Plant and Soil **257:** 341–356, 2003.

Preclearing hydrology of the Western Australia wheatbelt: Target for the future?

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Received 31 January 2002. Accepted in revised form 2 January 2003

Key words: Australia, clearing, hydrology, salinity

Abstract

The wheatbelt of Western Australia largely corresponds to a zone of ancient drainage, characterised by highly variable rainfall, long dry summers, low hydraulic gradients, intermittent surface flows and high regolith salt loads. The accumulation and distribution of salt, the rudimentary aquifers with deep watertables, the intermittent flooding and subsequent transpiration of water from the valley sediments, and the low yields of water reaching the ocean were a product of the underlying physical environment and vegetation types capable of using deeply infiltrated water through the dry season. The hydrological and hydrogeochemical changes induced by widespread clearing of this vegetation for dryland agriculture are profound and enduring. Run-off onto and through the valley floors has increased by a factor of five; combined with local rainfall on these valley floors, the resulting increase in groundwater recharge is filling the deep sedimentary materials and bringing highly saline water to the surface. Diffuse recharge has also increased on the slopes and ridges, with saline watertables rising in these lateritic formations as well, providing additional hydraulic heads forcing groundwater towards the valleys. The resulting increase in the groundwater discharge areas is projected to greatly increase flooding risk downstream into the future. A variety of natural, built and agricultural assets are either already impacted or at risk to these phenomena. It is hypothesised that restoring the original hydraulic and hydrological functions of the system will lead to its recovery. This raises several issues: can we design remedies in terms of restoring the original rates of flux (recharge, runoff, etc) or in terms of the original balances (recharge less than aquifer discharge, input of salt into the root zone equal to output)? Secondly, to what degree can revegetation or engineering now restore these original conditions? Finally, we examine the potential for the landscape to recover to its original hydrological and hydrogeochemical state once salinised. Given the advanced state of saline watertable development, with its implications for successful revegetation and restoration of valley transpiration, the changes in soil structure and chemistry, and the immediate implications to valued assets, we posit that an aim of restoring the landscape solely with revegetation, either in terms of rates or balances, is not feasible or even possible. To a degree, one can only restore certain aspects of the original balance via revegetation combined with discharge enhancement and flood mitigation.

Introduction

The profound and enduring environmental changes wrought as a result of widespread land clearing for agriculture in Australia are due, in large part, to changes in underlying hydrological and hydrogeological processes on a grand scale in space and time. These processes include rising groundwater levels, increased waterlogging and flooding, and salinisation. Concern over current and future impacts is driving Australian society to attempt to restore the landscape towards its original condition and function. Several questions immediately follow from this aspiration. What was the original land condition, and how did this condition translate to the aboriginal hydrology and hydrogeology? What are the nature, trend and ultimate equi-

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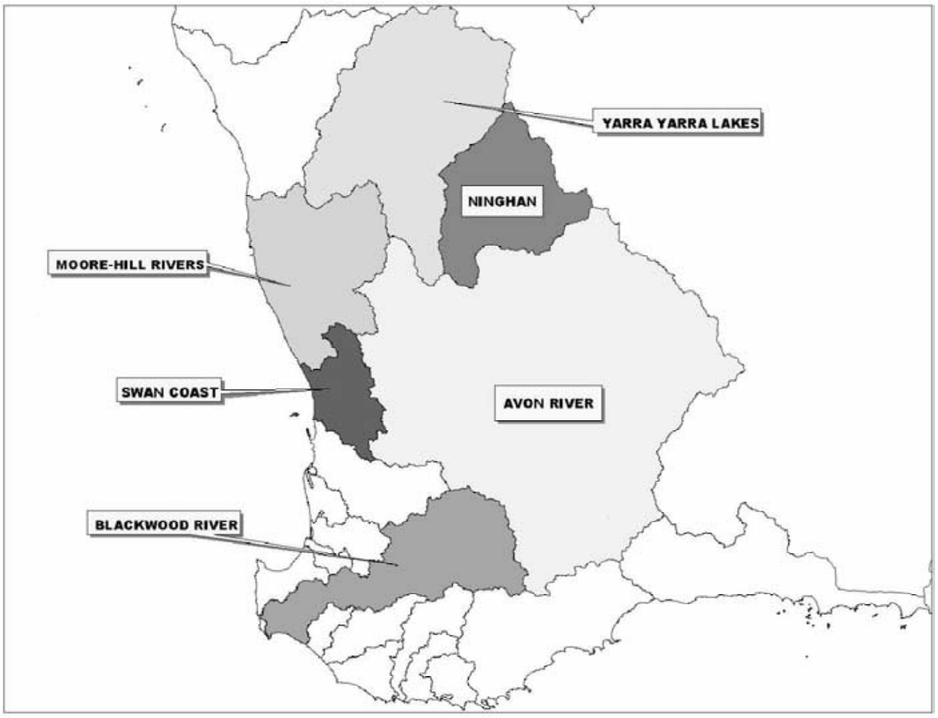

Figure 1. Drainage Basins of Western Australia strongly influenced by the surface hydrology of wheatbelt valleys. The Avon drains through to the Swan. The Ninghan basin potentially drains into the Yarra Yarra, which potentially flows through to the Moore River.

librium in hydrological processes induced by historic clearing and modern agriculture? Most importantly, what changes in the current hydrology are required to recover this landscape from salinisation, and to what degree can revegetation with new farming and silvicultural systems functionally more similar to the original land cover, or engineering, recreate aboriginal hydrology, and in what timeframe?

In this paper, the preclearing hydrology of southwestern Australia is recapitulated, with particular emphasis on the relationships amongst climate, vegetation, the landscape salt balance, groundwater and surface hydrology. While the impacts of agricultural clearing through salinisation extend across the continent, they are particularly severe and extensive in the wheatbelt of southwest Western Australia, where over 1.8 million hectares is currently salt-affected (Anon, 1996) with up to 8.8 million hectares (33%) at risk by 2050. Associated with this risk is up to 1.8 million hectares of remnant vegetation, 80,000 hectares of important wetlands, 2665 k of highway and main roads, 22 930 k of minor roads, 2180 km of rail, and 29 townsites at risk of salinisation (National Land and Water Resources Audit 2000). Some 450 plant species are subject to extinction as a result (Keighery et al., 2001). Finally, all of the significant river systems in this region are in an advanced state of salinisation (Hatton and Ruprecht, 2001), with an associated elevated risk of extreme flooding (Bowman and Ruprecht, 2000). To a large degree, the generalities regarding preclearing and post clearing hydrology will extend across southern Australia (cf. Hatton and Nulsen, 1999), but in fact the river systems of this region are quite distinctive and extrapolation eastwards is problematic.

We first examine the underlying geology, landforms and climate of the region, then reconstruct how water and salt originally moved through the ecosystems of southwestern Australia, followed by how these processes have changed with the development of agriculture. Finally, we look at the degree to which the original hydrological functions might be restored with revegetation or functionally equivalent farming or agroforestry systems or engineering, and the feasibility of doing so.

Physical setting

The region under consideration drains large portions of the South West Drainage Division of Western Australia (Mulcahy and Bettenay, 1972), and comprises the drainage basins of the Swan-Avon River, the Moore-Hill Rivers / Yarra-Yarra / Ninghan system (also known as the Monger System, *sensu* Beard, 1999), and the Blackwood River (Figure 1). Drainage Basins with some similarities to these also include Frankland-Gordon River, Kent River, upper Pallinup, Gairdner, Fitzgerald, Lort and Young rivers.

The best and most recent treatments of the evolution of these rivers are given by Salama (1994, 1997) and Beard (1999). The first distinctive feature of these rivers is that mean annual rainfall (900–1200 mm) is highest at or near their outlets to the sea, and lowest (less than 350 mm) in their uppermost headwaters. The second distinction is the fact that their headwaters start in an older landscape with remarkably low gradients, and the rivers do not steepen until they approach the younger parts of the system in the vicinity of the Meckering Line. The Lockhart - Pingrup River for instance, falls 51 m over 200 km (0.26 m km^{-1}) from Lake Chinocup (near Pingrup) to the Caroline Gap; the Yilgarn River to the Avon River at Toodyay falls 345 m over 420 km (0.82 m km^{-1}), and then falls 140 m over only 90 km (1.55 m km^{-1}) from Toodyay to the coast at Fremantle (Beard, 1999). Salama (1997) and Beard (1999) estimated mean grades of 0.35 m km^{-1} and 0.38 m km^{-1}, respectively, for the Yilgarn River from head of channel to the confluence with the Avon. A key feature of this grade, however, is that it is interrupted by large, essentially flat playas that drop water from one to another when they overflow. Grades along the Lockhart and Pingrup rivers, the southern tributaries of Salt River, are very low, and from this Beard (1999) concluded that significant discharges are unlikely except in extreme rainfall events. Unlike the valleys of most rivers worldwide, which usually broaden downstream, the valley of the Avon is wide near its source (77 km) and narrows to 5 km or less after Toodyay. These broad shallow valleys of the upper Avon and other rivers are characteristic of the wheatbelt landscape.

The flatness of the bulk of the wheatbelt river systems has led to historic, and amusing, arguments regarding catchment boundaries, the putative connections between systems, and even which way water flows. It is essential to appreciate that these river systems do not all flow as one linked system except in the most extreme events. In the Blackwood catchment, the Coblinine River and Dongolocking Creek are two headwater streams draining to Lake Dumbleyung. This section of the river has very low grades, approximately 0.17 m km^{-1}. The combined drainage enters Lake Dumbleyung, which is a permanent salt lake that is said to have been dry before land clearing (Beard, 1999). Since clearing, Lake Dumbleyung is thought to have overflowed into the Lower Blackwood only three times since the 1870s. The chains of (mostly dry) lakes form a series of local storages that in most years are not overtopped by the surface flows from upstream.

Commander (2001) reviewed the geological history and background to the evolution of the wheatbelt landscape, and George and Coleman (2001) provided a description of the hydrogeology with special reference to regolith salinity. Several aspects of the wheatbelt landscape must be understood to fully appreciate the fundaments of hydrology as it existed at the time of European settlement. The first and most important of these is that Australia's geology has been relatively stable over the past 60 million years; in some cases, what uplifting has occurred has actually restricted drainage. Little renewal of surface material means that soils are old and nutritionally poor, profiles are deeply weathered, and geomorphological units result from differential erosion of an ancient surface (McArthur, 1993). This geological history resulted in the flattest continent on earth, with generally low hydraulic gradients and transmissivities. Water and solutes generally cannot move quickly through the Australian landscape as surface water or groundwater.

The seasonality in climate in the southwestern part of the continent tends toward a Mediterranean distribution of rainfall, ranging between 250 and 800 mm annually. Summer rainfall does occur from northwest cloud bands and less frequently from tropical depressions. The summer events are typically the most extreme rainfall events. Mean potential evaporation exceeds rainfall in most months and in all months in the lower rainfall zones. The potential evaporation gradient is the reverse of the rainfall, with 800–1200 mm mean annual evaporation near the coast and over 2000 mm in the most inland parts of the catchments. This general aridity and lack of predictability has major implications for the evolutionary adaptation of Australian biota and the productivity of Australian ecosystems.

In the extensive upland areas, the deeply weathered regolith typically encompasses several, often interacting, aquifers including a shallow, seasonal perched system, a local semi-confined aquifer, and often a deeper, confined regional system (George and Conacher, 1993a,b; George et al., 1994; MacFarlane et al., 1993; Salama et al., 1993a,b). In the native state, these latter systems may be only rudimentary and normally water tables, if present, are quite deep (Salama et al., 1993a). The overlying unsaturated zone typically contains a large amount of accumulated salt of largely atmospheric origin. These catchments receive approximately 0010 – 0.017 kg/m^2/yr salt via atmospheric deposition near the coast, reducing to about 0.002 kg/m^2/yr at their eastern edge (Hingston and Galaitis, 1976). It is probable that the catchments in the wheatbelt were accumulating salt prior to clearing. Salt tends to be stored below the major rooting zone of the native vegetation; this salt is largely immobile prior to land clearance. The original groundwater table was generally quite deep ($>$30 m) if present at all, with very low rates of recharge and associated build-up of salt in a thick overlying unsaturated zone.

The wheatbelt catchments were essentially completely vegetated by a diverse range of woody plant communities whose distribution was controlled by climate and soil type (Beard, 1981). In response to the above geological and climatic conditions, the native vegetation is adapted in a number of ways that distinguish its ecohydrology. By far the most distinctive characteristic is sclerophylly. The other aspect that characterises the vegetation is that it is generally dominated by a perennial, evergreen, woody component, ranging from shrublands and heaths to woodland and forest. Understorey vegetation normally consists of grasses and shrubs, but in the drier areas can be largely bare ground for most of the year. Specht (1972) showed that the leaf area index of a wide range of Australian sclerophyll communities have a similar relationship to an index of evaporation and rainfall. Pook (1985) and Hatton and Wu (1995) showed that Australian sclerophyllous plant communities vary their leaf area index with the changing availability of water over long wet-dry cycles. There is, in general, ecohydrological equilibrium between leaf area index and climate (*sensu* Eagleson, 1982) in southern Australian ecosystems (Ellis et al., 2001).

The aerial architecture of the overstorey canopy is effective at capturing rain and directing it down the stem to infiltrate around the bole. Nulsen et al. (1986) showed that the infiltrating water percolated to considerable depth down the annular pathway around the roots. Thus the water is stored at depth and is available during the dry period. Removal of the stems deactivates this mechanism and dramatically changes the hydrology on a micro scale.

In the natural state, the hydrological cycle of the agricultural areas of southern Australia has the following functional generalities resulting from the combination of the above attributes:

1. Virtually all of annual rainfall is evaporated or transpired;
2. The vast majority of rainfall reaching the soil infiltrates locally, and thus surface run-off to streams and valleys is usually small, fresh and generally episodic in nature (McFarlane et al., 1993; Nulsen et al., 1986). However, occasional intense summer storms or prolonged winter events generated more extensive flooding (George and Conacher, 1993a);
3. Water use by native vegetation is somewhat low in winter, when water is quite plentiful, with much more physiological activity toward summer (Farrington et al., 1992);
4. Net groundwater recharge to the semi-confined and confined systems is a very small proportion of rainfall, usually less than 1 mm yr^{-1} except in the higher rainfall areas (George, 1992a; Johnston, 1987; Nulsen et al., 1986; Peck et al., 1981; Salama et al., 1993a);
5. What little groundwater discharge and run-off that is generated supports limited areas of riparian vegetation on valley floors, which are able to switch their source of plant water from local rainfall to groundwater over the dry season (Salama and Bartle, 1995);
6. In some cases, there is sufficient groundwater discharge to form natural saline surface features, but alluvial systems were often fresh at the surface (Farrington and Salama, 1996);
7. There is generally little or no natural base flow of rivers in streams originating in the agricultural zone ($<$600 mm annual rainfall).

In short, the water use patterns of the native vegetation of southern Australia resulted in systems in which very little rainfall was discharged in liquid form. As one consequence, atmospherically deposited salts built up over millennia in the unsaturated zone at some depth near the root zone. The exchange of water between the soil and the atmosphere can be characterised as mostly *vertical*, with the rain that falls on a given piece of ground evaporated from that same surface. Surface water flows were occasional, tended to infiltrate into relatively fresh, deep, unsaturated val-

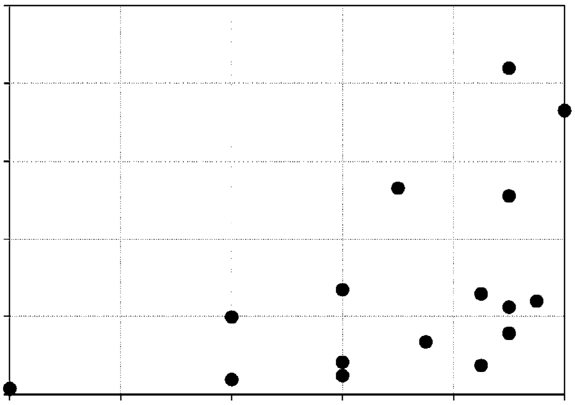

Figure 2. Mean annual run-off for wheatbelt rivers (mean annual rainfall < 460 mm) as a function of clearing. Data from Water and Rivers Commission.

ley floor sediments and later locally discharged by transpiring valley floor vegetation.

From aboriginal to postclearing hydrology

The hydrological impacts of land clearance for agriculture in southwestern Australia were documented and reviewed in detail by a number of authors (Farrington and Salmam, 1996; McFarlane et al., 1993; Nulsen, 1993; Peck and Hurle, 1973; Schofield, 1990; Williamson and Bettenay, 1979). These impacts result from the replacement of the native sclerophyll vegetation with annual crops and pastures over vast areas, largely last century. Some of these impacts were recognised early on (e.g., Bleazby, 1917; Teakle and Burvill, 1938; Wood, 1924), but with little influence on land policy. About 65% of the Avon catchment was cleared for agriculture, mostly between 1940 and 1970. However, many catchments in the upper Avon and Blackwood rivers having cleared proportions ranging from 85 to 95% (Hatton and Ruprecht, 2001).

The pattern of water use in these agricultural systems varies dramatically from that of the original vegetation. The cool-season annual crops and pastures are active during the wet winter and early spring period, and senesce thereafter. Some perennial pasture systems such as lucerne (alfalfa) persist longer into the summer. During the growing season, the leaf area index of these systems can exceed that of the native vegetation. Physiological activity (growth) during this season is not accompanied by particularly high rates of evaporation, for atmospheric demand is quite low, but again can exceed that of the native systems. McFarlane et al. (1993) asserted that annual crops evaporate more water than annual pastures; this was demonstrated by Nulsen and Baxter (1986) and Farrington et al. (1992). In either case, however, annual evaporation falls significantly short of that under native vegetation (Farrington et al., 1992; Greenwood and Beresford 1982; Greenwood et al., 1985).

Other aspects of the hydrological cycle can change in addition to the seasonality and amount of evaporation. Tillage and grazing can have a direct impact on the hydraulic properties of soils, while soil erosion has obvious and dramatic impacts on fertility, structure and water-holding capacity. Land degradation issues such as soil acidification, soil structural decline and waterlogging have strong impacts on the hydrological cycle, and contribute to more regional-scale phenomena such as salinisation and streamflow (Flavell et al., 1987; Nulsen, 1993; Nulsen et al., 1986; Williams and Bettenay, 1979).

A major consequence of agricultural clearing is a dramatic increase in diffuse and localised groundwater recharge; two orders of magnitude increases are typical (George, 1992a; Peck and Hurle, 1973; Salama et al., 1993a). The principal change to the water balance is the reduced annual evaporation and interception in the agricultural catchment and increased runoff and recharge. Interestingly, McFarlane et al. (1992) reported lower infiltration rates in four uncleared wheatbelt soils with an undisturbed surface crust compared with nearby cleared soils. They surmised that an organic crust caused local redistribution of surface water within uncleared areas. In addition, water repellency was reduced in a gravelly soil after clearing. Sharma et al. (1997) in jarrah forest soils found the impact of clearing for pasture led to a reduction in surface saturated hydraulic conductivities by an order of magnitude.

Median annual streamflow for many of the smaller catchments in the wheatbelt would have been close to zero prior to clearing. For the Avon, the annual average streamflow prior to clearing was estimated to be 18% of the current water yield, approximately consistent with experimental results in Ruprecht and Schofield (1991) (Figure 2). This increase in run-off onto the valley floors and into the playas provides significantly enhanced localised recharge into the valley sediments (Salama and Bartle, 1995).

The local-scale hydrological characteristics of conventional agricultural systems in southern Australia can be summarised as follows:

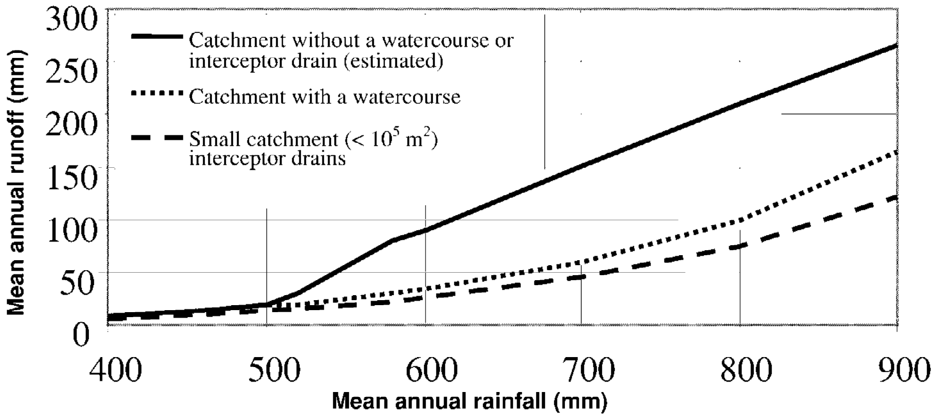

Figure 3. Runoff as a function of rainfall for cleared catchments with a defined watercourse (adapted from McFarlane et al., 1995).

Table 1. Comparison of hydrology statistics for Avon River tributaries

Station Np	River	Area (km^2)	Mean annual rainfall (mm)	Clearing (%)	Mean annual flow m^3	Median annual flow m^3	Mean annual runoff (mm)	CV$^{(1)}$
615012	Lockhart River	32 000	350	85	7900 000	1960 000	0.24	1.7
615015	Yilgarn River	56 000	300	50	6500 000	890 000	0.12	2.1
615022	Yenyenning	92 000	340	70	12 980 000	87 000	0.1	1.4

^{1}Coefficient of variation in mean annual runoff.

1. A dominance of physiological activity and evaporation during the wet (winter–spring) season;
2. Soil moisture surplus during the growing season;
3. Enhanced groundwater recharge and rising groundwater tables;
4. The development of perched and/or active near-surface aquifer systems, and the activation of deeper aquifers and the mobilisation of stored salts;
5. The increased discharge of water and salt to streams.

In describing the hydrological impacts induced by the clearing of the wheatbelt catchments, it is important to emphasise that their hydrology is characterised by *high variability* and *nonstationarity*. The rivers of this region have higher variability of streamflow than others worldwide (McMahon et al., 1992), indicating a usually unpredictable climate from year to year and season to season (Table 1).

The smaller rivers may not flow for many years, and then either a major summer event or a wet winter will lead to flow events. The larger rivers cease flowing in the wheatbelt regions during summer, except when extreme tropical cyclonic events or severe thunderstorm activity lead to heavy, intense summer rainfall. In 'normal' years, winter rainfall is not enough to move water continuously through the catchment from the extreme eastern and southern boundaries to the coast.

The other key feature of the hydrology, *nonstationarity*, refers to the fact that the underlying hydrological processes in these systems are still undergoing profound but subtle changes as a result of historic clearing. These changes include increasing run-off source areas due to rising regional groundwater, soil acidification, and decadal climate variability. In the longer term, climate change may lead to decreased winter rainfall, increased summer rainfall and possibly more extreme events.

Very low run-off is observed from the first order eastern wheatbelt catchments, ranging from 5% down to less than 1% (recognising that this may be a 5-fold increase over preclearing runoff, nevertheless). There is a clear increase in runoff with increased level of clearing within the catchment (Figure 2). Mean annual run-off for small agricultural catchments increases

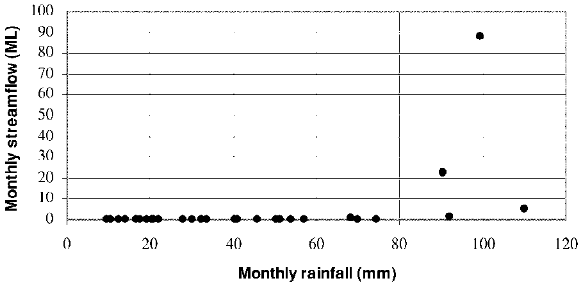

Figure 4. Monthly streamflow compared with monthly rainfall for Lake King catchment Note that the rainfall required for significant runoff is over 80 mm. Data from Water and Rivers Commission.

slightly with a defined watercourse (Figure 3), and significantly with both a defined watercourse and interceptor drains; Salama et al. (1992) stated that prior to clearing there were no defined creek lines in most of the areas where well developed streams now exist. These recently developed streams were originally low-lying depressions covered by native vegetation whose transpiration kept groundwaters deep. After clearing, the additional run-off eroded the clay cover on the stream base and exposed more permeable material. This resulted in increased localised groundwater recharge and eventually increased saline discharge into the stream as groundwater levels reached the surface (Salama and Bartle, 1995).

Some generalities of the present hydrological state can be made. In typical years, winter run-off is generated by a combination of shallow aquifer throughflow, saturation excess rainfall (particularly in the wetter regions near the coast) and some infiltration excess generation due to non-wetting soils and from soils with low hydraulic conductivity in cleared country. For instance, George and Conacher (1993a,b) found that 37% of streamflow arose from saturation-excess overland flow, and 52% was from throughflow. These same authors found that saturation-excess overland flow occurred, but with a much reduced variable source area and a longer lag following rain. They also report infiltration excess overland flow due to soil compaction and hydrophobicity (up to 70% of summer streamflow). Summer run-off can be generated by intense cyclonic events and is then dominated by infiltration excess processes. Much of the run-off that enters into the main channels is generated by rainfall directly on the valley floors themselves.

Infiltration-excess overland flow is considered an important mechanism in fine-textured soils, surface-sealing soils, non-wetting soils and surface-compacted soils (McFarlane and Davies, 1988). Saturation-excess overland flow is considered more important in duplex soils, soils in groundwater discharge areas, and fine-textured soils in valley flats (McFarlane and Davies, 1988).

The amount of rainfall required to initiate run-off in the low-rainfall wheatbelt catchments can be relatively high as shown in Figure 4. The Lake King catchment (86 km^2, 95% cleared, and mean annual rainfall of 320 mm) experiences many years of no flow, interspersed with either extreme summer events or a wet winter.

The rivers of the wheatbelt show variable source areas at both a small sub-catchment scale and at the larger river catchment scale. At the small sub-catchment scale, the variable source is related to the saturation of the valley floor. The larger scale variation in sources and amounts of runoff relates to the capacities and connections of the lake systems common in the wheatbelt.

It is not known exactly how much of the land area was affected by primary salinity (salinity existing prior to clearing), but it was likely less than 1%. The region currently has a salinised area of some 11%, and it is expected to increase to over 30% at groundwater recharge-discharge equilibrium (Ferdowsian et al., 1996). Many ephemeral freshwater lakes have salinised as a result, and run-off is now increasingly saline. For the Avon River system, while there can be much redistribution of salt within the upper reaches, most of the salt that reaches the ocean outlet in most years is sourced from between Yenyenning Lakes and Northam, and from the North Mortlock River (Viney and Sivapalan, 2001). Sources to the east and south of these contribute only in extreme flooding events when the internal storages overflow (Pen, 1999).

The combination of variations due to rainfall (and its spatial distribution) and the internal storage or overflow of run-off leads to high variability in stream salinity from year to year (Figure 5). This can make the estimation of trends, and the detection and evaluation of mitigation efforts, difficult. However, it is clear that the mean annual salinity in the Blackwood River has risen from less than 2000 mg L^{-1} to greater than 4000 mg L^{-1} over the last 40 years. The seasonal variability in salinity is also high, but salinity remains above saline ($>$ 5000 mg L^{-1}) as shown in Figure 6 for the Coblinine River in the upper Blackwood River. There is usually increased stream salinity in the early winter flows, followed by a significant freshening (to 2500 mg L^{-1}) and then a recession to a higher salinity. The average annual load export from the Avon River is

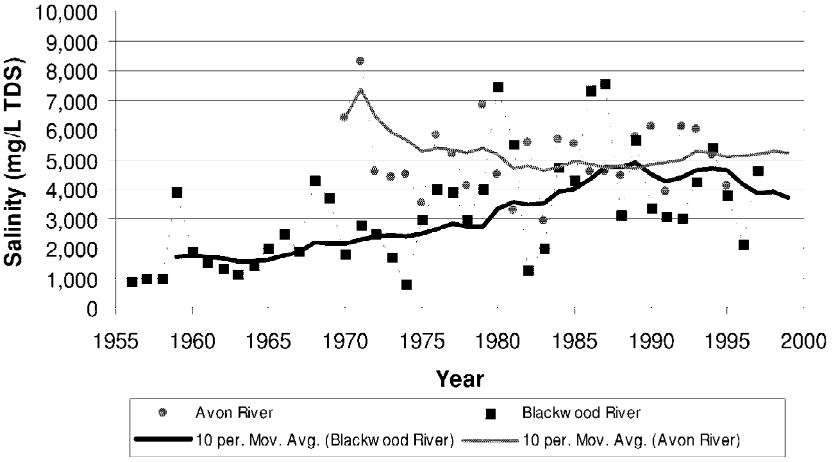

Figure 5. Flow-weighted annual stream salinity for the Blackwood (mostly cleared), and Avon rivers. The five-year moving mean trend is shown. Note the huge variation in salinity in the Blackwood River at Darradup. Avon data are from gauge at Walyunga. All data from Water and Rivers Commission.

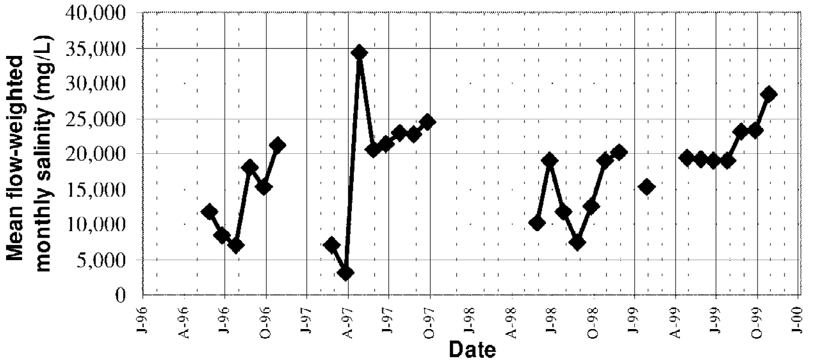

Figure 6. Flow-weighted monthly stream salinity for the Coblinine River, tributary of the Blackwood (mostly cleared). Data from Water and Rivers Commission.

2160 kt, compared to 1040 kt for the Blackwood River (Table 2).

The delivery mechanisms for salt into streams vary. At a local scale, they can include shallow throughflow delivery (even when the ultimate origin of the salts is the deeper aquifer), and early wet season wash-off (George and Conacher, 1993b). At a regional scale, the occasional overflow of the major ephemeral lakes due to extreme rainfall events pulses salt already in the channel systems further downstream.

The ratio of the salt outputs to inputs (O/I) is an important indicator of catchment salinity status. Prior to clearing of native vegetation, the catchments would have been accumulating salt with an O/I ratio of close to zero. After clearing the large fluxes of water resulting from increased recharge and runoff increases groundwater discharge and as such increased salt load, leading to a salt O/I of greater than one. Smaller catchments within the Avon system have very high salt output to input ratios, such as Mooranoppin Creek with an O/I of 39 and Dale River with an O/I of 28.

Based on the very high baseflow salinities as an indicator of salt storage for both the Lockhart and Yilgarn rivers, the leaching times or the time before most of the salt is leached from the catchment is of the order of 100 000 years. For catchments with lower salt storage and higher salt export, the expected leaching times are much less. For instance, Hookey (1987) and Salama et al. (1993a) estimated it would take a few hundred years for two first-order catchments to come into equilibrium with atmospheric salt inputs.

Much of what is characterised in terms of the sources and fluxes of water and salt out of wheatbelt catchments changes dramatically when large portions

Table 2. Summary salinity statistics for gauged rivers with significant wheatbelt catchment

River	Area (km^2)	Clearing (%)	Salinity$^{(1)}$ (mg/L)	Salt Load$^{(2)}$ (kT)	O/I$^{(3)}$
Lockhart River	32 377	85	29 700	377	6
Yilgarn River	55 921	85	20 500	214	2
Avon River	119 000	65	5200	2160	10
Blackwood River	17 600	90	3700	1043	30
Lort River	2800	60	23 700	109	9
Pallinup River	3600	85	15 600	493	30

(1) Mean annual flow weighted salinity TDS mg/L explain TDS – I prefer mg L^{-1}.
(2) Mean annual salt load TDS.
(3) Mean annual O/I, where O/I denotes salt load export from catchment divided by salt input from rainfall.

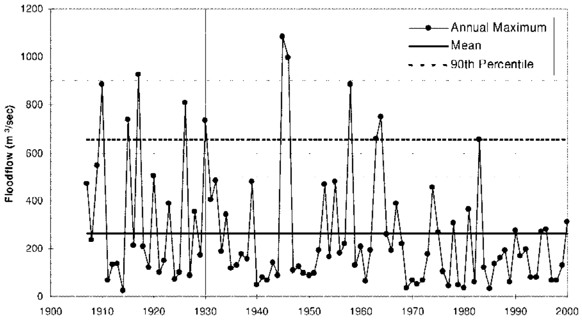

Figure 7. Annual floodflow for the Avon (at Walyunga), incorporating modelled floodflows from 1910 to 1969 and gauged data from 1970 onwards. Note the lack of floodflows above the 90th percentile in recent years. The 2000 event was only just above the mean annual flood, but was a significant summer event. Data from Water and Rivers Commission.

of these catchments are subject to extreme rainfall events, typically associated with tropical cyclones. Major flooding events of this type happened in parts of this region in 1926, 1930, 1945–46, 1958, 1963–64, 1974, and 2000. The annual floodflow in the Avon is presented in Figure 7.

The wheatbelt valleys east of the Meckering Line (Mulcahy, 1967) commonly consist of chains of saline lakes and braided channels, bordered by floodplains 2 – 3 km wide. These old valley forms are susceptible to flooding and waterlogging. However, these valleys as part of rivers, such as the Lockhart and Yilgarn river systems, have major flood storage that leads to major discontinuities in these watercourses. These lake systems, such as on the Lockhart and Yilgarn rivers, do not connect unless a major summer rainfall event or a prolonged and wet winter occurs. It is only then that the sediments separating the lakes are breached to connect the river system. However, there are some parts of the Lockhart and Yilgarn river systems that appear to have a very low probability of connecting. These areas such as downstream of Job's Lake (near Beacon) and the Lake Ace – King system in the lower Yilgarn River system would be highly unlikely to have been breached in living memory. It is only with the changing land use that there is potential for these river systems to connect as a continuous waterway.

Following significant rainfall in the Avon River catchment on 21–22 January 2000 (remnants of Cyclone Steve), high river levels were experienced from Lake King to Perth. The rainfall was in excess of 100 mm in a large area from east of Hyden to Beverley, with the highest reading being 172 mm east of Corrigin. Much of the mainstream Avon River upstream of Northam and the Salt River upstream of Yenyenning had flows in excess of 150 m^3 s^{-1} and below Northam in excess of 200 m^3 s^{-1}. Peak flow in the Swan River at the Great Northern Highway was 312 m^3 s^{-1}. The flood had an overall average recurrence interval (ARI) of 1 in 8 years (using all records since 1970), and an average recurrence interval of 1 in 20 years for summer events. Incorporating longer-term (modelled) rainfall data, the 2000 flood event for the Avon River was less than a 1-in-5 year ARI. Devastating floods occurred along the Swan/Avon in 1862 and 1872, which are not included in this analysis.

The volume of water reaching the Swan River during the event was 2.70×10^{11}GL (the approximate Swan-Canning estuary volume is 0.5×10^{11}GL). Downstream tributaries of the Swan River like Ellen Brook and the Canning River had contributed almost nothing. The Avon River carried 1200 kT of salt, 800 T of nitrogen and 35 T of phosphorus from 23 January 2000 to 1 March 2000. The flow-weighted salinity in the Avon at Walyunga averaged 4500 mg L^{-1} TDS, total nitrogen 3.0 mg L^{-1} and total phosphorus

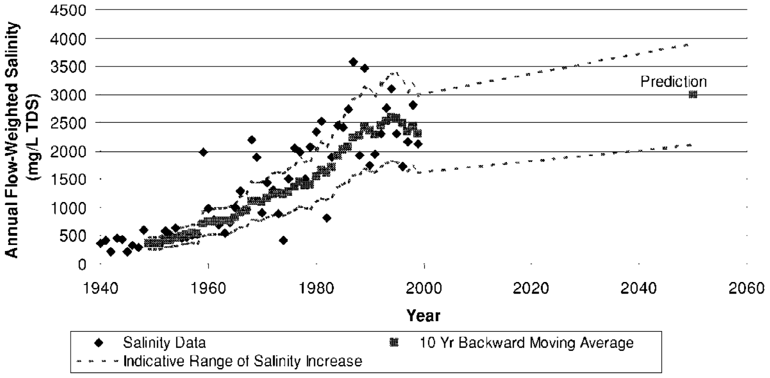

Figure 8. Salinity trend and prediction for Blackwood River at Darradup (adapted from Bowman and Ruprecht, 1999).

0.12 mg L^{-1}. The salinity of the Swan River at the Narrows Bridge *reduced* from its normal 24 000 mg L^{-1} TDS prior to the event to 4400 mg L^{-1} at peak flow. Note that the salt load over these five weeks was almost equivalent to the mean annual load in normal years estimated by Viney and Sivapalan (2001), and that it occurred in the 'dry' season.

This event was the first time that the Lockhart subcatchment had flowed significantly in summer for 40 years; even during winter, this system does not usually generate any flow that reaches the Avon. The consequences to the Swan-Canning estuary of this event were profound. High levels of nutrients, seven times the limit considered healthy for estuaries, combined with warm summer temperatures and a freshened estuary provided an ideal condition for algal growth. It is now believed that a strain of *Mycrocystis auriginosa* originating from stagnant pools of the Avon inoculated what became a catastrophic toxic algal bloom that closed the Swan River to the public for 12 days.

This event is significant in the present context in that the normal, average sources and fluxes into the Swan were overridden by material whose source was more from the upper catchment than usual, with magnitudes far in excess of normal loads as well as being rare. Tropical cyclones are expected in summer, however they do not occur frequently. In such events, the system operates more as a typical catchment from elsewhere in the world. Such flooding events belie the common perception that the health of the Swan is largely disconnected from the processes in the Avon.

Examples of flooding in wheatbelt areas include flooding in the Belka Valley (1963), Merredin (1978, 1979), and eastern wheatbelt (1978). In 1963, flood waters over 2 km wide spread out over the lower parts of the Belka Valley, 30 km east of Bruce Rock. About 1000 km^2 of the 1700 km^2 catchment was considered to be at risk from flooding. Further flooding occurred in 1968 and 1978, when heavy rains in the lower parts of the valley washed away 48 km of levees.

The Merredin townsite experienced major flooding in 1978 and 1979. These floods caused extensive damage to Merredin and led to the evaluation of a number of flood mitigation options. The flood mitigation options included retarding basins, diversions and absorption banks. A diversion bank was eventually constructed along the northern town boundary to divert flow past the town.

Following a wet January and February in 1978, widespread flooding occurred when thunderstorms occurred in late February in the area between Kellerberrin, Mukinbudin, Southern Cross, and Hyden. There has also been flooding experienced at Merredin (1978, 1979), Quairading (1983), Katanning, and Narembeen (1978, 2000).

Trends in salinity and salt load, flooding

It is difficult to project the future salt loads and salinities of these rivers. Based on historic trends since clearing, it is likely that they have not yet peaked in either of these quantities. Given the fact that groundwater levels are generally still rising in the majority of the cleared country, and areas with high water tables are expected to treble in area, one can expect increased salt loads and salinities (Macpherson and Peck, 1987; Salama and Bartle, 1995). Our technical capacity to quantify these forecasts is quite limited. Predictions for the Blackwood River indicate that further rises in salinity are possible (Figure 8). However, there is significant uncertainty relating to the potential for Lake Dumbleyung to more regularly overflow and

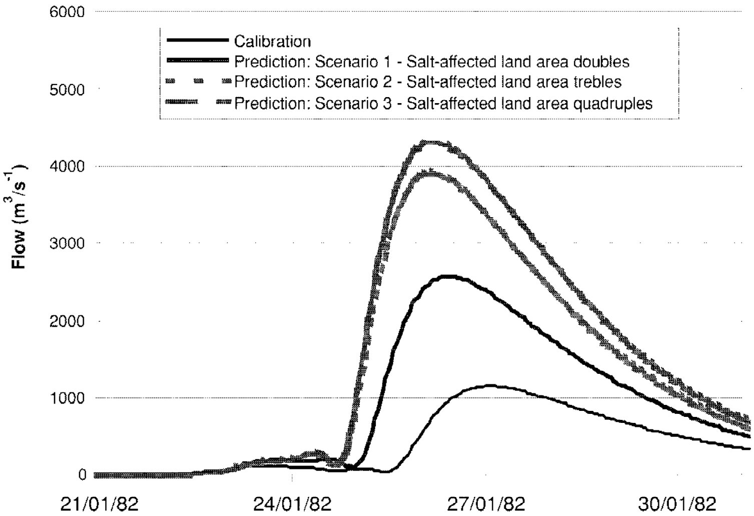

Figure 9. Predicted peak flows of the Blackwood River at Darradup with rainfall as recorded in January 1982 (Cyclone Bruno), under expanding source areas associated with rising regional watertables. The lower curve is the calibrated event as it happened under prevailing levels of groundwater discharge areas in 1982. That flood event had major impacts along the lower Blackwood to towns like Nannup. The three higher curves represent what may happen if groundwater discharge areas double, treble or quadruple.

contribute significant salt load to the lower Blackwood River.

George and Conacher (1993b) foreshadowed concerns over the long-term trends in flood risk due to the expanding groundwater discharge areas associated with valley salinisation. Bowman and Ruprecht (2000) developed a conceptual approach to the impact of land use change on flood risk, applied this conceptual model to a flood prediction model, and forecast the likely increase in peak flows in the Blackwood River under scenarios of increasing salinisation (Figure 9). Whilst this approach needs to be confirmed, these projections have profound implications to infrastructure risk and human safety along these rivers. These flood risks are not unique to the Blackwood River. The potential increased flood risk to towns like York, Beverley and Northam on the Avon is also significant. This could lead to significant increases in flood risk in areas within Perth, such as Bayswater, Bassendean and Guildford.

The future

In any debate about wheatbelt catchment management, it is crucial that an objective picture regarding the future of the rivers be painted and understood by everyone. The rivers do not look like they once did, *and they will continue to change*. The decisions we take must be considered in the context of the future state of these systems if we do nothing, not against the background of how they used to look or how they look now. Our technical ability to paint this picture is limited but must be developed. As for what options are open to significantly improve the state of the wheatbelt catchments, it is useful to distinguish amongst the goals of reducing flooding, reducing inundation and waterlogging, and reducing salinity.

The options for flood mitigation include revegetation of the variable source areas, i.e. saline discharge areas, increasing the storages along the chains of lakes, or widespread revegetation with trees. These options are not mutually exclusive, but the impediments to adoption of the latter are widely recognised. Davies et al. (1988) examined the potential for retarding basins, levees, road crossings and drainage to reduce or increase peak flows (Table 3). Davies et al. (1988) concluded that most soil conservation structures and treatments only have a mitigating effect on small to moderate floods and are less effective in controlling major flood events. Retarding basins located on main drainage lines can be effective in controlling major floods. There were no inexpensive control methods identified for major flooding in wheatbelt catchments.

Revegetation of discharge areas, e.g., with salt-tolerant vegetation, is technically feasible, but the effectiveness of this approach in mitigating flood risk is untested and is unlikely to dramatically mitigate

Table 3. Results for treatment scenarios for three wheatbelt catchments (Davies et al., 1988)

Study	Catchment area area (km^2)		Treatment scenario and results
Cowcowing Creek Study	187.5	1.	36 – 4 ML retarding basins reduced peak flow by 7%
		2.	6000 – 7500 ML retarding basin downstream reduced peak flow by 63%
		3.	Absorption banks reduced peak flows by 34–42%
Beacon Catchment Study	1375	1.	Levees can reduce floodplain storage and increase flood peaks downstream
		2.	Road crossing can cause substantial attenuation in flood peaks
West Nugadong Catchment Study	380	1.	Improved drainage increased flood peak for 1-in-10 year ARI by 10% explain ARI in legend
		2.	Road crossing lead to far larger increases in flood depth than improved catchment drainage

risk, particularly in winter. The potential to create detention basins by raising the outlets of natural lakes and thus effectively mitigate risk is higher, but also untested in practice. These basins may create a temporary impoundment, which releases water in times of ‘diluting high flows’, but not floodflows.

The options for reducing inundation and waterlogging are similar to flood mitigation, although the emphasis is more likely to be on surface water management, water harvesting, and engineering and vegetation options to increase discharge. The installation of shallow interceptor drains has been promoted to accelerate the removal of surface waters and to some extent drain shallow perched aquifers (Cox and McFarlane, 1995; McFarlane and Cox, 1990; McFarlane et al., 1990). When successful, these drains reduce perched waterlogging and thus lead indirectly to recharge control, however they can serve as points of localised recharge to deeper aquifer systems (Hatton et al., 2001). These same authors found no experimental or theoretical evidence for minimising seasonal (perched) upland waterlogging through the introduction of perennial pastures. In a more regional sense, surface water control aimed at keeping run-off off the valley floors where it would otherwise provide localised recharge to saline groundwater systems is crucial for salinity management now that the valley floor sediments have extensive saline watertables at or near the surface (Coles and Ali, 2000).

At the local scale, the re-introduction of perennials with summer activity is clearly essential in reducing run-off and groundwater recharge to pre-clearing levels. There is ample evidence that putting trees or shrubs (native and non-native) back into the landscape can achieve this result (Greenwood et al., 1992; Bell et al., 1990; Nulsen et al., 1986). It is less clear as to whether landscape position is more important than the actual proportion of the catchment planted for recharge control (Bell et al., 1990; McFarlane et al., 1993; Zhang et al., 1997). Arguments based on the results of Specht (1972) and Hatton and Wu (1995) suggest that however trees are put back into the landscape, effective control of recharge will be achieved only at a leaf area index approaching that of the natural state, implying revegetation of most or all parts of the catchment. Similar conclusions were reached by George et al. (2001). This view is supported empirically by long-term revegetation experiments in nearly coastal catchments: in both the Collie and Denmark catchments, limited clearing (26% and 18%, respectively) led to highly salinised rivers, and the subsequent revegetation (6% and 60% of cleared areas, respectively) have perhaps curtailed salinity in the Collie (Mauger et al., 2001) and may be recovering the Denmark.

Empirical work by George et al. (1999) indicated that the effect of tree plantations on groundwater levels is quite localised in most cases; the downslope impacts on watertables rarely extends more than a few tens of metres away from the plantation. In fact, Salama and Bartle (1995) point out that in such flat landscapes, the groundwater sink that can develop under a plantation (or remnant woodland) can cause a reversal of flow towards the trees with the potential to impact on their health through localised salinisation, and there is evidence of rising watertables under remnant vegetation by this phenomenon.

In stating the above, it is important to recognise that each individual hydrological system has an inherent capacity to discharge groundwater without significantly raising watertables. Thus, there may be some sub-optimal leaf area index associated with a sustainable level of groundwater recharge (e.g., Salama et al., 1993c). Further, there may be a few southern Australian systems that are not prone to salinisation following clearing, but these are likely to have other degradation issues such as waterlogging, soil structural decline, acidification, and erosion if cleared.

If we take a catchment-scale perspective on functional mimicry, the focus can be shifted towards the minimisation of saline discharge. While recharge control remains an option in this regard, there is the additional option of intercepting surface and shallow (fresh) groundwater before it interacts with deeper, saline aquifers. At face value, this is a more economically and socially attractive idea, for potentially less land may have to be afforested to achieve the same result. The idea is to place trees or similarly deep-rooted evergreen vegetation in landscape positions at which they can access not only local rainfall but shallow, fresh groundwater from upslope as well. Thus, recharge can be intercepted before it reaches saline discharge areas. Where aquifers are sufficiently fresh and transmissive, this option is feasible. For instance, George (1990) demonstrated the potential for drying up sandplain seeps supplied by a perched hillslope aquifer by planting trees in an interception belt. Schofield et al. (1989) reported a similar result. The long-term effectiveness of such treatments is less clear (e.g., Greenwood et al., 1995).

The key feature of the discharge enhancement strategy is the placement of trees in landscape positions in which (a) the groundwater is reasonably fresh, (b) the groundwater is reasonably close to the surface (< 3 m (Thorburn, 1997), (c) the aquifer has reasonable transmissivity and gradient, and (d) the saturated thickness of the unconfined aquifer is limited (<10 m). This generally precludes the planting of salt-sensitive trees on saline discharge areas *per se* and restricts application to a limited fraction of affected landscapes in southern Australia (generally sand country). The lack of sustainability of trees at saline sites without sufficient periodic leaching of salts that otherwise accumulate in the root zone is well documented and modelled (Thorburn et al., 1995).

As a most extreme engineering measure, groundwater pumping and deep open groundwater drains to reduce land salinisation has been widely practised at scales from managing local discharges (Bettenay, 1978; George and Frantom, 1990; Salama et al., 1994) to regional systems (Ali and Coles, 2001; Otto and Salama, 1994). An important limitation to engineering discharge enhancement is the disposal of drainage waters, particularly when they are saline. We also recognise that such drainage works do not restore the original streamflow or stream water quality.

Hatton and Salama (1999) concluded that neither revegetation nor engineering was likely to recover the wheatbelt rivers from salinity. However, it is now widely recognised that engineering can be effective in reducing the impacts and extent of *land* salinisation on infrastructure and natural assets, as well as in keeping land under crops. It is also generally acknowledged that even if the long-term strategy is to revegetate, the immediate protection of land and assets can require engineering. Such practices are already being employed in places such as Lake Toolibin, where surface water diversions and groundwater pumping is beginning to protect the reserve ahead of intended revegetation in the surrounding catchment.

There is a lot of groundwater drainage being constructed in Western Australia's wheatbelt, mainly on private land with private funds. The on-farm effectiveness of these engineering works varies, but to date has been subject only to modest research and development efforts to improve effectiveness and efficiency. There are serious concerns expressed by some downstream stakeholders regarding the negative impacts of disposal waters. In the absence of the evaluation of these broader aspects, it is difficult to advance a serious debate on the winners and losers, and who pays, associated with engineering. It is worth noting that none of these catchments are water supply catchments, with the kinds of downstream constraints on water quality that complicate and inhibit drainage in catchments such as the Murray-Darling Basin.

Discussion

Water cycling in the natural southern Australian landscape is dominated by the *in situ* evaporation of local rainfall. This results from deeply weathered regolith, low hydraulic gradients, high potential evaporation relative to rainfall, and a deeply rooted flora which remains physiologically active during summer. Current agricultural systems generally have vegetation that is quiescent in summer and shallow-rooted. The hydrological consequences of the resulting soil degradation and excess water are immense.

The structural and functional characteristics of the original system are well enough understood to specify the essential hydrological attributes of an agricultural mimic, at least at the local scale. These include deeply rooted perennial vegetation with physiological activity that extends through the dry season, growing at a canopy density approaching the original leaf area index. While there is hope that alternative production systems possessing these functional attributes can be proven and implemented, it is difficult to envisage sustainable systems not involving trees. It is likely that suitable tree species must be drawn from the original biota or from exotic locales with similar climate and regolith. While profitable agroforestry options exist in some environments, the scale of the tree planting required to significantly restore the original water balance across southern Australia is daunting.

Equally daunting is the response time of many hydrological systems to such changes. While remediation of saline seeps using trees can show results in a few years, the control of salt loads to southwest Australia's river systems may take hundreds of years to achieve following revegetation. This is due to the low gradients, low groundwater turnover, high salt loads and long length scales of these regional systems (Macpherson and Peck, 1987).

It is unlikely that the full complement of hydrological functions can ever be restored with revegetation, even using the original genetic material established at the fullest possible scale. Some hydraulic and hydrochemical characteristics of the system may be irreversible. The most pessimistic assessment suggests that Australia's southern landscape will not be renewed until the next geological orogeny or a large change in climate. Nevertheless, there is an ethical compulsion to bring to our agriculture as much of the original hydrological function as possible.

It is a cruel irony that we have salinity problems in these catchments precisely because they are in the process in the most global sense of *freshening*. More salt is coming out of the landscapes than is now going into them from the atmosphere, and if we take the longest possible view, at least the salinity and associated flooding will eventually, in thousands of years perhaps, self-correct. However in the process, we will be leaving behind much of the natural and human heritage we value.

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