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Modern and palaeogeographic trends in the salinisation of the Western Australian wheatbelt: a review

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Abstract. The Western Australian wheatbelt contains vast areas of agricultural land underlayed by saline and deeply weathered regolith derived from Archaean rocks and recent sediments. The region has been geologically stable since the late Permian, although the Archaean basement sustained some movement during the break-up of Gondwanaland and the northward drift of Australia from Antarctica. During the Early Cretaceous, Eocene and more recently, the wheatbelt region's weathered mantle has been successively eroded by rivers. The palaeovalleys have been infilled with terrestrial and marine sediments, and subjected to ongoing deep weathering. During the Pliocene and Quaternary the region experienced alternating arid and wetter climates. These cyclic episodes influenced regolith development, affected vegetation species and catchment water balances, and also promoted the accumulation of massive volumes of salt. In more recent times, these salt stores have interacted with vegetation, soils, surface water bodies, and groundwater systems and left a distinctive and pervasive legacy in the landscape.

Salinisation was manifest in the wheatbelt from as long ago as 2.8 Ma, concentrating in valley floors as arid and wetter cycles prevailed and while the continent migrated northwards. Today, agricultural development has altered the water balance on 20 Mha of cleared farmland. As a result, salinity is spreading, further degrading 300 000 ha of variably saline landscape that existed before the arrival of Europeans, and affecting an additional 1.1 Mha of formerly arable land. Unchecked by reduced rainfall or human-induced changes to the water balance, salinity may expand even further, potentially affecting 1.7–3.4 Mha of the wheatbelt's agricultural land and its unique natural resources.

This paper reviews the palaeogeography and palaeoclimates of the region and its hydrogeology and examines the nature of its susceptibility to salinisation. It poses questions about the relationship between palaeo-salinity and contemporary salinity, seeking geomorphic evidence to indicate whether salinity is likely to expand beyond extant palaeo-salinity markers. Finally, it considers the likely timeframes involved in salinisation and whether clearing-induced salinity will follow patterns similar to those observed from past saline episodes in the region.

Additional keywords: palaeoclimate, dryland salinity, playa, regolith, Western Australia.

Introduction

Accumulation of salt in the Australian regolith is a natural process established as a result of the antiquity of the landscape, its flatness, the magnitude of weathering, and climatic parameters that are typified by low rainfall and high evaporation rates. Limited rainfall and low relief in much of Australia's internal drainage systems inhibit flushing of the regolith and discharge of surface salt to the coast. The situation contrasts greatly with well-watered continents and much of Australia's coastal zone where river systems efficiently flush salts from steeper landscapes to the ocean before they accumulate in substantial volumes in the regolith and underlying groundwater system (Hatton *et al*. 2003).

This combination of intrinsic factors is particularly pronounced in the south-western region of Western Australia where intense salinisation of the landscape and waterways has occurred both before and since agricultural development (George *et al*. 1997; Dodson and Lu 2005). Here, deeply weathered, Archaean granite-gneiss of the Yilgarn Province is rich in stored salt (McFarlane and George 1992). Winter rainfall, ranging from 1000 mm/year in the south-west to 250 mm/year in the east, is followed by dry summers when evaporation rates greatly exceed rainfall by ratios of greater than 10 : 1. Rain from the nearby Indian Ocean brings with it dissolved marine salts that concentrate in the regolith and discharge from local and intermediate groundwater flow systems (Hingston and Gailitis 1976; George *et al*. 1997).

Primary salinity in the region is typified by the existence of salt lakes (playas) that developed during prolonged arid periods in the Cainozoic. The wheatbelt contains ~300 000 ha of salt lakes and associated landforms. Playas, lunettes, aeolian dust mantles (parna), and distinctive halophytic vegetation lay testimony to the earlier heritage of primary salinity in the region.

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Secondary or dryland salinity is caused by water balance changes wrought through the deliberate clearing of native vegetation. In WA the clearing of 20 Mha by consecutive land releases for agriculture, largely since the 1940s, has dramatically intensified and expanded natural processes of salinisation (Wood 1924; Hatton *et al.* 2003). Satellite based techniques have been used to estimate that currently at least 1.1 Mha of farmed and public lands are severely affected by dryland salinity (McFarlane *et al.* 2004). Depending upon future trends in land use and climate, it is predicted that salt-derived degradation may occur in a further 1.7–3.4 Mha in this important agricultural region.

Apart from loss of agricultural land, more than 50% of the usable water in the region has become saline, brackish, or marginal in recent decades, and almost half of the natural wetlands are potentially at risk from shallow saline watertables (George *et al.* 1997; Hatton *et al.* 2003). The region is one of the great centres of biodiversity in the world, rich in distinctive plants and animals. Many of these unique habitats are now geographically restricted and have become isolated by clearing. Some of these refugia are surrounded by salinised areas including salt-lake chains that infill ancient palaeochannel networks. Many plant species will be affected as salinity expands, with hundreds of species possibly at risk of extinction (Hatton *et al.* 2003). In addition, tens of thousands of kilometres of road networks and up to 40 rural towns may potentially be degraded to some degree (National Land and Water Resources Audit 2000; George *et al.* 2005).

In this paper we review the legacy of sedimentation and deep weathering of the wheatbelt. In particular, we focus on the palaeodrainages and their Eocene, Pliocene, and Pleistocene sediments, which dominate the modern landscape and its distribution of playas, dunes, and related hydrogeomorphological features. The antiquity of salinisation is then established by reviewing the climate and sedimentary records. Finally, we attempt to determine the degree and extent to which modern clearing and past climate-induced salinisation are analogous and whether dryland salinity differs from that which is ascribed to the palaeogeographic record.

Palaeogeography and regolith of the wheatbelt

The wheatbelt is an area of exceptional geological stability. It has not been glaciated since the Permian (Veevers 1984) nor has it undergone orogeny since the Proterozoic (Myers 1990). The region was subjected to major rifting episodes during the Mesozoic with the break-up of Gondwanaland and subsequent formation of the Perth Basin to the west and the Eucla Basin to the south. The basin sediments lap onto the edges of the Yilgarn Craton and also infill palaeovalleys on the craton.

Importantly, the region has undergone extensive shifts in palaeomagnetic latitude during the last >500 Ma (Veevers 1984). South-western WA from the Early Cambrian to the Early Ordovician drifted across the equator from 10°S to 10°N. From the Early Ordovician to the Middle Carboniferous, south-western WA then drifted south to a palaeomagnetic latitude of 70°S. Between the Middle Carboniferous and the Late Cretaceous the regions' palaeomagnetic latitude first decreased to 40°S in the Middle Jurassic before increasing to 80°S. Subsequently the region drifted north to its current latitude of around 35°S. As a result of these latitudinal shifts, south-western WA has experienced climates ranging from tropical to glacial, from humid to arid. Climatic extremes and swings, in turn, led to varied and commonly intense weathering of bedrock and valley fill.

Limited uplift and erosion and extensive weathering have fostered the development of a complex regolith that comprises deeply weathered saprolite (Anand and Paine 2002) where groundwater flow is largely controlled by bedrock structural features (George *et al.* 1997; Clarke *et al.* 1998) and distinctive depositional patterns of overlying sediments (Salama 1997; De Broekert 2003; De Broekert *et al.* 2004).

Palaeodrainage systems

An extensive network of modern valleys and palaeovalleys exists across the wheatbelt (Beard 1973; Van de Graaff *et al.* 1977; Clarke 2005). The palaeovalleys have a complex architecture, reflecting their long evolution, which is inferred to have extended at least as far back as the Jurassic (Clarke and Alley 1993). Most of the inland systems are inactive today, and exist as sumps—rather than channels—for surface drainage. Lower reaches of some palaeovalleys are contiguous with modern active, or ephemerally active, drainages along the west and south coast. Discrimination of palaeodrainage fill sediments in drillhole data is hindered by limited textural maturity of the sediments and a strong weathering overprint (De Broekert 2003). A summary of the architecture of wheatbelt valleys is provided by Commander *et al.* (2001).

Several classifications have been proposed for the palaeodrainage systems. The low relief of the landscape and very broad interfluves can result in varied interpreted positions of drainage divides, differing by an order of tens of kilometres among workers. For the Yilgarn as a whole, Van de Graaff *et al.* (1977) recognised, but did not name, three main divisions: an eastern system (associated with the Eucla Basin), a western system (associated with the Perth and Carnarvon basins), and a northern system (associated with the Canning Basin). Those workers also recognised a long, narrow drainage system associated with the south coast, but did not clarify whether it was a separate subdivision in its own right or associated with the eastern or western systems.

Mulcahy and Bettenay (1972) recognised and named the following divisions: the Eucla (equivalent to the eastern division of Van de Graaff *et al.* 1977), south-western (equivalent to the southern half of the western division of Van de Graaff *et al.* 1977, with the inclusion of the south-coast drainages), and Murchison (equivalent to the northern half of the western division of Van de Graaff *et al.* 1977). They also recognised a Pilbara and Canning division, roughly equivalent to the northern division of Van de Graaff *et al.* (1977).

Clarke (2005) proposed three major drainage divisions, based on those of Van de Graaff *et al.* (1977). These are an eastern division (which includes the eastern part of the south coast) associated with the Eucla Basin (see Clarke *et al.* 2003), a western division associated with the Perth and Carnarvon basins, and a northern division associated with the Pilbara region and

Canning Basin. The WA wheatbelt region, the focus of the present paper, occupies the southern two-thirds of the western division, i.e. west of the main divide and south to the coast in Fig. 1, and the southern part of the eastern division. These palaeodrainage system divisions may not have been completely stable over time. For example, Beard (1998, 1999) reconstructed the evolution of the major south-west river systems and unravelled several drainage reversals caused by marginal uplift of the craton during separation from Antarctica during the Cretaceous. Many rivers of the Yilgarn drainage system formerly drained southwards but now converge to a single outlet, Caroline Gap, 229 m a.h.d., in the Median Watershed (Fig. 1) where it escapes westward to the Avon-Swan Rivers (Beard 1999; also figures 5 and 6 in Commander *et al*. 2001 show the upper reaches of the south-draining Eocene system captured and diverted to the Miocene Avon River to the west). Such drainage evolution leads to dismembered palaeovalley fills and palimpsest deposits from earlier drainage patterns. Beard (1999) has also shown lakes developed in valley floors ~100 km inland when river courses became partially obstructed by upwarped or uplifted cratonic blocks to their immediate west, e.g. Yenyening Lakes. Such sites, near the boundary between intermittent and inactive runoff, have been particularly susceptible to salinisation and salt-lake development.

Palaeodrainage architecture

Eastern division

Palaeovalley fills of the eastern division have been well studied and documented. Forming the palaeo-catchment to the Eucla Basin (Clarke *et al*. 2003), these palaeovalleys have largely been filled by a succession of Eocene marine to non-marine sediments. Two main non-marine sedimentary packages are recognised in the overlying valley fill succession: Miocene fluvio-lacustrine sediments, and Pliocene-Holocene playa sediments. These representative valley sediments are found as far west as Walpole on the south coast. The latter may, however, lack older (e.g. Pliocene) playa sediments; very limited available palynological data suggest that humid vegetation persisted into the Pliocene in these southern systems (Bint 1981) so playas were not necessarily ubiquitous in all catchments. Rainfall rates along the south coast increase westwards and some valleys in the drier east may have been only partly incised (Beard 1999) and, accordingly, have had relatively low sedimentation rates. This eastern system includes wheatbelt valleys north of the Stirling Ranges in which Commander *et al*. (2001) document over 60 m of contained Eocene sediments.

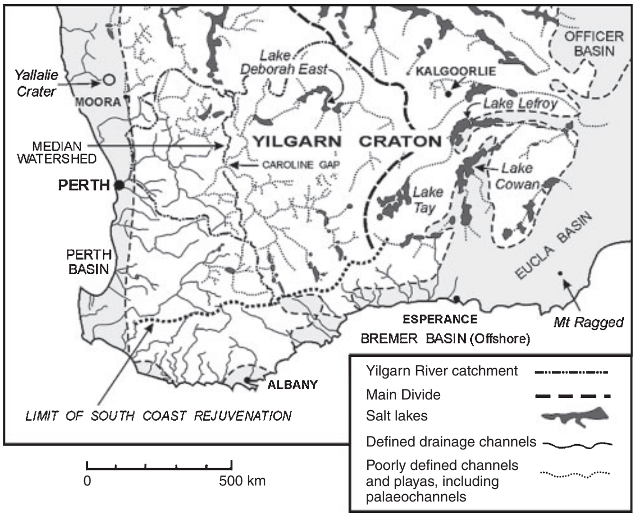

Fig. 1. Southern WA showing the network of ancient palaeo-valleys and associated salt lakes (after Beard 1973; Van de Graaff *et al*. 1977; Clarke *et al*. 2003). The Median Watershed and Caroline Gap are from Beard (1999) and the palaeo-catchment outline of the Yilgarn River is modified from Salama (1997). The main divide (thick dashed line) corresponds with the boundary between the eastern and western drainage divisions of Clarke (2005).

Western division

The palaeo-catchment of the Yilgarn River occupies much of the wheatbelt region (Fig. 2). Sedimentary fill in the palaeovalleys of the western division has been poorly documented compared with those of the eastern division, although deposits in the Salt River palaeovalley have been studied in detail by Salama (1994, 1997). The Salt River lies in the mid reaches of the Yilgarn River palaeodrainage system whose active lower reaches form the contemporary Avon River and whose inactive headwater is the Yilgarn River palaeodrainage, east of the Caroline Gap (Beard 1999). Up to 80 m of sediments are present in the Salt River palaeodrainage at Yenyening Lakes, comprising sands, clays, and peat. These palaeochannel sediments are Mio-Pliocene in age. Downstream, the palaeochannel of Salt and Yilgarn systems now lies truncated in the headwater of the Mundaring Catchment (Beard 1999). The age of these remnants are unknown. Headward progression of knick-points in major active

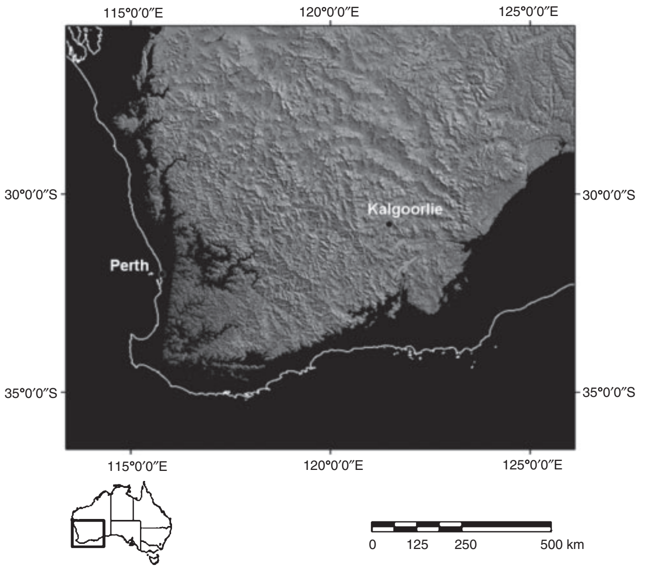

Fig. 2. Digital elevation model of south-western WA showing the area inundated by the Tortachila Transgression (~40 Ma) at ~260 m a.h. From Worrall and Clarke (2004).

drainages such as the Avon River (such as at Mundaring) is currently removing Miocene to Pliocene sediments from adjacent up-catchment palaeovalley reaches.

To the south-west, in a location within the present-day Blackwood Catchment, much older Eocene sediments from the western palaeodrainage division have been reported (George *et al*. 1994; Waterhouse *et al*. 1995). It is postulated that in the Cretaceous period, this system drained the Arthur and Beaufort Catchments westward into the Collie Catchment via a proto-valley, until tectonism and stream capture created the Blackwood system. The so-called Beaufort palaeodrainage system occupies a narrow, structurally defined drainage pattern; relict basal cobbles are present at an elevation of 190 m a.h.d., 50 km south-east of Collie. Above these cobbles are extensive lacustrine materials and lignite, infilling stranded drainage lines to depths of up to 50 m. The lacustrine sediment is also residual at elevations of up to 270–280 m a.h.d. on adjacent slopes and divides. These plateaux sediments sit below ridges of emergent deeply weathered landscapes, and are mapped as the Eulin Uplands by Tille (1996).

Additionally, fossiliferous (non-marine bivalves and plants) Eocene sediments are extant as silcrete caps on interfluves (Wilde and Backhouse 1978); these are located at elevations 310–320 m a.h.d. above the Eulin phase recognised by soil mapping. The occurrence of freshwater bivalves indicates that these upland Eocene sediments were seasonally waterlogged, pointing to inversion of former valley floors to their present disposition as ridges. De Broekert (2003) described structurally controlled bedrock relief beneath valleys at Yornaning with significant thicknesses occurring off axis. There has also been incipient development of relief inversion through differential removal of the former interfluves of exposed bedrock. Together, these observations support the contention that the western drainages have undergone significant uplift that has contributed to a post-Eocene tendency towards relief inversion.

Throughout the region, tributary palaeovalleys containing modern alluvia are reported to overlie deeply weathered regolith and the core palaeodrainage sediments such as described above. George (1992*a*) documents the hydraulic properties of these modern alluvial deposits and notes their thickness as 10–20 m. In the Wallatin Creek Catchment, Salama (1997) describes coarse infill successions, with 20 m of conglomerate, sandstone, claystone, and minor peat, and attributes a Pliocene to Holocene age to these sediments.

Eocene marine transgressions

Two Eocene marine transgressions occurred along the southern margin of Australia (Clarke *et al*. 2003). Sediments deposited during these events infill palaeovalleys in the eastern division to distances of 300 km inland from the present coastline and occur at elevations of at least 300 m a.h.d. The extent of equivalent transgressions in the western division is not known; however, siliceous spicular Late Eocene off-shore marine sediments have been reported at an altitude of ~225 m a.h.d. at Kalbarri in the Perth Basin (Haig and Mory 2003).

There is currently some conjecture in the literature regarding whether these data indicate that Eocene marine flooding reached this elevation in the wheatbelt, and possibly much higher, or as proposed by Beard (1999), that epirogenic uplift (of 140 m) suggests the marine invasion was at a lower elevation (i.e. 300–140 m) than implied. Sandiford (2007) estimates 250–300 m continent-scale tilting with SSW-up, north-down apparent vertical motion with respect to sea level since the mid-Miocene (15–20 m/Ma). Figure 2 shows a digital elevation model depicting areas that may have been subject to marine flooding.

Evidence suggests that it is most likely that the southern wheatbelt and palaeovalleys of the western region may thus have been submerged during the Middle and Late Eocene. The geomorphic imprint of the transgressions on marginal wheatbelt landscapes has been locally significant. Wave-cut surfaces are evident, for example on Mt Ragged, 150 km ENE of Esperance, and marine sedimentary successions up to 100 m thick occur in former drowned estuaries and coastal embayments. Although any marine salts deposited during these events have almost certainly been flushed from host sediments, the latter contained abundant reactive components, including carbonates, biogenic opal, organic material, and sulfides, which may locally change groundwater composition with respect to eH and pH and dissolved silica. Oxidation of relict sulfides has been suggested as one possible source of groundwater acidity in southern parts of the wheatbelt region (Worrall and Clarke 2004), although ferrolysis seems more likely (Shand and Degens 2008).

Antiquity of salinity in the wheatbelt landscape

Palaeoclimate patterns and the timing of regional aridity–salinity

Yallalie Crater on the western edge of the wheatbelt (Figs 1 and 3), in an area known as the West Midlands, is a 12-km-diameter astrobleme in the Perth Basin. The crater contains a well-preserved lake sequence that provides a palaeomagnetic record, sediment patterns, and chemistry, which record a rare history of environmental change in the region—including periods of aridity and salinisation—during the last 3 Ma (Dodson and Ramrath 2001; Dodson and Lu 2005) (Table 1). Chemical analysis of palaeolacustrine sediments from this closed hydrological system reveals that the lake varied in water depth and that salinity and diatom production were related to climate change rather than changes in major nutrients. Laminated sediments for the period 2.96–2.82 Ma indicate a variable and more seasonal climate than the overlying record. The palaeomagnetic record indicates short intervals of semi-arid climate occurring around 2.5 Ma, characterised by chenopod shrub land, and saline habitat diatoms along with carbonate and gypsum in the sediments (Dodson and Ramrath 2001). Thus, palynological data for the upper 20 m of Yallalie sediment show a woodland and heath similar to the vegetation of today, interspersed with some chenopod shrub land phases and *Nothofagus* associations.

Nothofagus (*brassii*-type) pollen is also reported from Early Pliocene sediments in the Lake Tay area (Fig. 1) by Bint (1981) (Table 1). Here it occurs with some podocarpaceous conifers in an assemblage that indicates a warm temperate open-forest with some lake edge or marsh component. The Lake Tay pollen may have derived from small refugia stands on higher country to the

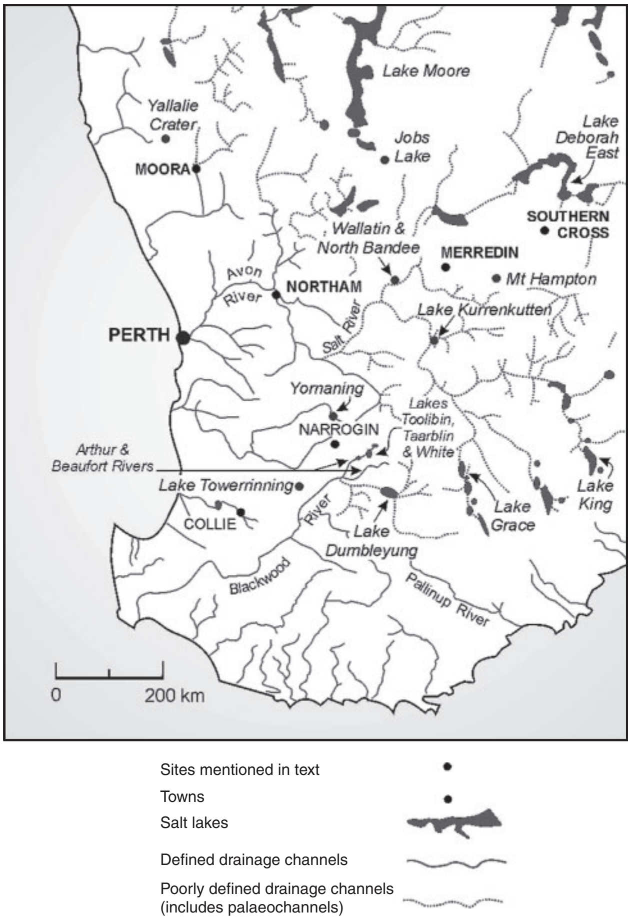

Fig. 3. The WA wheatbelt region with locations mentioned in text.

east or south of the lake. The assemblage shows similarities to Early Pliocene flora from south-eastern Australia, suggesting that regional differentiation of flora from across southern Australia was less pronounced in the Early Pliocene than today (Bint 1981). Wetter periods in the early Tertiary are indicated, at a time when the region was located much further south. At Lake Lefroy east of the wheatbelt (Fig. 1), the stratigraphic change from non-evaporitic lacustrine silts, sands, and clays to gypsiferous playa deposits is marked (Table 1). Based on palynology, the deposition of gypsiferous deposits is placed in the Early Pliocene (Clarke 1994*a*, 1994*b*). Other information from the Pliocene in south-western WA (Table 1) reveals that while the climate was a little wetter and probably warmer than today, cycles of aridity marked by expansion of saltbush occurred (Dodson *et al.* 2002) (Table 1).

Palaeomagnetic data from sites across the continent, additional to the work of Dodson and Ramrath (2001), outlined above, indicate varying records for the timing of the earliest extant evidence of salinity. For example, at Lake Amadeus, at the continental core, in central Australia, Chen and Barton (1991) interpret the onset of aridity occurring before 900 ka. Presumably, aeolian deposits blocked the drainage lines to force the development of playa conditions at the basin depocentre at this time. Based on palaeomagnetic data, Zheng *et al.* (1998) estimate the change from lacustrine clays to evaporites and dune sediments at Lake Lefroy to have occurred between 700 and 400 ka (Table 1). The latter estimated timing of the onset of pronounced aridity in southern WA is debated by Clarke *et al.* (2002), who identify a discrepancy between the palynological and palaeomagnetic data (see also Zheng *et al.* 2002). A post-Brunhes-Matuyama (780 ka) transition from perennial freshwater lacustrine to evaporites and dune sediments has been interpreted for both

Table 1. Major Cainozoic climate phases in south-western Australia

Age	Reference	Palaeo-climate/palaeo-salinity indicators
Early Pliocene	Bint (1981)	Lake Tay pollen: *Nothofagus*: humid rainforest conditions
Early Pliocene	Clarke (1994*a*, 1994*b*)	Lakes Lefroy: sparse pollen data: gypsiferous deposits: saline lakewaters/ groundwater
2.96–2.82 Ma	Dodson and Ramrath (2001)	Yallalie Crater: laminated lacustrine sediments: variable, seasonal climate
~2.5 Ma	Dodson and Ramrath (2001)	Yallalie Crater: palaeomagnetic data and pollen indicate 3 short intervals of semi-arid climate and salinity
700–400 ka	Zheng *et al.* (1998)	Lake Lefroy: sparse palaeomagnetic data: transition from lacustrine to evaporitic sediments
350 ka	Kershaw *et al.* (2003*a*, 2003*b*)	Diverse proxy data for southern Australia: trend towards drier and more variable climates
250 ka	Kershaw *et al.* (2003*a*, 2003*b*)	Lunettes commence
160–150 ka	Zheng *et al.* (2003)	Lake Lefroy: optical dating: sand dune formation
60–40 ka	Zheng *et al.* (2003)	Lake Lefroy: opptical dating: aeolian sand sheet
~27–17 ka (last glacial maximum)	Zheng *et al.* (2003)	Lake Lefroy: optical and ESR dating: gypsum dune formation; pronounced aridity, aeolian activity and salinity
20–15 ka	Bowler (1976)	SW WA: ^{14}C dating: widespread lunette building (Lakes Kurrenkutten, Grace, King, etc.)
18–0 ka	Harrison and Dodson (1993)	Australia-wide lake levels and pollen: regional reductions in effective moisture; drier
15–14 ka and ~12 ka	Zheng *et al.* (2003)	Brief rise in lake levels
6–4 ka	Dodson *et al.* (2002); Dodson and Lu (2000)	Several SW WA sites: peat accumulation, greater influence of Westerlies, wetter conditions
4–3 ka	Churchill (1968)	Wet phase in WA inferred by relative abundance of Eucalypt pollen

the palaeo-Lake Bungunnia in the Murray Basin (Zhisheng *et al.* 1986) and Lake Lewis in central Australia (English 2002). In contrast, at Lake Buchanan, Queensland, Chivas *et al.* (1986) recorded a low lacustrine sedimentation rate and numerous palaeosol layers for the Brunhes Chron, indicating drying of the lakebed and lowering of the watertable to promote pedogenesis, before Late Brunhes salt lake development. The lacustrine records reflect the wide range of climate regimes, catchment parameters, sediment supplies, and deflationary histories. At Halletts Cove and Sellicks Beach, South Australia, Pillans and Bourman (2001) estimated a major arid shift in regional climates, represented by a marked change from an oxide-dominated weathering regime to a carbonate-dominated regime, to have occurred at ~500–600 ka.

Charcoal is abundant in the Yallalie Pliocene record, indicating that fire was a major environmental feature long before Aboriginals inhabited the continent. The sediment profile and palaeomagnetic record indicate high climatic variability and major environmental changes during the Pliocene rather than a uniform cooling trend leading to the Quaternary glacial episodes (Dodson and Ramrath 2001) (Table 1).

Quaternary climate and environmental change

Between 900 and 600 ka, oxygen isotope fluctuations in deep-sea cores show a pronounced change in frequency, from a 40 ka to a 100 ka pattern, forced by changes in the Earth's orbit and tilt in relation to the sun (obliquity-dominated to eccentricity-dominated) and possible variations in the solar output influencing climate changes (Dodson *et al.* 2002). Glacial-interglacial amplitudes increased, with marked enrichment of glacial δ^{18}O values consistent with larger continental-based ice-sheets. Lower sea levels during glacials and colder global temperatures may have influenced the mid-Pleistocene arid shift recorded in southern Australia, and associated variations in the strength of the warm Leeuwin Current may also have affected rainfall patterns in the region (Pillans and Bourman 2001).

Ice-volume forced glacial-interglacial cyclicity is the major cause of global climate variation during the late Quaternary period. Within the Australian region this variation is expressed predominantly as oscillations in moisture availability (Kershaw *et al.* 2003*a*, 2003*b*) (Table 1). Quaternary records for southern Australia accordingly show glacial maxima characterised by expansion of semi-arid conditions, while interglacials are represented by humid periods (Chappell 1991; Dodson 1994). Dry glacial periods are typically associated with shallow, ephemeral, or dry (sometimes saline) water bodies, reduced fluvial activity, and widespread aeolian activity across the continent.

While ice sheets did not effect on WA directly at this time, the extension of aridity and the effect of sea level change that accompanied each global ice expansion were significant. The main path of the Westerlies moved poleward, cutting off some winter rains, while monsoon rains decreased in the north as land, rather than warm oceans, dominated the south-east Asian to Australian region. The arid core of the continent expanded possibly by 20%. Major and varied shifts in climate and habitat ranges during the numerous warming and cooling cycles implicated substantial fragmentation of vegetation types and extinctions, especially the most moisture-dependent species (Dodson *et al.* 2002).

Superimposed on the glacial-interglacial cyclicity is a trend towards drier and/or more variable climates within the last 350 ka. This trend may have been initiated by changes in atmospheric and ocean circulation resulting from Australia's continued movement northward and the onset or intensification of the El Niño-Southern Oscillation (ENSO) system and reduced summer monsoon activity. Aeolian activity peaked around 250 ka, 200–100 ka, and during the Last Glacial Maximum (LGM), 27–17 ka, indicative of strong winds and reduced vegetation associated with glacial periods (Kershaw *et al.* 2003*a*, 2003*b*). Optical dating of lunette dunes and electric spin resonance (ESR) dating of relict gypsum dunes on the lake floors of lakes Lefroy and Cowan, east of the wheatbelt (Fig. 1), indicate that pronounced aridity set in during the mid-Quaternary, with substantial aeolian activity spanning the period 60–40 ka, intensifying during the LGM (Zheng *et al.* 2003). This timing correlates with major dune-building episodes in southern and south-eastern Australia (Bowler 1983; Wasson 1989). Increased biomass burning from increased climatic variability resulted in more open and sclerophyllous vegetation, increased salinity, and a further reduction in water availability in the surface environment (Kershaw *et al.* 2003*a*, 2003*b*).

Compilations of Australia-wide lake-level and pollen data show concordant patterns of regional changes in effective moisture between 18 ka and the present (Harrison and Dodson 1993) (Table 1). In southern Australia, lake levels were lower between 18 and 12 ka and conditions were drier than at present across most of the continent, including south-western WA. In the eastern wheatbelt region, radiocarbon (^{14}C) ages of 12–13 ka for lunette *Coxiella* shells from near Lake Kurrenkutten and Lake Grace (Fig. 3) indicate a minimum age for shell growth associated with high water level and dune building (Bowler 1976) (Table 1). Radiocarbon (^{14}C) from carbonate-rich lunettes surrounding Lake King (Fig. 3), and from charcoal on a quartz-gypsum lunette near Merredin, indicates a short-lived dune-building episode between 20 and 15 ka, arguing for a period of hydrological stress coincident with that documented from eastern Australia (Bowler 1976). There is some suggestion of a brief rise in lake levels between 15 and 14 ka and even around 12 ka. Lake levels generally appear to have dropped from the mid to late Holocene to levels similar to the present, although ^{14}C dating of lacustrine sediments from high lake stands along the margin of Lake Cowan suggests a significant high-lake event during the early to mid Holocene (Zheng *et al.* 2003). The palaeo-dune evidence is consistent with a southward expansion of the southern margin of the subtropical high-pressure belt, a southward displacement of the Westerlies to a position south of Tasmania, and a weaker summer monsoon over northern Australia after 12 ka.

Thus, palaeo-environmental changes during and following the LGM may be due to a contraction of the subtropical anti-cyclonic belt reducing the influence of the Westerlies, increasing summer insolation, and strengthening of the Walker Circulation (Harrison and Dodson 1993). Alternatively, Shulmeister (1999) points to evidence for a strengthening of the summer monsoon in northern Australia between 7 and 5 ka, followed by a strengthening of the westerly circulation after 5 ka contributing to a decrease in the evaporation-precipitation ratio in southern Australia. Shulmeister *et al.* (2004) further interpret a westerly maximum at the LGM and strengthened westerly circulation in historical times, in the Little Ice Age (*c.* 1400–1850), and strong centennial-scale variability associated with poleward shifts in the circumpolar trough in the Southern Ocean. Hesse *et al.* (2004) suggest that changes to the temperature and humidity of the westerly circulation have been more significant over southern Australia than the small fluctuations in latitude of the subtropical high pressure ridge.

Whereas south-eastern Australia saw a great expansion of semi-arid vegetation during the Holocene with the development of steppe grasslands and reduction of forest to small fragments, in the south-west, woodland persisted throughout this period. There was some reduction in eucalypts while *Casuarina* expanded and rich heathlands persisted. While the south-east of the continent registered an increase in moisture and warmth between ~6 and 4 ka, this trend either did not occur in the south-west or it had little effect on vegetation (Dodson *et al.* 2002). Rainfall changes in the south-west may have been mediated by the Indian Ocean and/or the westerly wind field may have been relatively stable during this period. Alternatively, in the south-west, the great degree of biodiversity in the local flora and mix of habitats may have equipped the vegetation assemblage to cope with the magnitude of climate change imposed on the region (Dodson *et al.* 2002). Notwithstanding, a mid to late Holocene change in conditions may be reflected in an increased number of sites that were conducive to peat accumulation, possibly indicating a shift in the pattern of influence of the Westerlies (Dodson and Lu 2000).

Environmental change during the Late Quaternary was no doubt a consequence of both climate change and the increased frequency/intensity of fire related to the arrival of early inhabitants in the last ~45 ka. Loss of natural vegetation and species extinction—whether from changes in rainfall, evaporation-precipitation ratios, or human-induced fire regimes—would have impinged on regional and catchment-scale water balances, runoff and groundwater recharge rates, watertable levels, and the manifestation or intensification of salinity across the landscape. Reduction in eucalypt forests in lieu of chenopods over broad-scale regions, for example, may reduce moisture interactions between vegetation cover and the atmosphere and consequently decrease the effectiveness of rainfall in the inland. In the wheatbelt palaeovalley systems, changes in watertables would have influenced vegetation changes and *vice versa*, vegetation changes would have influenced watertables as well as groundwater salinity levels.

Hydrogeomorphic responses and salt lake evolution

Our understanding of the evolution of primary salt lakes in Australia is substantially informed by the benchmark work of Bowler (e.g. Bowler 1973, 1976, 1981, 1983, 1986, 1998; Bowler *et al.* 1976). Salinity manifested itself widely in the Australian landscape in response to aridity during the glacial periods, described above. Extinction of plant species and contraction of habitats resulted in less demand for rainfall in the surface environment, which resulted in any excess runoff and an additional flux going to groundwater recharge. Freshwater lakes and rivers occupying palaeodrainage networks contracted and became disaggregated as surface water diminished. Moreover, sea-level lowering during the glacial maxima increased the magnitude of continentality, making it even more difficult for river systems to reach the oceans. Flushing of the landscape of dissolved salts was thereby inhibited and formation of internal drainage networks was promoted. Increased windiness during the glacial maxima—particularly in areas denuded of vegetation—caused widespread deflation and aeolian landform development. Salts that had been resident in the regolith of catchments since at least the Late Pliocene were mobilised as watertables rose in response to groundwater recharge. When the capillary fringe of rising watertables came into contact with lower landscape positions, sequestered salts became concentrated under the influence of solar radiation. Salt lakes developed as a result of the combined influences of local tectonic activity, groundwater seepage, and deflation in valley floors. Continued aeolian activity deflated and scoured saline playa surfaces with two consequences: formation of proximal saline landforms from transported salt lake sediments, particularly lunettes; and lowering of lakebed levels, which increased the areas exposed to rising watertables, enhancing groundwater discharge, salt efflorescence, and salt lake evolution. Development of curvilinear sand dunes and lunettes served to augment disaggregation of (palaeo) drainage systems, further inhibiting the effectiveness of surface water processes in catchment depocentres and promoting groundwater as the dominant geomorphic agent.

Detailed descriptions of primary salt lakes in the wheatbelt are provided by Salama *et al.* (1992), Salama (1997), and Beard (1999). For example, Lake Deborah East lies in the upper reaches of the disaggregated Yilgarn River palaeochannel network, in the centre of the Yilgarn Craton (Fig. 1). The irregular-shaped lake is closely surrounded by granite and greenstone outcrops and basement structures (Salama *et al.* 1992). The playa surface is covered with a halite crust that is up to 0.70 m thick in the central part of the lake, comprising halite-cemented columnar halite crystals. This hard crust is underlayed by an unconsolidated layer of coarse cubic halite crystals, which varies in thickness from 0.20 m at the lake edges to >1.50 m in the centre, and which is submerged in saturated grey silty brine. The unconsolidated layer is underlayed, in turn, by black sulfide-rich mud, clastic sediment, and mudstone. The latter represent lacustrine deposits; these are stratified and intercalated with gypsum and salt layers. Palynological data show that the earliest sediments infilling the palaeochannel were deposited during the Late Cainozoic and the top 2 m are Quaternary. The salt crust has formed from groundwater discharge and surface water sources through a continuous process of salt recycling. The salt budget indicates prolonged arid periods during which no salt has been added to the lake and suggests additional losses by deflation and overflow during other periods. The mudstone layers at the bottom of Lake Deborah East act as a permeability barrier controlling upward brine migration, which is additionally restricted by basement highs. As a consequence, this lake is very highly evolved chemically and bromide and bitterns have become concentrated in the brine pool (Salama *et al.* 1992). In this regard, Lake Deborah East differs from typical salt lakes in eastern Australia where salt deposition is controlled by downward fluxes of solutes (e.g. Teller *et al.* 1982; Bowler and Teller 1986).

Salt sources and recycling

A variety of gypsum types from modern playas across WA have a regular pattern of $\delta^{34}S$ values with highest values, ~+21‰, near the coast decreasing to $\delta^{34}S$ ~+14‰ 1000 km further inland (Chivas *et al.* 1991). Sea-salt sulfate is the dominant source of sulfur to the salt lakes, although the proportion decreases from ~100% near the coast to ~55% in inland areas. A secondary airborne source of sulfate is derived from volatile biogenic sulfur compounds of largely marine origin, supporting the delivery of salts to the Australian landscape as aerosols following dominant wind patterns. The $\delta^{34}S$ data negate the possibility of derivation of lacustrine 'seawater-like' brine chemistry from either marine transgressions or weathering of connate salts from marine strata (Chivas *et al.* 1991).

Low, uniform radiochlorine/stable chlorine ratios ($^{36}Cl/Cl$), of the order of $35 \pm 7 \times 10^{-15}$, have been documented by Chivas *et al.* (1988) and Keywood *et al.* (1998) from surficial halite crusts in salt lakes in a 600-km-long transect across WA. Similarly, $^{36}Cl/Cl$ ratios for Australian inland salt lakes elsewhere tend to be low (Fifield *et al.* 1987; English 2002), indicating dilution by remobilised salts that have been in residence in salt lake settings for considerable durations. Wide-ranging chloride concentrations plot on a trend that additionally indicates mixing of rainwater and local recycled salts in these inland settings. Two underpinning observations have been flagged by Bird *et al.* (1991): (*a*) large-scale dust storms redistribute chloride from surface layers, including salt lakes, and make it impossible to distinguish dry precipitation of cosmogenic ^{36}Cl from recycled chloride; and (*b*) major floods, although they occur infrequently, wash surface chloride of whatever origin into the salt lakes, playas, and palaeovalleys. The role of recycled chloride obtained from Quaternary salt lakes is likely to be more significant in secondary salinity processes in the palaeodrainages of the WA wheatbelt than modern meteoric salt input. Importantly, older recycled salts have contributed greatly to the salt concentrations in brine pools and shallow groundwater bodies beneath contemporary palaeovalleys.

Contemporary hydrogeology

Groundwaters of the wheatbelt are contained within heterogeneously weathered Archaean granites and associated igneous rocks, and inset or overlying sediments. The weathering patterns tend to be locally controlled (George 1992*a*). Typically, valley soils are underlayed by mottled transported colluvial deposits (1–5 m thick), deeper alluvium (2–20 m thick), and deeply weathered *in situ* materials (10–30 m thick). A saprock aquifer occurs at the base of most profiles, and forms the dominant local aquifer where sediments are absent (George 1992*a*). While fracture systems are known to exist beneath the unweathered basement, there is little evidence of their significance in the transport of saline groundwater in the low-gradient wheatbelt region.

Groundwater systems within the regolith tend to function as local and intermediate flow systems. The latter occur in the palaeodrainages; the former on weathered slopes and beneath alluvium that covers many lower landscapes. Local flow systems in the deeply weathered regolith typically have circulation depths of less than 20–40 m, and flow paths of less than 5 km. In the western terrain, faults may function as longer conduits for catchment flow (Clarke *et al.* 1998).

In the intermediate-scale palaeodrainages, sediments and weathered materials are known to reach a maxima of 80 m thickness (Salama 1997), and flow systems of up to 30 km length are feasible. Local flow from sandplains and arkosic-dominated uplands may reach the intermediate systems occupying the palaeodrainage valleys. Notwithstanding, few wheatbelt valleys contain effective flow paths of the order of tens of kilometres because local structures interrupt flow and can promote groundwater discharge and playa development. Geological structures that serve to impede groundwater flow include buried bedrock highs (basement topography), faults, weathered mafic dykes, and discordant alluvial networks (Salama *et al.* 1993).

Groundwaters within the regolith vary from fresh (<1000 mg/L total soluble salts, TSS) near outcrops to brines beneath palaeodrainages (>300 000 mg/L TSS), reflecting patterns of salt storage. Investigations of groundwater geochemistry from regional monitoring bore networks (Mazor and George 1992) indicate strong evaporative signatures, which suggest cell-like behaviour that is enhanced by the physical characteristics described above. Shand and Degens (2008) also note that patterns of salt accumulation mirror the distribution of hydrogeomorphic domains, with saline and low pH waters ($pH < 3$) occurring in palaeodrainage discharge zones (playas), and more neutral and alkaline waters in recharge areas.

McFarlane and George (1992) reviewed salt storage in two adjacent wheatbelt catchments (Table 2) and concluded that salt

Table 2. Average total soluble salt stores (TSS) in tonne/hectare (t/ha) beneath a hectare of land above bedrock in typical central (Wallatin Creek) and eastern wheatbelt (North Baandee) catchments (after McFarlane and George 1992)

The two catchments are adjoin each other

Landform (position)	Av. TSS storage above bedrock (t/ha)	Range (t/ha) (0.1 kg/m^3)	No. of profiles sampled	Av. depth (m)
Danberrin (hilltop)	247	7–657	7	5.9
Ulva (sandy hillside)	289	139–422	5	19.7
Booraan (clayey hillside)	802	43–1798	10	13.5
Collgar (sandy low slopes)	1056	109–2231	12	16.5
Belka (broad valley)	2571	44–6206	14	20.4
Baandee (saline & playa)	13 533	5752–21 314	2	51.0

store was directly linked to landscape type, showing ranges from as little as 247 t/ha TSS in skeletal soils (Danberrin) to >21 314 t/ha. TSS (Baandee; valley palaeodrainage channels). At present rates of deposition (~25 kg/ha.year; Hingston and Gailitis 1976), stores of 1000 t/ha would require 40 000–100 000 years to generate the measured load (McArthur *et al*. 1989; McFarlane *et al*. 1993).

Current salinity processes and magnitude

Groundwater dynamics in response to clearing of native vegetation for agriculture are well understood, although less well quantified in the drier wheatbelt systems. George (1992*b*) suggested that pre-clearing recharge was likely to range from 0.01 to 1 mm/year, being derived from episodic events rather than annual recharge. In contrast, recharge following clearing was increased by 1–3 orders of magnitude. The area of discharge has, accordingly, increased from <0.1% to as much as 10% of catchments. The periodicity and spatial extent of recharge has also increased, from former irregular recharge episodes in permeable soils and water accumulation zones, to contemporary seasonal recharge, as leakage from beneath annual crops and pastures in most if not all soils and landforms.

Resultant changes in groundwater storage are reflected in rates of watertable rise. In the wheatbelt, the WA Department of Agriculture and Food manages a surveillance network comprising over 1500 bores in over 50 catchments. These bores have been progressively installed since the late 1970s. Time-series data indicate trends in aquifer development and enable the risk of salinisation to be assessed. These bores also provide access to groundwaters for geochemical assessment. Bores established before 2000 show a dominant rising trend in water levels of ~0.1 m/year. Water level rise rates range from 0 to 0.9 m/year, the latter being exceptional, with rates of rise of 0.1–0.3 m/year being common. Since 2000, groundwaters have been falling in the northern areas in response to reduced rainfall.

Trends driving the spatial assessment of salinisation cannot be reliably assessed by time-series data alone. Aquifer characteristics and flow-system geometry are also required. Based on an analysis of over 10 wheatbelt catchments, George *et al*. (2001) document aquifer behaviour and forecast the extent of discharge likely to result from continued rates of groundwater rise. Their analysis predicts that most valley floors with gradients of less than 0.1 m/m will contain shallow watertables (<2 m depth) by 2100 if observed trends continue unabated. A precursor of this analysis was implicit in the development of a valley hazard map for use in assessing the extent of hydrologically based degradation such as dryland salinity (Campbell *et al*. 2000). The map, derived by mapping land occurring 2 m above the lowest point in any valley floor, using an accurate digital elevation model (±1 m), was then compared with modelled salinity risk maps (estimating 19% of the valley floor). The map identifies 23% of the valley floors of the wheatbelt as having a salinity hazard. A representative valley hazard map, with saline land and vegetation, is shown for the Toolibin area (Fig. 4).

Within this modelled area lies all of the pre-existing saline playas and saline soils recognised at the time of settlement (up to 300 000 ha), plus areas of post-clearing dryland salinity (1.1 Mha), and land identified as 'valley hazard'. This hazard map incorporates 1.7–3.4 Mha of additional land not currently affected, or terrain too mildly affected to be classified as saline.

Significant questions which require evaluation are: (*i*) whether anthropogenic-induced salinity will be more extensive than that which has occurred previously during the late Cainozoic, (*ii*) the extent to which the trends of modern dryland salinity have ancient analogues, and (*iii*) whether human-induced salinity is occurring at a more rapid rate than primary salinisation processes. The potential for recovery of salinised areas, or to avert the onset of salinisation of identified hazard areas (e.g. Fig. 4), whether in response to climate change effects or to deliberate land use change, also needs to be elucidated in the immediate future.

Modern salinity and palaeohydrologic markers

Historic markers of salinisation and/or shallow watertables

The review above indicates that the wheatbelt region exhibits the legacy of multiple phases of aridity and wetter periods across the Cainozoic. In particular, the late Quaternary has imparted a unique geomorphology to the region. As a consequence of climate changes, geomorphology, landscape salt stores, and geochemical evolution, imprints of phases of high watertables and consequent salinisation remain in the landscape. Some key indicators of past phases of shallow groundwater, surface water accumulation, and salinity are summarised in Table 3. Several of these hydrogeomorphic elements (playa-lunette, hardpan, and saline/acid groundwaters) are described below to provide evidence upon which to indicate that clearing-induced salinity shares many analogous characteristics with climate-derived or primary salinity.

Bowler (1986) conceptualised the archetypal evolutionary sequence of Australian lakes to represent: (*a*) the progression of an individual lake from a fresh surface water body to a groundwater-dominated playa in response to increasing aridity during the Quaternary period, and (*b*) the range of contemporary lake types across a climatic gradient from humid to arid regions. Different geomorphic and sediment features reflect successive stages in the hydrological series from surface water to groundwater-dominated systems. Bowler (1981, 1986) devised a disequilibrium index from catchment and lake areas and climatic parameters to indicate the magnitude of deviation of the lake from steady-state surface water cover and from hydrological equilibrium. End-members are fresh surface water cover 100% of the time and dry, groundwater controlled playas at the other extreme. Today, in the wheatbelt, lakes typically range from ephemeral, groundwater-controlled playas to dry salt pans, although commonly bearing the signatures of expanded perennial lake phases in surrounding valley lowlands.

A key to understanding the nature of environmental and hydrological changes is provided by the almost ubiquitous presence of lunettes in (palaeo) lacustrine environments. Lunettes are crescentic or transverse dunes on the downwind margin of surface water bodies, formed from sediments sourced from shores during wet phases and from exposed lake floors during arid phases. Commonly they are relict and reflect past abundances of water in rivers and lakes in what is now an arid

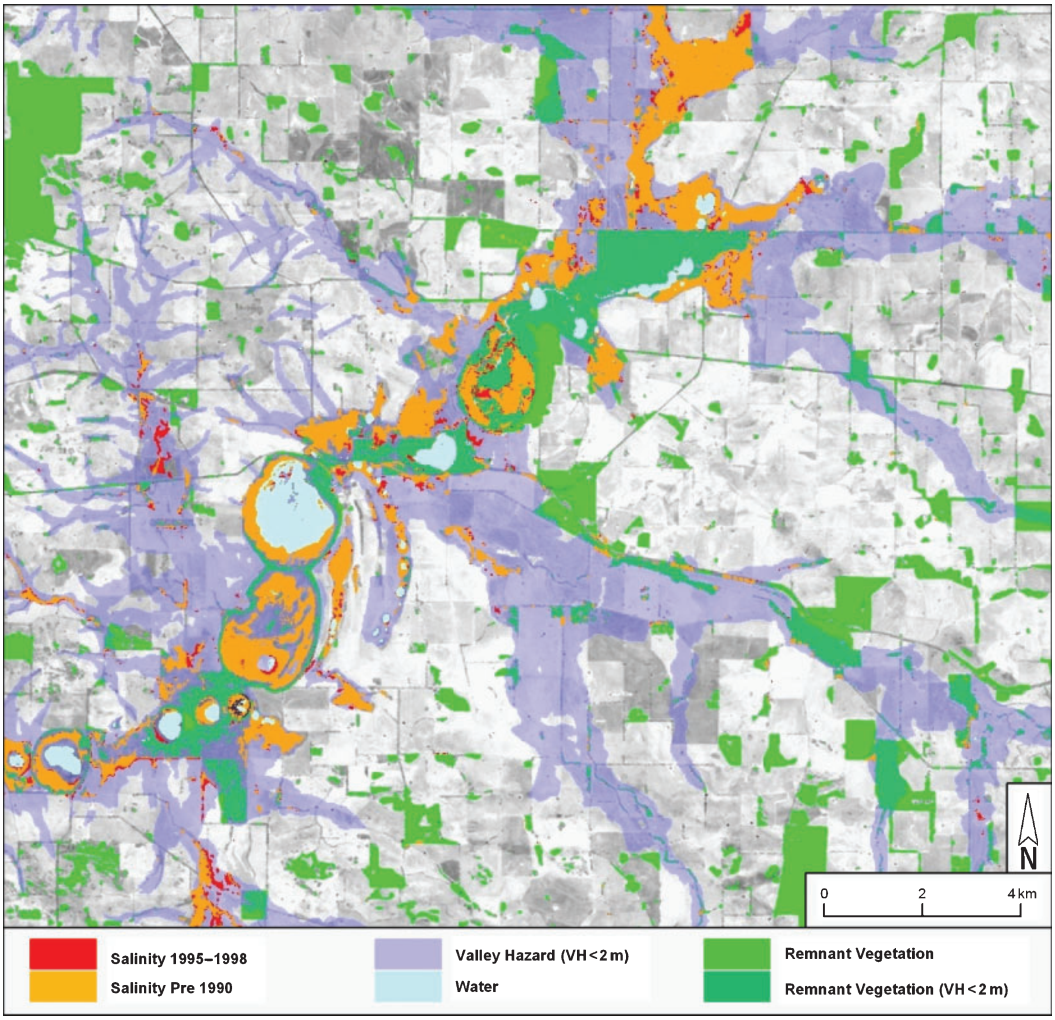

Fig. 4. An example of a Landsat TM-derived Land Monitor data product showing much of the Toolibin Catchment, areas of salinity, and valley hazard. Lake Toolibin (300 ha) and Lake Taarblin (800 ha, larger southern lake with two lobes) are depicted as vegetated and partially saline (see Fig. 8) and fully salt affected. An arcuate series of small playas is shown east (downwind) of Lake Taarblin and relic from a larger palaeo-lake.

landscape. By their different expression, lunettes inform on the nature of hydrological conditions (Bowler 1973, 1983, 1998). Quartzose lake shore or river-bordering dunes indicate a wet climate and wetter conditions. Saline clay or gypsum in lunettes indicate a dry climate and interaction of an adjacent lake bed or valley floor with saline groundwater. In WA a multitude of lunettes are scattered across the wheatbelt, indicative of the responsiveness of the palaeovalley systems to climatic/hydrological change. Crescentic quartz sand dunes associated with palaeo-shorelines are more common in uplands and are often fully vegetated. Gypsiferous lunettes associated with bare and saline floors are more typical in valley lowlands.

Settlers' reports and observations by pioneering families enable some comparative analysis of the condition of palaeodrainage lakes and lunettes at the time of European occupation. Large lakes (10–100 km^2) such as Lakes Grace, King, Baandee, and Dumbleyung are instructive of time-series changes. These lakes were reputed to contain fresh to brackish waters periodically after clearing (1890s), becoming extremely saline after the 1950s. Lake Dumbleyung was trafficable (by horse-drawn drays carting grain to Dumbleyung) and said to be fresh (moderate inflows) to brackish (low flows). It now regularly contains waters of over 50 000 mg/L, has a salt crust and up to 0.5 m of mud under the lake floor, and a perimeter of dead vegetation. Now only following large rainfall events (e.g. January 2006) do these lakes contain waters of marginally less than 20 000 mg/L. Similarly, many smaller lakes in these areas, slightly elevated from the larger playas were much fresher at clearing, as demonstrated by roads, fences and dams constructed in their floors, but have also become saline, or at risk of salinity (see Figs 5 and 6).

Stranded playas and lunette fields exist in the headwaters of some wheatbelt catchments. Lake Job and unnamed playas upstream and downstream (Fig. 5), and a series near Mt Hampton (Fig. 7), are or were examples of stranded fresh

Table 3. Proposed landform elements indicative of previous phases of salinisation and shallow water tables

Hydrogeomorphic elements	Brief description
1. Salt lakes (playas)	Multiple types existed before clearing; extent, abundance, hydro-period and salt loads varied. Some hypersaline at clearing, most brackish, dominated by surface waters and periods of groundwater discharge
2. Non-saline playas	Playas, clay pans, swamps. Many fully vegetated playas remain in upland catchments within cleared areas of the south-west WA and Yilgarn, e.g. Mt Hampton. These playas are reactivating in response to watertables rise
3. Lunettes and dunes	Both sand & gypsum-bearing lunettes, and aeolian sand sheets, some containing evidence of wetter phases, e.g. *Coxiella* spp., later stripped by aridity-driven deflation of playas
4. Saline creeks	Settlers report saline creeks, e.g. Pallinup on South Coast, before land use change. Similar observations in other landscapes indicate early presence of salt stores
5. Saline soils	Salt and gypsum laden soils typified by naturally saline aeolian soils, supporting salt-tolerant eucalypts such as *E. longicornis* (Morrell)
6. Specialist vegetation, e.g. chenopods	Extensive blue bush, saltbush, and halosarcia plains, some as woodland understorey systems; eastern areas; Yilgarn
7. Salt-tolerant trees, e.g. eucalypts	Salt tolerance is a characteristic of many WA plants (eucalypts, casuarinas, and melaleucas) in broad valleys, near playas, including widespread salt-tolerant eucalypt species in the palaeo valleys, e.g. *E. salicola* (salt salmon gum)
8. Saline groundwater	Saline (>35 000 mg/L) aquifers existed as historic waters in basement troughs behind barriers in catchments at the time of clearing. Few dates, ^{14}C, of the order of 10 000 years represent mixes of pre-clearing and modern recharge waters
9. Acid groundwater	Acid groundwater distribution reflect-patterns of recharge and discharge, and historic processes of oxidation from discharging groundwaters
10. Escarpments	Strong saline seeps in dissected areas generate escarpments as discharge drives headward erosion
11. Groundwater plains	Salt lake ‘boinkas’ (after terminology of Macumber 1991) near Esperance, alluvial plains of the Mortlock river
12. Hardpans/cements	Subsurface carbonate and silica hardpans, palaeosols, silcrete benches on sandplain seeps

Fig. 5. Askews Lake (rear) and vegetated playa below Jobs Lake.

Fig. 6. Playa upstream of Lake Toolibin, showing old road (last used 1970s), dead Casuarina vegetation, and halite crust.

water systems, with woodland, acacia, melaleuca, or heath-covered floors and sand-dominant lunette fields. In most cases, these and other playas lie near geological structures observed on regional aerial magnetic images. Lake Job became saline in the 1980s following salinisation of the lower Beacon River catchment, 40–80 years after clearing. In both these areas, watertables are now within 5 m of the playas, dryland salinity is encroaching and, with watertables rising (0.2 m/year) and saline groundwaters (>20 000 mg/L) present, salinisation is imminent. In such scenarios the playas are harbingers of approaching salinity. In these catchments, the existence of sand-dominant lunettes suggests that the lakes previously developed, or were most active, in wetter phases.

Palaeogeographical evidence suggests that the drying trend was established at 350 ka and peaked at 17 ka across the Australian continent (Kershaw and Nanson 1993; Kershaw *et al*. 2003*a*, 2003*b*), leaving a legacy of numerous sedimentary markers. Extensive lunettes that dominate the wheatbelt playas reveal patterns consistent with drying, lake contraction, and increased aridity.

At lakes Toolibin (Fig. 8) and Taarblin, evidence of the shrinkage in areas of the lake floors relative to the expansion of lunette fields is visible. Drilling at Toolibin beneath lunettes revealed lacustrine beds extending over 300 m to the east of the present contracted lakes (George *et al*. 2004), while at Taarblin, stranded playa lobes infill interdunal valleys up to 1–2 km east of the existing lake floor (Fig. 4).

Fig. 7. Vegetated playa (low dense foliage) taken from lunette near Mt Hampton (background).

Fig. 8. Lake Toolibin in January 2006 showing Casuarina-covered lake floor, salt diversion earthworks, and revegetation (taken from west).

George *et al*. (2004) used the abundance and density of siliceous and ferruginous hardpans 8–12 m beneath Lake Toolibin, the timing of salinisation of nearby playas (Lakes White and Taarblin), and regolith data as a means to set pre-clearing watertable levels as baselines to model the timing of the onset and projected recovery times for salinity. Their analysis predicted the emergence of shallow watertables over the century, current watertable levels and also forecast that shallow watertables may eventually lie beneath 24% of the valley floor by the year 2100. They also used the model to forecast the time to reset the watertables to pre-clearing conditions, estimating that ~1000–2000 years would be required. Lengthy phases of drying (e.g. from 3000 years ago, Table 1) are also consistent with the measured watertable observations that groundwaters were absent in uplands before clearing and only present at depth, and as residual brines in palaeovalleys.

Finally, as Macumber (1968) found in south-eastern Australia, Mazor and George (1992) and Shand and Degens (2008) proposed that in the WA wheatbelt, groundwater salinity and pH are likely indicators of long periods of groundwater discharge and consequent oxidation and geochemical alteration. Groundwater salinity data in the Wallatin Creek catchment (McFarlane and George 1992) show the existence of a brine pool (50 000 mg/L) behind a basement ridge that is perpendicular to the flow line, the latter detected in magnetic data. The mode of occurrence and timing of dryland salinity here suggest downward reflux of solutes derived from near-surface evaporites and accumulation in the underlying brine pool, the evaporites having been relict from when the area was previously saline. Similarly, in many other examples, acid groundwaters (pH 2–3) are noted near divides, beneath playas, and more generally in palaeodrainages in the eastern wheatbelt, where discharge areas now dominate (Shand and Degens 2008). The spatial relationship between palaeo-groundwater discharge areas and present-day acid groundwater is invoked, but causality is not yet fully explained.

Comparing the extent of clearing and climate-based salinity

As noted, previous phases of widespread salinisation are marked by the extent of playas, lunettes, and related discharge landforms (Table 2). Establishing whether the modern phase of salinity is likely to be smaller, the same, or greater in magnitude than that which was due to past changes in climate, is not straightforward. To begin with, the manifested extent of salinity that has been induced by clearing has not yet been established, especially in the eastern, more arid areas where primary salinity features dominate and any secondary salinity overprint is difficult to differentiate.

However, in the higher rainfall landscapes (500–750 mm), dryland salinity is at or near equilibrium and extends towards topographic divides, having filled previously empty and structurally controlled groundwater compartments, and is now discharging vigorously as saline seeps. Some of these active seepage areas that discharge 1000 $\mathrm{mm/m^2}$ (emitting perennial and saline baseflows >10 000 mg/L) are now established at the base of lateritic escarpments. Here the flows create soil erosion and escarpments atypical of the geomorphology of the normally subdued landscape.

In the palaeodrainages and tributary valleys to the east, groundwater discharge by capillary rise occurs at diffuse flow rates of less than 20 $\mathrm{mm/m^2}$ from watertables at 1–2 m depth (George *et al*. 2004). At such low rates, extensive plains become saline due the interaction of deep and surface waters, but salt loss in streamflow is less pronounced. Here iron, silica, and aluminium concentrate in subsoils, creating 'hardpans' near palaeo watertables. Across the region, siliceous and iron-rich hardpans occur in areas of modern groundwater discharge, suggestive of a precursor relationship that predates the time of clearing. Similarly, in the sandplains of the eastern wheatbelt, groundwater silcretes exist (George 1992*c*) where perennial aquifers develop at the interface with deeply weathered soils. These silcrete pavements crop out and create escarpments on some, but not all sandplain seeps. This may be indicative of both saline discharge and excess water derived in times of higher rainfall and recharge, such that it seems possible that some seeps emerging today have no historical analogue.

Of potential relevance to the WA wheatbelt situation is widespread active silicification in shallow calcrete aquifers documented from central Australia by English (2001, 2002), a case of contemporary primary salinity rather than palimpsest duricrusts or secondary processes caused by land clearing. These silcretes are attributed to brackish, silica-saturated groundwaters from weathering granites, with precipitation of opaline and chalcedonic silica occurring in response to evaporative concentration as the flow path approaches a major discharge zone. Silicification here is contingent upon the availability of a suitable host substrate, namely karstified calcrete, because in its absence, new clay minerals are more likely to form from excess aqueous silica in more alluvial soils. Precipitation of additional calcrete (and gypsum) is curtailed because dissolved calcium supplies in the closed hydrological system have already been largely depleted in earlier saline periods (English 2001). The evidence suggests that natural high recharge rates are occurring in the present post-glacial period, a function of the favourable orographic effect of the central Australian uplands with respect to incursions of the northern monsoon (English *et al.* 2001). The region additionally contains large intermontane or piedmont mesas of Late Miocene–Early Pliocene silcrete containing fossil evidence of antecedent lacustrine limestone (English 2002). The relevance of the respective central Australian examples is that relatively high runoff and recharge rates, very high E/P ratios (~10), and high watertables are indicated for both the Late Tertiary and present-day regimes of evaporative concentration and precipitation of solutes in shallow groundwater systems. These identified key factors are likely to be the major drivers behind WA wheatbelt salinity and silcretes as well.

Timing of palaeo and modern salinity

Analogues for modern land use-induced salinisation are difficult to contrast with onset patterns and rates of climate-induced change, because the water balance and timing of the past regimes are largely unknown. However, the works of Dodson and Lu (2005) provide some comparative evidence. They suggest that the three phases of salinisation identified in the Pliocene (2.9 Ma) developed over periods of one to two centuries and lasted some 2000–3000 years.

From the clearing record, it is apparent that salinity emerges in most regions within <30–50 years, although it may take up to 200 years to develop in areas where clearing is staggered, the per cent cleared is small (<50%), or where watertables are deep. What is more difficult to determine is the time required for salinity to retreat after it has reached its new equilibrium.

Two related datasets exist from which comparisons can be made. The first relates to the timing of the last wetter episode, pre-clearing, and the rate of rise of current watertables. Prior to clearing, and in forested catchments, regolith aquifers mainly existed in the wheatbelt near large monadnocks, at the base of long flow systems, and as residual brines in palaeovalleys. Water tables were either absent or deep (20–30 m) in upland areas. Given that the last wetter episode occurred ~3000 years ago (Churchill 1968; Harrison and Dodson 1993) (Table 1), and that the event was of sufficient duration to provide excess water to recharge aquifers to modern (2000) levels, it is apparent that it would take at least 3000 years for groundwaters to retreat significantly from those levels to those observed today. That is, it would take 3000 years for groundwater levels to reset to pre-clearing conditions.

At Toolibin, George *et al.* (2004) modelled the development and retreat of aquifers in the catchment from existing drill records, the timing of salinity, and human recollections of salinisation. Their data show that groundwaters were absent in the upper valleys and some hillslopes until recently, despite the elapsed time of 30–100 years since clearing. In other areas, watertables remained deep, but were now rising at 0.2 m/year. Experimental modelling and calibration using existing watertables and trends, reveal that a new watertable maximum (equilibrium) should be established by 2100. To determine the duration required to re-set watertables to pre-clearing levels, the model was run with recharge values reduced effectively to zero, consistent with the case in a fully vegetated and drying landscape. The model projects that re-establishment of pre-clearing watertables would take of the order of 1000–3000 years. Thus, the observed onset and recovery times to salinisation reported by Dodson and Lu (2005) on the basis of palaeomagnetics and pollen data, are similar to those reconstructed by the hydrogeological modelling.

Future climate change and salinity risk

The long-term trend towards a drier landscape in response to climate change has resulted in increases in sclerophyllous and halophytic vegetation and a reduction in freshwater ecosystems. The effect on the Australian terrestrial environment of a suggested 4°C increase in sea-surface temperatures several hundred thousand years ago was enormous (Kershaw *et al.* 2003*a*, 2003*b*). Recent ENSO-induced droughts in southern Australia indicate that potential future temperature increases through enhanced greenhouse warming will exacerbate environmental problems.

Two potential extreme scenarios with respect to dominant hydrological processes in the wheatbelt are envisaged. Long-term drought conditions and reduction of effective precipitation may serve to reduce groundwater recharge and discharge, lower watertables, contract upland areas of dryland salinity, thus promoting pedogenesis and colonisation by plants of former saline areas. Alternatively, reduction of vegetation cover, dominant vegetation species, and changes to surface soil properties in response to protracted winter drought conditions, and increased frequency of summer cyclones, may promote increased runoff and recharge with consequent increases in groundwater discharge and salinisation of parts of the lower landscape.

Individual catchments are expected to behave differently between these extreme responses, reflecting: (*a*) different catchment areas relative to discharge/salt lake areas; (*b*) catchment conditions, e.g. topography, gradient, regolith type, and vegetation cover; (*c*) the timing of rainfall events (winter/summer) and resultant evaporation-precipitation ratios; (d) the duration and intensity of drought conditions; (*e*) hydrogeological properties including aquifer connectivity, the magnitude of groundwater flow paths, and groundwater lag times between recharge and discharge.

A revised model of salinisation

Bowler (1976, 1983) and Macumber (1991), among others, describe the onset of salinity in Australian landscapes in association with periods of maximum aridity. Bowler (1986) documents periods of active dune building when either: (*a*) in wetter regimes and freshwater conditions, crescentic sand-dominated dunes are formed downwind from winnowed lakeshore beaches, and (*b*) in more arid, groundwater-dominated regimes, bare playa surfaces are deflated and stripped of saline clays and gypsum, which are transported as pellets that form downwind lunettes. However, *in addition* to such responses, in Western Australia at least, it can be argued that the development of *shallow watertables and salinity* would not reach its zenith unless the water balance was at a stage when rainfall and recharge were in excess of vegetative demand.

Under these circumstances, it can be envisaged that salinity would develop during the onset of the interglacial maxima, not only at the glacial maxima. We propose that excess rainfall and recharge would be greatest at the onset of interglacial pluvials, in the lag phase as biomass increases to the extent made possible by rainfall. Under these circumstances, recharge would raise watertables, groundwater flow would proceed to geological barriers, and seepage and evaporative concentration would result in saline areas. The larger wheatbelt playas would then be brackish, fed by runoff and, after extended periods of evaporation (summer), would be saline and in a condition to host gastropods such as *Coxiella*. Salt stores and salt residence studies indicate that in all but the wetter coastal margins, sufficient salt would be entrained to result in saline discharge throughout most of the wheatbelt.

As the wetter phase developed, surface water would begin to dominate, and groundwater-derived salts would become a smaller proportion of the mass balance. However, salts washed from saline tributaries and upland seeps would sustain a salt flux into the palaeodrainages. On the waning of the interglacial, it may be argued that plant water use would adjust, and given the extreme biodiversity and sclerophyllous nature of the south-western WA vegetation, would prevent excess recharge and would either maintain watertables or cause them to decline.

At the onset of the glacial maxima, excess recharge would be rare. As in regional flow systems of the Murray Basin, groundwater flow within intermediate flow systems would maintain the salinity of playas and enable arid-zone dune building. In such areas, chenopods could colonise the palaeovalley floors when saline groundwater levels were high, and later give way to woody species as watertables fell and after vadose-zone soils became flushed of resident salts and became more nutrient-rich following initial vegetation phases. Chenopods would maintain a competitive advantage on saline parna and sodic soils left from saline phases.

Conclusions

Salt is an inherent part of the wheatbelt of Western Australia and salinisation has been an integral part of the development of soils, changing climate, and vegetation successions throughout the Cainozoic. The wheatbelt's palaeogeographical evolution is testament to the widespread and commonly intense influence of salinity across the region.

The landscape in the eastern wheatbelt contains distinctive patterns of playas and clay and sand lunettes in trunk palaeovalleys and their upland tributaries, which provide evidence of both the importance of palaeodrainage networks in controlling groundwater flow systems and a long history of enhanced episodic runoff and shallow watertables. Palaeovalleys and resident groundwaters in underlying aquifers also contain acid brines (Benison *et al.* 2007) as a result of the combination of long phases of aridity, fluctuating watertables, and geochemical characteristics. In the western wheatbelt, comparable playas, in association with *Coxiella*-impregnated sand lunettes, and groundwater-derived escarpments, also tell of ancient phases of salinity.

Modern salinity appears to be reoccupying landscapes made saline by previous changes in climate. The advance of watertables and salinity into areas containing stranded playas is salutary evidence of persistent processes. Similarly, evidence from the condition of the wheatbelt palaeodrainages at the time of clearing, coupled with modelling and the distribution and disposition of palaeogeographic markers, suggest that salinity arrives quickly, but takes thousands of years to retreat, in both primary and secondary salinity scenarios. The question as to whether salinity induced by recent clearing is likely to affect a greater area of land than that caused by climate change in prior millennia, remains unanswered, because comparative evidence is still un-assessed. Notwithstanding, given the recurring pattern and mode of occurrence of currently active saline seeps, greater expansion of saline lands in the immediate future seems likely.

Finally, we suggest that in addition to previous studies which describe salinisation as a process of the glacial maxima, salinisation in south-western Australia also occurs during interglacial periods, especially when vegetation establishment lags behind the onset of more wetter phases. Salinisation thus has the potential to occur in any part in the glacial-interglacial climatic cycle when and where vegetation cover diminishes and groundwater recharge at specific locations in the landscape crosses critical thresholds.

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