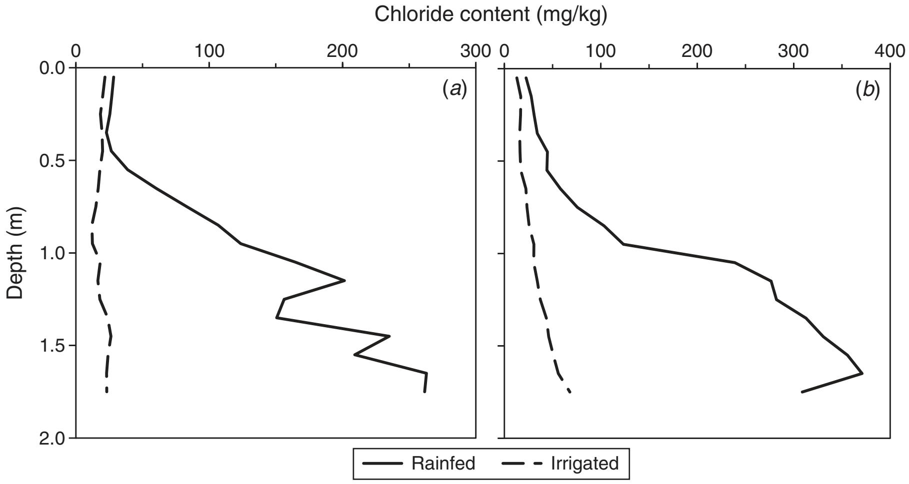

Fig. 5. Average chloride profiles in irrigated fields and in adjacent rainfed fields, for (*a*) grey clay (Black Vertosol), and (*b*) Red alluvial soil (Red Dermosol). Source: Montgomery (2003); Silburn and Montgomery (2004).

Thorburn *et al*. (1990) estimated deep drainage from paired Cl profiles and irrigation water quality data from 42 irrigated soils in the Lockyer Valley and in Central Queensland, using the transient CMB model SODICS. For soils with a wide range of properties (Table 3), deep drainage was 0–100 mm/year for half of the sites, 100–300 mm/year for 18 sites (43%) and 500–1200 mm/year for three sites. Time to establish a new soil Cl equilibrium (i.e. to attain steady-state) mostly ranged from 3 to 40 years, depending on the drainage rate and irrigation salinity, but was as short as 1 year with very high drainage and 50–100+ years for soils with low drainage rates. The new equilibrium under irrigation involved cases of both increased (salinisation) and decreased soil Cl. Dowling *et al*. (1991) used similar methods on a furrow-irrigated, sodic duplex soil in the Burdekin, North Queensland, with and without applied gypsum. Deep drainage was highest at the head-ditch end of the field (98 mm/year, without gypsum) and decreased towards the tail-drain (0 mm/year), or 200 and 70 mm/year with gypsum.

Willis and Black (1996) also found lower soil Cl for irrigated sites compared with non-irrigated sites in the Macquarie Valley for four soils (generally 'lighter textured' soils, although one was a Grey Vertosol). They used measured changes in soil Cl profiles and transient CMB to calculate long-term changes in deep drainage associated with flood irrigation. Their results (Table 3) indicate a wide range in the increase in deep drainage under irrigation, with a larger increase for the lightest textured soils. Partly because of their greater drainage, the lightest textured soils received more irrigation water, thus further contributing to greater drainage. The increase in drainage was lower on soils with higher clay content (Mullah and Mitchell), due to their higher water-holding capacity, leading to less frequent irrigation, lower drainable porosity and (presumably) lower subsoil permeability. The low drainage for the Grey Vertosol is roughly equivalent to the drainage estimated for sodic Grey Vertosols in the Namoi Valley (work of Hulugalle and Weaver, discussed below), but is much lower than the deep drainage measured on a similar soil by Willis *et al*. (1997) (Table 3).

Willis *et al*. (1997) compared deep drainage by measured water balance, steady-state CMB and Darcian flux calculation, for the Mullah cracking clay and Wilga duplex soil (Table 3). Deep drainage was 214 and 104 mm, respectively, using steady-state CMB for the years of irrigation, and 236 and 145 mm, respectively, for the one cotton season monitored. The CMB was considered the most reliable method, although the measured water balance did give deep drainage for individual irrigations. These results showed that deep drainage was greatest early in the growing season following initial wetting of the soil, when the crop had a low leaf area index.

Zischke and Gordon (2000) estimated the leaching fraction and thus deep drainage from soil properties at sites on the Darling Downs alluvia ($n = 7$) and in the Namoi Valley ($n = 5$) and Macquarie ($n = 6$), using a method originally based on steady-state salt mass balance (SaLF, Shaw and Thorburn 1985). They obtained average values of 270, 68 and 300+ mm/year for the regions, respectively, or 24, 5 and 30+% of water inputs. Moss *et al*. (2001) reported transient CMB results for some of the same sites, averaging 258 ($n = 4$), 64 ($n = 3$) and 224 ($n = 3$) mm/year, respectively, or 31, 8 and 27% of water inputs. The steady-state SaLF and transient CMB results appear reasonably comparable, and represent longer term estimates of deep drainage (i.e. for the period under irrigation).

Montgomery (2003) (see Silburn and Montgomery 2004) measured Cl profiles in irrigated and adjacent rainfed fields in the Gwydir Valleys, NSW. Irrigated fields had lower Cl concentrations in the soil profile than adjacent rainfed sites (Fig. 5), indicating that Cl has been leached downwards and drainage was greater than under rainfed cropping. Modelling with SODICS (Thorburn *et al*. 1990) indicates that deep drainage had increased by 62 mm/year for the Vertosol and 35 mm/year for the Red Dermosol over the 17 years since development (Table 3), or 123 and 69 mm/year, respectively, if only the years with irrigation are considered to cause increased drainage, compared with rainfed cropping (i.e. total deep drainage would be greater). Measured water balances for the same fields for one season gave deep drainage of 158 and 53 mm, respectively. The Red Dermosol had a higher potential for drainage (e.g. higher saturated hydraulic conductivity), but only drained in the first few irrigations, as indicated by moisture probes and tensiometers, due to under-irrigation and poorer infiltration (hardsetting) as the season progressed. In contrast, deep drainage on a Grey Vertosol in the Namoi Valley (ACRI, short furrows), by measured water balance, was only 9 mm for the season (may underestimate drainage by rainfall), illustrating again the low drainage on these soils and efficient furrow practiced on this research station, which so informed the industries early views on deep drainage being small.

Scientists at ACRI, Narrabri, have measured deep drainage using steady-state and transient CMB since about 2000, for continuous cotton and various crops in rotation with cotton at various sites in the Namoi Valley (Hulugalle and Weaver 2000; Weaver *et al*. 2002, 2005, 2013; Hulugalle *et al*. 2005, 2010; 2012). Soils were self-mulching grey clays (Vertosols, or Typic Haplusterts; Soil Survey Staff 1999). The data for continuous cotton are most relevant, because this system is most commonly practiced by cotton growers (Table 3). Values for irrigated cotton include: 98 mm/year for continuous cotton and 76–151 mm/year for cotton with various prior crops and incorporated or standing stubbles (Hulugalle *et al*. 2005); 35–78 for cotton sown into standing wheat stubble and 62–83 for cotton sown into incorporated wheat stubble, both with low rates of irrigation (Weaver *et al.* 2005); and 25 and 33 mm/year on average for four cotton monoculture crops with conventional tillage and permanent beds, respectively (Hulugalle *et al*. 2010).

Hulugalle *et al*. (2010) found that deep drainage was greater with permanent beds than for conventional tillage, with wheat in rotation on permanent beds, and with more frequent irrigation. Hulugalle *et al*. (2012) found that deep drainage under irrigated cotton on a Grey Vertosol (six seasons) at Narrabri was greater when rotated with wheat (41 mm) or wheat–vetch (31) than with cotton (24 mm) or vetch (19 mm), and under lengthy fallows than under short fallows, especially dry winter fallows. During wet winters, drainage was greater in fallow than crops. Reasonably large losses of nitrate-N, ions and salt (as EC) occurred in deep drainage. Similarly, Weaver *et al*. (2013) found salinity and sodium adsorption ratio (SAR) of drainage leachate were many times higher than those of irrigation water and that losses of nitrate (NO_3-N) in leachate were large.

It would be useful if all of these results could be tied together to summarise the main drivers of deep drainage, including the effects, if any, of soil properties, irrigation management and water quality, and crop and tillage practice. Figures 2 and 3 indicate that total rainfall plus irrigation should explain a considerable portion of the variation in deep drainage.

Measured water balances

Tennakoon and Milroy (2003) obtained production and water use data from 25 cotton farms and ≥200 individual fields representing the six largest cotton-production areas in Australia. They estimated ET by calculating a daily water balance for each field using a computer model. They assessed total water use, including in-season rainfall, change in soil water, and water pumped, harvested or taken from storages. Average water excess, i.e. total water use (1115 mm) minus ET (735 mm), was 379 mm/year, or 259 mm/year excluding an unusually large value for the Gwydir Valley. This excess could be lost in transmission and storage or by in-field losses such as deep drainage. Where water is stored on-farm in raised earth dams ('ringtanks'), losses can be large, mainly due to evaporation (Dalton *et al*. 2001; Roth *et al*. 2013). Runoff is not considered a loss (rather a cost) as it is recycled. If half of the excess (259 mm/year) is lost in transmission or storage, deep drainage is ~130 mm/year.

McHugh (2003) (also McHugh *et al*. 2008) used measured water balance on an alluvial Vertosol and found deep drainage of 118 mm/year for furrow irrigation with farmer practice and almost nil the following year with furrow irrigation after optimisation, in years when in-season rainfall was almost absent (Table 3). With subsurface drip irrigation (SDI) at 90% of the soil water deficit, considerably less water was applied and deep drainage was only 18 mm/year in one year and nil the next. Both SDI and optimised furrow irrigation were shown to be capable of high WUE when minimal rainfall occurred.

Dalton *et al*. (2001) and Dalton (2003) measured deep drainage by measuring water balance on the Border Rivers alluvia and Darling Downs, respectively. In the Border Rivers, they measured deep drainage in single seasons on eight fields on various Vertosols and determined values of >75–235 mm/season (11–30% of water input), averaging >136 mm (Table 3). On two other fields (Table 3) they determined deep drainage of 128 and 166 mm/season (11–12% of water input). Dalton (2003) measured deep drainage by volume balance, furrow advance and soil CMB, on a heavy clay on the Darling Downs, obtaining values of 124, 144 and 72 mm/season, respectively (Table 3). The lower rate from CMB may indicate deep drainage by bypass flow not detected by CMB, or errors inherent in each method.

Analysis of furrow advance data for 79 furrow irrigation events conducted by growers in southern Queensland found average deep drainage losses of 42.5 mm per irrigation and potential annual losses of up to 250 mm (Smith *et al*. 2005) (Table 3). This represents a loss of up to2.5 ML/ha of water that could be used beneficially to grow more cotton. The same methodology was used to estimate application efficiencies (percentage of water applied that infiltrated into soil) for each irrigation. Application efficiencies were shown to vary widely from 17 to 100%, with an average of 48%. Smith *et al*. (2005) used the SIRMOD model, calibrated with data from each field, to model strategies that would lead to gains in efficiency and reductions in the deep-drainage losses. Deep drainage could be halved or better using improved irrigation management (Table 3). Smith *et al*. (2005) concluded that: '*Additional simulations of selected events showed that further significant improvements in performance can be achieved by the application of more advanced irrigation management practices, involving infield evaluation and optimisation of the flowrate and irrigation time to suit the individual soil conditions and furrow characteristics. Application efficiencies in the range 85–95% are achievable in all but the most adverse conditions. The dependency between deep drainage and irrigation management was demonstrated, confirming that substantial reductions in deep drainage are possible by ensuring that irrigation applications do not exceed the soil moisture deficit*.'

Modelled water balances

Connolly *et al*. (1999) used the GLEAMS model to assess water balance and soil erosion in the EIA, while Connolly *et al*. (2001) assessed water balance and the potential and management of endosulfan runoff in the EIA and in fields at Auscott, Warren (Macquarie Valley). Rainfall, irrigation and runoff data measured at each site were used to calibrate the models. Deep drainage was not reported in those papers, but the results were reported by Silburn and Montgomery (2004). The results (Table 3) indicate considerable deep drainage is likely when irrigation of 7.2 ML/ha. year is applied (720 mm/year), that is, about the average used for cotton crops (Hearn 1998). Drainage (246 mm/year) and leaching fraction (19%) are similar to those from the furrow-irrigated lysimeter study (leaching fraction ~20%) of Moss *et al*. (2001) and SaLF model results for Darling Downs soils (Table 3). Average annual runoff is similar to the average measured over 12 years in the EIA (174 mm) (Silburn *et al*. 1997, 1998).

When considerably less irrigation is used (2.6 ML/ha.year), mimicking a system with 'perfect' irrigation, that is, only just refilling the soil water deficit to field capacity, then considerably less drainage is predicted (75 mm or 9% of R + I) (Table 3) (Silburn and Montgomery 2004). This drainage is due to rainfall occurring during the season and is greater than for rainfed cotton, due to rain falling on soil wet by irrigation. This provides a leaching fraction for maintaining the soil salt balance, even though irrigation is not causing drainage. With no irrigation (rainfed cotton), deep drainage was 6 mm (1%), runoff 16 mm (3%) and ET 589 mm (96% of rainfall), consistent with other drainage estimates for rainfed cropping in the Fitzroy Basin (Radford *et al*. 2009).

Modelled deep drainage (56 mm/year, 4% of R + I) for furrow-irrigated cotton in the Macquarie Valley on a hard-setting, red-brown alluvial soil was less than at Emerald. This is due to slightly greater runoff and less irrigation, the soil's lower permeability and differences in irrigation management.

It is surprising that other modelling studies of deep drainage for irrigated cropping were not found, except for those reported from China and the USA. This may indicate a lack of confidence in modelling except where the terms in the water balance are reasonably well defined, as in the case of Connolly *et al*. (1999, 2001). Most currently available models do not represent bypass

Table 3. Deep drainage estimates from native vegetation, rain-fed cropping and irrigated soils (mainly Vertosols) relevant to Australian cotton growing areas

R + I, Rainfall + irrigation; SS, steady-state; CMB, chloride mass balance; MWB, measured water balance; n.a., not available

Study	Av. ann. Rainfall	Av. ann. Irrigation (mm/year)	Deep drainage		Method	Source
			Av. ann.	% of R + I		
Native vegetation and rain-fed cropping—Qld and NSW						
Queensland (Qld), native vegetation	600	nil	1–3, max. 12	0.17–9.5	Salt balance on 600 soils, ESP 15	Shaw and Thorburn 1985, SaLF model
22 Soils Qld and N NSW, native vegetation	n.a.	nil	1–19 mean 8	0.2–3 1.2	Salt balance (SaLF)	Moss *et al*. 2001
14 Qld rain-fed cropping site, Vertosols, Sodosols, Chromosol (Isbell 2002)	497–730	nil	2–18	0.4–2.5	Transient CMB with SODICS	Tolmie *et al*. 2011
5 Qld rain-fed sites, cropping, Vertosols	616	nil	10, 3–25	1.6, 0.5–4	Transient CMB with SODICS	Silburn *et al*. 2011
Pasture, mounds/depressions			3.3/5.1	0.5/0.8		
Irrigated—furrow irrigation, Australia						
Lockyer Valley SE and Central Queensland	≤800	1190			Transient CMB with SODICS	Thorburn *et al*. 1990
42 irrigate soils, clay 17–70%, ESP 1–40		740–2280				
Half of sites (lowest 50%)			0–100	n.a.		
18 sites (43%)			100–300			
3 highest sites (7%)			500–1200			
Burdekin River Irrigation Area, sodic duplex soil, solodic-solodised solonetz, Typic Natrustalf					Transient CMB paired soil Cl profiles irrigated *v*. dryland	Dowling *et al*. 1991; irrigated for 1 year (2 crops); infiltration determined by furrow advance modelling
No gypsum (head, tail)	394	1044, 966	98, 0	7, 0		
Gypsum added (head, tail)		1617, 966	200, 70	10, 4		
Lower Macquarie Valley, New South Wales					Transient CMB paired soil Cl profiles irrigated *v*. rainfed (dryland)	Willis and Black 1996
Mullah Grey Vertisol	n.a.	491	17 ± 1	3		
Mitchell poorly drained, Luvisol uniform silty loam		400	45 ± 6	11		
Wilga non-Calcic Luvisol duplex		811	206 ± 6	25		
Macquarie Fluvisol duplex		860	131 ± 6	15		
Lower Macquarie Valley, New South Wales						Willis *et al*. 1997; MWB and Darcian flux for one season (1992–93), CMB for years of irrigation; MWB and CMB were preferred methods
Mullah soil, cracking clay, fine Entic Chromustert continuous cotton	335	501	236 ± 17%	31	MWB	
			214	28	SSCMB	
			67	8	Darcian flux	
Wilga soil, red brown earth, fine typic palleustaf continuous cotton	328	378	145 ± 7%	23	MWB	
			104	17	SSCMB	
Emerald Irrigation Area, basaltic Black Vertosols					Calibrated soil water balance model, annual cotton	Connolly *et al*. 1998, 1999:
EIA furrow irrigation, farmer practices, cotton	604	720	246	18		runoff 177 mm (13%)
EIA, 100% deficit irrigation, cotton	604	260	75	9		runoff 42 (5%)
EIA, no irrigation (rain-fed cotton)	604	0	6	1		runoff 16 (3%)
Macquarie, Auscott Warren, red-brown alluvial soil	626	705	56	4		runoff 184 (14%)
Qld and N NSW cotton fields—22 soils					Salt balance (SaLF) on paired native vegetation and irrigated sites	Zischke and Gordon 2000; R. Zischke (unpub. data.)
Average	n.a.	n.a.	210	30		
7 Darling Downs soils			270	24		
5 Namoi soils			68	5		
6 Macquarie soils		Greater	300+	30+		Greater irrigation than other sites

4 Darling Downs soils	n.a	n.a.	258	31	SODICS TCMB	Moss *et al*. 2001, table 2; leaching fraction w/o highest per region
3 Namoi soils	DD if R + I = 840		64	8		
3 Macquarie soils			224	27		
Darling Downs, Qld, sodic grey clay, Grey Vertosol					Large 2-m-deep suction lysimeters	Moss *et al*. 2001, table 1; subsurface drip was actually pressurised buried tape
Furrow irrigation—3 years: 1996–97	478	327	182	19		
1997–98	667	343	162	18		
1998–1999	579	337	152	17		
Subsurface drip—2 years 1996–97	478	150	305	49		
1997–98	667	142	95	12		
Border Rivers, alluvium, Grey and Brown Vertosols and red duplex, 8 fields, 1 year each	714	800–900	>136 >75–235	11–30	Measured water balance	Dalton *et al*. 2001: RWUE
Field 19 Grey Vertosol 2000–01	405	775	128	10.8		Tail-water runoff = 198 mm
Field 20 Grey Vertosol 2000–01	405	967	166	11.8		192 mm
Darling Downs, Qld Macalister, cracking clay, Vertisol, furrow irrigation.					MWB	Dalton 2003, table 1
1 year. Volume balance	n.a.	n.a.	124	n.a.	Furrow advance	
SIRMOD furrow advance			144	n.a.	CMB	
Chloride mass balance			72	n.a.		
Emerald, Queensland, alluvial Gypsic Vertosol					Measured water balance	McHugh 2003; McHugh *et al*. 2008
Furrow 2001–02—farmer practice	78	922	118	16		
Furrow 2002–03—optimised	10	848	~0	0		
Subsurface drip (SDI) (90% deficit) 2001–02	78	519	18	3		
SDI 2002–03	10	657	0	0		
Gwydir Valley, NSW, Black Vertosol			62 (123*)	4.2	SODICS TCMB average of 17 years	Montgomery 2003; Silburn and Montgomery 2004
Red Dermosol, alluvial			35 (69*)	7.6		
Black Vertosol	390	397	$40^{**}/158$	28	Measured water balance 1 year	*For years of irrigation only
Red Dermosol, alluvial	168	372	$8.8^{**}/53$	14		**Per irrigation/for season assuming 5 irrigations
Namoi Valley, NSW, Grey Vertosol	n.a.	440	$1.5^{**}/9$	1.7		
Cotton industry wide						Smith *et al*. 2005
Furrow irrigation events (*n* = 79), data per event	n.a.	19–285		Estimates	Furrow advance	
Farmer managed			42.5 ± 37,	160–250 mm/year	Volume balance	
Improved management (cutoff = advance)			25.8 ± 30		SIRMOD	
Improved management (cuoff = 90% advance)			16.0 ± 23		SIRMOD	
Three sites, lower Namoi Valley, NSW, 2000–01					SS and TCMB	Hulugalle *et al*. 2005.
Cotton, cotton stubble incorporated	300	700	98	10		
Cotton, wheat stubble incorporated	300, 579	700, 400	76, 118	8, 12		Dolichos had poorer root growth and poorer subsoil structure
Cotton, dolichos stubble incorporated	300	700	19	2		
Cotton, in standing wheat stubble	517	200	151	21		
After WaterPAK, deep drainage forum, NWUE initiative and during drought						Silburn and Montgomery 2004; Silburn *et al*. 2004
Five sites, lower Namoi Valley, NSW, self-mulching grey clays (Vertisols), Typic Haplusterts.	200–700 (seasons)	100–700			SS and TCMB	Weaver *et al*. 2005; irrigation applied was substantially less than typical application to fully watered cotton crops for most crops
Cotton sown into standing wheat stubble			62–83			
Cotton sown into incorporated wheat stubble			35–78			
Wheat (*Triticum aestivum*)			21–62			
Sorghum (*Sorghum bicolor*)			12–47			
Dolichos (*Lablab purpureus*)			12–21			

(*continued next page*)

Table 3. (*Continued*)

Study	Av. ann. Rainfall	Av. ann. Irrigation (mm/year)	Deep drainage		Method	Source
			Av. ann.	% of R + I		
ACRI, Narrabri, NSW, 2002–2009 (*n* = 4 for cotton). Soil—same as Weaver *et al*. (2005) above					SS and TCMB	Hulugalle *et al*. 2010; ACRI, Australian Cotton Research Institute
Cotton monoculture sown after conventional tillage			25			
Cotton monoculture sown on permanent beds			33			
Cotton–wheat rotation on permanent beds			70			
2006–09 with ‘frequent irrigation’ (*n* = 2)			54			
2006–09 with ‘infrequent’ irrigation (*n* = 2)			28			
ACRI, Narrabri, NSW, Self-mulching, Endohypersodic, Grey Vertosol, Typic Haplustert, 64% clay, subsoil ESP 12 (*n* = 6)	593					Hulugalle *et al*. 2012; 2005–06 summer to 2010 winter
Cotton monoculture			24			
Cotton–vetch (*Vicia benghalensis* L.) vetch stubble retained			19			
Cotton–wheat with wheat stubble incorporated			41			
Cotton–wheat–vetch with wheat/vetch stubble retained			31			
Northern Murray–Darling Basin, 9 sites each with 3 lysimeters (H, head; M, mid; T, tail), Vertosols, clay contents 38–75%, furrow lengths 53–1290 m, 2002/03–2008/09	308 av. season	469	H 0–235 M 0–196 T 0–92	0–27 0–28 0–10	‘Barrel’ lysimeters	Gunawardena *et al*. 2011; Silburn *et al*. 2013. See Fig. 6

flow and may not fully capture the change in deep drainage often seen across the season (Brett Robinson, pers. comm.), with higher deep drainage pre-irrigation and declining through the season. The soil hydraulic conductivity would need to be adjusted through the season (to represent subsoil swelling) to represent this behaviour.

Drainage lysimeters

Moss *et al*. (2001) measured deep drainage at 2 m depth on the Condamine alluvia, Queensland, using two, large-area (1.5 by 3 m), undisturbed constant suction lysimeters. These were in furrow-irrigated and SDI Vertosols (80% clay, EC ~1 dS/m, ESP 15–30% for the furrow site) (Table 3), for 3 and 2 years, respectively (Table 3). Measured deep drainage was 152–182 mm/year for furrow irrigation and 305 and 95 mm/year for SDI. The furrow site had a sodic soil but had been irrigated with poor quality groundwater; in any case, deep drainage was reasonably high (~18% of R + I) and typical of deep drainage for older style furrow irrigation. The maximum drainage rate after a furrow irrigation was 5 mm/day (i.e. driven by hydraulic gradient >1.0), which then settled to ~1–2 mm/day—consistent with Shaw (1995) for a sodic soil (Fig. 4)—resulting in 22 mm of drainage over a 16-day period before drainage ceased (including one 37-mm rainfall event). Deep drainage arrived at the lysimeter within one day of significant rainfall or irrigation. Soil water content at 1.75 m settled to 0.49 v/v between wettings and rose to 0.52 v/v (~total porosity) after wetting.

The high deep drainage resulted in leaching of large masses of nitrate (~200 kg N/ha.year) and Cl (~3000 kg Cl/ha.year). The herbicide prometryn was detected (0.5–1.1 µg/L) in leachate at both sites, which is expected given it is used in most years. However, atrazine (and its derivative desethylatrazine, DEA) and hexazinone were also detected in almost all samples (atrazine 16.8–1 µg/L declining with time, and DEA and hexazinone 0.8–0.1 µg/L), even though they were last applied 5 years previously. This is probably because the subsoil was near saturated (anaerobic), has low organic carbon and is alkaline, thus preserving these herbicides.

The deep-drainage results for SDI (in fact, pressurised buried tape at 0.4 m depth) are not representative of well-managed drip irrigation, which can achieve near zero deep drainage with irrigation at 100% or less of soil water deficit (Table 3; McHugh 2003; McHugh *et al*. 2008). Ponding of water over the SDI lysimeter in one year (due to poor local surface drainage) resulted in 857 mm of deep drainage, indicating that SDI may require land levelling and that, despite high clay and sodic soil, there is still a high potential for deep drainage.

Gunawardena *et al*. (2011) measured deep drainage in eight fields, some starting in 2002, to 2011, growing cotton and other crops watered with furrow irrigation, over 59 seasons of which 29 had a full record of rainfall, irrigation amount applied and deep drainage. One paired field with a lateral move irrigator was also monitored from 2005 to 2011. Drainage was measured with ‘barrel’ lysimeters, which apply a constant suction to the base of the lysimeter sufficient to lift the water to the soil surface. Three lysimeters were installed to capture water passing 1.5 m depth in each field at head, mid and tail locations. Gunawardena *et al*.

Table 4. Risks, mitigating factors and uncertainties associated with excessive deep drainage in alluvial areas in semi-arid and subtropical environments

Risks	Mitigating factors	Uncertainties
High salt in soil and shallow groundwater Shallow depth to bedrock or groundwater Furrow irrigation with high deep drainage Leaky dams and channels Dams and channel on/near permeable red soils Plus increased deep drainage under adjoining rainfed cropping Additive impact over region Water and salt moving to low areas- value of assets (land and stream)	Not all area is irrigated Not irrigated in all years (drought) Long time-lags, time to act Options for improved irrigation (furrow optimisation SIRMOD, laterals/pivots) Can fix leaky dams and channels (Wigginton 2012) Native vegetation strips	Continuity of sandy beds/aquifers in clayey alluvia Vertical connectivity in multi-aquifer systems Groundwater ,few monitoring bores in shallow aquifers Unsaturated zone capacity and status, time lag Stream incision not surveyed Diffuse groundwater discharge e.g. water use by trees

(2011) noted some seasons when the deep drainage was affected by blocked field exits, which led to large deep-drainage amounts; although this is real deep drainage that did occur, for our purposes we have removed these data (coded B in their table 2). Deep drainage ranged from 0 to 235 mm/season (27% R + I). However, there were many examples at all sites where little or no deep drainage was recorded, and only ~20% of seasons had measured deep drainage >100 mm (1 ML/ha). Low or zero deep drainage seasons were in part related to the combination of limited water supply and above-average evapotranspiration (due to the Millennium drought) and possibly to equipment failure on some occasions. Seasonal deep drainage was related to season total rainfall plus irrigation (Fig. 6) and generally required >500 mm of rainfall plus irrigation to cause drainage. However, there were seasons with 800–900 mm of rainfall plus irrigation where no drainage occurred, particularly at the tail sites. There are evidently other factors that determine seasonal deep drainage, including the occurrence of large rainfall events and various irrigation management practices. For instance, Smith *et al.* (2005) found that deep drainage could be halved using optimised management of furrow irrigation. The data of Dowling *et al.* (1991) from furrow irrigation in the Burdekin are comparable to the data from cotton sites (Fig. 6).

Some other conclusions are:

1. Deep drainage generally increased from head to mid to tail positions (except where the outflow of tail-water was blocked) due to decreasing opportunity time for infiltration (this is not always apparent in Fig. 6, e.g. due to the season with 1497 mm of R + I). Indeed waterlogging and reduced crop growth was often observed in the head position.
2. Deep drainage was most prevalent at the start of the irrigation season, so reduction in water applied in the pre- or first-irrigations can dramatically reduce deep drainage.
3. Infiltration capacity, measured by furrow advance, also decreased with irrigation later during the season at most sites, presumably due to smaller soil-water deficits and moister subsoil.
4. One site was under lateral-move irrigation, gave no deep drainage and had up to 59% reduction in water applied with equivalent cotton yield compared with a paired furrow-irrigation site. The lack of deep drainage could lead

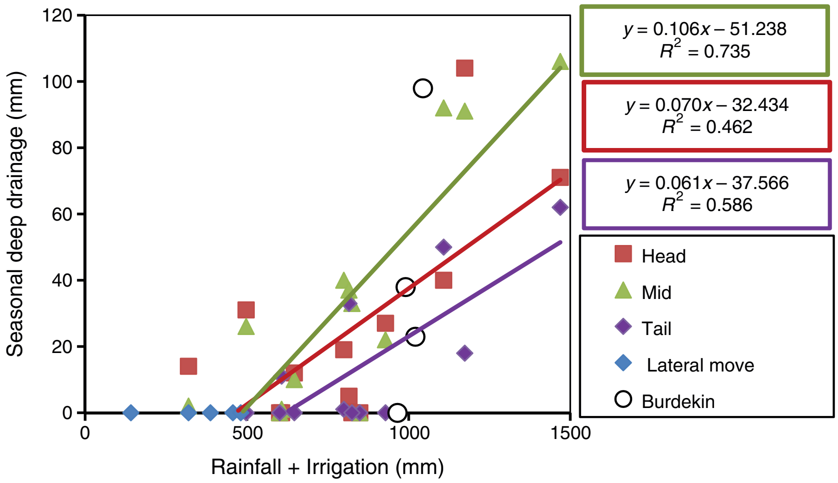

Fig. 6. Seasonal deep drainage measured at head, mid and tail positions in furrow-irrigated fields after excluding unusual occurrences (coded B by authors) and the first year of data (adapted from Gunawardena *et al.* 2011) and for a sodic duplex soil in the Burdekin (Dowling *et al.* 1991) using total infiltration instead of rainfall plus irrigation, at 50 m (highest drainage), 125, 200 and 260 m (lowest drainage) along the furrows.

to salt accumulation in the root-zone, although this may yet be leached by rainfall in wetter times. Longer term monitoring is required to derive conclusions at this site.

We note that barrel lysimeters applying a constant suction may overestimate deep drainage when the soil is more saturated than the applied suction (Foley *et al*. 2003). However, the magnitude of overall error (e.g. each season) is unknown and the results appear reasonable compared with other methods.

Deep drainage leachate at all sites was relatively saline, showing the potential for salts to be moved to groundwater and streams. Irrigation management needs to balance the need for a leaching requirement (some deep drainage) to minimise root-zone salinity and the need to avoid off-site drainage impacts. The deep drainage rates for furrow irrigation exceeded the leaching requirement for all sites except one (see table 3 in Gunawardena *et al*. 2011). In the long-term, the required leaching fraction for these sites is provided by deep drainage caused by rainfall on irrigated cropping (Yee Yet and Silburn 2003). The remaining site uses poor quality irrigation water which may not be sustainable.

Since 2006, Ringrose-Voase and Nadelko (2013) have operated equilibrium tension lysimeters (Foley *et al*. 2003) to directly measure deep drainage at ACRI, Narrabri (see also Silburn *et al*. 2013). Six lysimeter trays collecting drainage over an area of 1.6 m^2 were installed by tunnelling horizontally at 2.1 m depth from an access shaft, leaving the overlying soil undisturbed. This type of lysimeter (Foley *et al*. 2003; Pegler *et al*. 2003) is able to accurately measure drainage by applying a suction to the collection trays (with sintered metal plates in contact with the soil above) that is constantly adjusted so it is equal to the suction of the surrounding soil at similar depth. Deep drainage was measured under cotton, wheat and fallow conditions and ranged from 0 to 74 mm/season, confirming other lower drainage rates at ACRI.

It was also found that deep drainage in cracking clay soils occurs in two ways: bypass drainage and matrix drainage. Bypass drainage is more rapid than matrix drainage and can drain below 2 m without fully wetting the subsoil. It was mostly observed during furrow irrigation, particularly during the first few irrigations in the season. Bypass drainage typically has salinity of 2000–3000 µS/cm, whereas matrix drainage had salinities of ~8000 µS/cm. Leaching of dissolved nitrogen also occurs; for example, 9.5 kg N/ha was leached during the 2008–09 season. Preliminary observations of groundwater below the site suggest that the peak in seasonal recharge into the upper aquifer (at ~16 m below surface) may occur just 15 days after the peak in seasonal deep drainage at 2 m.

Deep drainage after 2004, the Millennium drought and improved WUE

The 'maximum' deep drainage *v*. R + I of Gunawardena *et al*. (2011) (Fig. 6) is compared with global data in Fig. 7. The more recent data from Weaver *et al*. (2005), Hulugalle *et al*. (2010, 2012) (Table 3) and Ringrose-Voase and Nadelko (2013) are compatible with, or lower than, those of Gunawardena *et al*. (2011). Although these studies are not a representative sample of all Australian cotton-growing districts, they do include nine diverse, commercial sites across the Queensland Darling Basin (Gunawardena *et al*. 2011) and five in the Namoi Valley (Weaver *et al*. 2005) and at ACRI, Narrabri. These data indicate that modern (~post 2004) furrow irrigation practices in Australian cotton are giving deep-drainage rates per unit of water inputs that are less than or equal to the lowest rates in global studies.

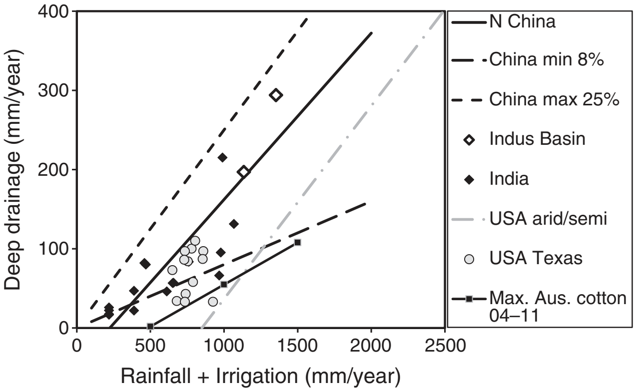

Fig. 7. Global deep drainage *v*. rainfall plus irrigation from previous figures compared with the maximum deep drainage data from Gunawardena *et al*. (2011) (equation fitted for mid-furrow position) and Dowling *et al*. (1991) in northern Australia.

Understanding flow processes in clay soils—variable-tension lysimeters and tensiometry

Foley *et al*. (2003) installed a variable-tension lysimeter (Pegler *et al*. 2003) in a cracking clay soil (Black Vertosol), with banks of tensiometers measuring matric potential over an extended fallow period (i.e. no crop) and for two simulated irrigations, reported by Silburn *et al*. (2010). Deep drainage measured at 1 m depth was dominated by matrix flow, with only 10% of drainage attributed to preferential flow (note that the soil was never dry enough to crack); that is, 90% of drainage was explained by Darcy flow. Findings include: (*i*) a compacted, throttle layer was important in determining flow through the profile; (*ii*) flow was usually unsaturated except in the throttle layer; (*iii*) downward travel time for ponded water was rapid (0.75 m/h); (*iv*) hydraulic gradient rather than hydraulic conductivity (K) was the largest term in determining flow; (*v*) the profile was never at unit gradient/steady-state throughout the study; (*vi*) downward gradients were up to three times the saturated hydraulic conductivity (Ksat) in wet soil and nine times at about drained upper limit, i.e. gradient dominated flow (gradient × K); (*vii*) maximum drainage rate was 6 mm/h compared with a saturated hydraulic conductivity of 0.85 and 0.63 mm/h (20 and 15 mm/day), respectively, measured by ponded rings and the lysimeter; and (*viii*) deep drainage during the irrigations was 23 and 18 mm, somewhat less than the drainage for commercial irrigation events determined by Smith *et al*. (2005), where irrigations were run for longer.

Soil moisture and matric potential

In the past, emphasis has been put on constant subsoil moisture content (e.g. from neutron moisture meters and capacitance probes) as evidence of no drainage. Figure 8*a* is an example of such data from a Black Vertosol in the Gwydir valley (Silburn

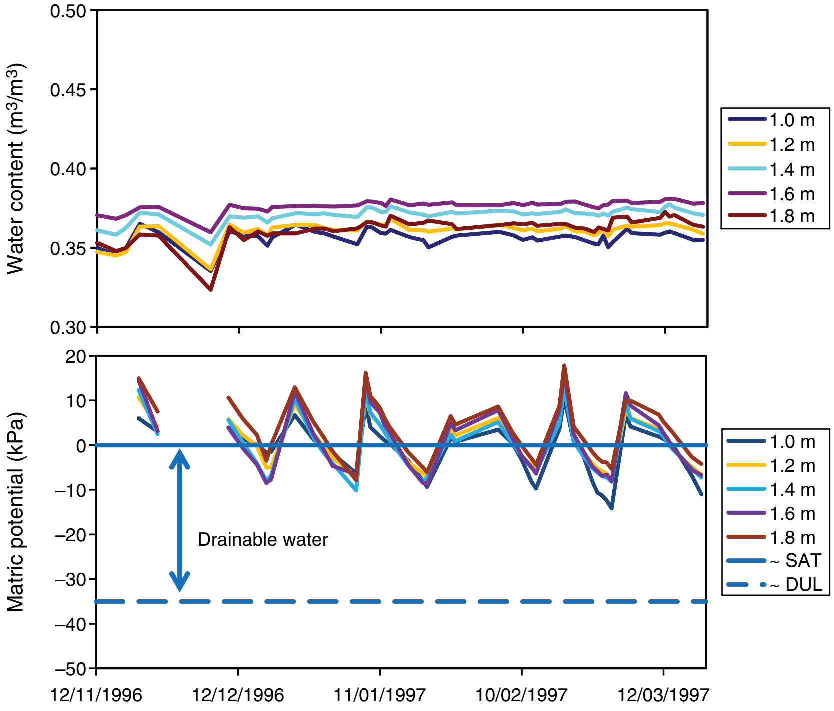

Fig. 8. (*a*) Soil moisture in subsoil layers of a Black Vertosol (Gwydir) through the irrigation season, and (*b*) soil matric potential in the same layers, indicating near saturation (SAT, zero matric potential) throughout, well above the drained upper limit (DUL). Source: Montgomery (2003); Silburn and Montgomery (2004).

and Montgomery 2004). All layers from 1 to 1.8 m show fairly constant moisture contents in the range 0.35–0.38 v/v, which would seem a moderate water content (i.e. wilting point in some Vertosols). However, with a bulk density of 1590 kg/m^3, total porosity is 0.40 v/v, so a water content of 0.38 v/v is in fact near saturation. We expect drained upper limit (field capacity) to be ~0.05 v/v below total porosity (typical air content in clay subsoils at drained upper limit; Gardner 1988), i.e. drained upper limit = 0.35 v/v. Thus, the measured subsoil moisture contents are likely to be between drained upper limit and saturation, and some soil water is drainable. This was confirmed by tensiometer data (soil matric potential) from the subsoil (Fig. 8*b*), which indicates that all layers between 1.2 and 1.8 m were at, or near, saturation throughout the irrigation season. (Roots appear to have penetrated to only ~1 m). Thus, water was probably draining through the subsoil throughout the season. Water balance measurements at the site indicated that 158 mm drained below 1.8 m during the season monitored (Table 4; Montgomery 2003).

Observations of soil water (or lack of change in soil water) have proved to be unreliable indicators of deep drainage; see, for example, discussion by Smith (2008) of early ideas that clays in the Ord River Irrigation Area (ORIA) were suitable for rice production—'*Marshall* (1944) *found that surface water infiltrated no deeper than 1.07 m into Cununurra clay after surface water ponding for 54 h. He postulated that groundwater accession beneath rice growing should not be a problem*'—compared with more recent observations of deep drainage for both wet season rainfall and furrow irrigation in the ORIA, from modelling and daily groundwater levels.

Moisture capacity and status under native vegetation and irrigation

Foley *et al*. (2010, 2012) and Silburn *et al*. (2010) measured soil moisture, matric potential and bulk density of deep soil cores (e.g. 6 m) in native vegetation, and irrigated cropped sites at crop lower limit, upper limit (after ponding as per Dalgliesh and Foale 1998) and drained to ~–20 kPa (verified with tensiometers installed at a range of depths), at three sites each in the Condamine alluvia and Lower Border Rivers, thus defining the plant-available water capacity (PAWC) and the moisture status of the unsaturated zone. At most sites, three positions were wet up in a paddock and four to six cores taken in the ponded area and again adjacent to the wet zone. Water retention characteristics at various depths and a range of physiochemical properties (including particle size analysis, pH, EC, Cl and NO_3-N) were measured.

Electrical resistivity tomography (ERT) transects were imaged at selected PAWC sites with (where possible) transects running through native vegetation and adjoining irrigated paddocks to look at differences in water and salt contents due to long-term irrigation (Foley *et al*. 2010, 2012). Soil cores were also taken along the transects to measure water content, particle size analysis and chemistry (pH, EC, Cl and NO_3-N) to assess the influence of salt and clay content on resistivity measurements. Two-dimensional resistivity images were inverted using the RES2DINV software. Data were converted to conductivity, with high conductivity generally indicating more water and salts, and higher clay content.

Consistently across the irrigated paddocks, the soil was wet to drained upper limit or above (i.e. actively draining) to 1–2 m

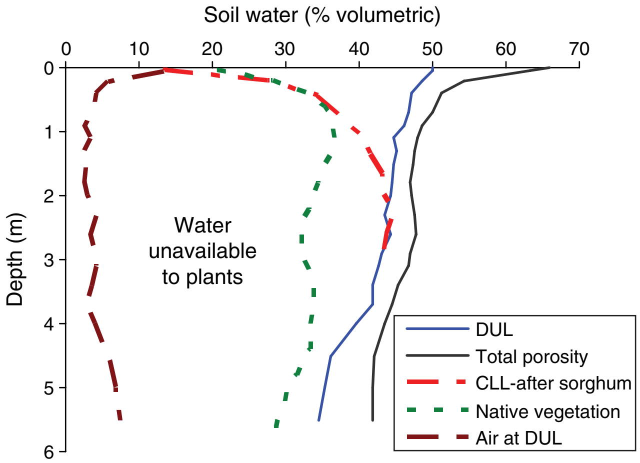

Fig. 9. Dalby Black Vertosol showing total porosity (TP), drained upper limit (DUL), crop lower limit (CLL) and air content at DUL, to 6 m in an irrigated paddock, and soil water in adjacent native vegetation (plant-available water capacity to 1.9 m, 240 mm; clay ~65%; bulk density 1390 kg/m^3) (Foley *et al.* 2010, 2012).

depth even after a crop had been grown (example given in Fig. 9). Beyond 2 m, most irrigated sites remained wet at depth; air content at drained upper limit was 3–5%. Coring in adjacent native vegetation revealed very dry soil to depth, indicating that under trees there is virtually no deep drainage, with trees able to extract more water and to greater depth.

The ERT images at all sites typically show a highly conductive zone of soil (very wet, with medium salinity typical of soils in the region) throughout the irrigated portions of transects. An example of this can be seen in Fig. 10, where the darker blue area in the top 6 m of soil, from 120 to 600 m along the transect, corresponds to the location of the irrigated paddock. Conversely, under native vegetation (0–120 m) the regolith remained dry in the surface. Trees were able to extract more water from the soil, indicated by measured soil water potentials of around –4 to –6 MPa compared with –1 to –2.5 MPa for rainfed crops and usually less that this again under irrigation. This maintained a 'buffer' against deep drainage losses. For example, there was a buffer (unfilled storage capacity) of 240 mm to 2 m or 580 mm to 6 m under native vegetation at the Dalby site (Fig. 11). This compares with a buffer of only 90 mm to 2 m in the irrigated soil. This 90 mm is smaller than a single irrigation application, and suggests that any irrigation application of approximately this volume would cause deep drainage.

Soil coring confirmed that (on average) the blue areas in the image were very wet (Fig. 11), with up to 250 mm of the water in the top 6 m above drained upper limit, i.e. actively draining. In Fig. 10, the soil texture changes at around 5–6 m, with increasing sand and occasional gravel layers. These layers have a lower conductivity due to the increasing presence of unsaturated sands (and hence the colour changes in the image). However, water continues to drain to deeper in the regolith at a rate proportional to the hydraulic conductivity of these deeper clay and sand layers.

The coring program has provided considerable data to support the widespread occurrence of an historical change in regolith water storage as a result of deep drainage under irrigation. This is further supported by results from the resistivity imaging, where a layer of near-saturated soil in the profile between 2 and 6 m was found in all irrigated paddocks (Foley *et al.* 2010). Kelly *et al.* (2011) and Foley and Silburn (2013) also observed water movement below the root-zone in Vertosols in ERT images in the Namoi Valley and Lockyer Valley, respectively. This coring and imaging has confirmed that deep drainage has been occurring extensively across these landscapes. This is in agreement with Scanlon *et al.* (2010*a*), who found that the unsaturated zone pore water beneath irrigated agroecosystems can be fingerprinted by higher matric potentials (wetter soils) than that beneath natural ecosystems.

Consequences of deep drainage

To understand the consequences of excess deep drainage, we must consider three topics: the quality of deep drainage/leachate; the effects on groundwater rise and possible lag times; and groundwater discharge, i.e. what effects it might have.

Quality of deep drainage/leachate

Duncan *et al.* (2008) found in a review of water and salt fluxes for irrigation areas globally that significant amounts of salt are mobilised and discharged. This is due to either the existence of large amounts of salt in the soil and groundwater system, or large amounts of salt imported into areas with irrigation water. In the Namoi Valley, Weaver *et al.* (2013) found that salinity and SAR of drainage water under irrigated cotton were many times higher than those of irrigation water: '*Salinisation and sodification of*

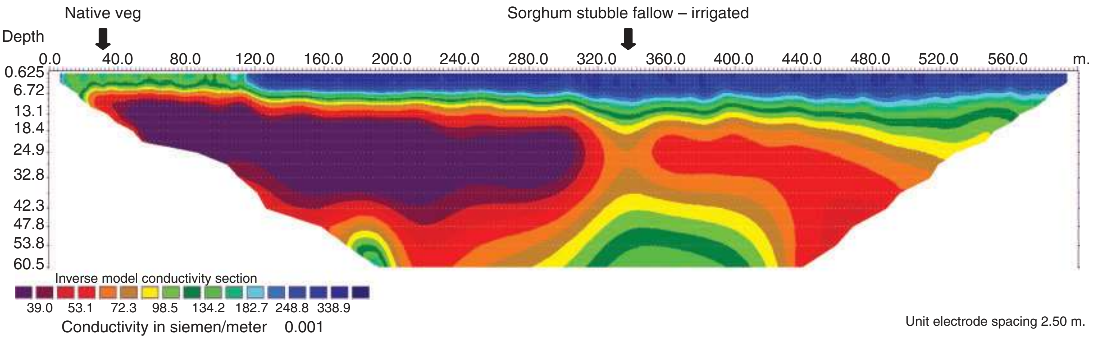

Fig. 10. Dalby electrical resistivity tomography (ERT) transect: L to R, native vegetation into sorghum stubble (irrigated). Groundwater level in the native vegetation is at ~20 m below ground level (Foley *et al.* 2010, 2012).

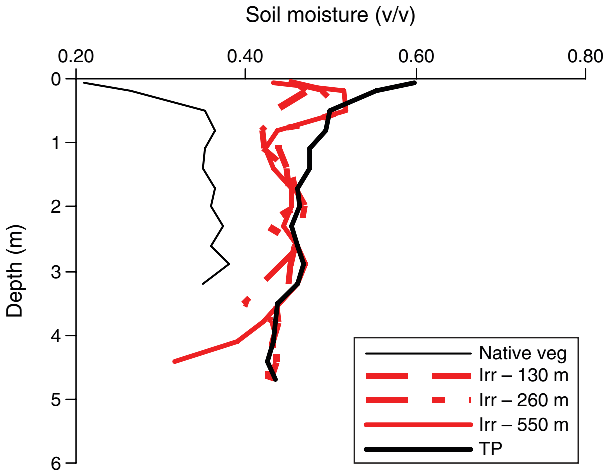

Fig. 11. Dalby electrical resistivity tomography (ERT) transect volumetric soil water contents, taken in native vegetation and at 130, 260 and 550 m (distances along transect in Fig. 10) (Foley *et al.* 2010, 2012). TP, total porosity.

shallow groundwater reserves under irrigated cotton in Vertisols are, therefore, a distinct possibility.' Similarly, Gunawardena *et al.* (2011) measured deep drainage and sampled leachate using multiple lysimeters in nine irrigated, commercial cotton fields in the upper Murray–Darling Basin, on Vertosols with a wide range of clay contents (38–75%). They consistently found high salinities in the leachate (e.g. 3700–13 400 µS/cm, mainly as NaCl), indicating that large amounts of salt were being mobilised and that irrigation-induced deep drainage is a source of poor quality recharge. McMahon *et al.* (2003, 2006) found large Cl, NO_3 and atrazine reserves in deep, unsaturated-zone soil water under irrigated fields in the central High Plains in south-western Kansas. Similar outcomes and issues occur in the southern High Plains (Scanlon *et al.* 2010*b*). Considerable fluxes of NO_3-N are often found in the deep drainage (Moss *et al.* 2001; Weaver *et al.* 2013).

However, in some situations, at some long time after the change of land use from native vegetation to irrigated agriculture, a new equilibrium is established in the irrigated soil, unsaturated zone and groundwater. In the Lockyer Valley, large masses of salts have been flushed from the unsaturated zone and deep drainage is now supplying recharge that is of no worse quality than that of the groundwater (Foley and Silburn 2013). While the previously leached salts have increased the aquifer salinity, in major parts of the Valley the groundwater salinity is still of reasonable quality (Gunawardena *et al.* 2013).

Groundwater rise and possible lag times

Three examples are given for the groundwater response to irrigation deep drainage. Irrigation began in the St George Irrigation Area (SGIA) in the 1960s. Compared with the regional groundwater surface, the SGIA appears as a groundwater mound (Kellet *et al.* 2004). However, in individual monitoring bores, responses are a mix of no response, rising or fluctuating. Figure 12 shows one bore near irrigated land rising and one remaining more-or-less steady, whereas reference bores under native vegetation or rainfed cropping typically show no response.

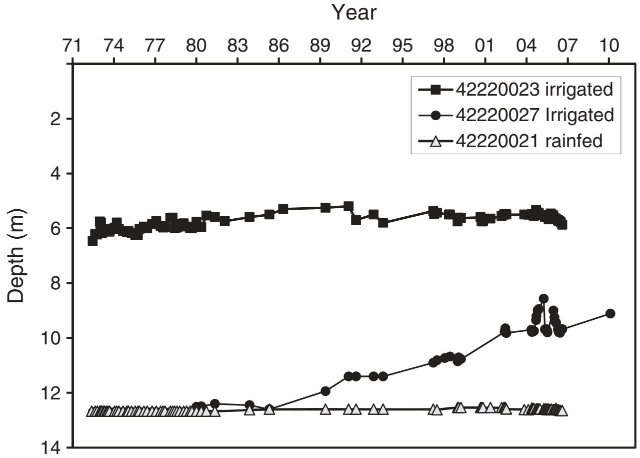

Fig. 12. Groundwater levels in two bores in the St George Irrigation area, and a reference (rainfed) bore outside the irrigation area.

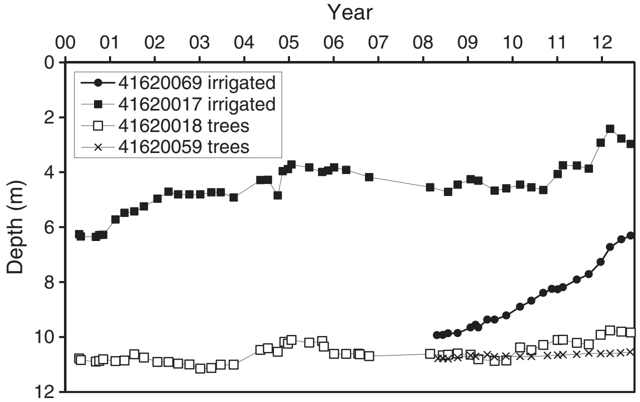

Fig. 13. Groundwater levels in monitoring bores near irrigated fields and in native vegetation (trees) in the Border Rivers alluvia.

Irrigation has only occurred in the western Border Rivers alluvia since the 1980s and monitoring only began in 2000 (Biggs *et al.* 2006). Groundwater levels near irrigated fields in the western Border Rivers alluvia are typically closer to the surface than those away from irrigation and have a more pronounced rising trend (Fig. 13). The water level in one bore has been rising at nearly 1 m/year since installation in 2009 and is currently at 2 m below ground surface (data not shown). Some bores show no discharge, that is, they rise continuously. Salinity in these aquifers is typically 40–50 000 µS/cm and the water is often acidic (pH ~4) (Biggs *et al.* 2005). Changes in groundwater levels do not occur in bores away from irrigated fields throughout the Border Rivers. This is because, for native vegetation, deep drainage rates are at or near zero and the unsaturated zone is very dry, and for rainfed cropping, deep drainage rates are low (~5–10 mm/year) and are slowly filling the remnant dry unsaturated zone from native vegetation (Silburn *et al.* 2011).

In the Condamine alluvia, irrigation using groundwater developed rapidly after 1960, and pumping has generally exceeded the range of estimates of recharge (Dafny and Silburn 2013). Thus, the deeper, good-quality, high-yielding aquifers have consistently had falling water levels throughout the Condamine alluvia. Generally, the shallowest aquifers were dewatered before irrigation development (including by hand-dug wells) and have remained dry or unmonitored. However, monitoring sometimes intersects shallow aquifers with water that is rising while levels are falling in deeper aquifers (Fig. 14). The falls in water level after each major rise (~3–5 m) in the shallow aquifer indicate discharge, either laterally and/or downwards. The salinity of the shallow aquifer was 11 500 µS/cm (in 2009), whereas the salinity in the deep aquifers was 2500 µS/cm. The salinity of the shallow aquifer is similar to the salinity of deep drainage leachate measured under irrigation (Gunawardena *et al*. 2011) and under rainfed cropping (Tolmie *et al*. 2011). There is a risk that the more saline water in the shallower aquifer is leaking into the deeper aquifers, particularly given the increased gradient between them, although few rising salinity trends have been detected thus far.

Groundwater discharge

The major pathways for discharge are via groundwater flow and seepage, particularly for irrigation areas beside incised rivers, and via groundwater use by trees. For groundwater rise and flow to occur, the systems must be in a mature state of hydrologic development, with the increase in deep drainage due to irrigation flowing through to groundwater rise and discharge (Grundy *et al*. 2007; Silburn *et al*. 2008). This is probably the case for some older irrigation areas in Queensland where groundwater is not pumped and high watertables occur (e.g. Emerald, which requires a su-surface drainage system, and Burdekin alluvia, Brough *et al*. 2008; ORIA, Smith 2008). However, it is not generally the case in most irrigated cotton valleys, either because the groundwater is pumped and water levels are below the streams (e.g. Namoi, Kelly *et al*. 2013; Condamine, Dafny and Silburn 2013), or because the groundwater has not yet risen to intersect streams or the land surface. That is, the system is not yet in equilibrium with the higher drainage rate under irrigation.

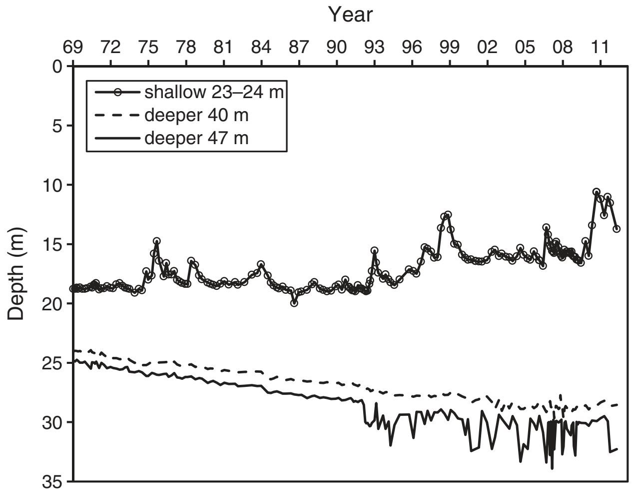

Fig. 14. Groundwater levels in monitoring bores screened in three aquifers near irrigation in the Condamine alluvia where groundwater pumping occurs (RN 42260025 pipes A, B and C).

In summary, deep drainage under irrigation is filling or has filled the dry unsaturated zone left over from native vegetation and will cause or has caused groundwater to rise, with high salinity from the soil or the groundwater, creating several risks to land and water resources. These risks, and several mitigating factors and uncertainties, are discussed in the following section.

Discussion

It is apparent from the studies reviewed above, that the statement that ‘clay soils don’t drain’ is well disproved. Rather, the key questions surround the magnitude and frequency of deep drainage, the potential impacts, ways to minimise the problem and opportunities to use the lost water productively. This points to the heart of the issue—are some soil types/irrigation areas or irrigation methods inherently unsustainable as a result of excessive deep drainage? Are some water types simply too saline for use in irrigation? Certainly history indicates that many irrigation areas are unsustainable, in that economically and environmentally significant impacts have resulted on- and off-site. Even with best case irrigation management, there will always be certain soils and landscapes where risk factors are such that an adverse outcome is virtually a certainty. While the body of knowledge regarding deep drainage in cotton-growing soils needs further refinement in terms of process understanding, it also needs to be more effectively utilised to describe the potential risks associated with irrigation,either at the paddock or district scale.

A variety of frameworks and methods exist by which to asses these risks, including the salinity risk assessment framework (Grundy *et al*. 2007), which has been applied extensively in Queensland. Within such frameworks, the level of complexity can also vary. For instance, a simple, conservative ‘bucket’-type calculation, which only requires an estimate of the deep drainage, size of the unsaturated zone and an assumption of no outflows, has been an effective tool in areas such as the Border Rivers, whereas in other localities, more complex approaches using real paddock data, geophysics, complex groundwater models, etc., have been used. Table 4 presents a simple list of risks and factors that have been proven to be relevant to assessing the impacts of excessive deep drainage from irrigated lands. Associated with these are a variety of uncertainties, in terms of either process knowledge or spatial knowledge. Many of the uncertainties relate to the lack of characterisation of the landscape at the local scale. Despite these uncertainties, the mitigating factors and management actions related to excessive deep drainage are well known, as they largely relate to the gross amount of water added to the landscape, irrigation efficiency and management (see discussion below).

Management of deep drainage

A thorough review of management for reducing deep drainage is beyond the scope of the paper. However, the review of deep drainage has highlighted that irrigation globally is in dire need of improved management. The Australian cotton industry has made good progress, prompted in part by water shortages, but further improvements are possible. Ultimately, deep drainage is related to the total rainfall and irrigation (Figs 6 and 7) or their excess over the crop water requirement, and the largest deep drainage losses occur due to over-application of water.

The need for further improvement is particularly so given that the approaches needed are available and well proven; i.e. for furrow irrigation, controlling irrigation application to less than the soil water deficit and optimisation of furrow irrigation. This involves monitoring or modelling the soil water deficit, and irrigating to match that deficit on a schedule fitting the crops water stress and yield response (e.g. Constable and Hearn 1980). Optimisation of furrow irrigation involves field-specific measurements of inflow, furrow advance and outflow during selected irrigations, modelling to derive that field's infiltration characteristics and performance (estimating deep drainage, uniformity etc.), and then modelling to minimise deep drainage and runoff and maximise uniformity (McClymont and Smith 1996; Smith *et al*. 2005). The National Centre for Engineering in Agriculture (NCEA) has developed a suite of equipment (IRRIMATE©), software (INFILT and SIRMOD) and training for consultants to perform these optimisations. Management options include reducing furrow lengths, increasing inflow rate and reducing irrigation duration (early cut-off) (Dalton *et al*. 2001; Smith *et al*. 2005). These can result in a reduction of deep drainage by >50% (Table 3) (Smith *et al*. 2005), or near elimination of deep drainage in some cases when rainfall is low (McHugh 2003). Further tools need to be developed to calculate the leaching requirements to prevent soil salinity, including considering the leaching provided by rainfall. The authors and NCEA have been contracted by Cotton Research and Development Corporation to develop these tools.

Alternatively, deep drainage can be nearly eliminated by replacing furrow irrigation with centre-pivot or lateral-move irrigators (Gunawardena *et al*. 2011) or drip irrigation (McHugh 2003). High capital and energy costs can limit this approach (Baillie *et al*. 2007) but benefits will accrue in the longer term, particularly as adoption of CPLM methods can also increase crop choice. In summary, there is a large increment of excessive deep drainage that can be prevented reasonably simply.

Conclusions

A large body of evidence shows that clay soils, of most types, do have considerable deep drainage under irrigation that supplies a surplus of water, such as surface/furrow irrigation. This is because: they have structure and bio/macro-pores; they have large sorptivity and develop large gradients in matric potential which overcome their low to medium hydraulic conductivity; there are long opportunity times for drainage; and they have generally been watered to well above the crop water requirement or soil water deficit. Interpretation of soil infiltration rates and hydraulic conductivities has often been overly simplistic and over-generalised (as being low); final infiltration rates can be from >30 to <1 mm/day. Observations of constant subsoil moisture contents have been misinterpreted as no drainage; measurements of matric potential show they are near-saturated and draining continuously. Similarly, measurements of changes of profile soil moisture with less-than-precise instruments have often been misleading.

Reasonably rapid losses of soil Cl from the soil profile and increases in unsaturated zone moisture status provide compelling evidence of deep drainage under irrigated fields. Losses of Cl from the soil matrix indicate that matrix flow occurs. Bypass flow also occurs, but the amount is poorly defined and is dependent on the degree and rate of wetting/saturation.

Management options for reducing deep drainage are available and well proven, whether by optimising furrow irrigation management, which can reduce deep drainage by >50%, or by changing to lateral move, centre pivot or drip systems. Leaching fractions to prevent accumulation of soil salts are often provided by deep drainage from rainfall on irrigated soil, except when water of the poorest quality is used. Experience globally has shown that over-dependence on excessive leaching fractions or on constructed drainage works, which both assume a licence to pollute the wider environment, will fail eventually. They simply export the problem.

While the Millennium drought and a general decline in water availability led to substantial improvements in WUE in the cotton industry in Australia over the last decade, this has not entirely negated the risk and potential for adverse impacts. This risk exists purely as a function of the increase in deep drainage that occurs as a result of a change from native vegetation to agriculture (irrigated or not), but irrigation changes the time response. Further effort is required to better characterise the local landscape risks and potential impacts in cotton-growing areas and, in particular, the likely time-frames for risks to express and the capacity of management actions to reduce risk to an acceptable level.

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