Geogr. Fis. Dinam. Quat.,
16 (1993), 47-64, 7 figg., 6 tabb.

RICHARD J. GEORGE (*) & ARTHUR J. CONACHER (**)

THE HYDROLOGY OF SHALLOW AND DEEP AQUIFERS IN RELATION TO SECONDARY SOIL SALINISATION IN SOUTHWESTERN AUSTRALIA

Abstract: GEORGE R.J. & CONACHER A.J., *The hydrology of shallow and deep aquifers in relation to secondary soil salinisation in Southwestern Australia* (IT ISSN 0391-9838, 1993).

Results are reported from detailed research which has been carried out since 1984 on several Western Australian wheatbelt catchments, ranging in size from 12 ha to 1000 km^2, in order to quantify the nature and roles of groundwater aquifers in relation to secondary salinisation.

Secondary soil salinisation in the semi-arid wheatbelt has increased by 600% over the past 34 years to 440 000 ha, and is likely to increase by at least another 500% in the next 30-50 years. Changes in groundwater hydrology following the replacement of the native, woodland vegetation with agricultural crops and pastures during this century, have been responsible for the increasing problem. Current recharge rates to groundwater aquifers are approximately two orders of magnitude greater than pre-clearing discharge rates, resulting in increased groundwater pressures and the accumulation of saline water in low-lying parts of the landscape.

In wetter (>400 mm mean annual rainfall), western wheatbelt areas with texture-contrast soils, ephemeral to seasonal throughflow may contribute about 50% of the water discharging in salt-affected areas, but only about 2% of the soluble salts. Deep aquifers contribute the remainder. In drier (<400 mm/yr) and flatter areas in the central and eastern wheatbelt, contributions from ephemeral throughflow in shallow soils appear to decrease. However, perennial aquifers perched above silicified mottled or pallid zones of the deeply-weathered soils, at the base of deep, coarse, yellow «sandplain» materials, are wholly responsible for the formation of small, saline, «sandplain seeps», which account for about 10% of secondary, salt-affected land in the region. In all parts of the wheatbelt, both types of perched aquifers provide significant quantities of recharge to the deep, perennial aquifers which are responsible for most of the large-scale, valley salinisation.

KEY WORDS: Hydrology, Aquifers, Soil salinisation, Wheatbelt, Southwestern Australia.

Riassunto: GEORGE R.J. & CONACHER A.J., *Idrologia di acquiferi superficiali e profondi dell'Australia sud-occidentale in relazione alla concentrazione secondaria di sali nel suolo.* (IT ISSN 0391-9838, 1993).

Ricerche di dettaglio sono state eseguite a partire dal 1984 in numerosi bacini della fascia del grano dell'Australia occidentale, di dimensioni variabili tra 12 ha e 1.000 km^2, al fine di quantificare la natura ed il ruolo degli acquiferi sotterranei in relazione alla concentrazione secondaria di sali nel suolo. Quest'ultima, nella fascia del grano semiarida, ha subito un incremento di oltre il 500% negli ultimi 34 anni e probabilmente subirà un ulteriore aumento del 500% nei prossimi 30-50 anni. Durante questo secolo, le modificazioni delle caratteristiche idrogeologiche del sottosuolo, conseguenti alla sostituzione della vegetazione forestale originaria con vaste coltivazioni ed alla diffusione della pastorizia, hanno causato questo inconveniente che si aggrava progressivamente. L'attuale velocità di ricarica degli acquiferi è due ordini di grandezza maggiore dei tassi dell'emungimento, determinando un aumento della pressione degli acquiferi e la concentrazione di acqua salata nelle depressioni della superficie topografica.

Nella fascia del grano occidentale, più umida (con precipitazioni > di 400 mm/anno), afflussi effimeri o stagionali possono contribuire per il 50% circa alla concentrazione di sali da parte dell'acqua nelle aree interessate da alta salinità, ma solo per circa il 2% dei sali solubili. Gli acquiferi profondi forniscono la parte rimanente. Nelle secche (<400 mm/anno) e piatte aree della fascia del grano centrale ed orientale, il contributo degli afflussi effimeri in suoli superficiali sembra diminuire. Comunque, gli acquiferi perenni sospesi sulle macchie silicizzate o zone particolari dei suoli profondamente alterati, alla base dei materiali profondi e grossolani che costituiscono le «sandplains» sono completamente responsabili della formazione di piccoli filtri sabbiosi, ad alta concentrazione di sali, che contribuiscono, per circa il 10% alla formazione di sali secondari. In tutta la fascia del grano, entrambi i tipi di acquiferi sospesi forniscono una quantità significativa di acqua per la ricarica degli acquiferi profondi e perenni, che sono responsabili della maggior parte della concentrazione di sali nelle valli, su vasta scala.

TERMINI CHIAVE: Idrogeologia, Salinità del suolo, Fascia del grano, Australia Sud-occidentale.

INTRODUCTION

In 1989, more than 440 000 ha of previously fertile farmland in the predominantly wheat/sheep region of southwestern Australia had been rendered unproductive by secondary salinisation (GEORGE, 1990a). This area of degraded land, which affected 39% of the 13 400 farmers in the region, had increased by more than 600% from

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(*) *Department of Agriculture, PO Box 1231, Bunbury, WA 6230, Australia.*
(**) *Department of Geography, University of Western Australia, Nedlands, WA 6009, Australia.*
Communication presented at the I.G.U.-COMTAG Symposium on Geomorphology of active tectonics areas, May-June 1990, Cosenza (Italy).

the time the first saltland survey was conducted in 1955 (Burvill, 1956).

It is widely accepted that the fundamental cause of the problem is the replacement of indigenous woodland vegetation with introduced annual crops and pastures (Peck, 1978; Conacher, 1982, 1990). The native forest and woodland vegetation has deep roots (20-40 m: Dell & *alii*, 1983; Nulsen & *alii*, 1986) which enable the plants to draw on deep soil moisture and groundwaters, and to transpire water throughout the year. In contrast, the exotic species can only draw on soil moisture from the top 1-2 m of soil during the short September-November period of significant transpiration. During the rest of the year climatic conditions are too dry (November-May, <30% annual rainfall), too hot (November-May, 20-40°C temperature range) or too cold (May-August, <10°C minimum temperatures) for crop and pasture growth (Bureau of meteorology, 1989). Hence the replacement of the native vegetation has resulted in an hydrological imbalance, or an «excess» of water in the landscape. This excess water has in turn mobilised and redistributed the soluble salts — predominantly (80-90%) sodium chloride — which have accumulated previously over tens of thousands of years in the groundwaters and deeply-weathered soils which characterise the Archaean granite-gneiss craton on which the wheatbelt is located (Mulcahy, 1973; Peck & Williamson, 1987). During this century, increasingly-saline groundwaters have been raised from depths of up to 50 m below the surface to within 1-2 m of the soil surface, causing the soluble salts to be either precipitated at the surface following capillary rise and evaporation, rendering the soil toxic to plants, or leached into waterways. Indeed, only 48% of divertible surface water resources in the region are still fresh (with total soluble salt concentrations of <500 mg/L) (Western australian water resources council, 1986).

What is less clear are the precise mechanisms or pathways of water movements in the landscape by which the salts have been, and are being, redistributed. For many years the prime mechanism thought responsible for the secondary salinisation problem in southwestern Australia was the raising of deep, regional groundwater tables due to increased recharge following clearing of the native vegetation for agriculture, as indicated above (for example Holmes, 1971). A practical implication of this view was that, at that time, the agency responsible for soil conservation in Western Australia, the Department of Agriculture, recommended to farmers that they fence off their salt-affected land (to control grazing) and establish salt-tolerant plants (Smith, 1961; Malcolm, 1972). In other words, the problem was considered to be insoluble and the management response was, essentially, a «learn to live with the problem» approach. Although alternative mechanisms including the roles of perched groundwaters and surface runoff were implicit in the work of Wood (1924), and were explicitly put forward by Bettenay & *alii* (1964), their work seemed to have little impact: indeed, there were very few researchers working on the problem until the 1970s. In 1975, Conacher proposed a throughflow model of secondary salinisation. Williamson & Bettenay were the first to present, in 1979, field-derived data demonstrating not only that groundwater tables do rise following clearing, leading to land and stream salinisation, but that mixing between near-fresh, perched, ephemeral or seasonal throughflow aquifers and the much more saline, deeper groundwaters was taking place.

Later work in higher rainfall (>900 mm per annum) parts of the State also demonstrated that at least two aquifer systems are involved (Anon, 1981; Stokes & Loh, 1982; Conacher & *alii*, 1983). The practical significance of this work was that it raised the prospect of land managers being able to manipulate some of the near-surface water movements, in the hope that, by controlling waterlogging, this would at least alleviate the secondary salinity problem (Barrett-Lennard, 1986). However, until the relative roles of the aquifers can be quantified, particularly in drier (<600 mm per annum) wheatbelt areas, it is not possible to develop specific and practicable remedial measures.

Accordingly, an initial, detailed study was undertaken of a small (12 ha) catchment in the western wheatbelt in order to assess the relative contributions of the two aquifer systems (George 1992a). Mean annual rainfall here is 520 mm. This work formed an early stage of a longer-term project which extended the study to processes in much larger catchments (to 1000 km^2) in drier (<400 mm) parts of the wheatbelt (George, 1992b, 1992d. The feasibility of several options for dealing with secondary salinisation was also tested (George, 1990c, 1992c. Sandplain seeps, an important manifestation of secondary salinisation in the drier, central and eastern wheatbelt, were also investigated (George, 1990b, 1991, 1992d. This paper summarises the findings of the above research programme with respect to aquifer characteristics and processes. The work is seen as making an important contribution to the provision of quantitative data on the relative roles of the aquifers, thereby enabling land managers to devise effective remedial measures. Methods used are outlined here and are described in detail in the references cited.

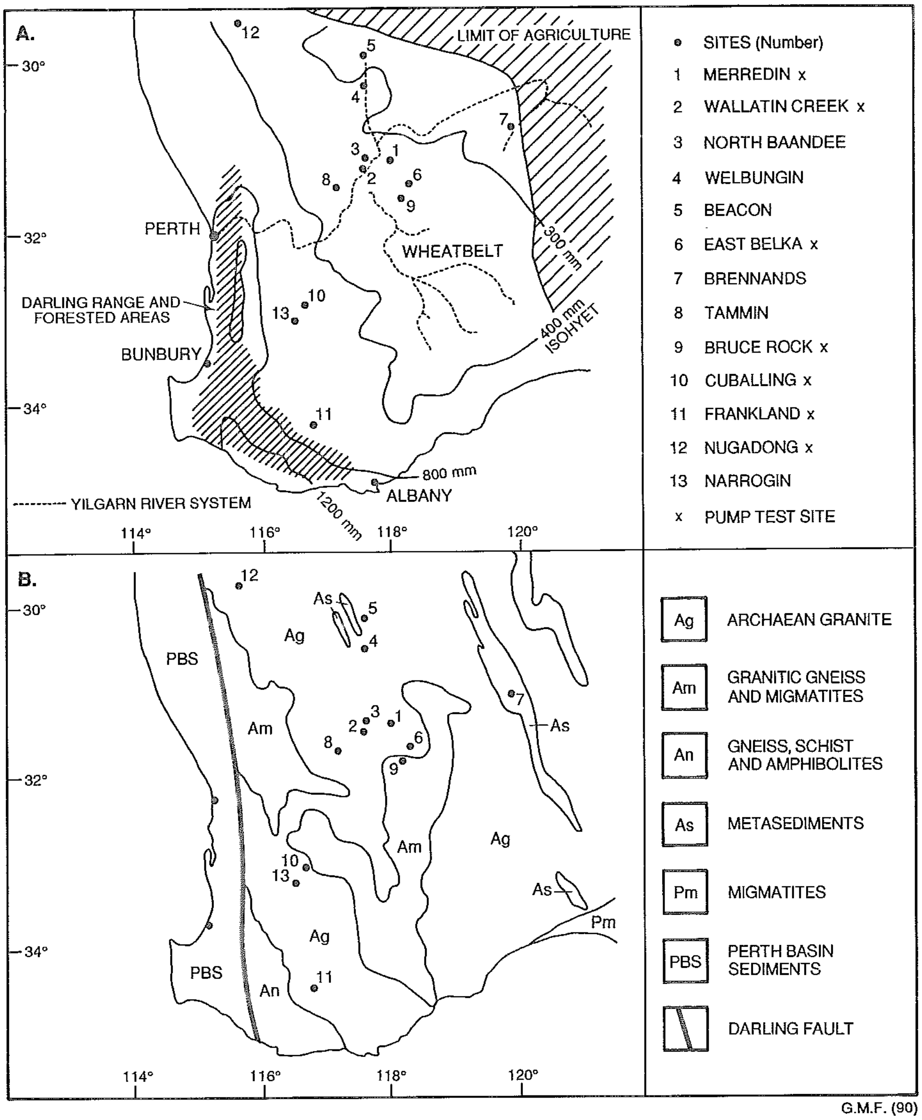
METHODS

The Narrogin Catchment

The initial catchment selected for intensive study is located 17 km NNW of Narrogin in the western part of the Western Australian wheatbelt (site 13 in fig. 1). The climate is semi-arid Mediterranean. Clearing of the native, Eucalypt, woodland vegetation for agriculture took place in the 1950s, and subsequently the catchment has been grazed by sheep and intermittently cropped with barley (*Hordeum vulgare*) on a 1 in 4 to 1 in 6 rotation.

The small (12 ha) catchment was selected because the hillslope has soils which are representative of the Narrogin region (Mcarthur & *alii*, 1977). Aquifer boundaries are apparent in the form of a dolerite dyke (Engel & *alii*, 1987), bedrock outcrops and a saline seep. The catchment has a concave slope which was considered likely to enhance perched aquifer formation and throughflow processes (An-

Fig. 1 - Locations of experimental catchments or sites, broad land use, rainfall isohyets, and generalised geology of southwestern Australia. Most of the experimental sites are located in the low rainfall (<350 mm/yr) wheatbelt region, on the Archaean granites. From George (1992b, fig. 1).



derson & Burt, 1978). Most of the 500 m slope length has gradients ranging between 3.6 and 4.6%, reducing to less than 1% towards the saline seep at the slope base. The slope was studied intensively during 1984, with further observations extending over an additional four years. Instrumentation included: networks of 12 piezometer nests and observation wells drilled to the deep aquifer in the deeply-weathered lateritic saprolite; 54 shallow wells installed to depths of 0.3-0.8 m; four nests of tensiometers to measure soil moisture conditions; a 30°-150° sharp-crested, composite V-notch weir at the end of an erosion gully which drains the saline seep; electromagnetics and magnetics systems to locate salt storage and magnetic anomalies (dolerite dykes) responsible for influencing groundwater flow, respectively, and a range of soil and water analyses (fig. 2). From these measurements it was possible to construct water and salt balances and to determine the relative contributions of the shallow and deep aquifers to saline seep formation and stream runoff generation. Full details are presented in George (1992a) and George & Conacher (in press a, b).

The Central and Eastern Wheatbelt

Following the detailed investigation of the small Narrogin catchment, research into the groundwater systems in relation to secondary salinisation was extended into the central and eastern wheatbelt (George, 1990c, 1992b, 1992c, 1992d). Catchments were selected in order to obtain representative data on groundwater systems over a wide area of the wheatbelt, by representing the local geomorphological provinces and the major lithological environments (sediments and weathered zones) of the region. More than 203 bores from the 12 additional catchments located in fig. 1, including eight pumping test sites, were analysed for the hydraulic properties of deep and shallow aquifers in the saprolites and sediments of the low rainfall (<400 mm rain per annum) region. Further details are presented in GEORGE & FRANTOM (1990a, b, c and d).

The extent of the drilling pattern reflected the size of the catchment and the objectives of each study. For example, a grid network of bores at East Belka (discussed further below) permitted a detailed study to be undertaken of the interactions between perched and regional groundwater systems (GEORGE, 1992d), whereas at Beacon the bores were drilled to provide data on the depth to saline groundwater and the nature of the aquifer materials (GEORGE & FRANTOM, 1990c). Details of drilling and bore construction methods are presented in GEORGE (1992b).

Sandplain Seeps: the East Belka Catchment

The perennial, regional groundwater systems examined above are generally considered to be responsible for most of the secondary salinity problem in the Western Australian wheatbelt, as outlined in the Introduction. However, BETTENAY & *alii* (1964) and WILLIAMSON (1978) have also noted the presence of numerous, usually small, saline areas («sandplain seeps») adjacent to extensive deposits of deep, coarse yellow sands («sandplain»), relatively high in the landscape. GEORGE & FRANTOM (1988) suggested that these seeps, formed by a perched groundwater system, may be responsible for as much as 60% of the eastern wheatbelt's secondary salinity problem, and possibly for 10% of the total area of secondary, dryland soil salinity in Western Australia. Perched sandplain groundwater systems, as well as the more ubiquitous ephemeral throughflow systems perched in duplex soils, are also considered to be a significant source of recharge to the regional aquifers (GEORGE 1992d; MCFARLANE & *alii*, 1989; JOHNSTON, 1987a).

In order to investigate these sandplain seeps in more detail, and to propose remedial measures, the East Belka catchment (fig. 5) was selected for study following the inspection of 32 sub-catchments with sandplain seeps throughout the eastern wheatbelt. This and six other sites were assessed for salinity management by tree planting, open drainage and buried tube drainage.

TABLE 1 - Hydraulic conductivities of soils and saprolite (fig. 3) in the Narrogin catchment (fig. 1). Bores were drilled using a rotary auger rig: cf. Table 2 for comparative data from two drilling methods. Source: GEORGE (1992a, table 2.1)

Zone	Mean Hydraulic conductivity (m/day) **	Range (m/day)	Number of samples
Shallow soils	1.15*	0.14 -3.82	60
Pallid-mottled	0.009	0.002-0.04	10
Weathering	0.039	0.007-0.11	4
Saprolite grits	0.09	0.01 -0.14	6
Hardpan	0.004	<0.001-0.012	4

* Method - REYNOLDS & *alii* (1983).

** Method - HVORSLEV (1951).

The East Belka catchment is located 300 km east of Perth and 30 km south of Merredin (fig. 1). It has an area of 4200 ha, although the hillslope on which the investigated sandplain seep is located is only 200 ha in extent. The catchment was cleared in 1958. It is a first order tributary of the Belka valley, which has been discussed by BETTENAY & *alii* (1964). A detailed description of the site, experimental design and instrumentation is presented in GEORGE (1992d).

RESULTS AND DISCUSSION

The Narrogin Catchment

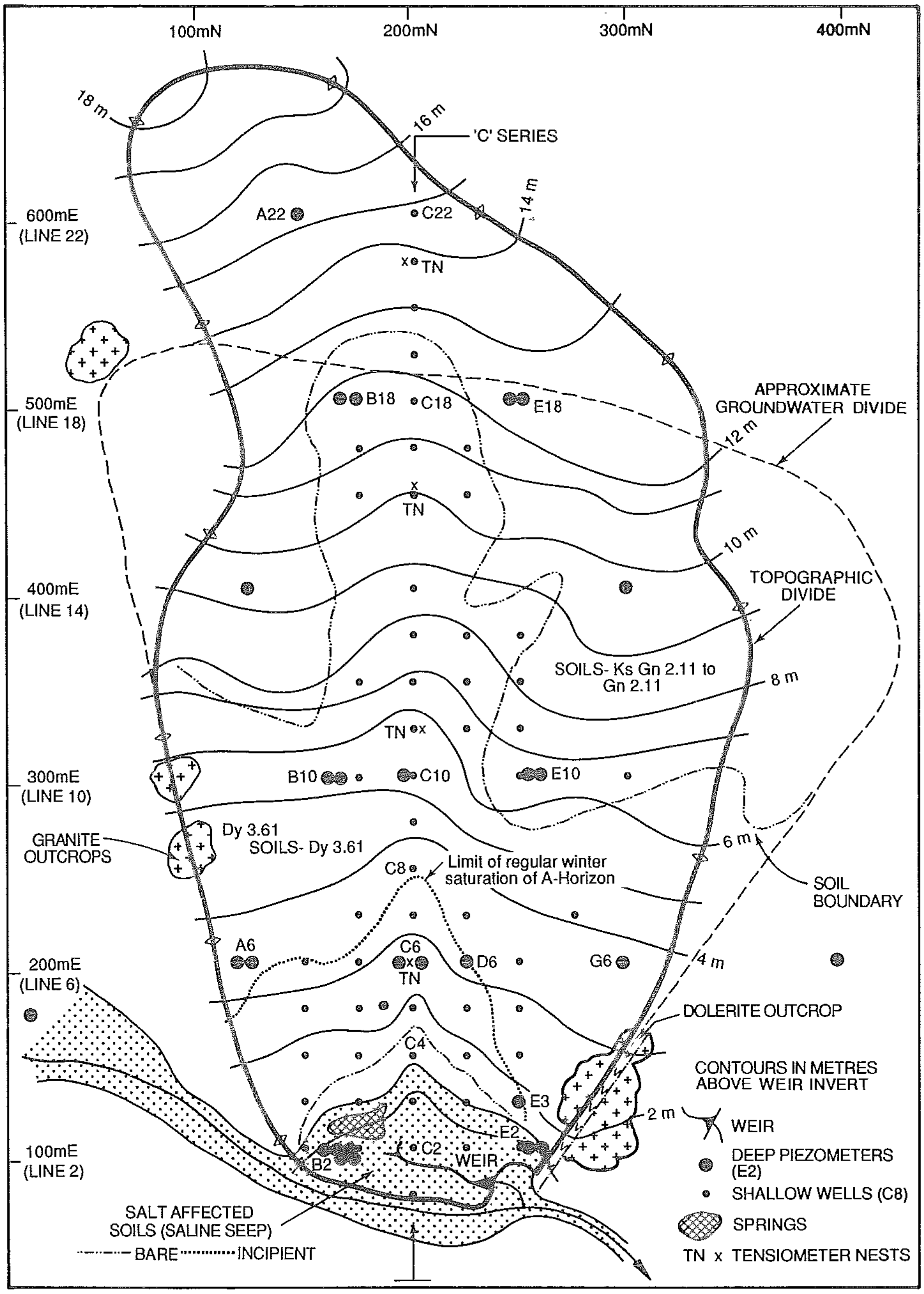
As is the case for much of JUTSON'S (1934) «Yilgarn block» (the granite-gneiss craton), the Narrogin hillslope is characterised by deeply and intensively-weathered soils. Surface soil materials, which contain a perched aquifer during the winter months, are predominantly gradational (Gn2.11-KsGn2.11) on the upper slopes and interfluves and yellow duplex (Dy3.61) in the lower to midslopes (soil terminology from NORTHCOTE & *alii*, 1975). A-horizons (0.3-0.8 m) are sand-textured with a low clay-sized (<0.002 mm diameter) content (0-7%), low bulk density (1.42-1.69 gm/cm^3), high porosity (0.30-0.46%) and high hydraulic conductivity (0.14-3.82 m/day). In contrast, B-horizons have high clay contents (21-35%), bulk densities (1.64-1.96 gm/cm^3) and gravel contents (15-33%), but lower porosities (0.27-0.36%) and significantly lower hydraulic conductivities (0.002-0.02 m/day). Measurements in the B-horizon at B2 (fig. 2), which included part of the indurated hardpan in the saline seep, revealed consistently low permeabilities of about 0.001 m/day (range 0.0005-0.003 m/day).

Below these surficial materials, there is a «lateritic» sequence similar to that reported by ACKWORTH (1987) and JONES (1985) in Africa, and GILKES & *alii* (1973) and BUTT (1981) from elsewhere in Western Australia. The profile comprises a continuum from a «mottled zone» beneath the surface soils, to a «pallid zone», followed by «saprolite grits» (cf. fig. 4). Mottled sandy clays in the mottled zone contain haematite and goethite-rich minerals. The pallid zone consists of quartz and kaolinite in a clay sand to sandy clay matrix. The completely weathered bedrock in this zone is represented by isovolumetrically-weathered quartz and decomposed feldspar and biotite (granite-gneiss to granite), merging into partly-weathered bedrock at the base of the saprolite (figs. 3a, b). Here, the saprolite grits are a coarse, granular clay sand to coarse sand which exhibits relatively little influence of chemical weathering, retaining biotite and fresh feldspar and containing clasts of both minerals with quartz. However, there are localised variations to the above sequence.

Hydrology of the Narrogin Catchment

Groundwater discharge occurs in a salt-affected area extending over 9900 m^2 at the base of the slope. The potentiometric surface of the deep aquifer ranges from 0.5

FIG. 2 - Site details of the Narrogin catchment, including tensiometer nest sites, soils and spot heights, as well as bedrock outcrops and the area of salt-affected soils. The bore reference system uses an alpha-numeric grid. Note that the alpha letters run from north to south (left to right) and numbers from west to east (bottom to top). The recharge-discharge hinge line is the same as the boundary of the incipient salt-affected area. From GEORGE (1992a, fig. 2.1).



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to 1.5 m above ground level in the saline seep, but decreases to 12 m below ground level at the top of the catchment. Both the potentiometric surface and the groundwater table intersect the base of the A horizon between shallow well locations C5 and C6 on fig. 2 (see also fig. 3A). This intersection marks the location of the recharge-discharge hinge line. The deep aquifer occurs in the < 3.0 m thick saprolite grits, and it is separated from the perched, ephemeral or seasonal aquifer by an aquiclude (< 15 m), comprising the mottled and pallid zones of the deep-weathered profile. At the top of the slope the aquiclude is 20 m thick, thinning to less than 10 m towards the slope base (fig. 3).

Hydraulic conductivities of the deep and shallow materials are summarised in tab. 1. There is a wide range of values, from < 0.001 m/day associated with the hardpan in the seep, to 0.14 m/day in the saprolite grits at E18. Permeability increases with depth, consistent with the changes in weathering status described above. The relative difference in mean permeability between the pallid/mottled zones (0.009 m/day) and the surficial soil materials (1.15 m/day) provides the potential for infiltrating water to be impeded above the mottled zone, and to produce throughflow.

Throughflow occurred frequently during the detailed study period from April to December 1984. Perched groundwaters developed briefly in the area immediately adjacent to the saline seep following a storm of about 25 mm in March, but did not develop fully until some 50 mm of rain had fallen in April. By May, perched groundwaters occurred over the area of duplex soils downslope of bores A6-C8-D6-E3 (fig. 2) (cf C6 in fig. 3A). The perched aquifer retreated downslope by 25-50 m during a dry August and was restricted to the central depression between C4 and C9, but extended 25-100 m upslope on duplex and gradational soils after further rainfall (30 mm) in September. As a result, throughflow was observed as both saturated flow within the A-horizon and as returnflow, issuing from the A-horizon, where positive heads developed. When throughflow occurred for any length of time, its characteristically low salt concentration of about 160 mg/L was reflected in fresh streamflow at the gauging weir; and it also contributed much of the annual water yield from the catchment.

Hydrographs from bores monitoring the deep aquifer showed little seasonal fluctuation during the detailed monitoring period in 1984, although the piezometer at G6 showed a 2 m rise of the potentiometric surface at the onset of winter. Trend analysis of the water level data over the five-year extended period of observations showed that water levels remained generally unchanged over time, suggesting that the catchment is in equilibrium between the annual input and output of water. In contrast to the responses of the deep piezometers, shallow wells installed in the A horizon showed marked water level responses to rainfall.

Deep aquifer flow across the recharge-discharge hinge line was estimated by multiplying the average transmissivity of the profile (0.4-0.8 m^2/day), width of each flow cell (38-56 m) and horizontal gradient (0.018-0.036). The calculated flow of 1100 m^3/yr assumes that the catchment is in equilibrium, as discussed above, and that no other losses occur from the groundwaters upslope from the seep. Since this is a realistic assumption in the absence of deep-rooted, transpiring vegetation, it follows that the recharge rate is a function of the annual flux and recharge area. Since recharge to the seep takes place from an area of 11.2 ha, the average recharge rate is about 10 mm/yr or 2% of mean annual rainfall. Aquifer and gradient dimensions could be measured accurately. Variation of the estimate of transmissivity by up to 100% (due to errors arising from the auger rig method of drilling and reliance on slug-test rather than pump-test data), produces recharge estimates which range from 5 mm to 20 mm/yr. Alternative estimates of recharge using the chloride flux and specific yield techniques favoured by other researchers in southwestern Australia (BESTOW, 1977; LOH & STOKES, 1981; SHARMA, 1987; MCFARLANE & *alii*, 1989, and FARRINGTON & BARTLE, 1989) yielded results within the same range.

Fluctuations in seasonal water level responses were identified in some deep bores during the five-year period. These fluctuations suggested that recharge rates are greatest in the concave depression in the mid to lower slopes, correlating with the area where the perched aquifer develops.

Recharge processes attributed to macropore channels or «by-pass mechanisms» have been discussed by JOHNSTON (1987a, b) and ENGEL & *alii* (1989). JOHNSTON showed that perched aquifers may cause saturated flow processes to develop in macropore channels (root holes, cracks and other structural features) in the deeply-weathered zone, producing groundwater mounds and «spiky» hydrograph responses. Similarly, ENGEL & *alii* noted that groundwater levels build steadily in response to matrix recharge processes in the absence of perched aquifers, whereas macropore processes are implicated when groundwater hydrographs respond seasonally.

Detailed observations at specific bores were carried out at the Narrogin catchment to determine whether recharge occurred down macropore channels in the area where throughflow developed periodically. As a result of dry seasonal conditions in July and August 1984, the perched aquifer did not develop until September 14, when 23 mm of rain fell in approximately 12 hours. However, the deep aquifer rose 0.26 m during the 72 hours before the rain, in response to a fall in barometric pressure from 1022 HPa to 992 HPa. Within hours of rainfall commencing, the perched aquifer rose from 0.62 m (dry) to 0.19 m from the soil surface, while the water table of the deep aquifer responded by 0.5 m within 2.5 hours. Three hours later the water table of the deep aquifer began to fall again, when barometric influences again controlled the shape of the hydrograph (GEORGE, 1992a). Chloride concentrations in the deep aquifer indicated that a large input of fresh water had occurred, and the pattern of terrain conductivity also reflected those observations.

The results suggested that recharge through macropore channels is a major factor affecting the amount of water reaching the deep aquifer. Using an estimated specific yield of 0.01, the response of the deep bore was calculated to account for approximately 5 mm of recharge, which in turn suggests that large storm events produce a significant amount (of the order of 25-30%) of the annual recharge within a few hours of the rainfall event. Such quantities of water are difficult to manage by agronomic means alone, and probably require treatment by drainage as well as tree planting.

Throughflow estimates were made by applying Darcy's law to hydraulic properties of the near-surface soils and changes in aquifer thickness at the recharge-discharge hinge line (PALKOVICS & PETERSEN, 1977; ANDERSON & BURT, 1978). Mean daily throughflow volumes were calculated to be of the order of 2.4 m^3/day. In comparison, seepage flows were measured from drains constructed in 1987 on the same catchment, yielding maximum flows of 10.5 m^3/day with an average rate of approximately 2.6 m^3/day - similar to the 1984 calculation. The annual throughflow rate in 1984 was determined to be 530 m^3.

Using chloride estimates of about 160 mg/L from shallow wells in nonsaline soils, maximum solute loads from throughflow were unlikely to exceed 100 kg/Cl/yr. In contrast, solute movement from the deep aquifer, with an average chloride concentration of about 6000 mg/L at the recharge-discharge hinge line, and a discharge of the order of 1100 m^3/yr, would produce 6500 kg/Cl/yr, or 98% of the salts exported from the catchment.

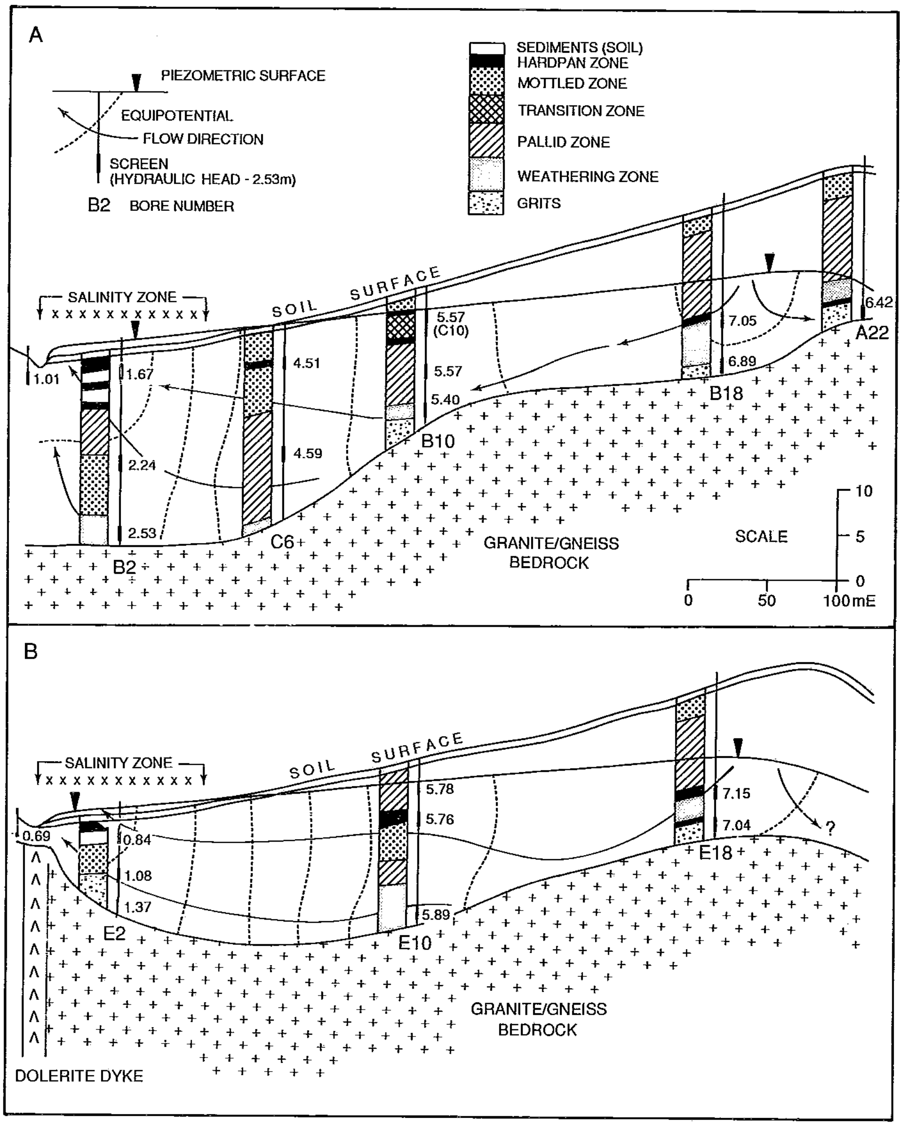

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FIG. 3 - Sections of transects A22-B2 (Fig. 3A) and E18-E2 (Fig. 3B) from the Narrogin catchment, from fig. 2, showing deep-weathered profiles, bore locations and groundwater flow and head directions. From GEORGE (1992a, fig. 2.2).

Groundwater loss from the catchment was calculated by assuming that the annual recharge is lost through vertically upwards flow from the deep aquifer under the seep, and subsequent evaporation and stream runoff (baseflow). Since 1100 m^3/yr of groundwater move out of the catchment through 9900 m^2 of saline soils, the average discharge rate is about 110 mm/yr. However, parts of the discharge area, such as the seepages in the salt-affected area, are likely to contribute greater volumes of water per unit area.

This spatial variability of discharge can be indicated by using the hydraulic properties of the seep to calculate the vertical discharge flux density. Potential discharge rates estimated by this method vary from 50 to over 2000 mm/yr. However, since actual discharge rates are governed by the lowest discharge flux density at each site, a similar order of discharge (50-300 mm/yr) to that determined by the groundwater balance method (110 mm/yr) is indicated. Further, even though potential evaporation at the site is about 1640 mm/yr, the result indicates that actual discharge rates range from as little as 3% to 20% of the potential evaporation rate. This low discharge rate implies that the hydraulic properties of the deeply-weathered materials and associated hardpans and sediments restrict discharge, thereby helping to expand the area of salt-affected soils.

Aquifer Systems of the Central and Eastern Wheatbelt

The region is characterised by large catchments of the order of 10 to 1000 km^2 and low relative relief (20-100 m). Drainage in the eastern part of the region is limited by low gradients (1:1000) associated with the major palaeodrainage lines. Soils and landforms of the region have been described by BETTENAY & *alii* (1964), BETTENAY & HINGSTON (1964) and BETTENAY (1983), and the variability of the basement geology has been discussed in detail by WILLIAMS (1975). Annual evapotranspiration exceeds annual rainfall (snow is negligible) throughout the region. East of the 350 mm rainfall isohyet, mean daily and monthly potential evaporation (which totals 2500-3100 mm annually) exceeds both mean daily and mean monthly rainfall throughout the year (BUREAU OF METEOROLOGY, 1989).

The nature of the deep-weathered profiles is similar to that described above from the Narrogin catchment. However, extensive sequences of coarse-grained, sand-like saprolite materials, or «saprolite grits» (GEORGE, 1990c), are usually developed in coarse-grained granites, adamellites and low-grade gneissic rocks, whereas other bedrock materials of the Yilgarn block, such as dolerite, amphibolite and granodiorite do not produce such coarse-grained or thick saprolites.

Lateritisation also appears to have occurred in sediments in the major palaeodrainages. In the eastern wheatbelt, these sediments range in thickness from 1 to 25 m, and are predominantly alluvial, colluvial and lacustrine deposits derived from the low-angled (generally less than 4%) valley sides during pluvial periods. Deeper sedimentary sequences are predominantly poorly-sorted clay sands to sandy clays (GEORGE & FRANTOM, 1990a), although coarse, red-brown sands also occur within some of the major valleys (GEORGE & FRANTOM, 1990c). Alluvial and colluvial materials overlie the sandy phases of the sediments, and are themselves overlain by aeolian materials derived from the saline playas located throughout the region in the palaeo drainage systems (BETTENAY & HINGSTON, 1964, BOWLER, 1976).

The deeper sediments are usually bleached, are often mottled, and are similar to the Westonia formation described by GLASSFORD (1987), which he considered to be late Tertiary in age. There is extensive, regional silicification of the sediments, with silica commonly replacing the original matrix minerals such as kaolin. Morphologic and mineralogic differences were used to define the base of the sediments and the beginning of the deeply-weathered, *in situ* basement materials. The gamma radiation log of the coarser sediments in the zone from 3 to 12 m also distinguishes the boundary between the weathered *in situ* and sedimentary materials (fig. 4).

Two shallow sedimentary phases can be observed. The deeper phase of the colluvial and aeolian sediments, represented in the eastern wheatbelt as the «Norpa» series by BETTENAY & HINGSTON (1964), consists of 1-8 m of yellow, clayey sands overlying deeply-weathered, basement materials. The shallow (colluvial, aeolian or alluvial) phase is sand-textured and altered by pedogenesis. It overlies both deeply-weathered basement and Cainozoic sediments. This shallow phase ranges in thickness from <0.3 m to only 1.0 m, and is described as the «Collgar» series by BETTENAY & HINGSTON (1964).

The aquifer Systems

The «perched ephemeral aquifer» is situated in these thin, Collgar soils. It is distinct from the «perennial sandplain aquifer» (Norpa) system, and aquifers located in the deeper, alluvial sediments which underlie the valley soils throughout the region (Westonia Formation). The intensely, chemically-altered basement materials are the pallid zone of the lateritic profile. This zone has previously been referred to as an aquifer (BETTENAY & *alii*, 1964), but its hydrological properties as determined by the work reported here cause it to behave as an aquitard. Finally, the poorly-weathered materials near the unweathered basement are termed the «saprolite grit aquifer». The pallid and mottled zones which overlie it have a high porosity but low specific yield and hydraulic conductivities.

From the regional drilling programmes, it was found that the saprolite grit aquifer is usually located at depths of 20-40 m below ground level (BGL), although it can occur at 0-60 m BGL. Its thickness ranges from a thin zone of 1-2 m when developed above fresh (often factured), fine-grained bedrock, to more than 18 m above coarse-grained granites and gneisses. The aquifer is characteristically about 10 m thick.

The distribution of aquifers, their depths, saturated thicknesses and potential for use (hydraulic properties and quality) are linked to geology, position within the landscape, salt storage, rainfall and recharge characteristics. On the upper valley-side slopes, the proximity of deep sand and bedrock outcrops usually results in relatively low salinity ($<10\,000$ mg/L) groundwaters beneath them. However, relatively high salinity (10 000-30 000 mg/L) groundwaters occur below areas of exposed pallid zone and beneath lateritic residuals or «breakaways». Groundwaters are commonly very saline (50 000-300 000 mg/L) in the lower valley-floor areas, especially when located downstream from saline playas (areas of primary salinity).

Aquifer Hydrology

Saprolite grit aquifers range from confined to semi-confined (KRUSEMAN & DE RIDDER, 1983), depending on aquitard permeability and position in the landscape. They have relatively low transmissivities (2-50 m^2/day) and storage coefficients ($10^{-2} - 10^{-4}$). In zones of groundwater discharge and silica deposition the saprolite aquifer is often confined to semi-confined, but on valley-side slopes the aquifer may receive recharge from exposures of country rock or leakage through overlying soil or sedimentary materials (GEORGE & FRANTOM, 1990a, b, c, d). In the latter cases, thin aquifers and low transmissivities may lead to dewatering during pumping, and unconfined responses (GEORGE, 1992b).

A wide range of conductivities occurs within specific aquifer and aquitard materials and catchments (tab. 2). However, both the saprolite grits and the sediments are relatively permeable, with mean hydraulic conductivities of 0.57 m/day and 0.55 m/day respectively. Pallid zone materials are the least permeable, with a mean hydraulic conductivity of 0.065 m/day. Standard deviations show that there is a large variation in the sampled population, which also occurs with the data from the saprolite grits and sedimentary aquifers. The high permeability (1.05 m/day) of the near-surface (<0.03-1.0 m) soils in which perched, ephemeral or seasonal winter aquifers develop, is characteristic of wheatbelt soils and has been discussed

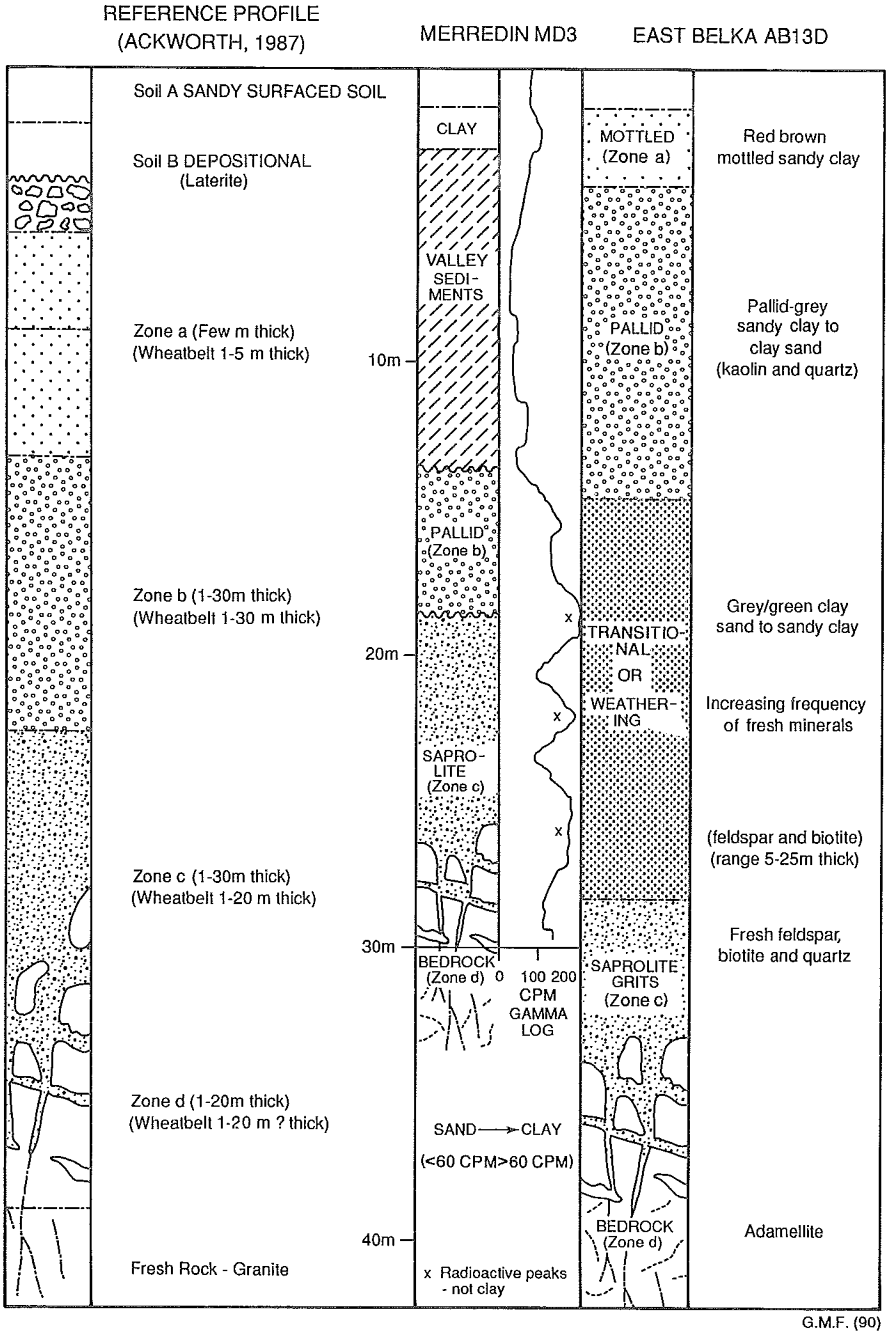


Fig. 4 - Comparison of an African deep-weathered soil (after Ackworth, 1987) on the left with two profiles from the Western Australian wheatbelt: Merredin MD3 (Site in fig. 1) and East Belka AB13D (Site 6), showing similarities in weathering depth and composition. However, the Merredin profile displays deep (about 12 m) sediments (the Westonia Formation, after Glassford, 1987), and the East Belka profile contains a transitional, «weathering zone» between the intensely-altered pallid zone and the saprolite grits. From George, 1990c, fig. 2.

in detail by Conacher (1975), Conacher & *alii* (1983), Peck & *alii* (1980) and Peck & Williamson (1987). Perennial sandplain groundwater systems developed above indurated, weathered zone materials also have relatively high, saturated hydraulic conductivities (0.15 m/day), and are discussed further below.

Groundwater gradients are very low, reflecting the flat to gently undulating nature of the landscape (relative relief of 20 to 100 m over several kilometres) and the relatively considerable depths to groundwater (20-50 m) on the broad interfluves and upper hillslopes. Table 3 summarises the data, showing vertical and horizontal gradients, vertical discharge flux densities (VDFD - Kessler & De Ridder, 1973) for groundwater discharge areas, the type of seep/aquifer (Peck, 1978), and the scale of the aquifer involved.

Maximum potential discharge rates from the salt-affected areas are limited by the low permeabilities of the pallid zone materials and the fine-grained, near-surface sediments. Actual discharges may increase by an order of magnitude in cases where sandy sediments or saprolite grits are exposed at the surface. Here, springs, swamps and other forms of groundwater seepage occur. They are more usually found in hilly terrain in the western and wetter parts of the region, or at the base of sandplain aquifers. Most of these once-fresh seeps are now saline.

Available flow rates from the saprolite grit aquifer are variable, with a mean yield from the pump-test sites of 110 kL/day (tab. 4). Analysis of a further 162 bores drilled throughout the region, in sedimentary and pallid zone as well as saprolite grit materials, indicates a wider range of values (tab. 5). Most (57%) bores yielded only 0-4 kL/day, and the majority of those were installed in deeply-weathered, predominantly pallid zone materials. Higher flow rates (5-21 kL/day) were usually derived from sedimentary materials or poorly developed saprolite aquifers, whilst

TABLE 2 - Hydraulic conductivities of near-surface materials, sandplain, sediments, pallid zone and saprolite grits, using slug-test and pump-test methods from bores drilled using the rotary auger (with asterisks in the final column) and rotary air-blast drilling rigs, from 13 wheatbelt catchments. Holes in the perched aquifer were drilled by hand. Source: GEORGE (1992b, table 1).

Aquifer Domain	Catchment (Fig. 1)	Slug-Test (m/day)	Pump-Test (m/day)	Standard Deviation	No. of Observations
Perched (ephemeral or seasonal)	8	0.87	—	1.11	16
	13	1.15	—	1.01	27
Mean		1.05		—	43
Sandplain (perennial)	6	0.05	—	0.04	11 *
	2	0.15	—	0.21	7
Mean		0.10		—	18
Sediments (Westonia Formation)	1,2	0.12	0.45	0.14	13
	3	0.005	—	0.002	3 *
	4,5	0.85	—	0.68	17
Mean		0.55		—	30
Deeply-Weathered (Pallid Zone)	1	0.08	—	0.06	6
	2	0.06	—	0.04	14
	2	0.008	—	0.008	6 *
	3	0.012	—	0.011	4 *
	6	0.068	—	0.04	5
	7	0.05	—	0.001	3
	8	0.007	—	0.009	5 *
	13	0.009	—	0.011	9 *
Mean*		0.009		—	24 *
Mean		0.065		—	28
Saprolite Grits	1	1.42	—	2.22	4
	2	0.39	0.44	0.24	20
	3	0.05	—	0.07	7 *
	5	0.34	—	—	1
	6	0.25	0.60	0.27	9
	7	0.44	—	0.22	5
	8	0.03	—	0.05	3 *
	10	—	3.27	—	1
	11	—	1.60	—	1
	12	—	3.00	—	1
	13	0.09	—	0.13	11 *
Mean*		0.057		—	21 *
Mean		0.57		—	39

TABLE 3 - Groundwater gradients and estimated vertical discharge flux density (VDFD) for groundwater discharge associated with three types or scales of secondary soil salinisation. Source: GEORGE, 1992b, table 3.

Seep/Aquifer (scale)	Horizontal (m/m)	Vertical (m/m)	VDFD (mm/yr)
Sandplain/Perched ($\approx$0.01 km^2)	<0.01 -0.025	<0.001	50
Hillside/Local ($\approx$1.0 km^2)	<0.006-0.02	<0.006-01	230
Valley Floor/Regional ($\approx$100 km^2)	<0.001-0.004	<0.001-0.018	150

flow rates exceeding 21 kL/day were obtained from bores screened into saprolite grits, or occasionally into coarse-textured, sedimentary sequences. In the latter cases (13% of the bores) flow ranged from 21 to 230 kL/day.

These data suggest that pumping can be used to both lower groundwater tables, thus alleviating secondary salinity problems, and provide a source of stock water. Indeed, groundwater aquifers currently supply between 18 and 25% of all water used in the agricultural areas of south-western Australia, but representing less than 1% of the available groundwater resource (ANON, 1987). However, the above yield data probably over-estimate the potential supply from small bores in small catchments relatively high in the landscape. From long-term (22 days) pumping tests at such sites, actual yields ranged between 20% and 100% of the estimates. On the other hand, increased aquifer thickness and homogeneity lower in the landscape allow more accurate estimates of yield to be made.

Sandplain Seeps: the East Belka Catchment (fig. 5)

The surficial, yellow, sandplain materials occur as aeolian and colluvial sediments on the mid to upper slopes, and overlie the mottled, pallid, weathering and saprolite grit zones (fig. 6A). The mottled zone is well developed beneath the sandplain seep and the valley floor, where it may be 3-5 m thick. Beneath the sandplain, however, it is only 1-2 m in thickness. In contrast, the pallid zone thickens from 3 m to 20 m towards the valley floor, while the weathering zone decreases in thickness (from 25 to 5 m). The saprolite grits are relatively uniform across the entire hillslope (8-12 m thick), although the bedrock surface is uneven (not shown). Fresh bedrock was encountered at depths of 20-40 m, although adamellite outcrops around the perimeter of the catchment.

Groundwater occurs at the base of the sands, and in the pallid, weathering and saprolite grit zones of the deep-weathered profile. Analysis by Jacob's straight line and

TABLE 4 - Summary results from pump-tests to determine discharge (Q), transmissivity (T) and storage coefficient (S) of wheatbelt groundwater systems. Aquifer thickness (AT) and saturated thickness (ST) of the profiles, and groundwater quality data are also given. Refer fig. 1 for catchment/site number locations. Source: GEORGE, 1992b, table 2.

Catchment (Site No.) (test duration = mins)	Aquifer	Q (kL/day)	T kL/day)	S —	ST (m)	AT (m)	Groundwater Quality (mg/L TDS)
East Belka (6) (t = 2,880)	Saprolite Grit	70	6.0	1.6×10^{-4}	30	10	9,000
Harveys (2) (t = 1,440) (t = 31,680	Saprolite Grit	80 32	6.5 2.0	1.2×10^{-2} 1.0×10^{-2}	11 11	9 9	30,900
Cuballing (10) (t = 7,200)	Saprolite Grit	230	50.0	3.2×10^{-2}	23	18	7,000
Frankland (11) (t = 5,850)	Saprolite Grit	14	10.0	2.3×10^{-3}	12	6	12,000
Nugadong (13) (t = 1,440)	Saprolite Grit	200	30.0	1.9×10^{-2}	35	10	29,000
Wallatin (2) (t = 360)	Sediments	25	3.0	1.0×10^{-2}	10	10	34,000
Ardath (9) (t = 360)	Fractured Rock	<3	<1	N/A	50	N/A	490

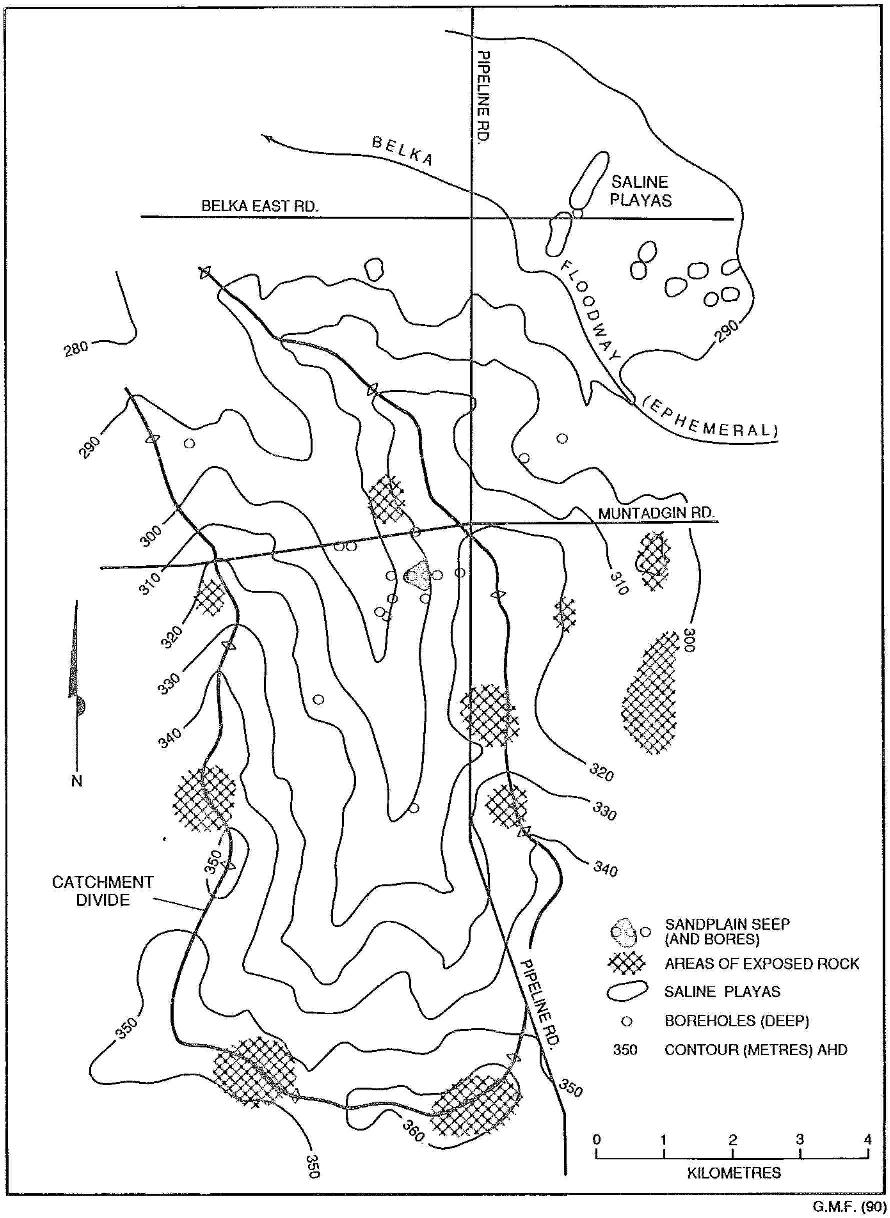


FIG. 5 - Location of the East Belka hillslope, bores and sandplain seep in relation to the East Belka catchment and the main Belka valley floodway. From GEORGE, 1992d, fig. 1.

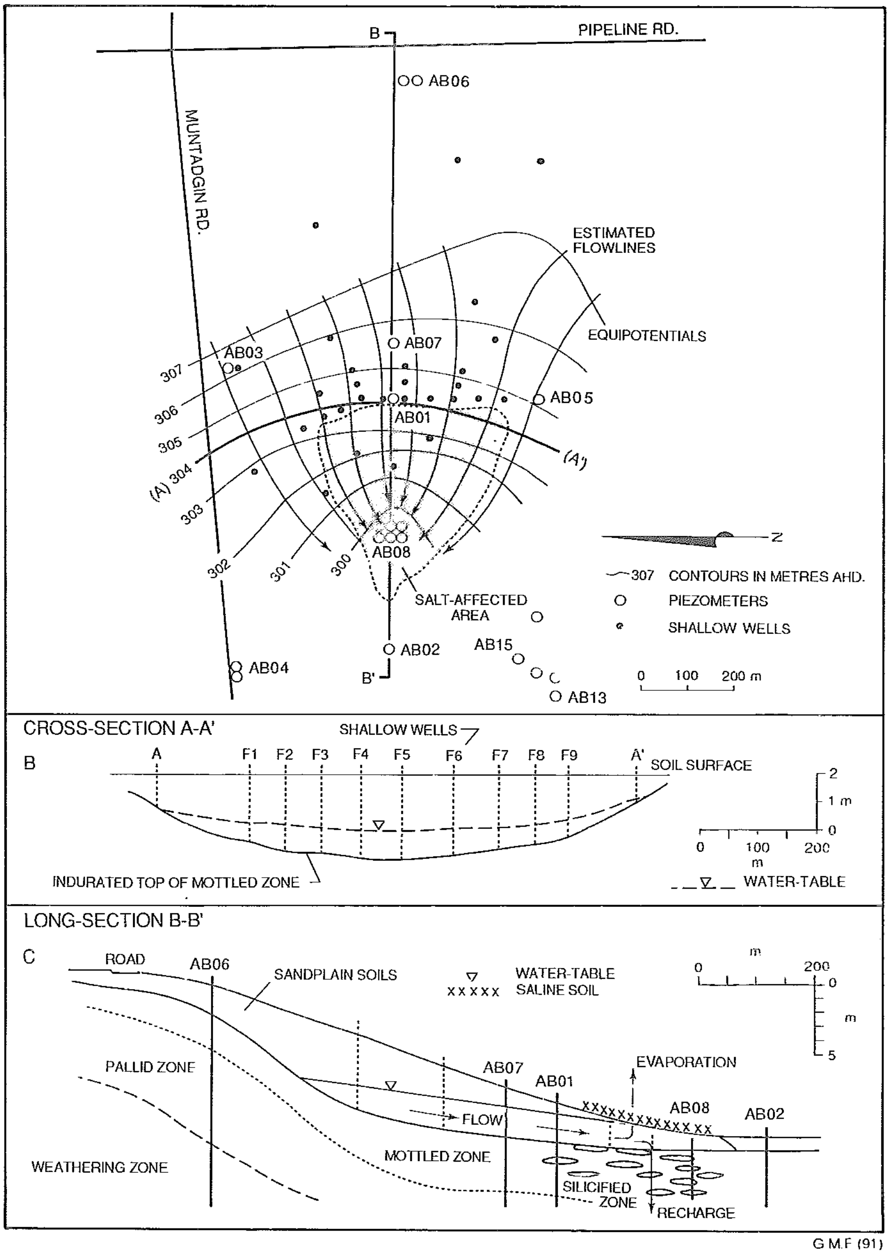
TABLE 5 - Aquifer yields of 162 bores drilled with the rotary air-blast rig in the eastern wheatbelt. Source: GEORGE, 1992b, table 4. (* = rotary auger rig, except for Catchment 3).

Aquifer yield Range (kL/day)	Catchment number (Fig 1)							(%)
	1	2	3	4	5	6	7	
0 - 4 *	10	40	8	7	15	3	9	57
5 - 11	3	19	—	—	6	1	5	21
12 - 20	1	5	—	—	2	5	1	9
21 - 50	1	7	—	—	2	2	—	7
51 - 100	—	2	—	—	—	1	—	2
101 - 230	1	1	—	1	1	3	—	4
TOTALS	16	74	8	8	26	15	15	100

Theis curve matching methods (KRUSEMAN & DE RIDDER, 1983) of water-level responses to constant-rate pumping tests suggested that the regional aquifer is semi-confined, and that some horizontal flow is likely to take place in the lower permeability weathering and pallid zones as well as in the main saprolite grit aquifer. Hydraulic data on the aquifer systems are presented in table 6. They indicate that the pallid zone has a much lower permeability than the saprolite grit zone and the sandplain materials.

The perched aquifer covers approximately 22 ha (about 20%) of the sandplain materials and ranges in saturated thickness above the perching interface (the mottled zone) from approximately 1 to 3 m, decreasing towards the sandplain seep (figs. 6A, B, C). The perched aquifer is separated from the deeper, regional aquifer by 10-25 m of unsaturated mottled and pallid zone materials. Figures 7A and B show the plan and cross section of the groundwater

FIG. 6 - The flow system of the shallow aquifer at the East Belka hillslope (fig. 6A), its cross-section along line A-A¹ (fig. 6B) and the long-section B-B¹ (fig. 6C) down the hillslope. From GEORGE (1992d, fig. 4).



systems in the deep aquifer, and indicate the dominance of low horizontal groundwater gradients, and a groundwater (or water table) mound beneath the sandplain seep.

Hydrographs from shallow bores in the sandplain materials show the effects of winter rainfall events at both the storm and seasonal levels. Seasonal changes have an amplitude of the order of 0.5 to 2.0 m, while major storms produce responses of 0.1-0.5 m within 6-24 hours of the event. Bores with a shallow depth to the perched water table have more rapid and more marked responses.

Groundwater responses in the deeper aquifer do not define seasonal events as clearly, being dominated by small (0.1-0.5 m) and rapid (12-48 hr) changes in height. Groundwater levels monitored over a five-year period (1986-1990) show a rising trend in most of the deep bores, increasing by about 0.05-0.25 m/yr. Although consistent with observations elsewhere in southwestern Australia (PECK & WILLIAMSON 1987; LOH & STOKES, 1981), these trends occurred during a period of above-average (10-50%) rainfall. Responses to barometric pressure changes were similar to those measured at the Narrogin catchment, and were similar in magnitude (0.05-0.15 m from 10-30 HPa) and timing (commencing 12-48 hours before rainfall) from both intermediate and deep bores (to bedrock) screened 10-30 m below the water table. Rapid increases in water tables (0.1-0.5 m) occurred within 0.5-1.5 days of rain.

Groundwater Chemistry

Groundwater salinities range from 3000 to 13 000 mg/L (TDS), and are higher in the regional groundwater systems and in areas of high salt storage. The perched groundwaters

TABLE 6 - Hydraulic conductivity (Ks), transmissivity (T), storativity (S) and horizontal hydraulic gradients (i) for the shallow and deep aquifer systems at East Belka. Source: GEORGE, 1992d, table 1.

	Hydraulic Properties					
Aquifer	Ks (m/day)	Range (m/day)	n —	T m^2/day)	S —	i (range) —
Sandplain						
Sandy Zone	0.15	(0.09 - 0.29)	16	0.1 - 0.5	—	2.0 to 2.5×10^{-2}
Gravel Zone	0.29	(0.06 - 0.59)	3	—	—	—
Regional						
Pallid Zone ***	0.07	(0.03 - 0.13)	5	0.1 - 1.0**	—	3.0 to 6.0×10^{-4}
Saprolite Grits	0.25	(0.18 - 0.96)	9	1.0 - 3.0**	—	—
(Pump Test)	0.20***	(0.18 - 0.23)	5	5.0 - 6.5	1.6×10^{-4}	—

* Mean Ks from slug tests.
** Inferred trasmissivity using the means ks and saturated thickness.
*** Mean ks from pump test.
n = Number of observation wells used for analysis.

range from 3000 to 8000 mg/L (TDS) upslope from the seep, to 13 000 mg/L in the seep. The chemical composition of both shallow and deep aquifers is dominated by chloride, while Na, SO_4, Mg, Ca and HCO_3 are also major constituents. The dominance of seawater salts is typical of groundwaters throughout southwestern Australia, and it reflects the deposition of cyclic salts derived from rainfall originating from the sea, as well as dryfall from wind-blown materials derived from playa surfaces. Saltfall in the East Belka region is of the order of 30 kg/ha/yr, but it varies from 10 to 100 kg/ha/yr depending on proximity to sources of dryfall (HINGSTON & GAILITIS, 1976).

The chemistry of the waters of the East Belka hillslope is distinguished by a high SiO_2 content. Regional aquifer waters are consistently high in silica (63-78 mg/L), independent of their salinity or landscape position, while perched waters are more variable (19-114 mg/L). There are also different chloride to bromide (Cl/Br) ratios in each of the aquifers (GERRITSE & GEORGE, 1988). The sandplain aquifers have a mean Cl/Br of 379, while in the regional aquifer the mean is only 286. Rainwater sampled nearby has a Cl/Br ratio of 288. The relatively high ratio in the perched aquifer suggests that bromide loss is occurring, possibly due to absorption on to soil organic matter or removal in harvested agricultural crops and pastures. The lower Cl/Br of the deeper aquifer may result from rapid recharge down macropore channels, where the waters may not be resident in the root zone for a sufficient period for the ratios to be modified.

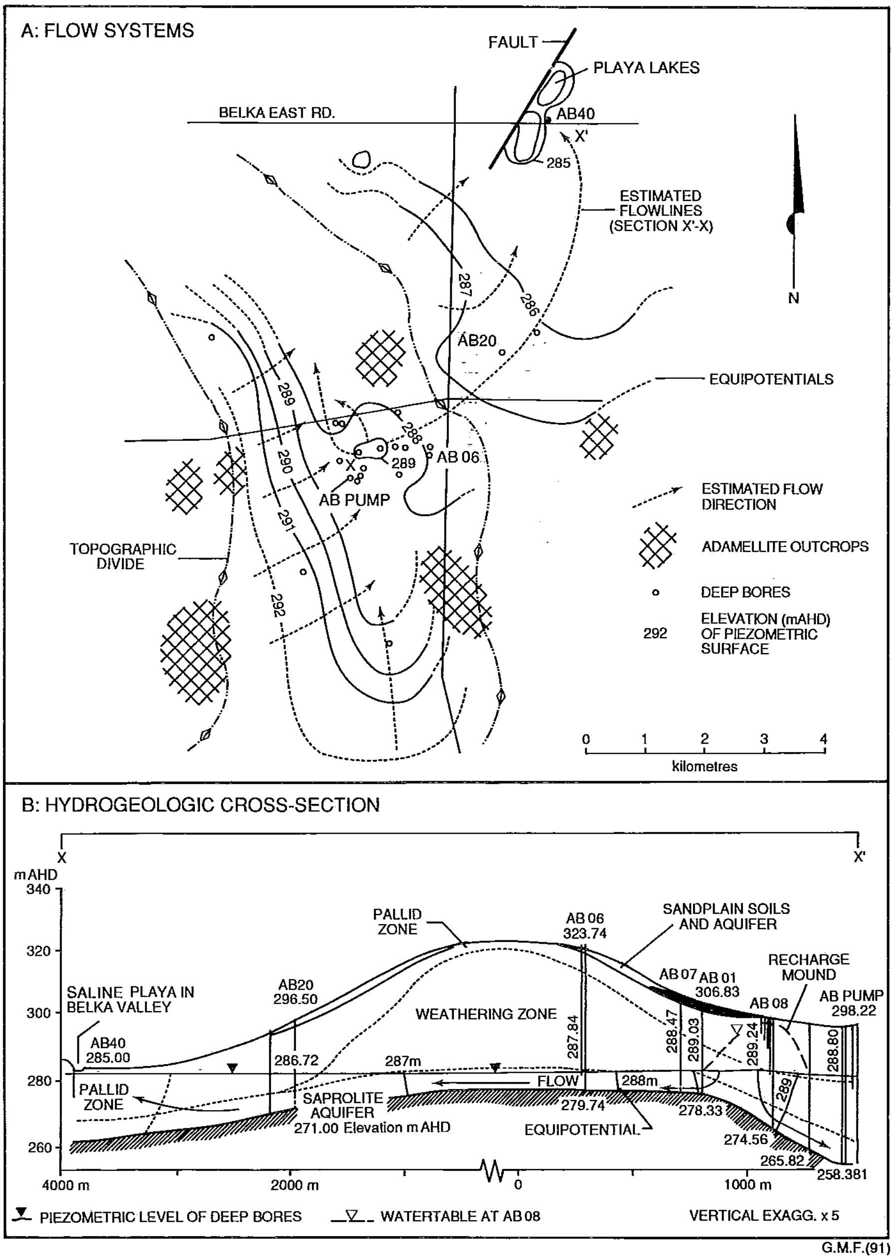
Nitrate levels are also higher in the perched aquifer water, ranging from 4 to 49 mg/L (mean 17 mg/L), than in the regional aquifer system (1-4 mg/L). This may be due to leaching of nitrogenous fertilisers which are applied annually to cereal crops and pastures. However, higher levels of nitrates (41 and 73 mg/L) were measured from a deep (screened from 26 to 28 m) and an intermediate (12-15 m) bore respectively, beneath the sandplain seep. It is possible that rapid recharge from localised runoff on the seep may be responsible for these higher nitrate concentrations.

Groundwater Discharge and Recharge

Annual discharge from the perched, sandplain aquifer was estimated (using Darcy's law) to range between 700 and 1300 kL/yr (GEORGE, 1992b). Assuming that incoming recharge through the sandplain soils balanced discharge through the seep on an annual basis, recharge (as groundwater flow) across the upslope boundary of the seep was estimated to range between 3 and 7 mm/yr. However, recharge of the deep, regional aquifer system was also taking place through macropore channels in the mottled and pallid zones. These losses were estimated at 700-1800 kL/yr, at rates of 3-8 mm/yr. Thus the combined recharge moving beneath agricultural crops and pastures was estimated to lie between 6 and 15 mm/yr.

Taking rainfall and potential evaporation trends into account, these estimates compare favourably with those of WILLIAMSON (1978) and LOH and STOKES (1981). However, the East Belka estimates are significantly lower than those calculated by SEDGLEY & *alii* (1981) and NULSEN (1984) from similar soils. The latter authors estimated recharge as the missing term in the water balance equation after attempting to measure evapotranspiration by crops and pastures. To be applicable to the East Belka site, their estimates of recharge (40-80 mm/yr) would require significant increases in measured saturated thickness and

FIG. 7 - The flow-net for the regional aquifer (fig. 7A) and cross section through X-X^1 through the hillslope (fig. 7B). The piezometric surface of the regional, saprolite aquifer is shown as well as the saline playas in the Belka valley. Note that the topographic divide of the studied hillslope is not equated with the groundwater divide. From GEORGE, 1992d, fig. 5.



permeability, and estimated discharge rates, in comparison with those determined by GEORGE (1992d). Their estimates would also suggest that recharge accounts for about 10-20% of annual rainfall which, on the balance of the available data, is unlikely.

Recharge to the deep aquifer through the sandplain seep is indicated by the development of a recharge mound beneath the seep (fig. 7B) and by the characteristic Cl/Br ratios and nitrate and salinity levels discussed above. Annual groundwater responses were of the order of 2-6 m, indicating recharge rates of 20-60 mm/yr. However, discharge from the perched aquifer into the seep, when distributed across the seep area, provides only 20 mm/yr for both evaporation and recharge (transpiration is negligible since there are virtually no plants growing on the salt-affected area). Localised runoff (overland flow) on to the seep is thought to account for the balance.

Vertical hydraulic gradients within the deep aquifer indicate that recharge to it takes place in areas where there is no perched aquifer. Indeed GEORGE (1992b) hypothesised that, given the similarity in soil conditions, all of the 6-15 mm/yr leaks through the pallid zone-sandplain interface in such situations. However, when an often-silicified, mottled material is present beneath the saturated zone, vertical leakage through the perching interface with the sandplain is reduced to 3-7 mm/yr. Thin sections were obtained for optical and SEM analysis of the cementing materials. At East Belka, aluminosilicates were observed blocking macropores and forming a cement throughout the matrix. At the Holleton site south of Southern Cross (fig. 1), however, a QAZ (quartz-anatase-zircon) or «grey billy» silcrete (Butt, 1981) was observed. These silcretes may comprise cemented pavements beneath the sandplain, and also form occasional outcrops of fractured silcrete 1-2 m thick, extending over 1-2 ha, following the erosion of the overlying materials.

Estimates were made of the amount of deep groundwater movement out of the catchment, and recharge to the deep aquifer (George, 1992b). The combined annual flux was estimated to be of the order of 3600 kL/yr, equivalent to a recharge rate of approximately 0.1 mm/yr across the 4200 ha catchment. Sensitivity analysis, by changing the estimates of transmissivity and cross sectional area by up to 100%, increased or decreased the flux by a maximum factor of 4, and altered the recharge estimates to a range of 0.05 to 0.3 mm/yr. In other words, a maximum of approximately 0.3 mm/yr can leave the East Belka catchment in the deep aquifer.

Recharge estimates from other parts of southwestern Australia range between 10 and over 100 mm/yr, varying with annual rainfall and experimental method (Peck & Hurle, 1973, Loh and Stokes, 1981; McFarlane & *alii*, 1989, Peck & Williamson, 1987; Johnston, 1987a). In the discussion above, it was noted that recharge rates at the East Belka site are about 6-15 mm/yr above the sandplain perched aquifer zone, 3-7 mm/yr beneath the sandplain and hardpan, and up to a maximum of 20-60 mm/yr beneath the seep.

Assuming an average recharge rate of 10 mm/yr across the 4200 ha catchment, it is clear that recharge under agricultural crops and pastures is almost two orders of magnitude greater than the maximum discharge flux possible from the catchment's deep aquifer system.

The effect of increased recharge since agricultural development, and the inability of the aquifers to cope with the increased recharge, are reflected in rising water levels in the deep bores. At current rates of water table rise of 0.05-0.25 m/yr, groundwater discharge may develop at the surface near the mouth of the East Belka catchment in a few decades and could affect most of the valley floor by the middle of the 21st Century unless appropriate management systems are introduced.

In a further paper, George 1992c used three techniques at six large wheatbelt catchments, ranging in size from 100 to 1000 km^2, to estimate hydrologic conditions prior to clearing for agriculture (the groundwater balance method), conditions at the present time (specific yield), and a combination of both (chloride mass balance). The results suggested that recharge and discharge rates have changed significantly since clearing, and George concluded that if left unmanaged, secondary soil salinity could develop across 10-30% of individual wheatbelt catchments.

Various management systems have been discussed by George (1990c, 1992a, b and c) and experimented with by George (1990b, 1991), amongst other researchers. Techniques include deep drainage of salt-affected land, pumping, interceptor banks and drains on catchment slopes, water harvesting upslope from saline seeps using tube drains, and agronomic measures, including establishing high water use conventional and salt-tolerant vegetation on saltland and re-establishing perennial fodder and native vegetation in catchments. All methods have shortcomings, with the small seeps being the easiest to deal with and extensive, valley-floor salinity the most difficult. Space does not permit further discussion of saltland management here, other than to comment that methods adopted by farmers need to be environmentally and economically acceptable as well as effective.

CONCLUSIONS

The distribution of hydraulic properties in the Western Australian basement complex is related to the specific weathered or sedimentary zone being investigated, and the nature and weathering history of the parent material from which that zone has been derived. Isovolumetrically-weathered, saprolite grit aquifers tend to have moderate to high transmissivities (as do near-surface soil and sandplain materials) in comparison with the aquitard (pallid and mottled zones) and Cainozoic sediments which overlie the saprolite grits.

As at East Belka and elsewhere in the wheatbelt, groundwater flow in the deep aquifer at the Narrogin catchment occurs in a coarse-textured, «saprolite grit» aquifer at the base of the deep-weathered profile. At Narrogin, groundwater recharge occurs in the mid and upper slopes at rates of approximately 5-20 mm/yr, while discharge occurs at 50-300 mm/yr from the saline seep, as a result of hydrological discontinuities caused by a dolerite dyke and associated bedrock ridge. The source of salts at the seep is groundwater discharge from saline aquifers at depth. However, the data suggest that throughflow and returnflow are the major mechanisms of streamflow generation and the removal of salts from the hillslope, and that throughflow is responsible for the saturation of surface soils and waterlogging, and recharging the deep aquifer via macropore channels.

Where perennial, perched aquifers develop at the base of deep sandplain materials, as at the East Belka catchment, throughflow mechanisms are the main source of both water and solutes to sandplain seeps. Here, secondary salinisation has been caused by discharge from a perched, sandplain aquifer due to aquifer convergence and silica induration of the inherently low-permeability, mottled zone (the perching layer). Groundwater recharge from the deep sands is about 6-15 mm/yr, of which approximately 3-8 mm/yr are evaporated at the sandplain seep. The remainder recharges the deep aquifer below, with recharge being greatest beneath the seep.

Both the potentiometric surface and the water table are influenced by barometric pressure, which needs to be taken into account in future studies of recharge processes, or where hydrograph data are important.

Throughout the wheatbelt, significant recharge to the deep aquifer takes place down macropore channels following saturation of surface soil materials after major rainfall events. This is evidenced by rapid water table responses in the deep aquifer following the saturation of the shallow aquifer, rapid groundwater table recession, and the development of a mound of fresh groundwater beneath the area where perched aquifers regularly develop (as at East Belka). In contrast, Cl/Br ratios can be used to identify the locations where the deep aquifer is contributing a large proportion of solutes. Deep groundwaters are being recharged at rates of up to two orders of magnitude greater than the rates which occurred under natural vegetation. The deep aquifers are unable to discharge this increased recharge, and the ensuing rise of saline groundwater tables will result in the current 2,8% of wheatbelt soils rended unproductive by secondary salinisation to increase to 10-30% within individual catchments, unless effective management systems are developed and then adopted by farmers.

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