ESTIMATING AND MODIFYING THE EFFECTS OF AGRICULTURAL DEVELOPMENT ON THE GROUNDWATER BALANCE OF LARGE WHEATBELT CATCHMENTS

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Abstract

Seven large catchments, cleared progressively from 1912 to 1985, were studied to determine the groundwater conditions responsible for salinization of both the pristine and disturbed environments. Detailed drilling was conducted to provide information on the nature and distribution of the physical and chemical properties of these groundwater systems. First-order estimates of recharge and discharge rates were derived from the groundwater balance, chloride mass balance, and specific yield techniques.

Recharge rates under pristine conditions estimated from the groundwater balance method were of the order of 0.02-0.14 mm/yr and 0.05-3.0 mm/yr using the chloride method. Recharge was greatest in the deep sandplain and arkosic-outcrop soil associations and least in the heavy textured midslope and valley soils. Higher rates were obtained from the specific yield technique, where recharge under current agricultural conditions was considered to be between 6 and 10 mm/yr. Recharge rates of up to 30 mm/yr were noted when flooding of the sandy-textured, valley floor soils occurred.

Clearing of the native vegetation for agriculture is estimated to have increased groundwater recharge by between one and three orders of magnitude. Equilibrium groundwater balance estimates suggest that discharge rates have only increased ten-fold. As a result of the changes to the water balance, 5-30% of particular catchments may need to become discharge areas to balance increased recharge of 6-10 mm/yr. Native woodlands and halophyte communities are considered to have played an important role in providing a complex discharge mechanism before clearing.

The management of catchments to contain soil salinity should include improved recharge control systems using specialized crop rotations. To date, however, little evidence of the success of this method exists. Therefore, discharge enhancement should also become a part of catchment management systems. Discharge can be manipulated by planting phreatophytic vegetation and by pumping groundwater from basement aquifers to improve agricultural water supplies. The results presented in this paper suggest that discharge enhancement has an important role to play and, as a part of integrated catchment water management, has the potential to control and eventually reduce dryland salinity.

Résumé. Estimation et modification des effets du développement agricole sur le bilan d'eau souterraine de grands bassins de la région des Terres à blé. Sept grands bassins versants, défrichés progressivement de 1912 à 1985, ont été étudiés afin de déterminer les conditions de salinisation des eaux souterraines pour des environnements primitifs et modifiés. Une campagne de forages a fourni des informations sur les caractéristiques physiques et chimiques des eaux souterraines et sur leur répartition. Les estimations de premier ordre des taux de recharge et d'écoulement ont été déduits du bilan hydrique, du bilan de masse de chlorure et des techniques donnant le débit spécifique.

Les taux de recharge sous environnement primitif, estimés à partir du bilan hydrique de la nappe, sont de l'ordre de 0.02-0.14 mm/an, alors que la méthode du bilan de chlorure donne 0.05-0.30 mm/an. La recharge est la plus forte dans la plaine à formation sableuse profonde et dans les associations d'affleurements arkosiques et de sols; elle est la plus faible dans les sols lourds de mi-pente et de fond de vallée. Les taux les plus élevés ont été obtenus grâce à la technique du débit spécifique; sous des conditions de cultures courantes, la recharge s'établit à 6-10 mm/an. Des taux de recharge atteignant 30 mm/an ont été observés lors de l'inondation de sols sableux de fond de vallée.

Le défrichement de la végétation primitive pour l'agriculture a pour effet d'accroître le taux de recharge d'un à trois ordres de grandeur. L'estimation du bilan d'eau souterraine montre que le taux d'écoulement n'a augmenté que de dix fois (unordre de grandeur). Du fait des modifications du bilan hydrique, 5 à 30% des bassins peuvent devenir des zones de décharge pour équilibrer l'augmentation de recharge de 6 à 10 mm/an. On considère que les forêts primitives et les communautés halophytes ont joué un rôle important en alimentant avant le déboisement unmécanisme de décharge complexe. L'aménagement des bassins en vue de limiter la salinité des sols comporterait, pour le contrôle de la recharge, des systèmes adaptés s'appuyant sur la rotation de cultures spécialisées. Cependant, pour le moment, la réussite de cette méthode n'est pas évidente. Par conséquent, l'augmentation du débit deviendrait aussi une part des dispositifs d'aménagements des bassins. Le débit peut être manipulé en plantant une végétation phréatophyte et en pompant l'eau souterraine pour l'irrigation. Les résultats présentés ici font apparaître que la hausse du débit doit jouer un rôle important et que, en tant qu'élément de la gestion intégrée de l'eau des bassins versants, elle peut être utilisée pour contrôler et éventuellement réduire la salinité des terres arides.

INTRODUCTION

The progressive clearing of 15.7 million hectares of native vegetation for the development of dryland agriculture has occurred in southwestern Australia during the past century (George, 1990a). As a consequence of this clearing, soil salinization has occurred over much of the agricultural zone (Williamson and Bettenay, 1979). Clearing is considered to be responsible for decreased transpiration and increased groundwater recharge (Peck, 1978). Salinization of previously arable land currently affects 4,430 km2 or 2.8% of land developed for agriculture, having grown at an average rate of 10,000 ha/yr since 1955 (George, 1990a).

The chloride and water balance methods (Peck and Hurle, 1973; Bestow, 1976) have been used to estimate groundwater recharge and discharge in catchments affected by secondary salinity in the higher rainfall (600-1,200 mm/yr), mainly forested fringe of Western Australia (Sharma, 1987). However, there is a lack of quantitative research in the drier agricultural areas. The methods used in these areas have included the bore hydrograph, or specific yield technique (Loh and Stokes, 1981; McFarlane et al., 1989).

Loh and Stokes (1981) suggested that recharge under agricultural conditions is proportional to the rate of water table rise and rainfall. They considered that recharge increases from 12-30 mm/yr in the 390-600 mm/yr rainfall region, to 30-100 mm/yr in the 600-1,150 mm/yr rainfall zone. Their estimates concur with those of Peck and Hurle (1973), who estimated recharge rates of between 23 and 65 mm/yr in the high rainfall area. The recharge estimates of up to 45 mm/yr by McFarlane et al. (1989) for the lower rainfall ($\approx$400 mm) valley soils are higher than those suggested by Loh and Stokes (1981). Both authors assumed a specific yield of 0.05 to calculate recharge, because, at the time there were no published data from aquifers in the low rainfall areas.

Alternative methods of recharge estimation have been proposed by several authors. Sedgley et al. (1981), Nulsen and Baxter (1982), and Nulsen (1984) estimated recharge by using water balance methods based on measured evapotranspiration data from agronomic species. Sedgley et al. (1981) estimated that recharge rates over the winter period ($\approx$ 200 mm of rain), in a 300 mm annual rainfall zone, were of the order of 7-21 mm. Later, Nulsen (1984) reported that, under annual pastures (subterranean clover) grown on sandy soils, recharge ranged from 86 to 150 mm/yr, even though growing season rainfalls were only 162 and 258 mm, respectively. The inclusion of deeper-rooted legume crops such as lupins and cereals (wheat and barley), at the expense of subterranean clover was considered to reduce recharge to between 44 and 72 mm/yr (Nulsen, 1984).

The purpose of this paper is to estimate groundwater recharge and discharge by the groundwater balance, specific yield, and chloride mass balance techniques, using data from extensive hydrogeologic investigations conducted in the eastern wheatbelt of Western Australia. The methods are recognized to be first approximations and, therefore, surrogates for more detailed studies. However, they are necessary to construct simple groundwater balances for representative catchments to enable management decisions to be made. The effect of the replacement of indigenous vegetation with agricultural species is considered. The groundwater balance is then used as a starting point from which to discuss the effectiveness of various forms of recharge and discharge manipulation.

STUDY AREA

The project was undertaken in the low rainfall (< 400 mm/yr) agricultural areas of southwestern Australia on catchments which have been cleared (75-90%) of their woodland and shrub vegetation for dryland cropping and pasture production (George, 1990a). Seven major catchments, selected as being geomorphologically representative of the region, were chosen for study (Figure 1). The hydrology of these major catchments, defined from a regional drilling program, is used to construct the water balances discussed in this paper. More detailed accounts of the hydrology and weathering products are presented in George (1992a,b). The catchments are described in more detail in George (1992a), George and Frantom (1990a,b,c,d), and McFarlane and George (1992). Only a brief outline is given below.

The geomorphology of the region has been described and mapped by Bettenay and Hingston (1964), Bettenay et al. (1964), and Mulcahy (1967). It consists of deeply weathered Archaean granitic and gneissic rocks which have been modified to produce a landscape of low relief (< 100 m) and poor internal drainage. Major palaeodrainage lines cross the region and form the headwaters of the Swan-Avon-Yilgarn drainage basin (Figure 1). Saline playas and broad discharge areas (400,000 ha) covered by halophytes are typical features of the naturally saline drainage lines (Bettenay et al., 1964).

Bettenay and Hingston (1964) recognized the existence of several major soil-landform associations considered typical of the region. The associations were mapped on the basis of their physical, chemical, and agricultural properties and were classified by landscape distribution. A summary is presented in Table 1. These form the basis of the hydrologically distinctive soil associations used later.

Catchments in the wheatbelt are typically of the order of 100-1,000 km^2 in area and have a mainstream length to catchment width ratio greater than 10. Runoff in the region usually accounts for less than 1% of annual rainfall and is sporadic, depending on large rainfall events for its generation (Anon., 1984). Mean annual rainfall ranges from 330 mm in the south and west to less than 280 mm in the north and east of the study area. Mean monthly evaporation (which totals 2,500-3,100 mm/yr) exceeds mean monthly rainfall throughout the year, reflecting a semi-arid climate.

Table 1. Brief description of the major soil associations after Bettenay and Hingston (1964). All of the associations, except Merredin and part of Stirling and Booraan units, are sand textured. Only the Ulva association contains deep (>0.9m) sandy soils.

Soil Association	Brief Description of Soil Materials	Slope/Position
1. Ulva	Gravels and sands-lateritic	Upper-slope/crests
2. Booraan	Soils on exposed weathered basement	Upper-slope
3. Danberrin	Arkosic sands and loams near bedrock	Mid-slope/crests
4. Collgar	Sandy red/yellow duplex soils	Lower-slope/valley
5. Merredin	Red/brown sandy clay/loams	Valley
6. Belka	Riverine deposits of mixed soils	Major valleys
7. Stirling	Aeolian/saline mixed soils	Major saline valleys

MATERIALS AND METHODS

Site Selection, Drilling, and Sampling

The five larger catchments, and the smaller East Belka and Brennand's catchments, were drilled as part of an extensive program which aimed to assess the nature of the groundwater systems, their hydraulic properties, the risk of salinization, and appropriate management systems. The specific methodology used to carry out these tasks and a more descriptive picture of the catchments studied are given elsewhere (George, 1990b; 1991a,b; 1992a,b; George and Frantom, 1990a,b,c,d; McFarlane and George, 1992).

In brief, a rotary-air blast drilling system was used to install 250 observation wells and piezometers

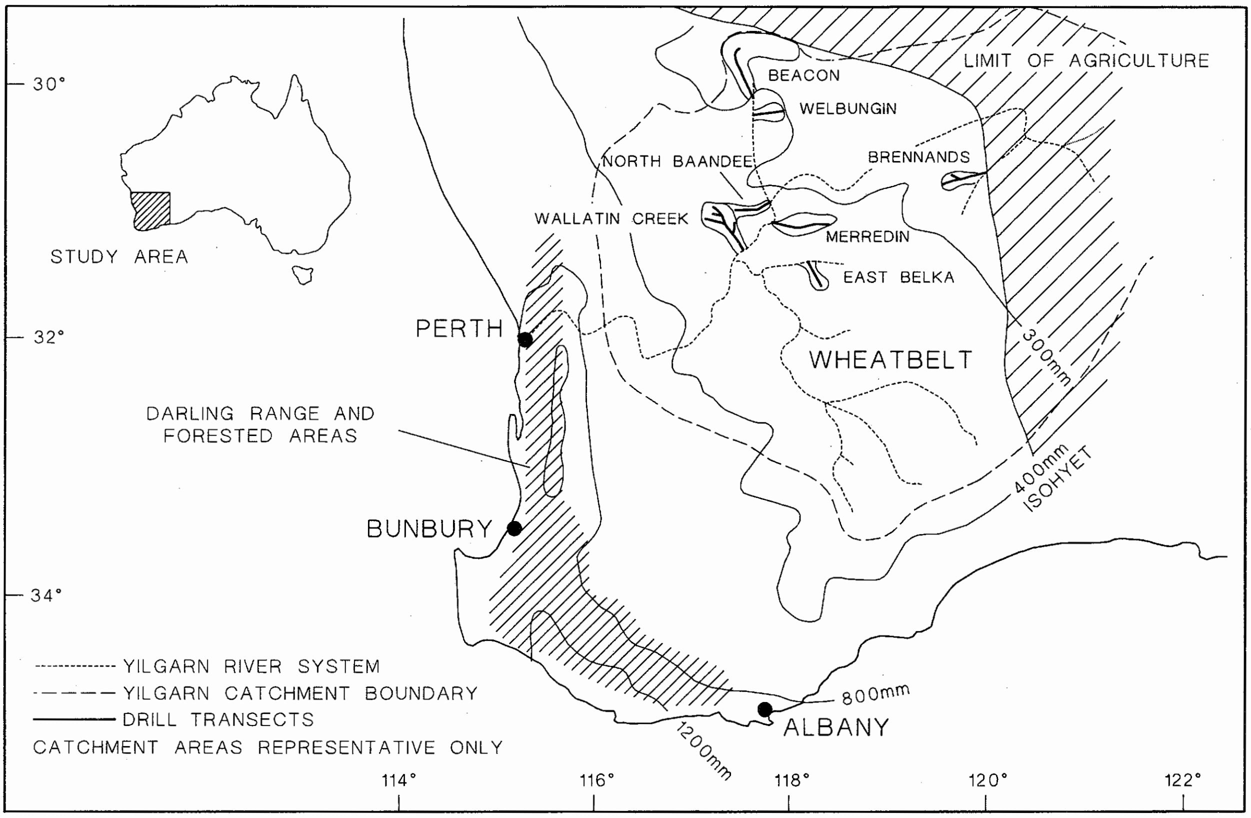

Figure 1. The location of the seven experimental catchments studied. The Swan-Avon drainage basin, rainfall isohyets, and major towns. The locations of bore transects are shown with lines drawn through each catchment.

into the seven catchments. Bore sites were located along transects adjacent to major drainage lines and in representative soil-landform associations (Table 1). The number of transects varied from the more intensive studies at Wallatin Creek (McFarlane and George, 1992), where 6 transects of up to 15 bores each were constructed, to as few as 1 transect (Brennand's catchment) comprising 9 bores (George and Frantom, 1990a). In all of the catchments, drilling was conducted after routine electromagnetic (Geonics, EM38, EM31, and EM34), magnetic (Geometrics, G856), and occasional seismic (McSeis, 500) traverses had been com-pleted.

Traverses were used to locate areas of variable salt storage (electromagnetics), intrusive dykes (magnetics, Engel et al., 1987), and bedrock ridges (seismic, McFarlane and George, 1992) considered to affect groundwater behavior. Of the 250 bores drilled, approximately 120 were drilled to bedrock, while the remainder (130) were drilled to the water table. Only the latter bores were sampled for chloride and used to estimate recharge (Sharma and Hughes, 1985).

Drill cuttings obtained from the air stream of the 120 boreholes drilled to bedrock were collected at each meter interval and sampled for chloride content. Chloride storage within the weathered zone was estimated using an average bulk density of 1.7 gm/cm^3 (McCrea et al., 1990). Groundwater was extracted from each borehole for chloride analysis. Samples were taken once bailing, pumping, or surging of the borehole had been completed and the bore adequately developed.

Test pumping to calculate the transmissivity, hydraulic conductivity, and storage coefficients of both the sedimentary and saprolite materials was carried out using the methods outlined by Kruseman and de Ridder (1983) for unconfined and confined aquifers. Slug tests were used to determine the hydraulic properties of other sites using the methods outlined by Bouwer and Rice (1976). Hydraulic gradients were assessed from ground surveying. A detailed description of the methods used to estimate hydraulic properties is given elsewhere (George, 1992a).

Methods of Recharge Estimation

Groundwater Balance Techniques

Groundwater balance techniques to estimate recharge and discharge have been favored by hydrogeologists over more expensive, complicated, or derived methods (Ghassemi et al., 1987). Therefore, estimates have relied on the calculation of vertical discharge rates (Domenico, 1971) or on annual groundwater balance (Kessler and de Ridder, 1973).

Water and salt balances have also been used effectively to define recharge and discharge rates in cleared and forested catchments (Peck and Hurle, 1973; Williamson, 1983).

The vertical discharge rate (q) is equal to the product of the saturated hydraulic conductivity (Ks) of the aquifer or its confining material and the vertical hydraulic gradient (i) such that:

$$q = Ks \cdot i \tag{1}$$

In unconfined aquifers where the Dupuit-Forchheimer assumptions are valid or where details about aquifer-aquitard conditions are known, groundwater balance equations can also be solved to estimate recharge. Under steady-state conditions, the annual groundwater flux (Q) estimates and recharge area (RA)-discharge area (DA) measurements can be combined (Equation 2) to estimate recharge (R) if:

$$R = \frac{Q}{RA} \tag{2}$$

where Q (m^3/year) is calculated from Darcy's law:

$$Q = T \cdot W \cdot i.\ (365) \tag{3}$$

where T (m2/day) is the aquifer transmissivity (Ks by aquifer thickness), W (m) is the effective width of the recharge-discharge hinge line (Freeze and Cherry, 1979), and i is the hydraulic gradient across the hinge line. Equation (2) can also be re-written to estimate mean annual discharge rates (D) such that:

$$D = \frac{Q}{DA} \tag{4}$$

The groundwater balance Equation (2) may also be modified and used to estimate the annual chloride movement (C_t) out of a catchment (T/Cl/ha) such that:

$$C_t = Q \cdot C_g \tag{5}$$

where Q is the annual groundwater flow, and C_g is the mean chloride content at the water table (mg/L). The chloride ion is chosen because it is environmentally conservative, is easily analyzed, and is the major ion in wheatbelt groundwater systems (Williamson, 1983; Gerritse and George, 1988).

To determine pre-clearing recharge rates of the seven catchments studied, groundwater balance calculations assumed that no discharge occurred above the recharge-discharge hinge line, located adjacent to the playas and halophytic areas, evident at all of the catchments. It was also assumed that the native vegetation within the catchments was not phreatophytic and, as a first approximation, that the annual groundwater flow under current hydrologic conditions is similar to that which occurred prior to clearing. The validity of these assumptions is discussed in more detail later.

From Equation (3) and drilling results outlined for each of the catchments by George (1992a,b), George and Frantom (1990a,b,c,d), and McFarlane and George (1992), estimates of the transmissivity of the sedimentary and deeply weathered profiles at the recharge-discharge hinge lines were obtained. Transmissivity estimates were derived by multiplying the average hydraulic conductivity of the material by the thickness of the particular lithologic zone, if pumping test data were unavailable.

The annual chloride flux or output (0) from the catchments, estimated from Equation (5), requires knowledge of the chlorinity of groundwaters near the recharge-discharge hinge line (C_g) and the annual groundwater flow. Annual chloride input (I) was estimated from the chloride fall (8 mg/L-oceanic aerosols and dryfall) obtained from studies by Hingston and Gailitis (1976) in the eastern wheatbelt. However, if dryfall from local terrestrial sources is omitted from the total chloride accessions, the actual chloride fall is reduced to about 4 mg/L (or 13.5 kg/ha/yr). Both estimates are used to derive a range of values for recharge as the chloride concentrations near the water table may be influenced by both sources.

Chloride Mass Balance

The long-term average recharge rates of particular landforms and their soil associations, under steady-state conditions, are functions of the distribution and flux of chloride above or below the water table (Allison and Hughes, 1978; Sharma and Hughes, 1985). In the study area, where the chloride content of groundwaters represents the long-term average chloride flux of drainage below the root zone, and where the chloride content has not been significantly altered since clearing, historic recharge rates can be estimated when:

$$R = \frac{P \cdot C_p}{C_g} \tag{6}$$

where R = long-term average recharge rate (mm/yr), P = mean annual precipitation (mm), C_p = chloride content of incoming rainfall (mg/L), and C_g is the average chloride content (mg/L) near the phreatic surface of the groundwaters in recharge areas (Sharma, 1987). Allison and Hughes (1978), Sharma and Hughes (1985), Sharma and Craig (1987), and Allison et al. (1990) suggested that, despite limitations, the results obtained using the chloride method agree with other methods of estimating recharge such as the groundwater balance and radioactive isotope techniques.

Specific Yield Method

The specific yield of unconfined aquifers is defined by the volume of water released or gained per unit change in water table elevation. For confined aquifers, specific yield can be estimated from long-term pumping tests as the storage coefficient eventually approaches specific yield values (Freeze and Cherry, 1979). In this paper, specific yield was calculated using methods outlined by Kruseman and de Ridder (1983), from pumping test data obtained in the region by George (1992a). Recharge was calculated over a suitable water balance period (a year) by multiplying the annual fluctuation of water table levels observed in the region over the period between 1985-1990 (George and Frantom, 1990a,b,c,d; George, 1992a,b) by the specific yield. Application of the specific yield technique has been discussed in detail by Johansson (1987) and has been used in other salinity studies by Bestow (1976), Loh and Stokes (1981), Jenkin and Dyson (1983), and McFarlane et al. (1989).

RESULTS AND COMMENTS

Catchment Hydrogeology

The deeply weathered, lateritic profile ranges in thickness from 10 to 60 m and comprises four characteristic horizons. These are the mottled, pallid, saprolite grit, and fractured zones (George, 1991b). Drilling revealed the existence of significant thicknesses of relatively permeable valley sediments (6-18 m), in addition to the extensive, deeply weathered pallid and altered bedrock zones (5-30 m) and the regionally extensive, saprolite grit aquifer (1-18 m) (George, 1992a). The permeabilities of the sedimentary and saprolite grit aquifers are similar (0.5-0.6 m/day), while that of the intensely weathered pallid zone (0.06 m/day) is significantly lower (George, 1992a).

The saprolite aquifer is often confined when covered by deep sequences of sediments and/or the pallid zone (valley areas) and unconfined on valley sides. The specific yield obtained from several tests on the ubiquitous saprolite aquifer is typically about 0.02 (George, 1992a). It should be emphasized that more test pumping is required to accurately define the specific yield.

Groundwater Balance Estimates

The transmissivity of the catchments varies from approximately 2 m^2/day to 8 m^2/day (Table 2). Higher values at Beacon, Wallatin Creek, Merredin, and Welbungin are the result of more transmissive sediments and greater depths of weathering of the lateritic profile. At Brennand's, with shallow (< 15 m), intensely weathered materials and no sediments, the transmissivity is lower (George and Frantom, 1990a). At North Baandee, despite a profile which consists of 10 m of sediments and 30 m of pallid, sandy clays (McFarlane and George, 1992), the transmissivity is also lower. Here, the sediments are clay textured and the hydraulic conductivity of the pallid zone lower (0.012 m/day) than at other sites (George, 1992a). At the East Belka site, a higher transmissivity aquifer (5 m^2/day) within the saprolite was found.

Table 2. Annual groundwater flux (Q, m^3/year) in each catchment estimated by multiplying the average transmissivity (T, m^2/day), width (W), and hydraulic gradient (i) obtained in studies by George (1992a,b), George and Frantom (1990a-d), and McFarlane and George (1992).

Catchment	T (m^2/day)	W (m)	i -	365 Days	Q (m^3/year)
Wallatin Creek	6	2,200	0.0024	365	11,600
North Baandee	4	1,800	0.0026	365	6,800
Merredin	6	2,400	0.003	365	15,800
Welbungin	6	5,000	0.001	365	10,900
Beacon	8	2,600	0.0025	365	19,000
Brennand's	2	1,000	0.001	365	730
East Belka	5	650	0.003	365	3,500

By applying Equations (2) and (4), the recharge and discharge rates of groundwaters within the catchment were estimated (Table 3). Given the assumptions outlined above, the data suggest that groundwater recharge under pristine, non-agricultural conditions ranged between 0.015 and 0.14 mm/yr. The mean value of recharge (0.06 mm/yr) was two orders of magnitude lower than the groundwater discharge rate (5.0 mm/yr).

Table 3. Recharge (R) and discharge (D) estimates in each catchment using the groundwater balance method. The annual flux (Q) is assumed to be a function of the size of the recharge (RA) and discharge area (DA).

Catchment	Q (m^3/yr)	RA (ha)	R (mm/yr)	DA (ha)	D (mm/yr)
Wallatin Creek	11,600	24,000	0.048	250	4.6
North Baandee	6,800	9,000	0.075	150	4.5
Merredin	15,800	36,000	0.044	300	5.3
Welbungin	10,900	14,000	0.078	200	5.4
Beacon	19,000	125,000	0.015	N/A	N/A
Brennand's	730	2,600	0.028	18	4.1
East Belka	3,500	2,400	0.140	N/A	N/A
Average Estimates			0.06		5.0

N/A = Not able to be assessed from available data. In both cases, the discharge area was remote from the topographic catchment.

CHLORIDE DISCHARGE IN GROUNDWATERS

Before clearing, the seven catchments were calculated to discharge between 20 (Brennand's) and 400 (Beacon) tons of chloride per year (Table 4). However, from the total saltfall figures (8 mg/L Cl) of Hingston and Gailitis (1976), which includes dryfall (4 mg/L Cl), the catchments appear to have been net importers of chloride. If only cyclic accessions from rainfall are included, both the North Baandee and Welbungin catchments were net exporters of salt (with I:O ratios of 0.75:1). The others remain importers of salts with I:O ratios of 1.75:1-4.25:1 (Table 4).

Chloride Mass Balance

The data presented in Table 5 summarize mean annual rainfall (P), chloride input at both 8 mg/L and 4 mg/L, and groundwater chloride contents (C_g) at the water table from 128 bores distributed within seven catchments. Bores were defined as being located in recharge areas if vertical hydraulic gradients indicated downward flow, if the water table was more than 2-3 m below ground level, and if no visible soil salinization was apparent in the locality.

Recharge estimated from the chloride mass balance method is of the order of 1.5 mm/yr in the Ulva and Danberrin soil associations (1 and 2) and 0.2 mm/yr in the valley floor or lower-slope soils (Associations 2, 4, 5, and 6). With an input to the catchments of only cyclic salts (4 mg/L), the effective recharge rates are halved.

Recharge and Specific Yield

Seasonal water-level responses are available from approximately 130 groundwater hydrographs derived from up to five years of monitoring of bores screened near the water table (George and Frantom, 1990a-d). Water-table responses to seasonal rainfall range from 0.3 to 1.5 m/yr (Figure 2). The maximum amplitude occurs in bores located along major drainage lines (George and Frantom, 1990c) or in areas of deep sandplain soils (George, 1991c). These responses are associated with major storm events (20-50 mm), localized flooding, and sporadic streamflow. In most cases, there is no difference between the responses of bores installed into either the saprolite or sediments at sites where multiple-depth piezometers and wells have been installed.

The typical amplitudes of wheatbelt groundwater hydrographs are approximately 0.30-0.50 m. Using the estimated specific yield from local pumping tests of 0.02 (George, 1992a), representative recharge rates of six to 10 mm/yr are derived. After major valley flooding events, hydrograph responses were observed to be between 1.0 m and 1.5 m. Consequently, recharge rates using a specific yield of 0.02 increase to between 20 and 30 mm/yr. However, annual hydrographs from bores near discharge areas normally show a marked recession during the summer months when groundwater discharge (evaporation from saline areas, e.g., BE01, Figure 2) and perhaps transpiration by phreatophytes from the water table take place.

Table 4. Estimated annual chloride loss (Ct) and equilibrium condition of the catchments calculated from Equation 5, derived from knowledge of the annual groundwater flow (Q), and the input (I) and output (O) of chloride and water.

Catchment Life	Q (m^3/yr)	Cg* mg/L	Cg* T/m^3	Ct T/yr	I** T/yr	I:O Ratio 8 mg/L Cl	I T/yr	I:O Ratio 4 mg/L Cl
Wallatin Creek	11,600	16,000	0.016	190	650	3.5:1	325	1.75:1
N. Baandee	6,800	25,000	0.025	170	250	1.5:1	125	0.75:1
Merredin	15,800	14,000	0.014	220	980	4.5:1	490	2.25:1
Welbungin	10,900	26,000	0.026	280	380	1.5:1	190	0.75:1
Beacon	19,000	21,000	0.021	400	3,400	8.5:1	1,700	4.25:1
Brennand's	730	26,000	0.026	20	70	3.5:1	35	1.75:1
East Belka	3,500	5,000	0.005	18	60	3.5:1	30	1.75:1
Summary	9,800	19,000	0.019	184	830	3.8:1	475	1.9:1

Cg* = Average groundwater chloride near the hinge line.

** = Inputs from cyclic salts is 4 mg/L Cl and doubles to 8 mg/L Cl when terrestrial accessions are included (Hingston and Gailitis, 1976).

(I:O = Input:Output Ratio)

Table 5. Estimate of the annual recharge from the chloride mass balance method using the annual rainfall (P), mean groundwater chloride content of the water table (Cg), and two estimates of saltfall (8 and 4 mg/L). Only the chloride contents of 104 bores screened near the water table in recharge areas were used.

Catchment	Soil-Landform Association (see Table 1)	P (mm)	Cg (mg/L)	n	Range of Cg (mg/L)	RECHARGE 8 mg/L (mm/yr)	RECHARGE 4 mg/L (mm/yr)
Wallatin Creek	1, 3	330	1,780	10	280-5,500	1.50	0.75
	2	330	16,400	8	9,050-21,400	0.17	0.08
	4, 5, 6	330	14,500	33	2,200-22,700	0.18	0.99
North Baandee	1, 3	330	3,727	2	2,800-4,500	0.70	0.35
	2, 4, 5, 6	330	10,600	8	2,800-43,000	0.25	0.12
Merredin	1,3	320	1,400	3	115-2,200	1.90	0.85
	2, 4, 5, 6	320	9,300	18	2,400-14,000	0.25	0.12
Welbungin	1, 3	300	800	1	(a)	3.00	1.50
	2, 4, 5, 6	300	23,000	8	17,000-23,000	0.10	0.05
Beacon	1, 3	300	-	-	(ND)	-	-
	2, 4, 5, 6	300	16,500	15	4,500-24,000	0.15	0.07
Brennands	1, 3	290	3,400	1	(a)	0.70	0.35
	2, 4, 5, 6	290	27,000	8	9,400-35,000	0.10	0.05
East Belka	1	330	2,152	6	259-3,500	1.20	0.60
	4	330	5,200	7	3,200-7,199	0.50	0.25
Summary	1, 3					1.50[1]	0.75
	2, 4, 5, 6					0.20[2]	0.10

1, 2: Best estimates of recharge for associations with similar soil characteristics.

(a) Range not appropriate due to insufficient number (n) of samples.

(ND) No data.

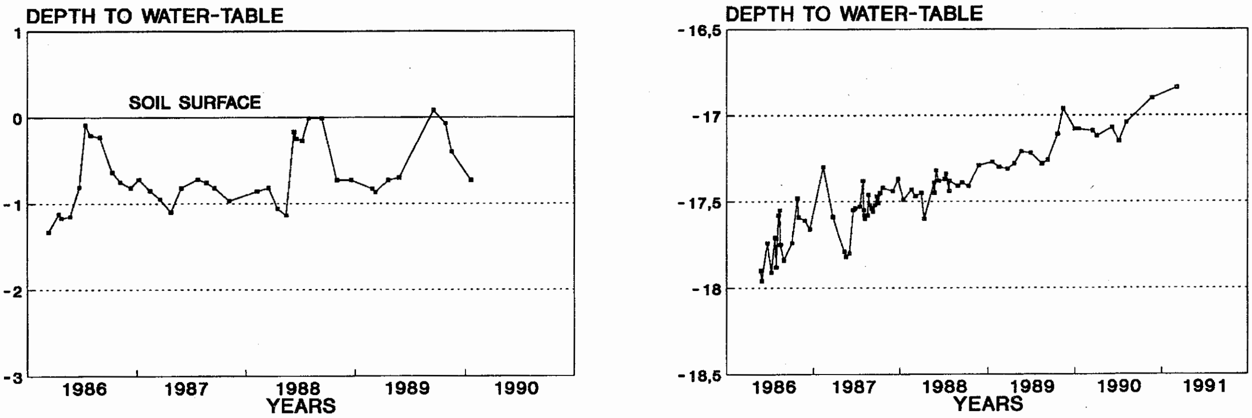

Figure 2. Wheatbelt hydrographs from unconfined aquifers in discharge areas in major valleys (Beacon, left graph) show a marked seasonal response (BEO1), while higher in the landscape in confined aquifers (right graph), there is less seasonal influence.

DISCUSSION

Estimates of Recharge and Discharge

The results presented above suggest that recharge and discharge rates have changed significantly since the clearing of native vegetation for agriculture took place. However, the lack of historic data and the limitations of the methods must be considered. This is especially important because management of landscape salinization requires knowledge of the pre-clearing and present conditions of salt and water equilibria within catchments. The three methods used can be seen to represent the hydrologic conditions of pre-clearing landscapes (groundwater balance and chloride mass balance) and the modern landscapes (specific yield technique).

Use of the groundwater balance method assumes that the saturated thickness, hydraulic gradient, and mean transmissivity of the aquifers adjacent to the recharge discharge hinge-line have not been altered substantially since clearing, and that other forms of discharge (e.g., phreatophytic losses) do not occur. However, evidence of water-table rise used to estimate recharge from the specific yield technique suggests that changes have occurred and are continuing. The role of phreatophytic losses is considered later.

Given that the rates of water-table rise found by Loh and Stokes (1981) and the author (0.05-0.2 m/yr) are consistent with long-term changes, then the estimates presented in Table 4 may be high. However, even a three to five m rise in regional water tables (considered an overestimate in the pre-clearing discharge area) only represents a 10% increase in the saturated thickness. By substituting higher values of transmissivity into the calculations, the errors introduced are probably less than those implicit in estimating hydraulic properties. Therefore, the results are proposed as first approximations which, if anything, are overestimates, but which are significant when compared with current aquifer recharge estimates of 12-30 mm/yr (Loh and Stokes, 1981) brought about by clearing. It is also significant that the rates of groundwater discharge suggested for the pristine wheatbelt environment compare favorably with estimates from other Australian studies reviewed by Lloyd (1986) and those obtained by Jacobsen (1988) and Barnett (1989).

The chloride mass balance method has been used extensively to estimate recharge (Sharma, 1987; Sharma and Hughes, 1985; Sharma and Craig, 1987; Allison et al., 1990). The method relies on the condition that the chloride flux immediately above and below the water table is in equilibrium with incoming chloride (Sharma, 1987). Given the lack of historical data describing changes in groundwater quality since clearing (Laing, 1983) and the conditions imposed for the calculations of Table 5, it is suggested that the results are again first approximations of aquifer accessions under native vegetation. However, the validity of the results is enhanced as much of the recharge areas in the eastern wheatbelt have been cleared only recently (0-30 years). Moreover, Barnett (1989) and Allison et al. (1990) reported similar recharge rates (0.04-0.09 mm/yr) under similar biologic and climatic conditions to those experienced in the local study area. Further confirmation is obtained from the results from Brennand's catchment (Table 5), which is still substantially wooded (partial clearing took place only 3-7 years ago) and which has a similar recharge rate to the other catchments (George and Frantom, 1990a).

The results from the specific yield technique do not relate to conditions developed under native vegetation. The implicit assumption of the method is that the annual fluctuations of the water table can be attributed to local recharge and that the specific yield (Sy) of these aquifers is of the order of 0.02. Bore hydrographs and pumping-test analyses validate the first assumption, while other estimates of Sy, calculated by Bestow (1976) 0.036; Martin (1988) 0.014; and P.R. George (Personal Communication, 1989) 0.015, are also in agreement with the local values.

Developing Salinity: Wallatin Creek Catchment

The Wallatin Creek catchment is considered to be representative of the hydrologic environment of the central-eastern wheatbelt (McFarlane and George, 1992), and it is the only one of the catchments studied which shows significant (2% of the arable area) secondary soil salinity. The catchment is used as a framework to review the effect of clearing and discuss methods of management to control salinity. A detailed account of the catchment is given by McFarlane and George (1992).

The catchment is considered to have been in hydrologic equilibrium prior to clearing, when mean annual recharge and discharge (from Method 1) were approximately 0.06 and 5 mm/yr, respectively. The estimated (maximum) annual groundwater flow from the catchment was about 11,600 m^3 (Table 2). However, calculations using the chloride mass balance technique (Table 5) suggest that recharge from the Ulva and Danberrin provinces was about 0.75-1.5 mm/yr. From the estimate of the area occupied by these soil associations within the catchment (42% or 9940 ha), it can be calculated that approximately 75,000-150,000 m^3 of recharge was entering the groundwater system annually. As a consequence, recharge from less than half of the catchment would have exceeded the maximum groundwater flow by about an order of magnitude.

This difference could be partly attributed to the lack of precision of the groundwater mass balance method. However, it may also suggest that groundwater discharge occurred within the catchment. In the Wallatin Creek catchment, where swamps, springs, and other forms of groundwater discharge were not evident prior to clearing, the phreatophytic behavior of Eucalypts, discussed recently by other researchers (Sonogan and Patto, 1985; Greenwood, 1986; Schofield et al., 1989), is the most likely method of establishing the balance between recharge and discharge.

If the local vegetation were phreatophytes, then the indigenous species must have been using either "brackish" groundwater (< 10,000 mg/L) at considerable depth in the upper and midslopes, or more saline water (> 10,000 mg/L) in the lower slopes and valley floor. Deep roots, observed to 28 m under native vegetation nearby (Nulsen et al., 1986) and up to 40 m in the Darling Range (Dell et al., 1983), would have access to groundwater across the entire catchment.

If the difference between the two methods of recharge estimation can be attributed to the phreatophytic behavior of native woodlands, it suggests that the water-table rise following clearing is due to both decreased groundwater discharge (0.75-1.5 mm/yr) and increased recharge (< 10 mm/yr). The implication for salinity management of the role of reduced discharge as a mechanism for water-table rise was suggested by Peck (1977). However, to date there remains little recognition of its importance and relatively little research into its role in the salinization process. Recharge area management remains the cornerstone for salinity reclamation despite recent evidence of the success of discharge enhancement schemes (Schofield et al., 1989).

The Role of Discharge

The clearing of native vegetation from the valley floor soil associations in the Wallatin Creek catchment occurred largely during the period between 1910 and 1960, and dryland salinity began to occur following the wet seasons of the early 1960s (McFarlane and George, 1992). In 1991, there were over 500 ha of salt-affected land in the catchment, representing a rate of increase of about 15 ha/yr. Using estimates of recharge (6-10 mm/yr) obtained under present conditions (calculated above), approximately 1.4 to 2.4 million m^3/yr of rainfall now reach the aquifer. This increase in recharge is approximately an order of magnitude greater than that considered possible if the indigenous vegetation were phreatophytes and over two orders greater than the initial pre-clearing groundwater balance estimate (11,600 m^3). Soil salinization is, therefore, dependent on both increased groundwater recharge and decreased discharge rates.

In a review of recharge and discharge in arid and semi-arid areas of Australia, Lloyd (1986) noted that discharge rates, obtained from groundwater balance methods, rarely exceeded 90-280 mm/yr (4-5% of potential evaporation – PE). In nearby areas, Greenwood and Beresford (1980) used a ventilated chamber to measure evaporation rates from a bare soil at a site 15 km west of the Wallatin Creek catchment. They measured rates of 0.4 mm/day over the 200-day summer period (80 mm/yr). Elsewhere, Jenkin and Dyson (1983) and George and Frantom (1990d) used the groundwater balance method and estimated discharge to be on the order of 73 mm/yr and 30-50 mm/yr, respectively. At other wheatbelt sites, George (1992a) used the vertical discharge method and found discharge rates to be between 50 and 230 mm/yr. From a range of different methods, the authors indicated that discharge rates were very low, between 1 and 10% of local potential evaporation rates.

In order to estimate the likely water balance at Wallatin Creek and to predict the resultant area of saltland and ramifications for management, a simple model to emphasize the significance of discharge is suggested (Table 6). In the catchment, discharge takes place by evaporation from the capillary fringe. Direct seepage, as baseflow or springs, is rare in the semi-arid, deeply weathered, and flat landscapes affected by salinity. Therefore, by limiting the rate of discharge to the maximum level of potential (pan) evaporation (2,600 mm/yr) and by calculating the resultant areas and rates of discharge, a new catchment balance can be projected (Table 6).

Using the regional estimates of discharge as a guide (30-230 mm/yr), it can be seen that about 5-30% of the catchment may need to become discharge areas to achieve a new equilibrium with the increased recharge of 2.4 million m^3/yr produced since clearing. The data suggest that the development of saltland is controlled partly by the restriction placed on discharge by the low permeabilities of soil materials and vertical gradients of groundwater beneath salt-affected areas and partly by extremely high recharge rates relative to those which occurred under forested conditions.

Recharge and Agronomic Manipulation

Agronomic manipulation of recharge areas has been considered an appropriate method of salinity

Table 6. Using the annual pan evaporation rates and maximum groundwater accession of 2.4 million m3, the implied area required to discharge the addi-tional water brought about by clearing can be estimated. The table emphasizes that, at the low discharge rates observed (30-230 mm/yr), large areas of land (5-30% of the catchment) must become saline to create a new equilibrium between recharge induced by agriculture and discharge.

Potential Evaporation (PE) (pan)* mm/yr	Actual Discharge Rate		Implied Discharge Area	
	mm/yr	% PE	ha	%
2,600	2,600	100	90	0.4
2,600	1,300	50	180	0.7
2,600	660	25	360	1.5
2,600	330	12.5	720	3.0
2,600	160	6.2	1,440	6.0
2,600	80	3.1	2,880	12.0
2,600	40	1.6	5,760	24.0
2,600	20	0.8	11,520	48.0
2,600	10	0.4	23,000	96.0
2,600	5	0.2	>24,000	>100.0

* Average pan evaporation (Bureau of Meteorology data).

control (Nulsen and Baxter, 1982; Nulsen, 1984). In the wheatbelt, these authors recommend an increase in cropping frequency and the use of deep-rooted annual plants to reduce recharge. However, at their study sites in the 350-400 mm rainfall environment, reductions of recharge (10-30%) due to rotation and species changes only reduced rates to 44-72 mm/yr. At such high recharge rates (up to 20 times those reported here), both the area of discharge and/or rate of discharge would have to increase. Given the results discussed above, this appears unlikely.

In addition, there have been no reported cases of reclamation having taken place in catchments treated with conventional annual crops and pastures. However, it should be noted that, in higher rainfall regions in Victoria (P.R. Dyson, personal communication, 1990) and particularly in North America, perennial species such as lucerne have reclaimed saline seeps when about 80% of the recharge area was planted (Halvorsen and Reule, 1980). However, observations of groundwater dis-charge and salinity in only partially cleared (> 70% forested) wheatbelt catchments suggest that plantings on small (< 25%) areas, omitting the lower slopes and discharge areas, are not sufficient to prevent salinity. Tree plantations with Eucalypt species are considered to be important for recharge and discharge control, when as much as 40-50% of the lower slopes of a catchment are planted (Schofield et al., 1989).

Discharge Manipulation

The inherent difficulties in recharge area manipulation such as cost, interfering with established farm practices, the lack of evidence of the effectiveness of agronomic methods based on annuals, and the time needed to reduce or reclaim saline areas make discharge area management attractive. However, few successful discharge enhancement projects have been attempted in Western Australia, apart from conventional drainage trials to lower water tables in selected saline seeps (George, 1986, 1991a).

The phreatophytic behavior of trees in reforestation projects on saline catchments in southwestern Australia has been reviewed by Bell et al. (1988) and Schofield et al. (1989). They reported evidence showing that water tables have fallen significantly (from up to 3 m) under (approximately 10-year old) plantations of Eucalypts where groundwater salinities were about 10,000 mg/L. Similar results using trees have been observed by Sonogan and Patto (1985), Engel and Negus (1988), and George (1990b).

In the eastern wheatbelt, groundwater salinities adjacent to saline seeps range from < 1,000 to 50,000 mg/L (Table 5). Therefore, only at sites where salinities are low enough (< 10,000 mg/L) would plantations of Eucalypts be able to intercept groundwater. To lower water tables, interception must occur at a rate quicker than the water table can be replenished (Engel and Negus, 1988; Schofield et al., 1989; George, 1990b).

To emphasize the role of trees planted in an agroforestry design (such as those discussed by Schofield et al., 1989), an example from the Wallatin Creek catchment may be used. By assuming that a phreatophytic woodland has a discharge rate of 100 mm/yr (2.6% of potential evaporation), an area of 1,000 ha could remove the equivalent of 40-70% (1,000,000 m3) of clearing-induced recharge. In doing so, water-table reductions and the reclamation of saltland could be achieved. Apart from practical considerations, such as economics, there remains some concern as to whether the trees will survive in the long term due to the buildup of salts in the root zone (Greenwood, 1986). However, Schofield et al. (1989) observed a reduction, not rise, in water-table salinity under reforestation. This was attributed to the downward flow of salt with the fresher rainwater, once the capillary contact of the water table with the soil surface had been broken. Mechanisms of salt exclusion and their longer-term consequences on tree performances require additional research.

An alternative method of discharge manipulation is both profitable (Salarian et al., 1986) and ecologically adapted to saline environments (Malcolm, 1986). Halophytes, or "saltbush", are salt-tolerant and perennial phreatophytic shrubs (< 3 m high) which establish and volunteer on saline seeps once correctly established (Malcolm, 1986). Greenwood and Beresford (1980) suggested that, apart from the 80 mm/yr lost by soil evaporation, an additional 250 mm/yr were transpired by Atriplex vesicaria from the water table.

More recently, Malcolm et al. (1988) suggested that the transpiration of other Atriplex species (e.g., A. amnicola), estimated from variations in chloride storage in the root zone, could be up to 400 mm/yr, or 16% of the potential evaporation rate. The effect of increased discharge on the water-balance calculations (Table 6) suggests that, when the catchments groundwaters reach equilibrium, the area of saltland could be reduced by halophyte plantings.

Finally, George (1991a) has shown that, in some cases, discharge can be improved and water tables lowered by establishing groundwater extraction wells. Test pumping and drawdown observations suggest that areas of 10 to 100 ha can be influenced by wells pumping from between 30 and 230 m^3/day. For example, George and Frantom (1990d) estimated that pumping at 30 m^3/d would withdraw the annual recharge in a small (40 ha) subcatchment within 100 days.

For the remainder of the year, even if the rate was reduced, water tables would be lowered. At this site, the disposal of saline groundwater (31,000 mg/L) and the cost of pumping could pose legal, environmental, and economic problems. However, at other sites, groundwater of a salinity less than 10,000 mg/L, produced from weathered zone and sedimentary aquifers, could be a major source of water for agriculture (George, 1991b). The increased availability of groundwaters would be an asset to farmers and would assist the reclamation of saltland.

The success of some of these management options assumes that a well-connected aquifer system exists. However, in complex sedimentary and weathered terrains, this may not always be the case. Research is, therefore, required to assess the connectivity of aquifers and the suitability of each of these options as a part of integrated management systems for dryland salinity control.

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