
Dryland salinity processes within the discharge zone of a local groundwater system, southeastern Australia

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Abstract Detailed study of a localised saline discharge zone in southeastern Australia shows that the salinisation is mostly due to the shallow water table (<1–2 m from the surface). Direct evaporation, particularly in summer, leads to extremely high soil–water salinities at the surface, even though the underlying groundwater is moderately fresh. Groundwater discharge is localised at a break of slope, where the water table intersects the surface, and where the transition from permeable sands to clay-rich sediments inhibits lateral groundwater flow. Higher salt concentrations build up in the clays because of the long residence times during which soil–waters are exposed to evapotranspiration and the reduced potential for salts to be flushed from the sediments. As a result the saline discharge area does not correspond to the part of the site with the largest salt store. Results of the study demonstrate that for dryland salinisation to occur, the groundwater beneath the discharge zone need not be saline, and the presence of a large salt store does not necessarily lead to problems of dryland salinisation if, as in the clay-rich sediments at the site, the salt lies below the pasture root zone. Furthermore, mobilisation of salt stores within low permeability sediments by rising groundwater may be minor.

Résumé L'étude détaillée d'une zone localisée d'émergence salée au sud-est de l'Australie montre que la

salinisation est surtout due à la nappe phréatique (<1–2 m sous la surface). L'évaporation directe, particulièrement durant l'été, conduit à des salinités de l'eau du sol extrêmement élevées à la surface, même si l'eau souterraine sous-jacente est modérément douce. L'émergence de l'eau souterraine est localisée à la rupture de pente, là où la nappe phréatique rencontre la surface du sol et où la transition entre sables perméables et sédiments riches en argiles inhibe les écoulements d'eau souterraine latéraux. Les plus fortes concentrations en sel s'accumulent dans les argiles du fait de temps de résidence élevés, durant lesquels les eaux du sol sont exposées à l'évapotranspiration et à un lessivage réduit des sédiments. Il en résulte que l'aire d'émergence des eaux salées ne correspond pas à la partie du site rencontrant la réserve de sel la plus importante. Les résultats de l'étude démontrent que pour que la salinisation d'une zone aride devienne effective, l'eau souterraine sous la zone ne doit pas être forcément salée, et la présence d'une zone étendue de réserve de sel ne conduit pas forcément à des problèmes de salinisation de zones arides si, comme dans les sédiments argileux du site, le sel ne repose pas sous la zone de pâture. De plus, la mobilisation des réserves de sel dans les sédiments peu perméables par la montée du niveau de l'eau souterraine devrait être mineure.

Resumen El estudio detallado de una zona local de descarga salina en el sudeste de Australia, muestra que la salinización es principalmente debido a un nivel freático poco profundo (<1–2 m de la superficie). La evaporación Directa, particularmente en verano, conlleva a salinidades de suelo-agua sumamente altas en la superficie, aunque el agua subterránea subyacente es moderadamente dulce. La descarga de Agua subterránea se localiza en una interrupción de la ladera, donde el nivel freático intercepta la superficie, y donde la transición de las arenas permeables a los sedimentos ricos en arcilla inhibe el flujo lateral del agua subterránea. Las concentraciones de sal más altas se forman en las arcillas debido a los tiempos de residencia largos durante los cuales se exponen el conjunto suelo-agua a la evapotranspiración y también por el potencial reducido para las sales de ser expulsadas de los sedimentos. Como resultado el área de la descarga salina no corresponde a la parte del sitio con el contenido de sal más grande. Los resultados del estudio demuestran que para que ocurra la salinización en terrenos secos, el agua subterránea bajo la de zona de descarga no necesita ser salina, y que la presencia de un almacenamiento

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de sal grande, no necesariamente lleva a los problemas de salinización en terrenos secos si, como en los sedimentos ricos en arcilla del sitio, la sal yace debajo de la zona de raíz de la pastura. Además, la movilidad de depósitos de sal dentro de los sedimentos de permeabilidad baja pueden ser menores, por causa del agua subterránea ascendente.

Keywords Salinisation · Conceptual models · Hydrochemistry · General hydrogeology · Australia

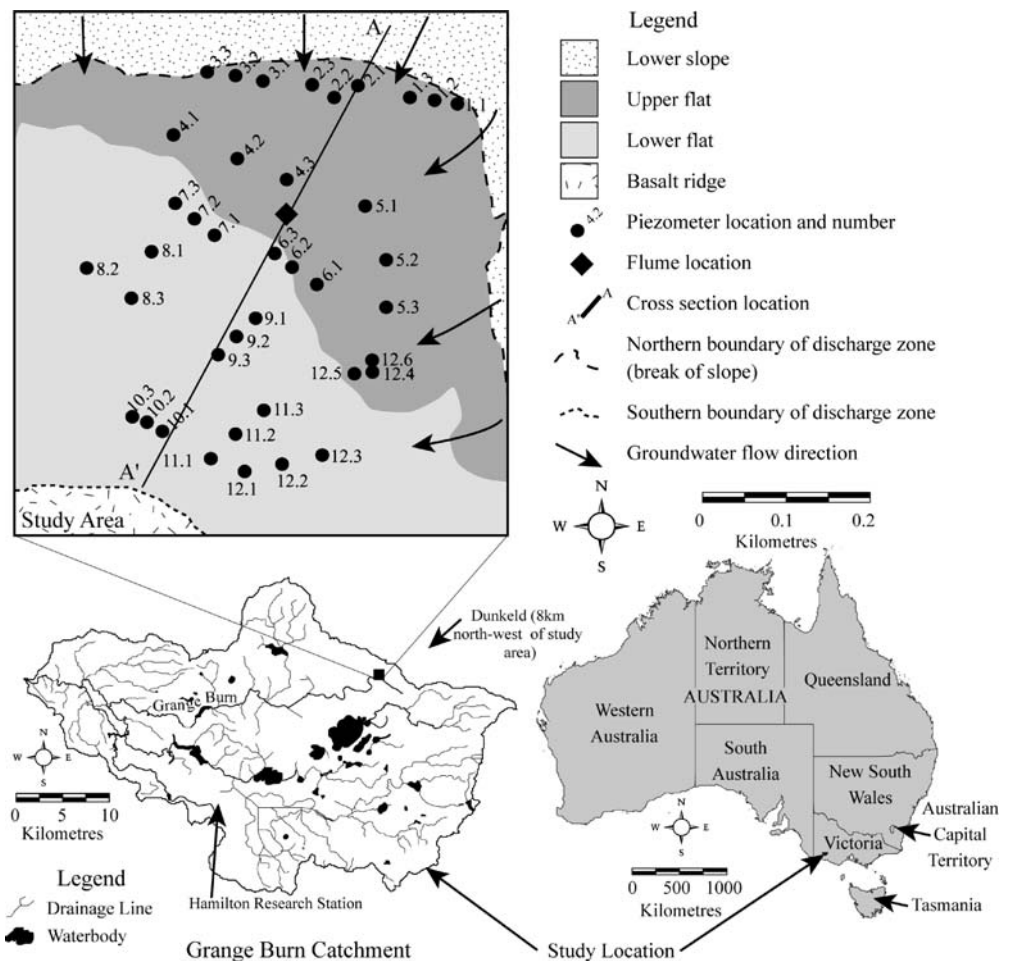
Introduction

In Australia, 5.7 million ha of land are estimated to be affected by dryland salinity, costing Australia millions of dollars a year through lost productivity and damage to infrastructure. In areas affected by dryland salinisation, groundwater discharge zones generally occur where the water table intersects the surface at the break of slope and in topographic lows (e.g. Dyson 1983). This saline discharge, when combined with the effect of waterlogging, detrimentally impacts stream and soil-water quality, native vegetation and biota, pasture establishment and growth, and slope stability. Groundwaters flowing into the

discharge zone may be fresh or saline, generally depending on the amount of evapotranspiration during recharge (e.g. Bennetts et al. 2006; Leaney et al. 2003; Arad and Evans 1987), but become increasingly saline within the groundwater discharge zone, because evaporation in the capillary zone increases groundwater salinity once water tables are less than 1–2 m below the surface (Malcolm 1982; Jenkin and Dyson 1983; Peck and Williamson 1987; Macumber 1991). In addition, rising water tables may bring to the surface salts stored in the soil zone. In southeastern Australia, saline groundwater discharge occurred naturally in many areas prior to European settlement (circa 1800s, primary salinity; Bowler 1971; Dahlhaus et al. 2000; Macumber 1991; Nathan 1999), but dryland salinisation has increased since then, giving rise to secondary salinity, as widespread land clearing replaced high water-use perennial native vegetation with low water-use annual pastures (Peck and Williamson 1987). For example, in South Australia (see Fig. 1), recharge to an unconfined aquifer is estimated to have increased by 2–5 times since clearing (Allison and Forth 1982).

There is general agreement on the various processes that lead to dryland salinisation, including the significance of high water tables, but the relative importance of these processes varies from site to site. The regional and

Fig. 1 Study area location, geomorphic units, piezometer locations and soil pit locations



catchment-scale approaches to assessing the causes of salinisation and salinity risk (satellite, airborne and ground mapping) are useful for identifying broad areas of high risk and implementing large-scale management strategies, e.g. land use change from annual to perennial cropping (Department of the Environment and Heritage and Department of Agriculture, Fisheries and Forestry 2005). However, detailed small-scale hydrogeological studies of individual farms such as this study, are necessary to determine the exact causes of salinisation at a particular site, so that appropriate management strategies to combat salinisation such as targeted tree planting regimes and engineering options, can be assessed.

Here the hydrogeology and hydrochemistry of a relatively small area (a local groundwater flow system) affected by secondary salinity has been characterised, in order to determine the relative importance of the processes leading to the formation of saline groundwater and soils, and to identify the management procedures that can best address the problem at this site. This study serves as an example of the level of detail required for a relatively complete understanding of the situation at a salinised location. Such studies need to be implemented in areas where broad-scale catchment studies have identified that there is a high risk of salinisation developing or worsening in the future.

Physiographic setting

The study site occupies 16 ha of saline land within a groundwater discharge zone near the township of Dunkeld, southwest Victoria (Fig. 1), and forms part of the national network of Sustainable Grazing on Saline Lands research sites (White et al. 2003). It lies at the headwaters of Grange Burn, a major tributary of the Wannon River; ~35 km² of the Grange Burn catchment is significantly affected by salinisation (Munro 2000).

The study area is located on the lower, southwestern side of a ridge flanking the shallow valley of Grange Burn (Fig. 2). The site gently slopes to the southwest from ~225 m above Australian Height Datum (mAHD) to ~215 m mAHD, and can be divided into three geomorphic zones: the lower ridge slope (1–2% slope), the upper valley flat (0.1–0.8% slope) and the lower valley flat (0.3–0.7% slope; Fig. 2). The upper flat represents a groundwater discharge zone, and is the wettest and most salinised part of the study area (Fig. 2).

Prior to European land use, the area was covered by an open grassy woodland comprising kangaroo grass (*Themeda triandra*), weeping grass (*Microlaena stipodes*), blown grass (*Agrostis* spp.) and tussock grass (*Poa australis*), with interspersed River Red Gums (*Eucalyptus camaldulensis*; Elmore 2002; Mitchell 1839). Most clearing in the Grange Burn catchment occurred between 1900 and 1920, when large properties were subdivided into smaller allotments and mechanised farm equipment was introduced (Bird 1986); little of the native vegetation now remains.

At the time of the study (February 2003–September 2004), the site was vegetated with salt-tolerant pasture species including bucks horn plantain (*Plantago coronopus*), Australian salt grass (*Distichlis distichophylla*), streaked arrow grass (*Triglochin striata*) and tall wheatgrass (*Agropyron elongatum*). These species were grazed by sheep.

The climate is temperate with wet, cool winters and dry, warm summers. At the Department of Primary Industries Research Station, Hamilton, 18 km southwest of the study site, records between 1965 and 2003 show average minimum and maximum daily temperatures of 10.8 and 26.1°C in February, the warmest month, and 4.2 and 12°C in July, the coolest month. Average rainfall was 691 mm/year, which was significantly exceeded by Class A pan evaporation of 1,310 mm/year. Specific climate data for the study period (February 2003–October 2004) are discussed below.

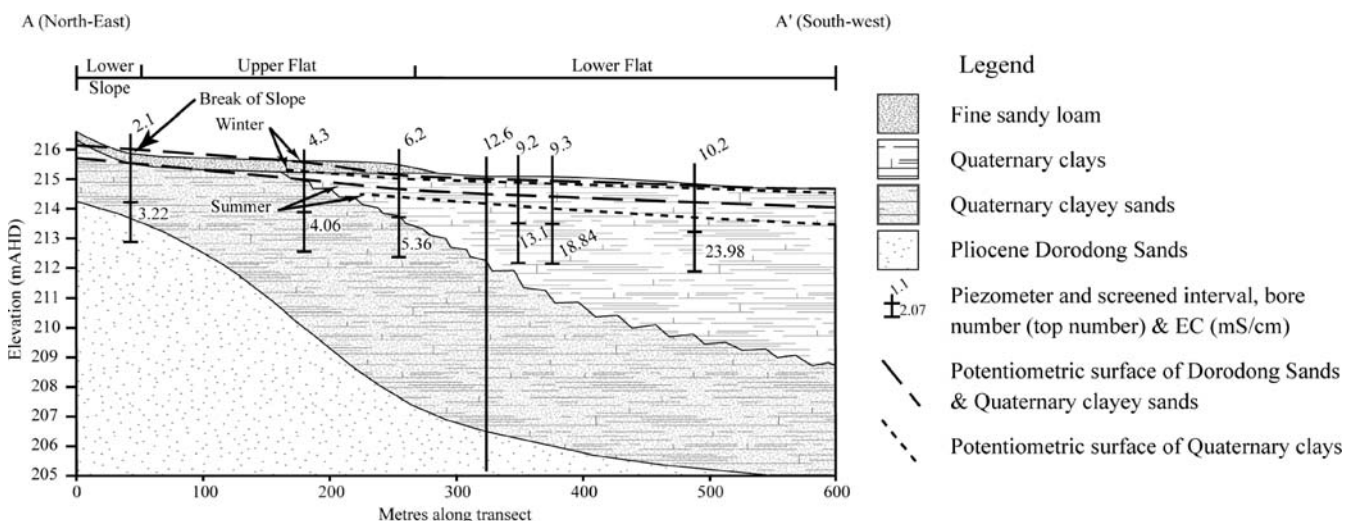


Fig. 2 Cross section through discharge zone showing summer and winter potentiometric surfaces for Dorodong Sands/Quaternary clayey sands and Quaternary clays. Refer to Fig. 1 for cross section (AA') location. Electrical conductivity (EC) in groundwater also shown

Geology

The study site lies on the southwestern flank of a dune ridge of Pliocene Dorodong Sands (Paine et al. 2004). To the southwest, on the far side of the Grange Burn valley, is a low basalt ridge formed by lava that flowed along the dune swale (Fig. 1; Bennetts et al. 2003); further south is the extensive flat to gently undulating plain of Plio–Pleistocene basalt lavas of the Newer Volcanics Province of western Victoria (Price et al. 2003).

Beneath the study site (Fig. 2), the Dorodong Sands are 20–25 m thick, moderately consolidated, fine to medium grained and quartz-rich, with an average porosity of 10–12%. The sands have a high permeability and groundwater yield (Mann et al. 1992). They are covered by a fractured, discontinuous 10–30 cm thick layer of cemented ferruginous magnetic pisolitic gravel, exposed on the surface of the dune ridge northeast of the study area.

Quaternary lacustrine, colluvial and alluvial sediments have been deposited over the Dorodong Sands along the shallowly incised Grange Burn valley to form the upper and lower valley flat (Fig. 2). Beneath the upper flat the sediments comprise clayey sands, with occasional discontinuous sand lenses (average porosity 8–10%). These sediments become more clay-rich downslope into the lower flat, grading into clays with rare discontinuous sand lenses; the average porosity of the clays is 0.8–1.2%. Across the lower ridge slope and upper valley flat is a surficial layer of unconsolidated, fine-grained quartz-rich sandy loam, 10–30 cm thick, which progressively becomes thinner and more clay-rich downslope.

Materials and methods

Across the study site 33 piezometers were installed to a depth of 3 m in February 2003, at an approximate density of two piezometers per hectare (Fig. 1). A further three piezometers were installed to shallower depths (numbers 5.1, 5.2, 5.3 at depths of 2.66 m, 2.47 m and 1.36 m respectively; Table 1). A deeper piezometer was installed to 10 m in June 2004 (number 12.6); this well was not monitored during the study period. All piezometers were slotted at the bottom 1.25 m of the casing, with bentonite packing above the slotted interval, and were all surveyed for elevation (mAHD). Fortnightly water level readings were taken from the installations until the end of September 2004. The piezometer screened intervals, topographic elevations, and average summer and winter standing water levels are presented in Table 1.

Soil samples were obtained during drilling of 16 of the piezometers throughout the site, at 50 cm increments to 3 m. A further 24 soil cores were taken adjacent to the piezometers in June 2003 with samples in 20 cm increments to 2 m. All soil core samples were analysed for gravimetric water content, and electrical conductivity was measured on the saturation paste extract (EC_e ; methods 2D1/14B3/14B1; Rayment and Higginson 1992). EC_e was converted to electrical conductivity in soil solution (EC) after allowing for the moisture content in the original

sample and the amount of water added to make the saturation paste.

Impregnated petrographic thin sections were made from six intact core samples representative of the three major sediment types found at the study site. Porosity was estimated by point counting across a regular grid with a minimum of 300 counts per sample. Groundwater samples were collected from the piezometers in December 2003 and analysed for their pH, EC and major element composition.

To measure runoff and salt wash-off from part of the site, a flume (Clemmens et al. 1984) was installed in September 2004 (Fig. 1). Water height recorders were installed in localised depressions or drains at four locations across the discharge zone in June 2004. Water height and EC were logged between 4:10 pm on 1 September 2004 every 10 min until 12:30 am on 30 September, and converted to water and salt flow using calibration equations. The flume drained an area of 4.25 ha of the lower slope and upper flat.

Climatic data including solar radiation, wind speed, rainfall, air temperature and humidity were collected from an automatic weather station at Hamilton Research Station. Net radiation was measured at the study site from October 2003 to March 2004. Potential evaporation was calculated by the method of Smith (1992), modified from Penman (1948).

Hydrogeology

General groundwater flow-system characteristics

The potentiometric surface slopes from NE–SW, consistent with the local topography. Most recharge occurs through the permeable Dorodong Sands ridge, which rises to the northeast of the study site; the surface layer of cemented ferruginous pisoliths is discontinuous and fractured, and does not significantly limit recharge. Therefore the study area forms a local groundwater system (using the classification of Coram et al. 2000), because the discharge and recharge zones are less than 1 km apart (Fig. 2).

The Dorodong Sands and Quaternary clayey sands are relatively permeable; the potentiometric surface in these units responds quickly to rainfall events, indicating rapid recharge. In contrast, bores in the Quaternary clays (numbers 8.2, 11.3, 12.2 and 12.3; Fig. 1) show a delayed response to rainfall events, owing to the substantially lower sediment permeability.

Groundwater discharge across the upper flat is driven largely by upward flow from the underlying Dorodong Sands (Fig. 2), and reflects recharge predominantly on the sandy ridge rising to the northeast, together with some direct recharge through infiltration across the discharge zone. The potentiometric surface in the Quaternary clayey sands of the upper flat is essentially the same as in the Dorodong Sands, indicating these two sandy aquifers are hydraulically interconnected. There is an upwards hydraulic gradient from the Quaternary clayey sands/Dorodong Sands into the much less permeable Quaternary clays.

Table 1 Summary of piezometer attributes and major element composition of groundwaters

Piezometer ID (Fig. 1)	Aquifer screened	Elevation (mAHD)	Screened interval (depth in m)	Average SWL summer (mAHD) ^a	Average SWL winter (mAHD) ^b	EC (mS/cm)	Na ⁺ (mg/L)	Ca ²⁺ (mg/L)	Mg ²⁺ (mg/L)	K ⁺ (mg/L)	Cl ⁻ (mg/L)	SO ₄ ²⁻ (mg/L)	pH	Saturation index halite
1.1	Dorodong Sands	216.17	1.75–3.00	215.58	216.16	2.07	300	22	47	105	660	41	6.48	-5.3
1.2	Dorodong Sands	216.1	1.75–3.00	215.51	216.10	6.38	990	95	180	202	2,400	220	6.15	-4.3
1.3	Dorodong Sands	216.01	1.75–3.00	215.45	216.04	3.77	580	41	90	208	1,400	78	5.83	-4.8
2.1	Dorodong Sands	215.91	1.75–3.00	215.63	216.04	3.22	520	29	61	3.1	1,100	99	6.09	-4.9
2.2	Dorodong Sands	215.93	1.75–3.00	215.57	215.96	2.48	420	19	37	2.4	800	110	6.38	-5.1
2.3	Dorodong Sands	215.88	1.75–3.00	215.66	216.10	2.39	400	20	33	3.3	780	91	6.12	-5.1
3.1	Dorodong Sands	215.84	1.75–3.00	215.60	216.05	1.64	290	10	18	1.9	490	87	6.31	-5.5
3.2	Dorodong Sands	215.88	1.75–3.00	215.38	215.94	1.25	220	7	12	1.5	380	53	6.40	-5.7
3.3	Dorodong Sands	216.09	1.75–3.00	215.26	216.00	1.38	240	11	19	1.9	440	47	6.36	-5.6
4.1	Dorodong Sands	215.68	1.75–3.00	215.56	216.08	1.72	290	16	25	2.8	560	62	6.09	-5.4
4.2	Dorodong Sands	215.8	1.75–3.00	214.83	215.68	2.98	500	31	56	4.1	1,000	91	6.09	-4.9
4.3	Quaternary clayey-sands	215.75	1.75–3.00	215.35	215.87	4.06	630	47	95	4.4	1,500	120	5.88	-4.7
5.1	Quaternary clayey-sands	216.06	1.41–2.66	215.11	216.06	4.32	760	45	92	2.6	1,500	150	6.60	-4.6
5.2	Quaternary clayey-sands	216.11	1.22–2.47	215.29	216.04	3.90	620	48	110	3.5	1,400	99	6.57	-4.7
5.3	Quaternary clays	215.99	0.11–1.36	215.28	215.96	16.12	2,800	200	440	8.1	7,000	510	6.67	-3.5
6.1	Quaternary clayey-sands	215.69	1.75–3.00	215.40	215.76	3.27	480	52	86	7.9	1,100	74	6.21	-4.9
6.2	Quaternary clayey-sands	215.42	1.75–3.00	214.67	215.17	5.36	930	54	110	5.4	2,000	150	6.61	-4.4
6.3	Quaternary clayey-sands	215.42	1.75–3.00	214.75	215.27	3.84	590	52	100	6.4	1,400	94	6.34	-4.7
7.1	Quaternary clays	215.31	1.75–3.00	214.32	215.03	18.01	2,500	400	900	6.7	8,300	640	6.10	-3.5
7.2	Quaternary clays	215.39	1.75–3.00	214.21	215.06	22.90	4,000	380	900	8.1	10,000	970	6.39	-3.2
7.3	Quaternary clays	215.38	1.75–3.00	214.19	215.12	17.90	2,700	390	780	4.9	7,900	640	6.32	-3.5

Table 1 (continued)

Piezometer ID (Fig. 1)	Aquifer screened	Elevation (mAHD)	Screened interval (depth in m)	Average SWL summer (mAHD) ^a	Average SWL winter (mAHD) ^b	EC (mS/cm)	Na ⁺ (mg/L)	Ca ²⁺ (mg/L)	Mg ²⁺ (mg/L)	K ⁺ (mg/L)	Cl ⁻ (mg/L)	SO ₄ ²⁻ (mg/L)	pH	Saturation index halite
8.1	Quaternary clays	215.1	1.75–3.00	214.05	215.02	21.64	3,300	430	1100	7.2	9,900	1,100	5.87	-3.3
8.2	Quaternary clays	215.01	1.75–3.00	213.60	214.78	31.91	4,100	800	1700	9.1	13,000	2,200	6.18	-3.1
8.3	Quaternary clays	215.06	1.75–3.00	214.10	214.94	28.57	3,100	770	1900	5.4	12,000	1,900	6.00	-3.2
9.1	Dorodong Sands	215.18	1.75–3.00	214.56	215.13	2.84	420	40	66	9.1	940	75	6.67	-5.0
9.2	Quaternary clays	215.2	1.75–3.00	214.16	215.01	13.08	2,000	310	500	16	5,300	600	6.36	-3.7
9.3	Quaternary clays	215.17	1.75–3.00	214.04	214.93	18.84	3,200	330	870	14	8,900	900	6.22	-3.3
10.1	Quaternary clays	214.97	1.75–3.00	213.82	214.74	4.47	710	53	98	1.8	1,600	150	6.95	-4.6
10.2	Quaternary clays	214.91	1.75–3.00	213.78	214.67	23.98	3,900	660	1100	8.8	11,000	900	6.69	-3.2
10.3	Quaternary clays	214.94	1.75–3.00	213.79	214.66	18.56	2,800	430	750	6.0	8,200	910	6.67	-3.4
11.1	Quaternary clays	215.1	1.75–3.00	213.97	214.83	16.26	2,300	410	720	4.2	6,800	960	6.88	-3.6
11.2	Quaternary clays	215.37	1.75–3.00	214.32	215.07	8.91	1,400	190	330	8.3	3,400	440	6.95	-4.0
11.3	Quaternary clays	215.5	1.75–3.00	214.02	215.07	10.80	1,600	240	430	7.5	4,200	460	6.16	-3.9
12.1	Quaternary clays	215.22	1.75–3.00	214.10	215.02	22.10	3,000	670	1200	7.5	10,000	1,100	6.73	-3.3
12.2	Quaternary clays	215.48	1.75–3.00	214.15	215.16	7.37	1,100	150	260	6.4	2,700	370	6.81	-4.2
12.3	Quaternary clays	215.53	1.75–3.00	214.01	215.16	13.85	1,900	340	680	8.5	5,600	810	6.24	-3.7
12.4	Dorodong Sands	215.62	4.75–6.00	214.65	215.53	2.93	470	44	80	6.3	1,000	89	6.19	-5.0

^a Average standing water level (SWL) calculated from fortnightly data collected in summer periods (between 28 February 2003 and 2 June 2003, and between 18 November 2003 and 20 February 2004).

^b Average SWL calculated from fortnightly data collected in winter periods (between 16 June 2003 and 3 November 2003).

The study area lies upslope of the drainage line of Grange Burn, so groundwater flow is not directly affected by the ridge of Newer Volcanics basalt on the opposite side of the valley; groundwater within the basalt discharges into the stream bed, which forms the topographically lowest part of the landscape. Moreover, the groundwater flux through the Newer Volcanics is significantly lower than in the Dorodong Sands due to the overlying relatively impermeable clay-rich soils (Bennetts and Webb 2004).

Surface runoff and stream base-flow

Water tables are close to or above the surface of the upper and lower flat during the winter-spring period (Fig. 2), and large quantities of surface runoff and groundwater discharge are generated from these areas. The surface water height recorders showed that low-lying areas were inundated for 4 months (mid June to mid October 2004), and close to the break of slope the median water depth was 0.94 cm over this period. During September 2004, a total of 6.4×10^6 L of surface runoff was measured at the flume, which is equivalent to 151 mm of runoff from the 4.25 ha catchment area of the upper flat and lower slope (Fig. 1). Visual observation during rainfall events showed that surface flow from the upper slope of the Dorodong Sands ridge was minimal due to rapid infiltration through the sandy soils. Since only 48 mm of rainfall fell in September 2004, two-thirds of the runoff represents groundwater discharge from the sandy ridge rising to the northeast, transmitted through the permeable Dorodong Sands. Therefore, groundwater discharge and surface runoff from the upper and lower flats control surface water flow into the Grange Burn. In summer there is typically no surface water flow at the study site; the water table is below the ground surface (Fig. 2), so groundwater discharge does not occur, and only intense rainfall events generate surface runoff.

Seasonal variations in potentiometric surface

The seasonal oscillation in the potentiometric surface is greater in the Quaternary clays (0.95 m) than in the Dorodong Sands and Quaternary clayey sands (0.58 and 0.61 m, respectively), so the difference in potentiometric surface between the Quaternary clayey sands/Dorodong Sands and the less permeable Quaternary clays is greater in summer (0.5 m) than in winter (0.15 m; Fig. 3). These differences reflect porosity and permeability variations between the three aquifers. The Quaternary clays have approximately one-tenth the porosity of the Dorodong Sands/Quaternary clayey sands (0.8–1.2 and 10–12/8–10% respectively), so the same amount of recharge would cause a ten times greater rise in the potentiometric surface in this unit. However, the rise is only about 1.6 times that in the more porous aquifers, because the lower permeability of the Quaternary clays allows much less recharge (~10 mm compared to ~60 mm in the sands/clayey sands).

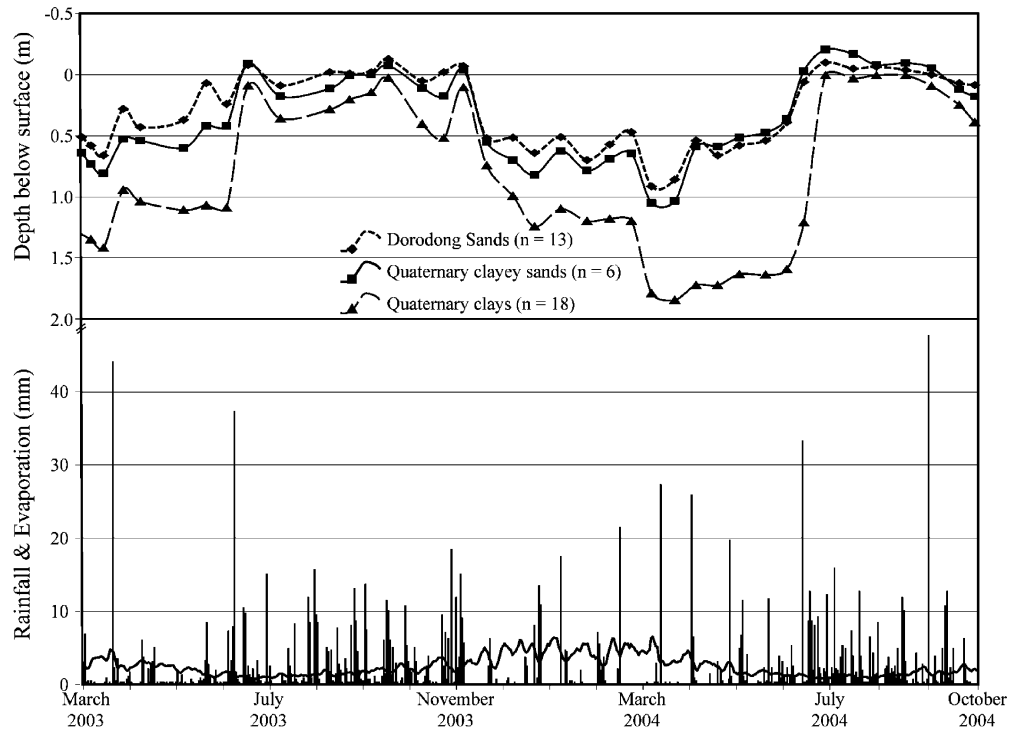
Piezometers in the upper and lower flats all show small rises in the potentiometric surface in response to significant rainfall events (Fig. 3). However, the main rise occurred with the onset of winter rainfall in June 2003 and June 2004, after which the potentiometric surface remained at much the same level despite variable rainfall over the winter months. This general seasonal trend is consistently observed in areas of southeastern Australia where a temperate climate prevails (e.g. Arad and Evans 1987; Cartwright and Weaver 2004; Dyson 1983). At the study site, during winter months (June–August in 2003 and 2004), potential evaporation (average 1.1 mm/day) was much less than rainfall (average 3.3 mm/day; Fig. 3); water loss from the site was primarily by surface runoff, and the overall water-table elevation remained relatively constant (Fig. 3). In contrast, during summer (December–February 2003/2004), potential evaporation (average 4.5 mm/day) greatly exceeded rainfall (average 1.3 mm/day; Fig. 3), and as a result recharge events caused only small rises in the potentiometric surface, followed by a relatively rapid decline. In the Quaternary clays of the lower flat, the median decline in potentiometric level of 1.14 m over late spring and summer (Fig. 3) was largely due to evapotranspiration rather than groundwater flow, which is very limited in these low permeability sediments (discussed further below). The drop in water table represents a water loss of 80 mm (using the average porosity), less than the total potential evaporation during this period (332.7 mm). The excess of evaporation over rainfall in the non-winter months means that this is the time when most salt accumulates in the surface soil.

Controls on location of groundwater discharge

Within the study site, the potentiometric surface is highest at the break of slope and upper flat, ranging from 11 cm below the surface in summer to 40 cm above the surface in winter (Fig. 2); as a result groundwater discharge occurs predominantly across the upper flat, and this is the wettest and most salinised part of the study area. Beneath the lower flat the potentiometric surface is deeper (3–43 cm below the surface), indicating that the change in slope is a more important determinant on discharge location than topographic elevation. The occurrence of saline groundwater discharge at the break of slope is well documented in many catchments throughout Australia (e.g. Dyson 1983; Peck 1978), and is the result of a dipping water table intersecting the ground surface where there is a sudden reduction in slope (Acworth et al. 1997).

In addition, downslope groundwater flow across the study area is inhibited by the clay-rich, less permeable sediments of the lower flat, forcing groundwater closer to the surface across the upper flat and thereby exacerbating discharge at the break of slope (Fig. 2). Thus sediment distribution has helped to determine the location of groundwater discharge and extend the zone of shallow water tables. This situation is echoed throughout southern Australia, where many slopes affected by groundwater

Fig. 3 Median fortnightly potentiometric surface response from piezometers for the three aquifers at the study site, and comparison with daily rainfall (vertical bars) and evaporation (expressed as a 5-point moving average) from Hamilton Research Station (Department of Primary Industries 2004)



discharge show a progressive trend toward finer, more clay-rich, less permeable materials downslope (e.g. Dahlhaus et al. 2000; Jenkin and Dyson 1983; Schofield and Jankowski 2003), and groundwater discharge has been documented occurring up gradient of particular low permeability lithologies (e.g. debris flows, dykes and basement highs (Acworth et al. 1997; Salama et al. 1993). Thus sediment type is a widespread control on the location of saline discharge zones, and can be used to predict areas at risk of developing a discharge problem, particularly at a fine scale such as applied in this study.

Groundwater chemistry

Groundwaters at the study site are similar in composition to groundwaters found throughout the surrounding region (Bennetts et al. 2006), and have comparable major element ratios across a broad range of salinities (1.2–31.9 mS/cm), although evolutionary trends in the composition are evident. pH values are circum-neutral, ranging between 5.83 and 6.95 (Table 1). The dominant source of salts in groundwater throughout the region is rainwater (cyclic salt), as indicated by major element chemistry and ^{36}Cl analyses (Bennetts and Webb 2004); there is no Cl^- input from rock weathering and connate water. Cl^- is the dominant species and accounts for 60% of the total dissolved solids (TDS) by mass and is linearly correlated with EC ($r^2=0.99$; Fig. 4); thus it is the major control on groundwater salinity. Due to chloride's abundance, relationship to EC and chemically inert nature, it is used here

as a direct tracer of chemical processes and the extent to which groundwaters have been influenced by evapotranspiration. Na^+ is also abundant (average=26% of TDS by mass), whilst Ca^{2+} , Mg^{2+} , K^+ and are minor constituents.

There is a trend of decreasing Na^+ and K^+ content with respect to Cl^- as groundwaters increase in salinity, and this is balanced by an increase in the relative abundance of Ca^{2+} and Mg^{2+} (Fig. 4). The molar ratio of $\text{Na}^+ + \text{K}^+$ loss to $\text{Ca}^{2+} + \text{Mg}^{2+}$ gain is $\sim 2:1$, indicating that cation exchange reactions are occurring within the clay-rich sediments, whereby one Ca^{2+} or Mg^{2+} ion displaces two Na^+ or K^+ ions; Arad and Evans (1987) observed a similar trend in saline groundwaters of the Campaspe River area, northern Victoria. The decrease in Na^+/Cl^- ratios with increasing Cl^- concentration is not due to halite precipitation as the groundwaters are undersaturated with respect to halite. SO_4^{2-} relative abundances (Fig. 4) are similar to those in Victorian rainfall (Blackburn and McLeod 1983; Bormann 2004).

Whilst the cation exchange reactions influence the relative abundance of the cations in solution, the overall salinity of the groundwater is unaltered, since the decline in Na^+ and K^+ is balanced by the gain in Ca^{2+} and Mg^{2+} . Moreover, the reactions have no bearing on the Cl^- concentration, which dominates the groundwater composition and is ultimately the key driver of groundwater salinities. The main influence on groundwater salinity is the concentration of cyclic salts within rainfall by evapotranspiration, shown by Bennetts et al.'s (2006) study in a nearby catchment, where comparison of groundwater compositions with rainfall demonstrated that water-rock interactions have little effect on the overall

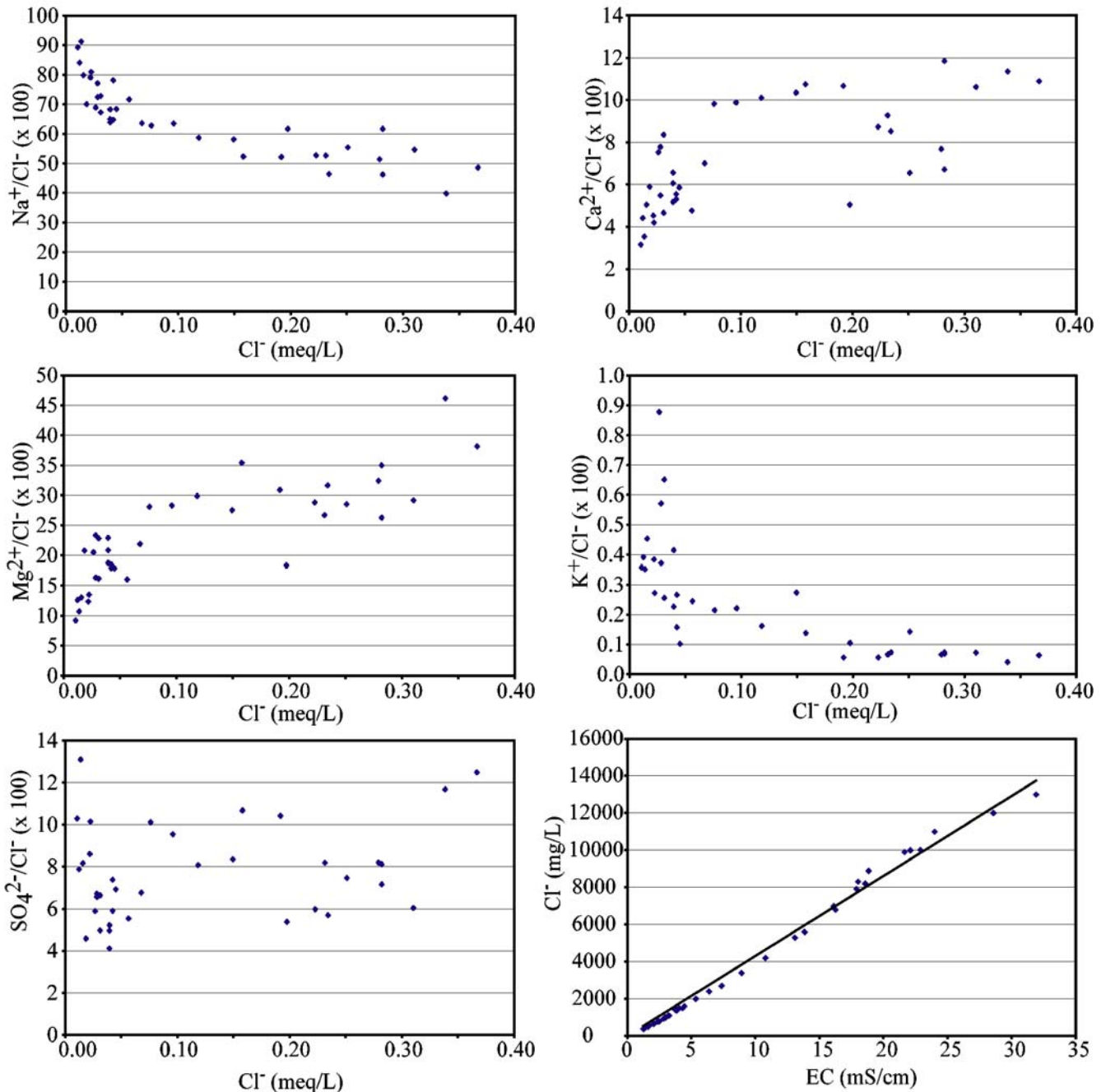


Fig. 4 Ratio of major elements to Cl^- (multiplied by 100) as a function of increasing Cl^- and correlation between Cl^- and salinity (EC)

groundwater salinity, which is ultimately controlled by evapotranspiration.

Soil and groundwater salinity

At the study site, groundwaters in the Dorodong Sands are fresher (median 2.5 mS/cm) than those in the Quaternary clayey sands (median 4 mS/cm) and Quaternary clays (median 18 mS/cm). The lower salinity in the Dorodong Sands reflects the rapid recharge through the permeable Dorodong Sands ridge rising to the northeast of the study area, such that there is little chance for evapotranspiration

to occur during infiltration. The more saline groundwaters in the surface aquifers of the upper and lower flats are due to different processes, which will now be discussed in detail with respect to soil- and groundwater salinity profiles.

Salinity at the break of slope and upper flat

Soil- and groundwater salinity profiles at the break of slope and upper flat (Fig. 5a) show high salt concentrations in the top 20 cm of the soil profile (up to 97 mS/cm), decreasing rapidly to relatively constant levels below the water table at 0.5–1.5 m depth (4–5 mS/cm). These profiles

are typical of areas where annual evaporation greatly exceeds annual rainfall and water tables are shallower than 1–2 m, so that evaporation from the soil surface concentrates salts at the capillary fringe (e.g. Jenkin and Dyson 1983; Malcolm 1982; Salama et al. 1994). The upper flat represents a groundwater discharge zone; the potentiometric surface ranges from 11 cm below the surface in summer to 40 cm above the surface in winter (Fig. 2), so evaporation results in very high soil-water salinities, even though the groundwater delivered to the discharge zone from the Dorodong Sands is moderately fresh (~2.5 mS/cm). The low permeability of the Quaternary clayey sands increases the amount of time in which the soil-water is exposed to evaporation. Transpiration has little effect on the upper flat, because vegetation is sparse in such a saline soil environment. Hence the depth of the water table is predominantly responsible for the development of salinisation at the study site; if the groundwater flowing to the discharge zone were more saline, even greater salt concentrations would occur in the soil. Since most evaporation occurs in summer, causing the water table to fall, most salt precipitation in the surface soil also occurs at this time.

Infiltration of saline soil-water beneath the upper flat increases the salinity of groundwater in the Quaternary clayey sands above that in the Dorodong Sands. Nevertheless, the groundwater salinity beneath the upper flat is much less than that of the near surface soil-water (Fig. 5a), indicating that the amount of downwards infiltration is limited; the majority of salt in the soil is probably lost through surface wash-off (see later discussion).

Salinity of the lower flat

Soil- and groundwater salinity profiles within the Quaternary clays beneath the lower flat (Fig. 5b) are very variable but characterised by generally high salinities (>10 mS/cm). The water table is close to the surface (3–43 cm; Fig. 2), so evaporation is again an important factor concentrating salts within the profile. However, soil-water salinities are generally lower than for the upper flat

(Fig. 5) because the water table does not consistently reach the ground surface. Nevertheless, groundwaters in the Quaternary clays beneath the lower flat are much more saline than in the Quaternary clayey sands beneath the upper flat (median 4 and 18 mS/cm respectively). The low permeability of the Quaternary clays means that salt introduced into the groundwater from evaporated soil-water is not flushed readily through the sediments by lateral groundwater flow, so groundwater salinities remain high. In contrast, salts are readily flushed through the permeable sediments beneath the upper flat, and therefore do not accumulate to the same extent. In addition, the upwards hydraulic gradient into the Quaternary clays (Fig. 2) means that loss of salinity by downward flow of saline groundwater is not significant.

A second factor is also involved. Soil- and groundwater salinity beneath the lower flat generally increase with depth to 50–100 cm, and then remain more or less constant or decrease (Fig. 5b). This profile shape is typical of those developed beneath vegetation, where the depth of maximum salinity represents the limit of effective water removal by roots (Ayers and Westcot 1976). The depth of 50–100 cm is much greater than expected from the present salt-tolerant pasture growing on the lower flat, but is typical of native eucalypt forest throughout southeastern Australia (e.g. Cook et al. 1994; Jolly et al. 1989; Walker et al. 1991). It is likely that the salinity profiles of the lower flat developed beneath the open grassy woodland that covered the study area before it was cleared ~100 years ago. In particular, eucalypts like the River Red Gums that once grew on the site are high water usage trees (Marshall et al. 1997) that concentrate salt in the soil-water beneath their roots. The elevated salinity of the profiles probably also reflects the relative impermeability of the sediments, so that soil-water moves slowly through the clays and is exposed to evapotranspiration for long periods of time.

The water table across the lower flat is at present 3–43 cm below the surface, considerably shallower than the past water table under native vegetation, which must have

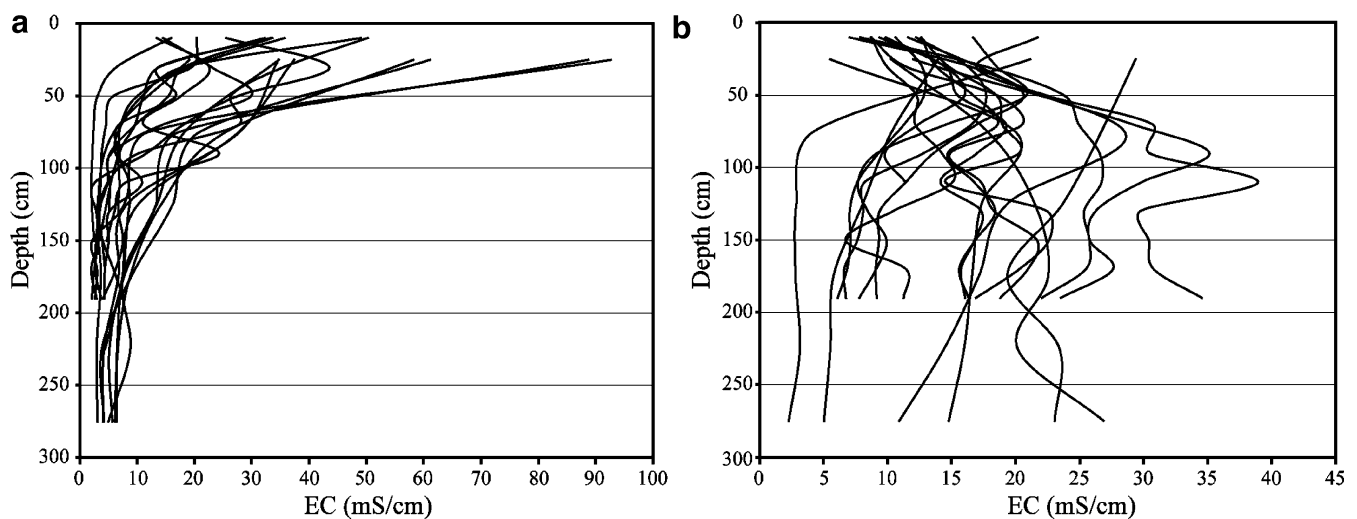


Fig. 5 Vertical salinity (*EC*) distribution in soil-water obtained from piezometer cores at the **a** break of slope and upper flat and **b** lower flat

been at least 100 cm deep (greater than the rooting depth implied from the salinity profiles). This indicates a rise in water table of perhaps 1 m, due to increased recharge across the area following the clearing of native high-water-usage vegetation and its replacement by pasture. Interestingly, the rise in water table has not mobilised the salt store within the low permeability clays to any great extent, in that many of the pre-clearing soil-water salinity profiles are still recognisable and may be at their original depth despite now being in the saturated zone. The pre-clearing profiles have been preserved by the low permeability of the Quaternary clays; similar profiles were probably present in the Quaternary sandy clays beneath the upper flat but have been flushed out of these higher permeability sediments.

Thus, at the study site, the lower permeability sediments of the lower flat have the more saline groundwater, but the higher permeability sandy clays of the upper flat have the more saline soil-water. This is due to the interplay between evaporation (which is most important where the water table is shallowest) and permeability (which inhibits the movement of water and salt through the sediment). Despite the upwards hydraulic gradient, there is little groundwater flow between the sediments of the upper and lower flats, as shown by their generally very different groundwater salinities.

The lateral variability of the salinity distribution below the surface of the lower flat (Fig. 5b) may at least partly reflect the scattered distribution of River Red Gums before the native vegetation was cleared; the maximum soil salinity developed directly beneath these trees would have been higher and deeper than under nearby grassy areas. There is also likely to have been some variation in the movement of these profiles due to the rise in water table in the ~100 years since clearing. In addition, a few profiles show salinity maxima at the surface, resulting from seasonal changes in salt accumulation where the water table comes close to the surface.

Salt wash off

Salt concentrated at or near the surface during summer, particularly across the upper flat, is largely removed by winter runoff, so surface salinity levels within the discharge zone vary considerably from season to season. Surface runoff measurements in September 2004 (Fig. 6)

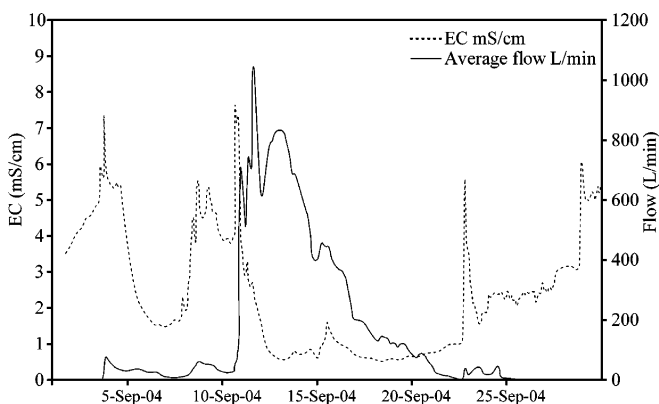


Fig. 6 Hourly runoff volume and salinity trends from discharge zone

showed that small flow events are saline; salinity was high at the beginning of major flow events and declined with increasing flow, due to the initial removal of salts concentrated at or near the surface. The thin layer of sandy loam which caps the upper flat probably enhances this effect, since sandier sediments are more readily leached than the underlying clay-rich sediments.

Dryland salinity processes in a groundwater discharge zone

The detailed study of the groundwater discharge zone at the Grange Burn site gives a clear understanding of the relative importance of the three factors that control the genesis of saline groundwater and soils here, and allows generalisations to be made about the applicability of these factors to areas of dryland salinity across southeastern Australia.

The first and most important requirement for the development of salinisation in this particular groundwater discharge zone is a shallow water table (< 0.5 m from the surface; Fig. 2). Direct soil evaporation by capillary action from the water table, particularly in summer, concentrates salts contained within the groundwater, leading to extremely high soil-water salinities, even though the underlying groundwater is moderately fresh (~2 mS/cm). Secondly, the break of slope largely determines the location of groundwater discharge, because the sloping water table intersects the surface where there is a reduction in slope.

Thirdly, sediment permeability plays a complex role. The relatively impermeable sediments of the lower flat acquire and retain more salt; the slow rate of infiltration means that soil-water spends a long period of time exposed to evapotranspiration, and slow groundwater movement prevents flushing of salt through the clays. More importantly, these lower permeability clays force groundwater discharge to the surface across the upper flat, where the sediments are more permeable. Elsewhere in southern Australia, sediment permeability plays a different but equally important role in determining the location of areas of dryland salinisation, e.g. some sites are underlain by low permeability subsoils formed directly on Palaeozoic basement, and develop transient shallow perched water tables during the winter months which may then be subject to evaporation over summer (Brouwer and Fitzpatrick 2002; Peck and Hatton 2003).

The Grange Burn site also demonstrates which factors are not necessary for dryland salinisation to occur, although they may be important at saline sites elsewhere in Australia. Firstly, the groundwater beneath the discharge zone need not be saline, although it often is (e.g. Macumber 1991; Salama et al. 1993). Secondly, the presence of a large salt store may not be a problem if the salt lies below the pasture root zone, as in the clay-rich sediments of the lower flat at the study area (Fig. 5b). Furthermore, although salt stores within sediments may be mobilised by rising groundwater (Arad and Evans 1987), this will not occur to any extent if the sediments have very

low permeability, as again shown by the lower flat at Grange Burn.

Therefore, salinisation can be caused by a wide range of factors, and an understanding of the salinity problem at any site must be based on as complete a knowledge as possible of the geological and geomorphological setting, sediment permeability and water-table location (proximity to surface and seasonal oscillations). Furthermore, although mapping soil and sediment salt stores is important, an understanding of salt accumulation and mobility is crucial.

Management strategies in groundwater discharge zones

The detailed understanding of the relative importance of the processes leading to salinisation at the Grange Burn site allows assessment of possible management strategies and their environmental and economic outcomes. The fine scale of the present study is particularly important in refining strategies and determining response times, increasing the likelihood of success and reducing costs.

Because the major influence on salinisation at the study site is the proximity of the water table to the surface, the first goal of any management strategy is to lower the water table. Revegetation strategies, applied in many areas of southern Australia, require specific targeting. Tree planting along the Dorodong Sands ridge, where most recharge occurs, is likely to prove difficult, due to the high permeability, deep water table and low water storage of the sandy soils, severely reducing the water available to the vegetation. However, revegetation on the side of the ridge immediately up gradient of the break of slope may be successful; here the soils are less saline, the groundwater is relatively fresh and water tables are within reach of tree roots. Trees planted in this area will intercept a component of groundwater flow to the discharge zone. Revegetation of the upper flat where most discharge occurs will be problematic, because the waterlogging and high salt content in the top 20 cm of the profile severely limit growth of even salt-tolerant pasture (McCaskill and Bennetts 2004). However, salt-tolerant grass species are likely to succeed on the lower flat, because here the water table lies beneath the surface and salts are stored deeper in the profile.

There is potential to pump relatively low salinity (2–3 mS/cm) groundwater from the high-yielding Dorodong Sands ridge for stock and domestic use; this will directly lower the water table in the hydraulically connected sandy clays at the discharge site. Groundwater pumping has proved successful in salinisation treatment in Western Australia (e.g. Salama 1994), but is not applicable in many areas of Victoria due to low aquifer yields and high salinity groundwater. Alternative methods of lowering the water table, e.g. subsurface drainage using buried perforated pipes and raised beds, could also be trialled.

Whichever strategy is applied, lowering the water table in the Dorodong Sands would impact on the saline

discharge zone of the upper flat in the relatively short term, given the high permeability (and hence responsiveness) of the sands and the local extent of the groundwater flow system. However, this would have little effect on the clays of the lower flat, which are hydraulically separate from the clayey sands of the upper flat.

Once the level of the water table across the discharge zone (upper flat) has been reduced, the relatively permeable saline surface soil will be quickly flushed by runoff, and to a lesser extent by infiltration into the underlying Dorodong Sands. Very approximate calculations based on the recorded rate of salt washoff (Fig. 6) suggest that the salt in the top 50 cm of the upper flat soil would be removed within 10 years. Salt export into Grange Burn will increase during this period, but there will be a longer-term drop in stream salinity due to lower salt accumulation in the soil. Once the surface soil salinity has been reduced, pasture species can be established, reclaiming currently unproductive land for grazing.

Conclusions

A detailed study of the hydrogeology and hydrochemistry at the Grange Burn site has allowed the relative importance of the factors leading to the development of dryland salinisation at this location to be assessed. A shallow water table is the single most important requirement for the development of the saline discharge zone, as it leads to the concentration of salts contained in groundwater by evaporation, mostly during summer, resulting in extremely high soil-water salinities (up to 97 mS/cm), even though the underlying groundwater is moderately fresh (~2 mS/cm). The break of slope localises groundwater discharge because the water table intersects the surface here. The distribution and permeability of the sediments play an ancillary role; the transition from permeable sandy sediments to more clay-rich sediments inhibits lateral flow and forces groundwaters toward the surface at the discharge zone. In addition, high concentrations of salt build up in the low permeability clay-rich sediments because long residence times allow soil-waters to be exposed to evapotranspiration for greater periods of time, and slow groundwater movement prevents flushing of salt through the clays.

It is notable, that in the study area, the higher permeability sandy clays of the discharge zone across the upper flat have the more saline soil-water, but the lower permeability sediments of the lower flat have the more saline groundwater. This is due to the interplay between evaporation (which is most important where the water table is shallowest) and permeability (which traps salinity in the sediment). The saline discharge area does not correspond to the part of the site with the largest salt store.

The salinity profiles of the lower flat may have developed beneath the open grassy woodland that covered the study area before it was cleared ~100 years ago, indicating a rise in water table of perhaps 1 m due to increased recharge following replacement of native high-

water-usage vegetation by pasture. The rise in water table did not mobilise the salt store within the low permeability clays to any great extent.

The Grange Burn site demonstrates that for dryland salinisation to occur, the groundwater beneath the discharge zone need not be saline, and the presence of a large salt store does not necessarily lead to problems of dryland salinisation if, as in the clay-rich sediments of the lower flat, the salt lies below the pasture root zone. Furthermore, although salt stores within sediments may be mobilised by rising groundwater, this will not occur to any extent if the sediments have very low permeability.

Management options at the study site include tree planting and pumping of the relatively fresh groundwater upgradient of the discharge zone; it is likely that lowering of the water table will be relatively rapid and washoff will remove the surface salt quickly.

This study has shown that salinity risk assessment and development of management strategies at individual sites must take into account the proximity of the water table to the surface, the permeability of the underlying sediments, and the topography.

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