Salinity Threatens the Viability of Agriculture and Ecosystems in Western Australia

Richard George[1], Don McFarlane[2], and Bob Nulsen[3]

Abstract: In Western Australia, an abundance of salt within the deeply-weathered soil profiles and the clearing of native vegetation have resulted in unparalleled hydrological changes and extensive salinisation. Groundwater levels have risen by more than 30 m, and aquifers now occur where none existed before clearing. Currently, an area consisting of more than 1.8 million hectares (9.4 percent) of cleared farmland in Western Australia is salt affected. The salt-affected area is expected to double in size within the next 25 years and double again before reaching a new equilibrium.

Salinity in streams is increasing at a rate of 10-90 mg/L each year. As a result, large areas of remnant vegetation and its contained biological diversity are threatened. Salinity management should be based on a sound knowledge of hydrogeological systems. Land managers should have access to cost-effective methods of treatment and packages of biophysical information that can be used to design and predict the impact of physical and economic management systems. To date, too few cost-effective methods exist. Furthermore, a complex hydrogeology has contributed to low success rates of predictions.

The fate of Western Australia's agriculture, water resources, and natural environment depends on acknowledging the lessons of the past and investing in the future. Priority areas for hydrologic research should be identified, and management methods that are currently available need to be incorporated into new farming systems.

Résumé: En Australie occidentale, l'abondance de sels dans les profils de sols profondément altérés et le défrichage du couvert primaire ont provoqué des modifications hydrologiques sans précédent et une salinisation étendue. Les niveaux des nappes sont remontés de plus de 30 m, et des aquifères existent maintenant là où il n'y en avait pas avant le défrichage. De façon général, une région de plus de 1,8 million d'hectares (9,4 %) d'exploitations sur défrichage en Australie occidentale est affectée par la salinisation. On s'attend à ce que cette région double son extension au cours des 25 prochaines années, puis double à nouveau avant d'atteindre un nouvel équilibre.

La salinité des ruisseaux augmente chaque année de 10 à 90 mg/l. De ce fait, de larges zones de végétation résiduelle avec sa diversité biologique sont menacées. La régulation de cette salinité doit s'appuyer sur une bonne connaissance des hydrosystèmes. Les responsables de l'aménagement du territoire doivent avoir accès à des méthodes portant sur les coûts réels et à des ensembles de données biophysique pouvant être utilisées pour définir et pour prédire l'impact de dispositifs de gestion physique et économique. Pour le moment, il existe trop peu de méthodes portant sur les couts réels. En outre, du fait d'une hydrogéologie complexe, le taux de réussite des prévisions a été faible.

Le sort de l'agriculture des ressources en eau et de l'environnement naturel en Australie occidentale dépend de la connaissance acquise à partir des leçons du passé et de l'investissement sur le futur. Les régions prioritaires pour les recherches hydrologiques doivent être identifiées et des méthodes de gestion actuellement disponibles doivent être introduites dans les nouveaux systèmes d'exploitation agricole.

Resumen: En Australia Occidental, la abundancia de sales en los suelos fuertemente meteorizados y el desbroce de la vegetación natural han provocado cambios hidrológicos muy significativos, que han dado lugar a una fuerte salinización. Los niveles freáticos han ascendido más de 30 m, y han aparecido acuíferos donde antes no existían. Actualmente un área de más de 1.8 millones de hectáreas (9.4 por ciento) de terreno agrícola en Australia Occidental está afectado por la salinidad. Esta área se espera que llegue a duplicarse en los próximos 25 años y que vuelva a duplicarse antes de alcanzar un nuevo equilibrio.

La salinidad en los arroyos se incrementa a razón de 10-90 mg/l por año. Como resultado, grandes áreas de vegetación remanente, con su correspondiente diversidad biológica, están siendo amenazadas. La gestión de la salinidad debería basarse en un profundo conocimiento de los sistemas hidrogeológicos. Los gestores deberían tener acceso a métodos de tratamiento coste-efectivos y a paquetes de información biofísica, que pudieran ser usados para diseñar y predecir el impacto de los sistemas de gestión físicos y económicos. Hasta la fecha existen muy pocos métodos coste-efectivos. Más aún, la compleja hidrogeología de la zona ha contribuido a un bajo porcentaje de éxito en las predicciones.

[1]Agriculture Western Australia, P.O. Box 1231, Bunbury, 6231, WA, Australia

[2]Agriculture Western Australia, Albany Highway, Albany, 6330, WA, Australia

[3]Agriculture Western Australia, Baron-Hay Ct., South Perth, 6151, WA, Australia

El destino de la agricultura, los recursos de agua y el medio ambiente en Australia Occidental depende del reconocimiento de las lecciones aprendidas del pasado y de la inversión en el futuro. Se deben identificar áreas prioritarias para la investigación hidrológica, y los métodos de gestión actualmente existentes se deben incorporar a nuevos sistemas de cultivo.

Introduction

Western Australia's agricultural lands and remnant forests lie in the southwestern corner of an arid state, bounded on the north and east by sparsely populated shrublands and deserts and on the west by the Indian Ocean. Fresh water comes from intermittent streams draining a narrow belt (~50 km) of sclerophyllous Eucalypt forest, which overlies the ancient, deeply-weathered soils of the Darling Ranges. The location of Western Australia is shown in *Figure 1*.

Catchments near Perth remain substantially forested, because of the early experience with clearing and salinity in the catchment of the Mundaring Reservoir, a major storage that supplies water to the eastern goldfields and the wheatbelt. Ringbarking of 8,100 ha of *Eucalyptus marginata* and *E. calophylla* in 1903 to increase catchment water yield was described by Kessell in 1920 (as quoted in Bennnett and McPherson, 1983) as "*. . .wholesale slaughtering . . .*" that produced an "*. . .increase in salinity of water flowing into the* (Mundaring) *reservoir.*" Realising the problem, Reynoldson in 1909 (quoted in Bennett and McPherson, 1983) recommended that the forest be allowed to regrow and additional trees be planted to try to reverse the salinisation of the catchment. It worked. Thus, the state's first lesson in salinity management was dramatically illustrated.

However, in the expanding agricultural areas, the lesson was not heeded, and the Government sponsored broad-scale clearing, despite early warnings by explorers, farmers, and scientists. In 1864, Henry Lefroy, Superintendent of Convicts on a farm east of York, commented, "*To the very important question of good water, it being evident that flocks must depend on well water, I record my opinion that subsoils must contain the salts brought into them annually for countless ages, as salts must be left in the soil by evaporation*" (Bennett and McPherson, 1983).

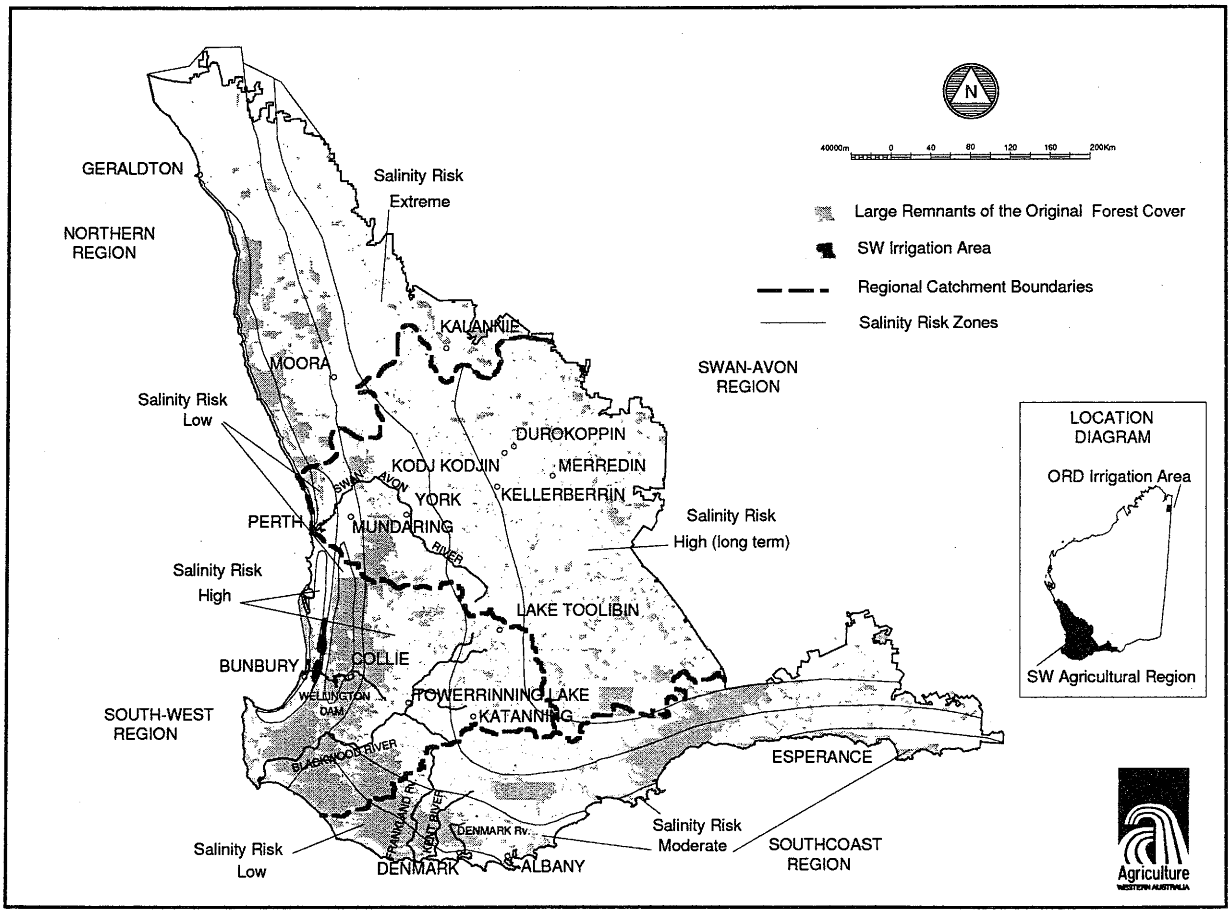

Figure 1. Location of the southwestern part of Western Australia, showing regional catchments, remnants of original forest cover, salinity risk zones, and location of South West Irrigation Area.

The hydrological factors responsible for dryland salinity were recognised in 1897 and then published in 1924 by W.E. Wood, a railway engineer working to retain fresh steam-engine water in the Great Southern (Wood, 1924). Wood reported that catchments cleared in about 1888 were delivering saline water to dams by 1905. However, Wood's theory of salinisation took another 60 years to be tested rigorously and accepted by much of the Western Australian community.

In 1917, J.W. Paterson, Professor of Agriculture at the University of Western Australia, presented soil samples and a report to the Royal Commission on Mallee Belt and Esperance Lands, claiming that probably one third of the area being considered for development was too saline for profitable farming. The Commission responded to the evidence with "*...the Commission having given the question close consideration, strongly urges that scientific prejudice against our mallee lands be not permitted to stand in the way of their being opened up for agricultural purposes.*"

Between 1928 and 1938, L.H.J. Teakle, a soil surveyor and later Commissioner of Soil Conservation, published accounts of salinity. Like others before him, Teakle's theories were not accepted, and indiscriminate, large-scale clearing for agriculture continued. Recognition that salinity was increasing in farmlands became evident when Burvill (1947) later stated "*. . .the salt water level in low lying situations or on extensive flats has come closer to the surface during the past 15 years and an increase of salt affected soils has developed.*" Between 1952 and 1955, Pennefather and Smith recommended community action to prevent salinisation of farmlands and emphasised the "*. . .considerable threat to fertility and productivity . . .*" that salinity had become (Bennett and McPherson, 1983).

Fifty years ago, George Burvill (1947) stated that "*Soil salinity is a State problem, that is, a problem of all the people of the community, not only of the individual whose farm is affected.*" This message is as important today as it was then.

Today, land clearing has almost ceased and agricultural industries, dominated by cereals, pulses, and pastures (sheep and cattle grazing), extend more than 1,200 km, from Geraldton to Esperance (*Fig. 1*). About 18 million ha has been cleared and only small areas of native vegetation remain, as shown in *Table 1*.

Current Extent and Future Estimates of Salinity

Some time before 1929, a committee of the Royal Society of Western Australia asked 29 farmers in the wheatbelt to estimate the area of their land affected by 'alkali' (soil salinity) following the clearing of native vegetation. The total area of the farms surveyed was 24,560 ha, of which 1,900 ha (3.1 percent) was salt affected (Teakle, 1929). Very few details of this survey remain, but it seems that it was the first attempt to obtain an assessment of the extent of the land-salinity problem in the state. The affected area has been increasing ever since and has now reached an alarming proportion of the agricultural land.

Table 1. Land use and vegetative cover in the agricultural region of southwestern Australia.

Land use	Area (millions of ha)	Percent of area within the agricultural region
Agricultural region	25.3	100
Private land	20.8	82
Cleared	18.0	71
Remnant vegetation	2.8	11
Public land (forested)	4.5	18

Hydrologists' Estimates

Regional hydrologists from Agriculture Western Australia have reviewed estimates of the extent of salinity derived from air-photo interpretations, soil and landform mapping, farm and catchment plans, remote-sensing images, ground-based geophysics, and extensive bore records to get a *best estimate* of the area affected and the area at risk. Results are shown in *Table 2*.

Estimates from Satellite Data

The extent of primary and secondary salinity in four smaller areas surveyed in 1988 and five areas surveyed in 1994 was estimated by the Commonwealth Scientific and Industrial Research Organisation (N. Campbell, pers. comm.) using satellite data and other landform attributes, particularly elevation data. Results are shown in *Table 3*.

The results of both forms of analyses (hydrologists and satellite) indicate that depending upon seasonal rainfall, the area of salt-affected land is likely to double over the next 15-25 yr and double again before a new equilibrium is reached in 100-200 yr (*Table 2*). More than 30 percent of cleared land and some uncleared public and private land may become affected to some extent in the long term unless land-management practices are changed. This percentage is very similar to that estimated by Professor Paterson many decades ago (Western Royal Commission on the Mallee Belt and Esperance Lands, 1917).

Processes

Salts

Salts of oceanic origin are responsible for salinity in Western Australia (Hingston and Gailitis, 1976). The salt, 90 percent sodium chloride, has been deposited annually in rain and dust in proportion to rainfall and distance from the ocean. Annual deposition ranges from about 100 kg/ha near the coast to about

Table 2. Estimated sizes of areas affected by secondary salinity (Ferdowsian et al., 1996). For agriculture, salinity is considered "severe" when the yield of the preferred crop or pasture is reduced by more than 50 percent, and it is considered "moderate" when the yield is reduced by 10-50 percent.

Hydrological region	Area cleared[1] (ha)	Area affected					
		1994		2010-2020		Potential	
		(ha)	(percent)	(ha)	(percent)	(ha)	(percent)
South Coast	4,078,960	395,400	9.7	687,580	16.8	977,180	24.0
South West	3,310,000	273,800	8.3	595,500	18.0	820,000	24.8
Swan-Avon	7,590,500	759,000	10.0	1,290,400	17.0	3,036,200	40.0
Northern	4,251,900	376,250	8.8	722,800	17.0	1,275,600	30.0
Total	**19,231,360**	**1,804,450**	**9.4**	**3,296,280**	**17.1**	**6,108,980**	**31.8**

[1] Includes some non-cleared land that is prone to salinisation in highly cleared catchments.

Table 3. Results of Landsat TM surveys showing changes in the area of salt-affected land, 1988-94.

Region	Area surveyed (km^2)	Salt-affected land		Percent increase
		1988	1994	
Moora	2,025	7.2	11.7	63
Kalannie	2,025	14.2	22.0	55
Esperance	1,580	9.2	14.1	53
Upper Kent	1,063	6.1	15.3	250
Upper Blackwood	13,500	No data	12.4	--

20 kg/ha inland. All of the salt present in deep soil profiles beneath higher-rainfall forests (750-1,100 mm/yr; Johnston, 1987) and the hillslopes and palaeodrainages in lower-rainfall wheatbelt areas (350 mm/yr; McFarlane and George, 1992) could have accumulated in between 13,000 yr (Johnston, 1987) and 500,000 yr (McArthur et al., 1989). Examples of total soluble salt stores are shown in *Table 4*.

Hydrogeology

Most of the agricultural region is situated on an Archaean-age craton, with a flat landscape (relative relief < 300 m) underlain by predominantly igneous rocks. Intrusions by Proterozoic-age dolerite dykes and more recent deformation by major faults, minor faults, and shear zones, following drifting of Gondwana's landmasses, have resulted in a strongly structurally controlled basement-aquifer complex. Aeolian, fluviatile, and lacustrine sediments of Holocene to Eocene age overlie deeply weathered saprolite, which consists of Cenozoic-age, iso-volumetrically weathered felsic and mafic rocks. These rocks were deposited during repeated cycles of aridity and minor pluvial periods, when palaeodrainages were active. Sedimentation of valleys is extensive in the eastern areas, although sediments also occur in truncated palaeodrainages, on isolated interfluves, and along coastal margins. Various hydrogeological settings are illustrated in the schematic sections of *Figure 2*.

The geological history of the region has resulted in a complex fractured-rock and regolith system through which water is transported slowly (Lewis, 1991). Aquifers occur in the relatively permeable zones at the contact between the bedrock and the saprolite (saturated hydraulic conductivity, $K_s \sim 0.5$ m/d); in fluvial palaeodrainage sediments ($K_s \sim 0.5$-5 m/d); in broad, aeolian sand sheets ($K_s \sim 0.5$ m/d); and in the more permeable surface soils ($K_s \sim 1$-3 m/d). Structurally-controlled, patchy, weathered-zone aquifers occur at a local scale, for example at the contact between intrusive mafic dykes and granitic materials (~10 x 500 m cells); and at a regional scale, for example within extensive (~1,000 x 5,000 m cells) fault systems (Clarke, pers. comm., 1996). Deeper fractured, hardrock aquifers are thought to be common throughout the region, as evidenced in open-cut gold mines; however, due to high costs of drilling and the high salinity of most groundwaters, few holes have been drilled to determine the hydraulic properties or water resources of such systems in the agricultural areas. Aquitards commonly include the highly weathered saprolite (pallid clays) and lacustrine sediments ($K_s < 0.05$ m/d; George, 1992).

Hydrology of Dryland Areas

Clearing of native woodland and forest vegetation decreases transpiration and interception (Nulsen et al., 1986; Williamson et al., 1987) and increases runoff and recharge. Clearing of catchments in an area where precipitation is 1,250 mm/yr

Table 4. Total soluble salt stores per hectare above bedrock in typical catchments of the central and eastern wheatbelt (McFarlane and George, 1992).

Catchment (landform position)	Total soluble salt stores above bedrock (t/ha)		Number of profiles sampled	Average depth (m)
	Average	Range		
Danberrin (hilltop)	247	7 - 657	7	5.9
Ulva (sandy hillside)	289	139 - 422	5	19.7
Booraan (clayey hillside)	802	43 - 1,798	10	13.5
Colgar (sandy hillside)	1,056	109 - 2,231	12	16.5
Belka (broad valley)	2,571	44 - 6,206	14	20.4
Baandee (valley playa)	13,533	5,752 - 21,314	2	51.0

resulted in runoff increasing by 30 percent (Williamson et al., 1987).

Recharge under Eucalypt forests in a zone receiving 750-1,250 mm/yr of rainfall increased from 0.05-3.7 mm/yr prior to clearing to 23-65 mm/yr after clearing (Peck and Hurle, 1976; Williamson et al., 1987). In the rainfall zone of 350 mm/yr, average annual recharge rates increased from < 0.01-0.1 mm/yr to at least 6-10 mm/yr after clearing (George, 1992).

Water-table trends

In catchments receiving 750-1,250 mm/yr of rain, water tables rose by 0.9-2.6 m/yr after clearing (Williamson et al., 1987). Groundwater levels in Lemon Catchment near Collie, deliberately cleared to study salinisation, rose dramatically after clearing, while water-table levels declined in nearby native forests due to a period of lower-than-average rainfalls. About 50 percent of the catchment was cleared in 1976, and groundwater levels reached the soil surface after 11 years. More than 20 percent of the cleared area is now discharging groundwater and is salt affected. Results through 1994 are shown in *Figure 3*.

In drier regions, groundwater levels from about 2,000 piezometers are being measured. Those drilled away from discharge areas have risen by 0.02-0.30 m/yr in the <350-mm rainfall zone, by 0.05-0.50 m/yr in the 350-500 mm/yr rainfall zone, and by 0.15-1.5 m/yr in the >500 mm/yr rainfall zone (Ferdowsian et al., 1996). These rising trends are typical of bores located away from discharge areas, whereas bores near discharge areas show seasonal rises and declines with little long-term trends, as shown in *Figures 3 and 4*. The cell-like behavior of aquifers makes unreliable any analyses of trends that are based only on topography, except as generalisations.

Episodic recharge is very important in some situations, and may be more common than is currently recognised (M.F. Lewis, pers. comm.). Such a recharge pattern also presents real problems in terms of land management to control it. George et al. (1991) reported that in one eastern wheatbelt catchment in 1989 significant recharge occurred as a result of a 85-mm storm in May and a 55-mm storm in October (*Fig. 4*). The May event caused a temporary 0.6-m rise in the water table on the hillside and a 0.15-m rise beneath the valley. In October, flooding occurred in the valley, which caused a 3-m rise in the valley and almost no response on the hillside. The valley water-table level has continued to rise by about 0.2 m/yr, whereas the rate of rise under the hillside has been lower (< 0.1 m/yr).

Soil and water salinity

As groundwater levels rise beneath catchments, some of the salts stored in the regolith are mobilised. When the groundwater nears the surface, salt accumulates in the topsoil by root uptake of water and capillary rise. With evaporation, the salt concentration becomes toxic to many plants.

Salts leached to streams have increased salinities in major water-resource catchments to the extent that now less than 50 percent of the divertible water is fresh, and stream salinities are increasing by 10-90 mg/L/yr. Greater rates of increase are occurring in low-rainfall catchments, which have less than 40 percent forest cover, whereas lower rates are occurring in high-rainfall catchments, which have more than 70 percent forest cover (Schofield et al., 1988).

Environmental consequences

Clearing has caused extensive habitat loss. Salinisation is most active in the lower parts of the landscape, degrading rivers and wetlands. Rising groundwater levels also threaten parts of many upland remnants, including parts of some relatively large (~1,000-ha) nature reserves (George et al., 1995). George et al. (1995) estimated that without remedial action, as much as 80 percent of susceptible remnants on farms and as much as 50

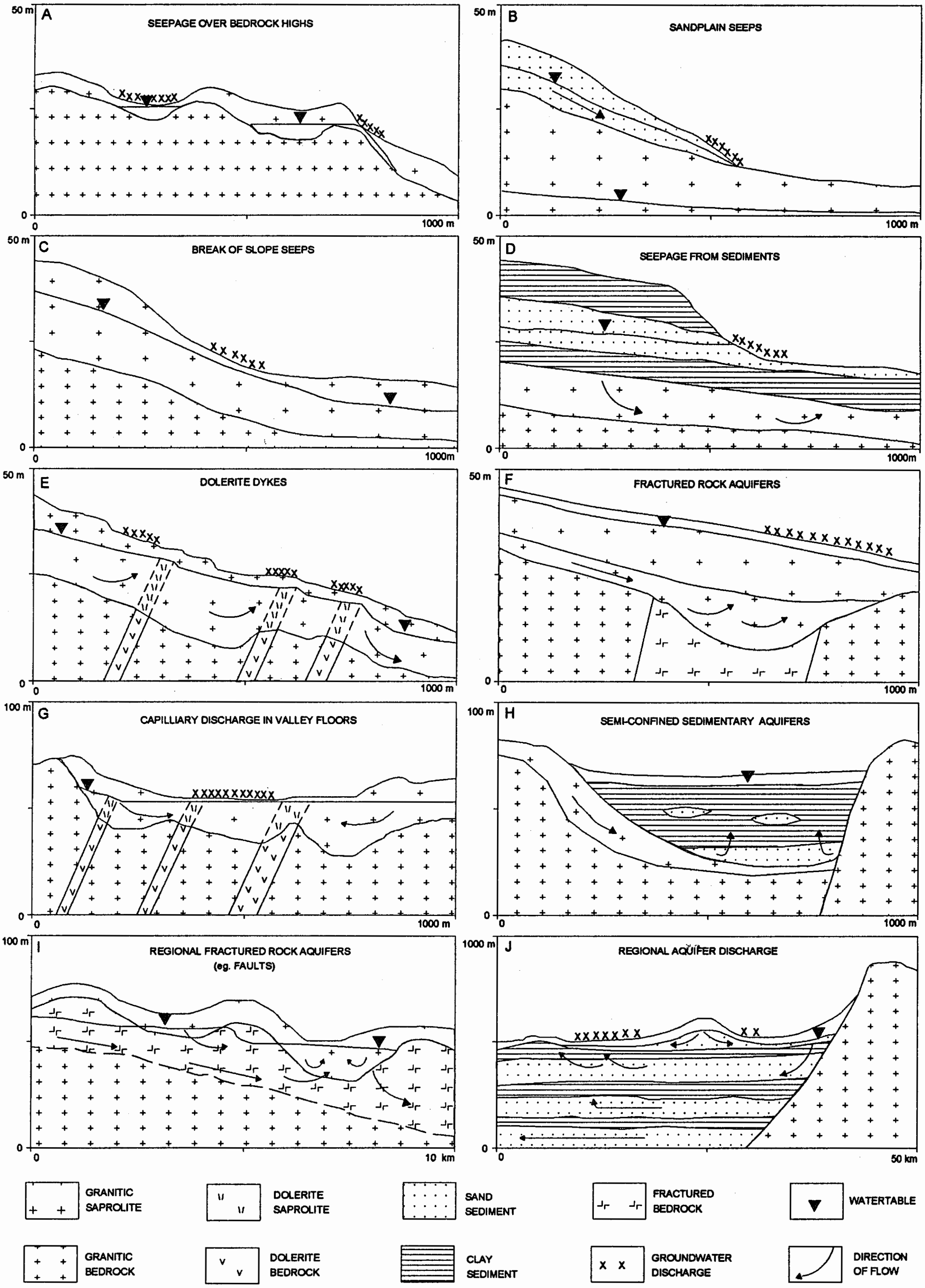

Figure 2. Conceptual models of groundwater flow at various scales, showing discharge conditions causing salinity. A-D, Local or hillslope scale; E, F, Effects of structural controls; G, H, Intermediate scale; I, J, Regional scale.

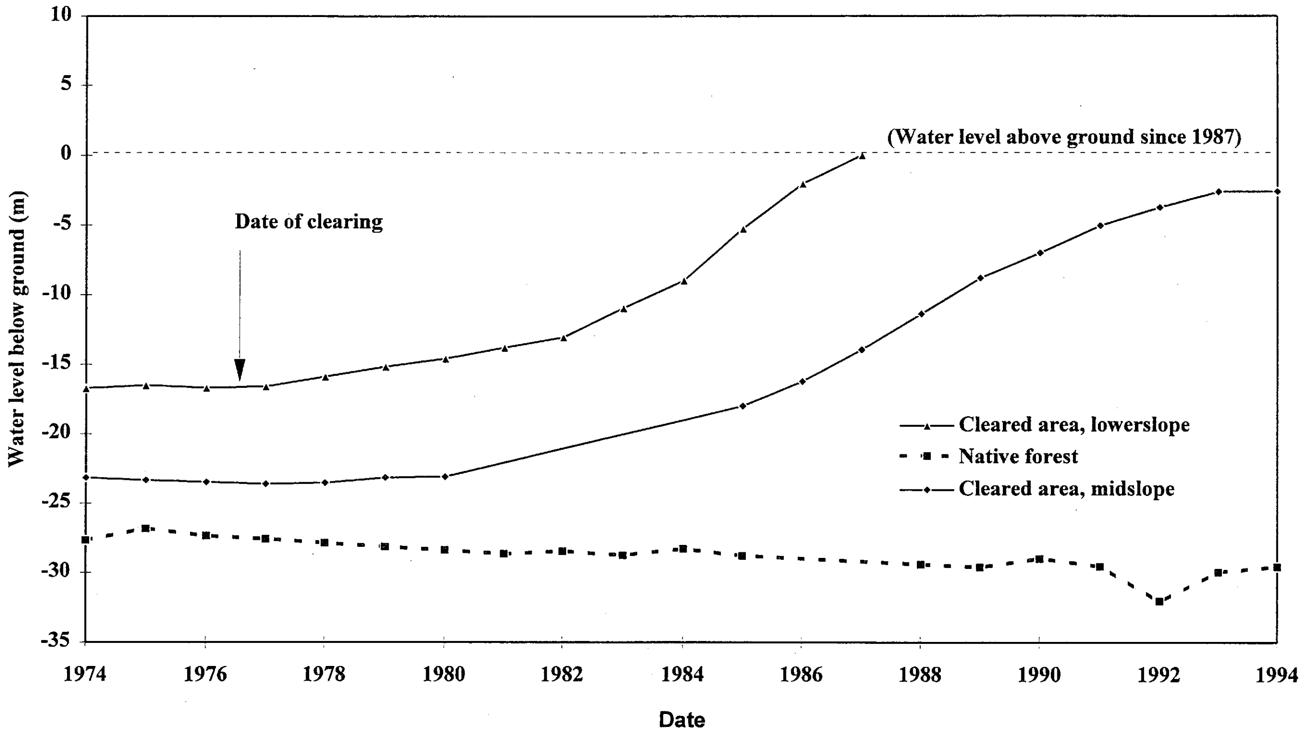

Figure 3. Hydrographs of groundwater levels in 1) the lower slope and mid-slope of cleared land in the Lemon Catchment, and 2) a subcatchment on a tributary above the Wellington Reservoir. Data supplied courtesy of the Water and Rivers Commission, WA.

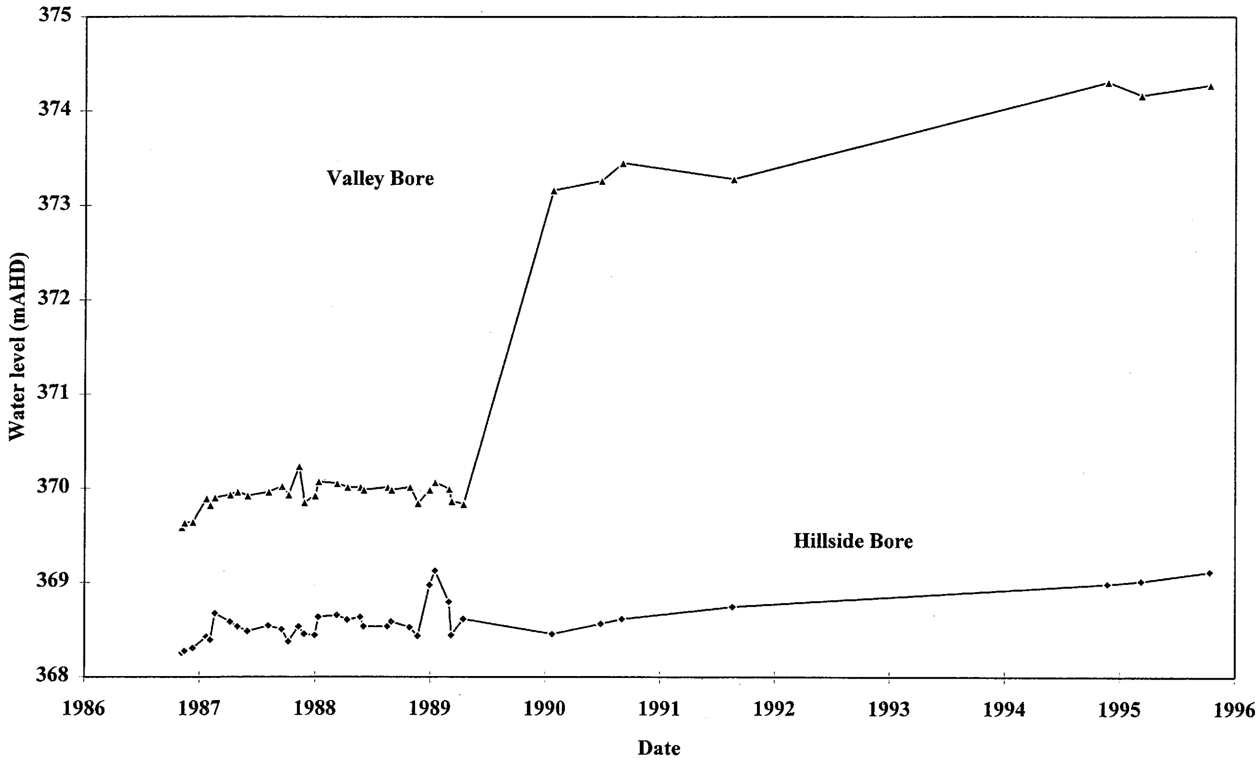

Figure 4. Hydrographs of groundwater levels of a hillside bore and a valley bore in an area of low rainfall (average <300 mm/yr), eastern wheatbelt catchment (Skeleton Rocks catchment, about 50 km south of Southern Cross), 1986-96. Landforms are exposed to seasonal and episodic recharge events.

percent of susceptible public lands in agricultural areas could be lost within the next century.

In addition, the beds and banks of 80 percent of the region's rivers and streams are seriously degraded (L. Pen, pers. comm., 1996), and the degradation of wetlands is well advanced and has gone largely unrecorded. Virtually all wheatbelt wetlands have been severely degraded. Increased salinity is considered to be a major factor in the extinction of the wetland plant *Roycea pycnophiloides,* and other wetland flora, such as the dragon orchid (*Drakonorchis drakeioides*), are under threat.

Specialist plant communities, such as swamp yate (*Eucalyptus occidentalis*), salt salmon gum (*Eucalyptus salicola*), and many *Casuarina* and *Melaleuca* populations could disappear at local and regional levels. Apart from their nature-conservation value, these species have a role in revegetation and may have some, as yet unknown, economic potential.

Social consequences

Some wheatbelt towns (e.g., Brookton, Dumbleyung, Katanning, Kellerberrin, Merredin, Morawa, Tambellup, and Wagin) have expanding salt problems. Lyons (1995) assessed the effects of salinity on 20 Shires in the Swan-Avon catchment, representing 31 country towns. An increase in the area of saltland in or adjacent to the towns was reported in 19 of the 20 Shires; 13 noted seeps within the town, and more than half reported that water supplies, waste-management systems, vegetation, recreation facilities, and buildings had been affected.

Hydrology of Irrigated Areas

Major areas for irrigation occur in the high-winter-rainfall South West Irrigation Area (SWIA) and in the summer-rainfall Ord River Irrigation Area (ORIA), in the northern part of the State. Unlike dryland salinity, irrigation salinity is caused both by increased recharge from clearing and by recharge from applied water. Flood irrigation may result in recharge rates of 50-200 mm/yr (Jeevaraj, 1991). In the SWIA, irrigation is carried out on a plain with naturally saline subsoils and regional groundwater discharge. By contrast, the ORIA has deep, alluvial soils.

Flood irrigation of perennial pastures is possible on as much as 34,000 ha in the SWIA. The area produces high-quality summer feed for dairy and beef cattle. Water is delivered from five reservoirs in the Darling Ranges. Four smaller reservoirs with largely forested catchments are fresh, whereas water from the Wellington Reservoir, with 23 percent of its mainly eastern catchment cleared, has relatively poor-quality water (1,070 mg/L) and a trend of increasing salinity of 42 mg/L/yr (Schofield et al., 1988). Jeevaraj (1991) estimated that irrigated land in the Collie Irrigation Area accumulates 200-800 kg salt/ha/yr as a result of irrigation practices, soil conditions, and the saline nature of supplied waters. This amount is 1-8 times the amount deposited as fallout in rain.

Terrain electrical-conductivity surveys (George et al., 1994) and plant-salinity productivity studies (Hojberg and George, 1995) in the SWIA using GEONICS™ EM38 meters showed that about 22 percent of the area has terrain conductivities greater than 125 mS/m (equivalent to an ECe > 600 mS/m), resulting in a reduction greater than 50 percent in perennial ryegrass and clover pasture production. In addition, 36 percent has conductivities greater than 80 mS/m (ECe 450 to 600 mS/m), with about a 50-percent reduction in annual subterranean clover production. About 10 percent of the surveyed area has terrain conductivities >185 mS/m (ECe>800 mS/m), which would kill most clover species, whereas more than 80 percent of the area would have a 10 percent yield reduction of both annual and perennial clovers. Salinity, waterlogging, sodicity, and soil structural decline combine to reduce productivity.

About 10,000 ha has been developed for irrigation in the Ord River Irrigation Area, where more than 20 crops are grown, including horticultural crops, sugar, maize (*Zea mays* L), and leucaena. Planning is underway to develop an additional 60,000 ha. Water tables under the current irrigation area on the Ivanhoe and Packsaddle Plains are rising at 0.2-0.8 m/yr, and, in the area under the greatest threat, they are now less than 2 m below the surface. Groundwater salinities range from about 300 mg/L TSS to about 2,000 mg/L (Clews, 1994), and in areas proposed for development, salinities are as great as 30,000 mg/L. Unless the rates of water-table rise are stemmed, severe reductions in yields could result, due both to salinity and waterlogging. For example, the Bureau of Sugar Experimental Stations observed that in northern Queensland a yield loss of 0.5 t/ha occurred for each day that the water table remained within 0.5 m of the surface ("Australian Canegrower," October, 1994).

Agricultural Salinity Management

Salinity reclamation aims to restore previous levels of either agricultural production, water quality, or ecological diversity. This goal is the preferred objective of any remedial program, but for a variety of reasons, it is rarely possible to accomplish. More often, salinity *management* is all that can be practically achieved. Salinity management has connotations of "living with salinity" by reducing its severity, rate of spread, and eventual extent, and of protecting priority resources only (e.g., prime agricultural land, high-value water resources, towns, and important nature conservation areas).

To develop and apply an effective salinity-management system in priority areas requires 1) the definition of salinity-control practices, 2) the ability to utilise planning tools, and 3) the existence of a community climate for action that is both politically and community driven.

- **Salinity-control practices** are the components of salinity-management systems, such as trees, drains, or high-water-use crops and pastures. These practices work by transpiring or disposing of the excess water that causes salinity.

- **Planning tools** are the basic and derived biophysical data (e.g., topography and airborne geophysics), and the support systems, such as Geographic Information Systems, simulation models, and catchment and farm planning.
- **Communication and cultural-change climate** is the capacity to transfer knowledge and build broad-based commitments to implementing the changes required to manage salinity.

In most areas of Western Australia, effective salinity-management systems cannot be prescribed, because too few salinity-control practices and planning tools have been developed and shown to be successful. The climate for cultural change is developing.

To achieve economical and politically acceptable salinity management, a full range of both control practices and planning tools must be developed. Failure of control practices to date has occurred because of:

1) The inability of annual-based agricultural plants, used singly or in rotation, to sufficiently reduce recharge;
2) The agronomic, management, and economic difficulties of introducing systems of perennials, based on either native (e.g., Eucalypts) or exotic (e.g., lucerne *Medicago sativa*) species, into traditional practices;
3) Climate, especially the summer drought and high evaporation (~200 "rainless" days; ~2,000 mm/yr class A pan evaporation);
4) Lack of research on management systems to match research on hydrological process;
5) Declining terms of trade and property amalgamations resulting in landholders managing larger areas, whereas systems with high water use require more intensive management; and
6) Inadequate incentives for farmers to adopt new systems.

Problems with planning tools include:

1) Lack of precision in data (e.g., contour intervals of only 10 or 20 m are available when intervals of 1 or 2 m are required), and lack of experienced practitioners;
2) Rapid changes in data-acquisition systems exceed the capacity of rural operators to respond;
3) Inadequate testing of new data sets (e.g., electromagnetic induction, LANDSAT);
4) Few methods that select and then inter-relate several biophysical data sets and produce support packages (computer models); and
5) Perceived high cost of development and use in comparison with the value of the land.

Types of Practices

Five types of practices can be used for salinity management, either alone (e.g., pumping) or as a part of salinity-management system (e.g., farm forestry). These types are:

1) Increase water use by conventional annual crops and pastures;
2) Increase water use by introducing perennial species;
3) Collect and re-use or dispose of surface water;
4) Drain or pump and re-use or dispose of groundwater;
5) Improve protection and management of remnant native vegetation.

Increase water use by conventional annual crops and pastures

Water use by annual agricultural plants can be increased by farming to land-management units, improving agronomy, removing impediments to root growth, and improving grazing management (Nulsen, 1993). For example, Nulsen (1993) calculated that if cereal crops growing on degraded sandplains (acid and compacted soils) were treated with lime and appropriately fertilised, water use could be increased by 17-56 mm/yr. Additionally, if compaction were eliminated by deep tillage, water use could increase by as much as 27 mm/yr. New species, such as the deeper-rooted pasture, serradella, developed for acid soils, may also increase water use.

Comparisons of cereal yields with available water shows that crops are only achieving about 70 percent of their biological potential of about 20 kg/ha/mm in the low-rainfall zone, and only 40 percent in the higher-rainfall zone. Pasture water use is highly variable (8-33 kg/ha of dry matter per mm of rain) and is substantially less than the potential, which is possibly as high as 40 kg/ha/mm, particularly in higher-rainfall areas. Small gains in water use could return large benefits for both salinity control and profitability, because annual pastures still occupy large parts of the medium- and high-rainfall areas.

However, increasing the water use by annual plants would not be enough to prevent salinisation, because annuals do not use water that falls in intense or prolonged rainfall events, or that falls when the plants are not growing. Reducing recharge under annuals is a problem in freely draining, low-fertility, and waterlogged soils, and on heavily grazed pastures. Furthermore, skillful management and widespread commitment is required to consistently achieve high water use with annuals on every farm in a catchment. Problems of soil-structure decline, acidification, and herbicide resistance may result in continuous cropping practices being unsustainable in the medium term. Thus, additional measures are needed for effective salinity management.

Increase water use by introduced perennial species

Perennial vegetation offers the most promising means of managing salinity in Western Australia. The deep roots of trees, shrubs, and some perennial pasture species give them a greater water-use potential than annual, shallow-rooted plants. Eucalypts growing on sites with access to fresh-to-brackish subsurface water may use volumes greater than incoming annual rainfall (e.g., Greenwood, 1986). Strategically placed plantations (Schofield et al., 1989; George et al., 1993) have lowered water tables by 1-3 m on both fresh and saline sites. Similarly, tagasaste plantations on deep sands and bluegum farm forestry have lowered water tables by 0.5-0.9 m/yr (Speed et al., 1993; Landscope, 1996)

Although examples exist of trees and shrubs achieving groundwater control on a local scale and on small experimental catchments, no documented examples exist of success on a whole farm or larger catchment in the agricultural region. This lack is partly due to the high cost of tree planting and the complexity of integrating trees into farming systems, partly due to the lack of species and systems available for lower rainfall areas, and partly due to the absence of adequate demonstrations of their effectiveness. *Table 5* shows costs of introducing perennial species.

The integration of trees into agricultural landscapes requires an optimum proportion and distribution to fully utilise their water-use potential while incurring minimal interference with farming activities. Economic analyses show that the on-farm benefit gained from commercial tree farming is high; however, returns from non-commercial trees do not offset the opportunity cost of withdrawing 10 percent to greater than 30 percent of land from production, which is the minimum amount that may be required to *manage* salinity (C. Campbell, pers. comm., 1996).

Farmers cannot economically justify implementing non-commercial tree planting on a large enough scale to solve the salt problem. For this reason, a concerted effort is underway to develop commercial tree crops (e.g., tree eucalypts, oil mallees, pines) and to improve the technology for efficient integration of tree crops into farming systems. Without commercial options, the community will either need to finance tree planting on a massive scale, or only focus resources on protecting priority assets, such as water resources and nature reserves.

One tree-crop system for low-rainfall areas that is being evaluated is mallee eucalypts, which produce stems 1-5 m high from a lignotuber beneath the soil. Oils within the leaves can be distilled to produce cineol and further refined to manufacture industrial solvents, biofuels, and other products (J. Bartle, pers. comm., 1996). When planted in belts, two rows wide and spread 15-100 m apart, the trees have the potential to permit the continued practice of annual-based agriculture and still reduce recharge. The amount of potential recharge reduction is still to be determined.

Lucerne, whether used in rotation with crops or in a management system with annual pastures, is the most likely deep-rooted perennial suited for salinity management. In farming systems in North America and in Eastern Australia, where lucerne persists and grows well, it uses significantly more water than annual crops and pastures. For instance, in

Table 5. Costs of revegetation systems with perennials. Costs are in Australian dollars.

Type of perennial	Revegetation system		Spacing (m)	Approximate cost ($/ha)
Reforestation	>70 % tree cover		5 x 5	>500
	Native species (seeded by air)		na	150
Trees in agriculture	Plantations: commercial bluegums or pines		4 x 2	1,200
	30-50 m bays; commercial alleys		3-5 rows (4 x 2)	1,000
	30-50 m bays; non-commercial alleys		3-5 rows (4 x 2)	800
	15-100 m bays; oil mallee alleys		2 rows (2 x 1.5)	1,000
	50 m bays; saline valley alleys		3 rows (4 x 2)	350
Shrubs	Tagasaste	Seedlings, pot/bare-rooted	4 x 0.5	800/300
		Direct seeded	na	150
	Saltbush	Seedlings	4 x 5	250
		Direct seeded	4 x 2	150
Pastures	Lucerne and others		na	80-150
	Native (if seed available)		na	200
	Salt tolerant (e.g., tall wheat grass)		na	75

Victoria, Oram et al. (1992) indicated that recharge under cereal/annual pasture rotations was about 10-30 mm/yr; under a continuous cropping rotation, recharge was about 10-20 mm/yr; and under a wheat/lupin/lucerne rotation, recharge was as low as 5 mm/yr. Under a continuous lucerne system or combined perennial pasture and revegetation system (incorporating 250 trees/ha), recharge was reduced to almost zero. At Burkes Flat (Victoria), lucerne has lowered water tables when planted on a large (~80 percent) portion of the landscape (C. Clifton, pers. comm., 1996).

Collect and re-use or dispose of surface and near-surface water

Floodwater (moving storm water), inundation (water ponding on the soil surface), and waterlogging (excess water in the root zone of plants) reduce the ability of plants to exclude salts (Barrett-Lennard et al., 1990), and they provide a hydraulic head to exacerbate recharge. Areas with excess surface water contribute salt, sediment, nutrients, and pesticides to streams, rivers, wetlands, and estuaries.

Systems for the collection and storage for later re-use and disposal for these surface waters, which are usually fresh in the upper landscape, can increase plant growth and water use and reduce recharge (McFarlane and Cox, 1992). Managing surface water with shallow, inexpensive drains is also an effective soil-erosion control measure. As shown for the surface-water structures listed in *Table 6*, the cost of taking land out of production is greater than the costs of construction and maintenance (Salerian and McFarlane, 1987a and 1987b).

Where water is drained into streams, consideration must be given to any adverse effects due to increased water, nutrients, and salts. Surface-water management is best planned on a catchment basis using engineering-design and risk-assessment principles that evaluate flooding and downstream impacts. Increased flood risk to infrastructures and increased inundation of native flora may be a consequence of poorly designed or cheaply constructed drainage systems.

However, surface-water management is a means of getting higher production and water use than can be achieved when waterlogging and inundation are widespread. Such a result can give landholders the confidence to invest in systems of high water use that are destroyed in wet years (e.g., lucerne). The right to discharge extra water into streams should be linked to an obligation to improve agronomic practices that would

Table 6. Costs of surface and subsurface drainage systems. Costs are in Australian dollars.

Main problem	Drainage-system element	Spacing (m)	Cost[1]	
			($/m)	($/ha)
Flooding and inundation	Spoon or V drains	50	0.4	80
	Levee banks	na	3-6	na
	W drains (double-trapezoidal)	100	1.5	150
	Spinner drains (small u-shaped drains)	15	0.1	70
Waterlogging	Seepage interceptors	75	0.5	70
	Grade banks (grader-built)	120	0.4	35
	Grade banks (dozer-built)	200	1.2	60
Salinity[2]	Pumping (electric and/or diesel power)	100-300	na	1,000-2,000
	Pumping (air-displacement)	>100-300	na	750-1,500
	Deep open drains	20-60	>4	500-2,000
	Tube drains	20-60	>8	1,000-4,000

[1] Costs do not include maintenance (2-10-yr cleaning cycle) or running costs (e.g., pumps).

[2] Salinity management costs for groundwater are an order of magnitude greater than for surface and near-surface management systems. If an evaporation basin disposal system is required, add about 25 percent to the total cost per hectare.

na, Not applicable or not available

reduce discharge in the long term. Many landholders have shown that surface-water management is an essential prerequisite to achieving high water use and is an essential step prior to sub-surface drainage.

Drain or pump and re-use or dispose of groundwater
Groundwater levels can be lowered with deep drains and aquifer pumping systems (George and McFarlane, 1993; Salama et al., 1993). The spacing and depth of drains and aquifer pumping systems can be designed to keep groundwater below a desired level of 1.2-1.8 m (Nulsen, 1981). Most systems designed to date have not been cost effective or environmentally sound (*Table 6*).

Drainage or pumping has been shown to be cost-effective only in situations where the land is very valuable (towns, nature reserves, infrastructure), the soils and aquifers are permeable and in hydraulic connection, and where a safe option exists for effluent disposal (George and McFarlane, 1993).

Water may be re-used if the quality is suitable or desalination is economic. Re-use of brackish waters drained from saline land and from beneath salt-sensitive crops could be 'sequentially' irrigated on less sensitive crops (wheat, barley, and other grasses), salt-tolerant crops (grasses and trees, e.g., *E. camaldulensis*, *E. occidentalis*), and halophytes (*Salicornia* and *Atriplex* spp.). Secondary drainage may be required to prevent excess salt build-up and final discharge to solar ponds, as suggested by Cervinka (1996). Crystallisation of salts for sale for industrial use, for the production of ceramic materials, and for power generation is being considered.

Retain and improve remnant native vegetation
The water-use and salinity-control functions of remnant vegetation may be significant in areas where it occupies a large area at both the catchment (e.g., Wellington Dam Catchment) or hillslope scales. For example, at the Durokoppin Nature Reserve, McFarlane et al. (1993) reported that water tables were 7 m lower and the area of saline land less in catchments that retained 22 percent of remnant vegetation. However, more recent monitoring has shown that water tables are rising beneath and adjacent to the remnant vegetation, and that more salinity is developing in the catchment (George et al., 1995). The rate of spread and final extent of salinity will likely be less because of remnant vegetation. In the high-rainfall south-western area, G. Mauger (pers. comm., 1996) suggested that if as much as 70 percent of the landscape remains in forest, or is reforested, it should prevent salinisation of water resources.

Where remnant vegetation occurs in small patches, it probably has limited value for salinity management, because:

1) The present distribution of remnants is the outcome of past land-development practices, which did not anticipate a water-use and salinity-control function;
2) Remnants usually occupy a small area relative to the size of the groundwater catchment;
3) Remnants have rarely been well managed and are often in depauperate condition;
4) Remnants that are exposed to grazing have lost their understoreys and are unable to regenerate naturally; and
5) Extraction of timber and thinning has reduced the crown cover and potential for water use.

Protection, rejuvenation, and on-going management of remnants enhance their water use and are of value for nature conservation. Maintaining remnant vegetation on permeable soils with high recharge rates is a priority. Protection of remnants in discharge areas may have few *long-term* hydrological benefits, although delaying the onset of salinity gives time for flora and fauna to adjust to the changed conditions. The remnants also help protect the soil against erosion, a common problem in saline areas. If priorities must be set, preservation of remnants on recharge areas should have a higher priority than preservation of remnants in discharge areas, unless the discharge areas contain priority nature-conservation values (e.g., wetlands) or a need exists to stabilise waterways for water-management purposes.

Management Systems
The salinity management practices discussed above are categorised into three development stages. The stages reflect current knowledge of how each practice can be used across regions to solve or manage salinity.

- Stage A: 'Solutions' are practices known to be effective and currently available for adoption.
- Stage B: Current 'best management practices' are promising practices that have not yet been fully evaluated or integrated into farming systems but that are likely to be proven within ten years.
- Stage C: 'Blue-sky' are practices that could be developed but little or no reliable information exists on them. These are long-term visions that depend on research and development.

Stage A practices consist of methods such as regional and local reforestation, farm forestry, perennial fodder shrubs, shallow and deep drainage, and aquifer pumping systems. To date, only alley farming with tagasaste (a leguminous fodder shrub; Speed et al., 1993), farm forestry (*E. globulus*, *Pinus radiata*), localised reforestation (Schofield et al., 1989; Landscope, 1996), and drainage (George and McFarlane, 1993) have been shown to be capable of lowering water tables and reclaiming saline land. Current adoption of these practices is on a small scale, limited to suitable regions mainly in the higher-rainfall areas, and where the practices are economic *per se* and more often environmentally acceptable.

Stage B practices consist of high-water-use and salt-tolerant agronomic systems, use of perennial pastures (lucerne) in certain locations, farm forestry, bedding drainage, and management systems for remnant vegetation. In some cases, these may be contributing to salinity management but as yet studies have not demonstrated how effective the practices are and how the practices can be integrated into a farming system. For example, if crops were able to achieve their water-use potential, they *might* eliminate recharge in many years in the lower-rainfall areas. Oil mallees in low-rainfall areas and lucerne, some native grasses, and eucalypts (e.g., *E. camaldulensis*) in medium-rainfall areas are also being used. Low-energy pumping systems (solar, wind) may be able to be used to manage some saline seeps.

Stage C practices consist of possible solutions based on the long-term development of such practices as bio-engineering; domestication of native vegetation for application in existing farming systems; development of energy, food, and fibre products from native vegetation; large-scale re-use and desalination of groundwaters; marketing of salt; and biosaline engineering.

Whereas government agencies in Western Australia have been primarily responsible for researching and developing practices of salinity-management systems, farmers have been active in systems development. Innovative farmers have 'hybridised' these practices and developed the embryos of new farming systems. For example, the commercialisation of tagasaste, bluegums, and oil mallees owe a great deal to the commitment of private individuals and companies.

Priorities can be established on a regional basis by considering the salinity threats in the region to both private and public assets, the opportunities for ameliorative actions in the region, and the private and public benefits flowing from those actions.

Priorities need to be considered for 1) acquiring data to assist in planning and plan evaluation; 2) assisting with regional catchment and farm planning; 3) investigations; 4) research and development; 5) technology transfer and communication; and 6) helping implement ameliorative works.

Biophysical Data

Developing accurate estimates of trends in salinity, calculating areas of tree planting, and assessing the condition of the environment rely on the existence of accurate and cost-effective biophysical data sets. In addition, to develop effective management systems, and to have those systems applied across a range of landscapes and for a range of purposes, requires that 'research-scale' information be increased and evaluated at the farm and catchment scale. Farmers require that expenditure on salinity be cost effective and that decisions can be made on sound biophysical information.

Catchment and farm planning is the first step in a long-term commitment to change the way in which the land is used and managed. Works implemented under a catchment or farm plan generally have a long life expectancy: perennial pastures (3-5 yr), bluegums (10-20 yr), pine plantations or pine farm forestry (20-30 yr), trees purely for environmental benefits (50-100 yr), re-fencing (20-50 yr), and earthworks for water control (20-30 yr).

Investing in works that are more-or-less permanent and for which an expectation exists of some permanent production benefit and on-site and off-site environmental benefits requires soundly based planning and an assessment, before implementation, of the anticipated biophysical benefits.

The biophysical data sets required to make informed salinity-management decisions include air photos, cadastre (land ownership), land use, infrastructure (roads, rail towns, etc.), climate, topography and drainage lines, geology, soils (land-management units), vegetative cover (flora, fauna), water table and streamflow (depth, flow, quality), multispectral data (satellite and airborne systems), magnetics and radiometrics and electromagnetics (airborne geophysics). The combination chosen and their priority depend on the region and its management objectives. The cost of obtaining these data sets in Western Australia is estimated to be \$5-7/ha for all except water-table data, which increase the total cost to \$10-15/ha. This expenditure is warranted if it increases the chance of success and improves the private and public benefit. The costs are small compared with the cost of implementing farm and catchment plans (*Table 5*) and funding systems that are required to maintain the capital base of the State.

In Western Australia, a priority exists for improving regional coverage of the following data sets:

- *Groundwater-level data:* hydrologic data for monitoring and prediction; electronic databases linked to hydrogeologic 'models';
- *Digital elevation data:* 2-m contours using soft photogrammetry;
- *Remotely sensed spectral data:* satellite (Landsat TM and/or SPOT) and digital video to support planning and monitoring;
- *Airborne geophysical data*: magnetics, electromagnetics, radiometrics (to evaluate local hydrogeologic processes, salinity risks, and control systems) linked to hydrogeologic models;
- *Environmental domains:* floristic, zoogeographies, and visual amenity to define the environmental values that need protecting in each region; and
- *1:25,000 colour aerial photography:* digital 1:25,000 orthophotomaps for all active catchment groups, as a base to support planning.

Is Salinity Worth Managing?

The Losses

About 1.8 million ha of formerly productive land is affected by salinity. Production from this land has either been lost or reduced. The total value of this loss is estimated to be \$1,445 million. This amount is an estimate of the capital value of the land and, therefore, includes the opportunity cost of lost production. If the current rate of salinity expansion continues, the resulting annual loss to agriculture would be approximately \$64 million each year until salinity reaches a new equilibrium, sometime in the next century (C. Campbell, pers. comm., 1996). In addition, farmers are spending about \$13.5 million/yr on 'on-ground' actions associated with salinity and a further \$14.1 million on related costs (McLennan, 1995). These costs are specified in *Table 7*. The total cost of \$27.6 million/yr is

Table 7. Annual cost of land-management practices related to salinity in the southwest (McLennan, 1995). Costs are in Australian dollars.

Measures taken		Annual cost ($ millions)
On-ground actions	Salinity and waterlogging management	3.8
	Planting of trees and shrubs	4.0
	Fencing	2.0
	Weeds and feral animal control	3.7
	Sub total	**13.5**
Related actions	Water storage and reticulation	12.8
	Farm planning	1.1
	Self education	0.2
	Sub total	**14.1**
Total environmental expenditure		**27.6**

about one percent of Western Australia's gross value agricultural production. In addition, Western Australia resource-management agencies are spending more than $10 million/yr on salinity and related land-degradation problems.

Further, costs associated with the provision of water supplies increase, because water utilities have to build replacement storages, industries must desalinate higher salinity water, and the community must forego potential sources and opportunities and pay higher domestic prices.

Replacement storages have already been built on two southwestern rivers (Collie and Denmark) in the last eight years, at a cost of $43 million. In order to limit future salinity, more than $46 million has also been spent on compensating farmers for not being able to clear their land, for purchasing land, and for initial reforestation of parts of Western Australia's five "Clearing Control Catchments." Using higher salinity water from the Wellington Reservoir is expected to directly cost industry at least $15 million in desalination and shortened machinery life.

Dryland salinity also imposes costs to infrastructures (e.g., rural towns, transport networks, buildings, pipe works), the environment (e.g., species extinction, loss of habitat, vegetation decline), and social and recreational decline and amenities. The economic impact of salinity on regional infrastructure and the environment has not been rigorously quantified. However, a preliminary benefit-cost analysis of salinity in the Kent River catchment indicated off-site costs of $210 million, comprising losses of wetlands, remnants, water resources, and damage to infrastructure. In the Lake Toolibin catchment, the direct costs of the initial protection works near the lake may exceed $0.3 million.

The Management Costs

During the past five years, the Gross Value of Annual Agricultural Production of Western Australia ranged from $2.25-3.78 billion. The potential to maintain this level of production is being threatened by salinity. Although increased production on the non-saline land is possible and is happening, is it acceptable for future generations of Western Australians that the capital base is allowed to diminish along with the environment (with its genetic diversity) and water resources?

Landholder and community partnerships should be established to develop and implement systems that would ensure maintenance of the capital base. With direct (e.g., rebates, taxation relief) and indirect financial assistance (e.g., collection of biophysical data, provision of technical advice), farmers could then afford to select options that result in managed salinity and maintainance or reduction of agricultural production. In addition, governments may be able to afford to fund the development of a *sustainable* agricultural system for the sake of its agricultural, water-resource, and environmental future. *Table 8* provides an approximate cost of financial investment required by the State to establish the bio-engineering systems to reduce the salinisation of agricultural land in Western Australia to 5 percent (i.e., to 1980 levels) and to protect all major water-resource and conservation-estate assets. Not all of the options are suited to all of the regions, and some are in a developmental stage. In addition, the costs have not undergone rigorous financial assessment. Maximum benefits should be gained within ten years for mechanical options and after 10-30 yr for biological options.

The costs associated with pumping and drainage are likely to be unrealistic for two reasons: 1) In some areas, the costs will be prohibitive because the absence of transmissive aquifers dictates closely spaced drains; and 2) drains become blocked, pumps and drains require maintenance, and disposal systems and salt removal create additional costs not accounted for here.

By contrast, if perennial woody tree crops are planted in alleys, the trees could provide a source of income and ecological value to the rural and urban community. For example, development of the *E. globulus* industry in the southwest has been predicted to provide an annual income of perhaps more than $0.5 billion and lead to the development of significant local employment.

An investment in the rapid adoption of either Case 1 or 2 would result in the need to expend $3.7-6.2 billion over a period of 20-30 yr. However, this expenditure should be seen against the ability to generate >$0.5 billion in the short-term by embarking on bluegum farm forestry in the high-rainfall areas (~600 mm/yr), where salinity is rapidly developing and where it will come to equilibrium quickly. Medium-term

Table 8. Estimated minimum cost solutions to maintain the capital base in Western Australia. Costs are in Australian dollars.

Case[1]	System	Estimated cost ($/ha)	Minimum amount of land area required to control salinity (M ha)	Total cost to Western Australia ($ billion)
1	Best perennial system: bluegums, pines, oil mallees, and tagasaste on 33 % of cleared land across the South West; perennial pastures on appropriate soils	1,000[2]	6.0	6.0
2	Best perennial system: bluegums, pines, oil mallees, and tagasaste on 20 % of cleared land across the South West; perennial pastures on appropriate soils	1,000[2]	3.6	3.6
3	Deep tube and open drainage (all potential saline land) and basic disposal	3,000	4.5	13.5[3]
4	Aquifer pumping (all potential saline land) and basic disposal (electric power)	1,800	4.5	9.0[3]
5	All "best management practice" (e.g., Stage A and B practices; see text)[2]	200	18.0	3.6

[1] Base case is five percent saline.
[2] Establishment cost is averaged for each of the bluegum, pine, oil mallee, and tagasaste options.
[3] Minimum cost. Only possible in permeable soils with safe disposal of effluent, which severely limits adoption in Western Australia.

returns from other tree crops (e.g., *Pinus pinaster* in the 450-600 mm rainfall zone) would add to the gross returns.

In the lower-rainfall eastern areas, where the rate of salinisation is less, alley-farming systems should be developed first in priority areas, around nature reserves and near towns. These areas can be used to test options and commercialise existing species and those with market potential. In the case of eucalypt oil mallees, it is essential for Western Australia to develop international market options for pharmaceuticals and industrial solvents, but an equally high priority may be to develop energy co-generation facilities, bio-fuels, and bio-saline agriculture for local use.

Today's actions must account for the values and needs of future generations. It is time in Western Australia to focus research and development on delivering quality information upon which to implement a massive program of commercial revegetation and high-water-use agriculture. Commercial-scale operations, designed by using sound biophysical information and supported by specialist advice, should be able to provide Western Australia with sustainable agricultural systems.

Acknowledgments

Some of the ideas in this paper came from discussions with colleagues in the Department of Conservation and Land Management, the Department of Environmental Protection, and the Water and Rivers Commission. The authors thank John Bartle, Ken Wallace, John Sutton, Geoff Mauger, and Ian Loh for their contributions. In addition, acknowledged are the contributions of the members of the Catchment Hydrology Group within Agriculture Western Australia, who supplied data and many of the thoughts and principles from which the conclusions were derived.

References

Barrett-Lennard, E.G., Davidson, N., and Galloway, R., 1990, Plant growth and survival in saline, waterlogged soils: Journal of Agriculture of Western Australia, v. 31, p. 56-57.

Bennett, D., and McPherson, D.K., 1983, A history of salinity in Western Australia: Perth, Commonwealth Scientific Industrial Research Organization, Division of Groundwater Research, Technical Memorandum 83/1, 20 p.

Burvill, G.H., 1947, Soil salinity in the agricultural area of Western Australia: Institute of Agricultural Science, Journal of Agriculture, v.13, p. 9-19.

Cervinka, V., 1996, Bio-engineering systems for salt removal to sustain productivity of irrigated lands, *in* National Workshop on the Productive Use and Rehabilitation of Saline Lands, 4th, Albany, WA, 1996, Proceedings: Canning Bridge, Promaca Conventions Pty Ltd, p. 373-378.

Clews, P., 1994, Groundwater in the Ord irrigation area, *in* Sherrard, J., ed., Seminar on Sustainable Agriculture on the Cununurra Clays, Kununurra, WA, Frank Wise Institute: Agriculture Western Australia, unpublished proceedings.

Ferdowsian, R., George, R., Lewis, R., McFarlane, D., Short, R., and Speed, R., 1996, The extent of dryland salinity in Western Australia, *in* National Workshop on the Productive Use and Rehabilitation of Saline Lands, 4th, Albany, WA, 1996, Proceedings: Canning Bridge, Promaca Conventions Pty Ltd, p. 89-88.

George, R.J., 1992, Hydraulic properties of groundwater systems in the saprolite and sediments of the Wheatbelt, Western Australia: Journal of Hydrology, v. 130, p. 50-278.

George, R.J., and McFarlane, D.J., 1993, Managing dryland salinity with drains and pumps, *in* National Conference, Land Management for Dryland Salinity Control Conference, Bendigo, Proceedings: Bendigo, Express Printing, p. 81-88.

George, R.J., McFarlane, D.J., and Lewis, M.F., 1991, A review of recharge and implications for management in saline agricultural catchments, Western Australia, *in* International Hydrology and Water Resources Symposium, Perth, Proceedings: Institution of Engineers, Australian National Conference Publication No. 91/22, p. 193-197.

George, R.J., Smith, A.D., and Bennett, D.L., 1993, Evolution and effectiveness of revegetation strategies for dryland salinity control in south-western Australia, *in* National Conference, Land Management for Dryland Salinity Control, Bendigo, Proceedings: Bendigo, Express Printing, p. 151-157.

George, R.J., Bennett, D.L., Arkell, P.T., and Vukelic, B., 1994, Soil salinity in the south west irrigation area, extent and management options, Soils 94, Proceedings: Busselton, Australian Society of Soil Science (Western Australia), p. 101-108.

George, R.J., McFarlane, D.J., and Speed, R.J., 1995, The consequences of a changing hydrological environment for native vegetation in south-western Australia, *in* Saunders, D.A., Craig, J.L., and Mattiske, E.M., eds., Nature conservation 4 - The role of networks: Sydney, Surrey-Beatty, p. 9-21.

Greenwood, E.A.N., 1986, Water use by trees and shrubs for lowering saline groundwater: Reclamation Revegetation Research, v. 5, p. 432-434.

Hingston, F.J., and Gailitis, V., 1976, The geographic variation of salt precipitated over Western Australia: Australian Journal of Soil Research, v. 14, p. 319-335.

Hojberg, L., and George, R.J., 1995, EM38 correlation with soil salinity and the yield of irrigated pastures in south-western Australia: Resource Management: Bunbury, Agriculture Western Australia, p. 25 (unpublished report).

Jeevaraj, C.G., 1991, Water and salt balances for an irrigated coastal plain catchment near Bunbury, Western Australia: Perth, Water Authority of Western Australia, Report WS81, p. 39.

Johnston, C.D., 1987, Distribution of environmental chloride in relation to sub-surface hydrology: Journal of Hydrology, v. 94, p. 67-88.

Landscope, 1996, Bluegums, salt and rising damp, *in* Landscope: Perth, Conservation and Land Management, v. 11, p. 8.

Lewis, M.F., 1991, Lineaments and salinity in Western Australia - Carriers or Barriers?, *in* International Hydrology and Water Resources Symposium, Proceedings: Institute of Engineers, Australia, 91/22, p. 202-209.

Lyons E., 1995, Rural town salinity survey: Northam Office, Agriculture Western Australia, Unpublished report.

McArthur, J.M., Turner, J., Lyons, W.B., and Thirlwill, M.F., 1989, Salt sources and water-rock interaction on the Yilgarn Block, Australia: Isotopic and major element tracers: Applied Geochemistry, v. 4, p. 79-92.

McFarlane, D.J., and Cox, J.W., 1992, Management of excess water on duplex soils: Australian Journal of Experimental Agriculture, v. 32, p. 857-864.

McFarlane, D.J., and George, R.J., 1992, Factors affecting dryland salinity in two wheatbelt catchments in Western Australia: Australian Journal of Soil Research, v. 30, p. 85-100.

McFarlane, D.J., George, R.J., and Farrington, P., 1993, Changes in the hydrologic cycle, *in* Hobbs, R.J., and Saunders, D.A., eds., Reintegrating fragmented landscapes: New York, Springer-Verlag, p. 146-186.

McLennan, W., 1995, Costs of environmental protection in Australia: Selected Industries, 1991-1992: Canberra, Australian Bureau of Statistics, p. 89.

Nulsen, R.A., 1981, Critical depth to saline groundwater in non-irrigated situations: Australian Journal of Soil Research, v. 19, p. 83-86.

_________1993, Changes in soil properties, *in* Hobbs, R.J., and Saunders, D.A., eds., Reintegrating fragmented landscapes: New York, Springer-Verlag, p. 107-145.

Nulsen, R.A., Bligh, K.J., Baxter, I.N., Solin, E.J., and Imrie, D.H., 1986, The fate of rainfall in a mallee and heath vegetated catchment in southwestern Australia: Australian Journal of Ecology, v. 11, p. 361-371.

Oram, D., Papst, W., Jeath, D., and Wilson, S., 1992, Economic analysis and farm planning for soil conservation and salinity control: Goulburn-Broken Catchment Case Study: Final Report to the Department of Conservation and Environment, La Trobe University, 33 p. + Appendices.

Peck, A.J., and Hurle, D.H., 1973, Chloride balance of some farmed and forested catchments in south-western Australia: Water Resources Research, v. 3, no. 9, p. 648-657.

Salama, R.B., Laslett, D., and Farrington, P., 1993, Predictive modelling of management options for the control of dryland salinity in a first order catchment in the wheatbelt of Western Australia: Journal of Hydrology, v. 145, p. 19-40.

Salerian, J.S., and McFarlane, D.J., 1987a, DRAINS: a method of financially assessing drains used to mitigate waterlogging in south western Australia: Agriculture Western Australia, Technical Report no. 54, p. 44.

_________1987b, BANKS: a method of financially assessing banks used to mitigate water erosion in south western Australia: Agriculture Western Australia, Technical Report no. 55, p. 54.

Schofield, N.J., Ruprecht, J.K., and Loh, I.C., 1988, The impact of agricultural development on the salinity of surface water resources of south-west Western Australia: Water Authority of Western Australia, Report no. WS 27, 69 p.

Schofield, N.J., Loh, I.C., Scott, P.R., Bartle, J.R., Ritson, P., Bell, R.W., Borg, H., Anson, B., and Moore, R., 1989, Vegetation strategies to reduce stream salinities of water resource catchments of south-west Western Australia: Water Authority of Western Australia, Report WS33, 81 p.

Speed, R.J., Wiley, T.L., and Simons, J.A., 1993, Tagasaste (*Chamaecytisus palmensis*) is profitable recharge control, *in* National Conference, Land Management for Dryland Salinity Control, Bendigo, Proceedings: Bendigo, Express Printing, p. 275-276.

Teakle, L.J.H., 1929, Soil alkali: Journal of Agriculture of Western Australia, v. 6, p. 88-99.

Western Australia Royal Commission on the Mallee Belt and Esperance Lands, 1917, A report of evidence, *in* Dempster, E.C., Chairman, Report of the Royal Commission on the Mallee Belt and Esperance Lands: Perth, Government Printer, 192 p.

Williamson, D.R., Stokes, R.A., and Ruprecht, J.K., 1987, Response of input and output of water and chloride to clearing for agriculture, *in* Peck, A.J., and Williamson, D.R., eds., Hydrology and salinity in the Collie River Basin, Western Australia: Journal of Hydrology, v. 94, p. 1-28.

Wood, W.E., 1924, Increase of salt in soil and streams following the destruction of the native vegetation: Journal of Royal Society, Western Australia, v. 10, p. 35-47.