

15 Element Mobility in a Mediterranean Environment

Jim W. Cox*

Abstract

When saline groundwater discharge areas are drained there is always concern over the level of salt within the discharge water. In this study, groundwater discharge rates and quality were measured in an erosion gully that drained a catchment with saline, sodic and acid sulfate-like soils (typical of discharge areas in the Mount Lofty Ranges, South Australia).

The research determined that contaminants other than sodium chloride will be of concern if discharge areas are drained. Even in very low rainfall years, drainage water contained up to 41 kg/ha/year of sodium but also 2 kg/ha/year of sulfur. Losses of sulfur, magnesium and calcium followed a similar trend to sodium losses. The losses of phosphorus were 0.005–0.007 kg/ha/year and nitrate losses were up to 0.002 kg/ha/year.

土地退化形成侵蚀沟，成为地下水渗出区的排水通道，水中含盐量的高低值得关注。在一个侵蚀沟测量了土壤水分的渗出率及其质量。该流域分布有盐土、碱土和硫酸类土，渗出的水流进入沟道排走。该沟在阿德莱德丘陵农业区具有代表性。研究发现，如果有排水系统，则除了氯化钠之外，其它的污染物也值得注意。即使在降水量很少的年份，水中钠的年含量高达每公顷 41 千克、硫的年含量为每公顷 2 千克。硫、镁、钙的流失趋势同钠的相似。磷年流失量是每公顷 0.005–0.007 千克，氮多达每公顷 0.002 千克。

THE VOLUME of sodium chloride that is discharged into streams as a result of rising saline groundwaters in the agricultural regions of southern Australia is well documented (e.g. Schofield et al. 1988). The transport of nutrients

such as phosphorus (P) and nitrate from agricultural catchments to waterways has also received a lot of attention in the international literature because of their environmental implications (Costin 1980; Greenhill et al. 1983;

* CSIRO Land and Water, PMB 2, Glen Osmond, SA 5064, Australia. Email: jim.cox@csiro.au

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Haygarth and Jarvis 1996; Nash and Murdoch 1997). Of particular concern is the eutrophication of water bodies caused by P attached to clay (e.g. Sharpley and Syers 1979; Sharpley et al. 1994).

In the > 600 mm annual rainfall region of the Mount Lofty Ranges, salt and colloids have recently been shown to be transported both over and through texture-contrast soils via overland flow and throughflow, respectively (Fleming and Cox 1998; Stevens et al. 1999). In the region of the Mount Lofty Ranges with < 600 mm annual rainfall, Pitman et al. (1998) showed that, over three years with average rainfall or less, overland flow was less than 1% of annual rainfall and was shed only from the lower slopes (near the drainage gullies). Thus contaminants are infrequently transported in large quantities via overland flow in these environments.

The removal of evergreen native vegetation for grazing in the Mount Lofty Ranges has significantly increased recharge to the fractured rock aquifer. Up to 20% of annual rainfall leaches below the root zone, even in below-average years (Pitman et al. 1998). Groundwaters have risen to the land surface in low-lying areas and brought sodium (Na) and sulfur (S) from the weathered schist regolith (Cox et al. 1996). Highly corrosive, acid-sulfate conditions have then formed (Fitzpatrick et al. 1996; Brown 1997). These conditions reduce the stability of the soils and result in gully formation. The gullies then drain these soils (Cox 1998).

Engineering options (e.g. drainage schemes) are being installed in some areas to rapidly lower shallow saline groundwaters. However, the biogeochemical and physical processes that are taking place in saturated, saline soils in groundwater discharge zones will vary depending on soil type, the nature of the groundwaters and the period of saturation (Fitzpatrick et al. 2000).

This study assessed the likely impacts on water quality of draining waterlogged, saline, sodic and sulfidic soils in the Mount Lofty Ranges. The

volume and quality of drainage water in an erosion gully cutting through a series of these soils were studied over three years. The aim was to gain a better perspective of the relative quantities of salt and colloids being exported from agricultural catchments in low-rainfall agricultural environments.

Materials and Methods

Site and climate

The Overview provides some background information on the Mount Lofty Ranges. The study was carried out in the Keynes catchment, near Keyneton, from 1994 to 1996. The catchment is located in the uppermost western part of the Murray–Darling Basin. Drainage flows southwest out of the catchment, then east to the Murray River (a major water supply for Adelaide). Climate, vegetation, soils and landscape features are typical of those throughout the Mount Lofty Ranges. A pluviometer attached to a weather station continually monitored rainfall and also measured evaporation (Table 1). The long-term (previous 30 years) average rainfall at Keyneton is 544 mm (Bureau of Meteorology). From May to September, rainfall exceeds potential evaporation by a total of 185 mm.

Vegetation, soils and hydrology

Native vegetation has been cleared from most of the catchment. A mix of grasses, subterranean clover (*Trifolium subterraneum* L.) and cocksfoot (*Dactylis glomerata* L.), with invasions of salvation jane (*Echium plantagineum* L.), storksbill (*Erodium moschatum* L.) and soursob (*Oxalis pes-caprae* L.), is now grazed by sheep and cattle.

The texture-contrast soils (Northcote 1960; Chittleborough 1992) of the catchment have formed over metasediments. They consist of 30–40 cm of sandy loam (A horizon) overlying an argillic layer; the clay content of the B horizon is 20% greater than the overlying layer. The A horizon has

Table 1. 1994–96 and long-term (30-year average) rainfall and potential evaporation (mm) at Keyneton.

| | J | F | M | A | M | J | J | A | S | O | N | D | Annual |
|--------------------------------------|-----|-----|-----|----|----|-----|-----|----|----|-----|-----|-----|--------|
| Rainfall | | | | | | | | | | | | | |
| 1994 | 20 | 1 | 4 | 6 | 28 | 119 | 18 | 27 | 25 | 29 | 22 | 5 | 304 |
| 1995 | 48 | 15 | 13 | 37 | 37 | 67 | 121 | 9 | 48 | 58 | 9 | 5 | 467 |
| 1996 | 47 | 8 | 30 | 10 | 10 | 132 | 84 | 80 | 73 | 53 | 15 | 7 | 549 |
| Long-term rainfall (mm) ^a | 18 | 23 | 20 | 35 | 62 | 64 | 80 | 76 | 63 | 49 | 29 | 25 | 544 |
| Potential evaporation | | | | | | | | | | | | | |
| 1994 | 183 | 139 | 149 | 81 | 50 | 21 | 40 | 44 | 68 | 100 | 101 | 168 | 1144 |
| 1995 | 150 | 126 | 95 | 47 | 20 | 16 | 9 | 21 | 47 | 66 | 98 | 112 | 807 |
| 1996 | 127 | 96 | 77 | 35 | 27 | 39 | 17 | 25 | 46 | 77 | 97 | 120 | 783 |
| Potential evaporation (mm) | 139 | 108 | 97 | 53 | 30 | 23 | 26 | 32 | 49 | 73 | 89 | 119 | 838 |

^a Long-term rainfall and potential evaporation data from the Bureau of Meteorology

a low water-holding capacity and a high saturated hydraulic conductivity; it is acidic to neutral (McMurray 1994; Pritchard 1998). The B horizon has a fine texture and generally low permeability but in places is 'leaky' due to macropores (Kirkby et al. 1997; Pritchard 1998). The B horizons are alkaline. The soils in the catchment receive 15 kg/ha of superphosphate each year. The soils are mostly a series of Chromosols, Sodosols and Dermosols (Isbell 1996) or Xeralfs (Soil Survey Staff 1996), from Typic Palexeralfs on the crests through Aquic Palexeralfs on the mid-slopes to Natrixeralfs on the lower slopes and flats (McMurray and Cox 1995). A gully cuts through and drains areas of acid sulfate-like soils that have formed in the valley (Brown 1997).

A concrete triangular profile flat-V weir (Bos 1976) was installed in an erosion gully draining approximately 200 ha of the catchment (Fig. 1). Stage height was recorded every 10 minutes for three years using a Dataflow Pty Ltd capacitance probe attached to a single channel data-logger.

Flow rates were calculated in litres per second (L/s) using Equation 1 (Bos 1976):

$$Q = C_d C_v \frac{4}{15} (2g)^{0.5} \frac{B}{H_b} (h_e)^{2.5} \quad (1)$$

where Q is the flow rate (L/s), C_d is the discharge coefficient (0.66), C_v is the approach velocity coefficient (1.0), g is the gravitational acceleration (9.8 m/s^2), B is the channel surface width (m), H_b is the height of the crest (m), and h_e is the adjusted height of water over the weir crest in metres calculated from the formula $h_e = h_1 - K_h$ where h_1 is the measured height of water in metres and K_h is a constant (0.0008 m).

Pitman et al. (1998) collected runoff and throughflow off fifteen $50 \times 50 \text{ m}$ plots in the catchment (Fig. 1) over a three-year period (which included the wettest year of this study). They showed that in years with average rainfall or less, overland flow in the catchment was less than 1% of annual rainfall, throughflow was up to 8% and

groundwater recharge reached 20%. Thus gully drainage must be predominantly groundwater discharge with some throughflow. We therefore measured groundwater levels continuously in a piezometer located in the valley, using a capacitance probe and data-logger (Dataflow Pty Ltd; Fig. 1).

Water chemistry and loads

Water samples were collected on 53 occasions at all stages of flow (from rising limb to recession) by grab sampling from the centre of the stilling well when the gully was flowing across the weir. Samples were prepared and analysed as per Cox and Pitman (2001). Total chemical loads were calculated by multiplying the chemical concentration by the discharges between sampling periods, and then by integration of the load versus time curve.

Results

Rainfall

In the first year of the trial, annual rainfall was 304 mm (44% below average), but June rainfall was

twice the average due to one exceptionally large rainfall event (61 mm/day). In the second year of the trial, there was 468 mm of rain, which was 14% below average. Unusually high falls (up to 30 mm/day) were measured in January and February. The last year of the trial had the highest rainfall (548 mm), although it was only about average; the wettest month was June.

Groundwater levels

Groundwater levels were lowest (about 394 m above the Australian Height Datum) in May of each year. Seasonal rises in groundwater levels were 1.2, 1.4, and 1.9 m each year, reflecting seasonal rainfall levels for the respective years.

Gully flows

Below-average rainfall in the first year resulted in relatively low flows (< 100 L/second), with one exception. The maximum flows occurred at the beginning of July, which corresponded to the highest daily rainfall event of that year (61 mm).



Figure 1. Location of catchment area, gully, weir, piezometer and overland flow/throughflow plots (from Cox and Ashley 2000).

Total flow in the first year was 9.8 megalitres (ML) (2.3% of catchment annual rainfall). Annual gully flow (**Flow**) was well correlated with seasonal changes in groundwater levels (**S**, m; Equation 2).

$$\text{Flow} = 3.87 \times 10^6 e^{0.877 \cdot S}, r^2 = 0.808 \quad (2)$$

The impact of relatively high rainfall in January (48 mm) and July (121 mm) in the second year could be seen in the change in flows. Two relatively high flows were recorded in January (230 and 120 L/second); an extreme flow (710 L/s) was recorded on 23 July in the second year. Total flow was 15.7 ML (2.4% of catchment rainfall). Total flow in the last year was 19.5 ML (2.5% of catchment rainfall). The maximum flow occurred on 14 March (640 L/s).

The low r^2 values showed that, in general, there was no relationship between daily rainfall and daily flow over the three years [daily gully flow = $3.9 \times$ daily rainfall (mm) + 15.1, $r^2 = 0.138$; daily gully flow = $2.78 \times$ previous day rainfall (mm) + 17.4, $r^2 = 0.070$] or between monthly rainfall and flow. However, the relationship between annual gully flow (**Flow**) and annual rainfall (**P**, mm) (3 measurement points only) was clearer:

$$\text{Flow} = 4.16 \times 10^6 e^{0.0028 \cdot P}, r^2 = 0.999 \quad (3)$$

The data imply that even in very low rainfall years the storage capacity of the highly weathered regolith is exceeded and the excess water is discharged through the gully system.

Seasonal changes in electrical conductivity and acidity of the discharge waters

The gully water was generally alkaline (around pH 8.5) but had slightly lower pH (about 8.3) in the wettest year. One rapid drop in pH (to 7.5) must have been due to a major volume of throughflow (fresh perched water) entering the gully, because it corresponded with the lowest electrical conductivity. At this time, discharge was high (310 L/s). Large changes were measured in the electrical

conductivity of the gully drainage waters between winter and summer each year. Electrical conductivity was high at the start of each season—around 30 decisiemens per metre (dS/m)—but dropped to about 5 dS/m each winter. The electrical conductivity was lowest (2 dS/m) in the winter of the third year. Electrical conductivities generally tended to be lowest in the wettest winters and highest in the driest summers.

Chemical concentrations

Table 2 summarises the average total nutrient and chemical concentrations in gully flow.

Concentrations of sodium (Na), magnesium (Mg), sulfur (S) and calcium (Ca) were always higher than those of other chemical species. Average Na concentrations in the first year were higher (2800 mg/L) than Mg (317 mg/L), S (198 mg/L), Ca (103 mg/L) or K (961 mg/L). This pattern was repeated each year. The average concentration of most contaminants was highest in the driest year (1994).

Table 3 is a summary of the annual loss (kg/ha/year) of chemicals in gully flow and shows that high chemical concentrations (Table 2) do not always mean high losses of these chemicals, because they can form during periods of low flow. The greatest losses of Na, Mg, S and Ca were 41, 4.5, 1.9 and 1.4 kg/ha/year, respectively. The trends in losses of Na, Mg and Ca over time were similar to that of S, which shows that the processes leading to loss of these chemicals are similar.

Na losses were highly correlated with Mg ($r^2 = 0.993$), S ($r^2 = 0.984$) and Ca ($r^2 = 0.804$); the relationships between these parameters were similar in all years (Table 4).

Average phosphorus (P) concentrations were similar each year (0.9, 0.6 and 0.5 mg/L; Table 2). Annual P loss was low, 5–7 g/ha (Table 3), but concentrations were of environmental concern. P loss was usually very high during the most intense gully flows, but there was no significant relationship

($P < 0.05$) between P loss and gully flow. In contrast to the other nutrients, the average nitrate nitrogen ($\text{NO}_3\text{-N}$) concentrations were clearly highest (0.6 mg/L) in the driest year and lowest (0.1 mg/L) in the wettest year. Annual $\text{NO}_3\text{-N}$ losses were 2–10 g/ha. There was no relationship between daily $\text{NO}_3\text{-N}$ loss and gully flow.

Discussion

Gully flow was very sporadic, with long periods of little or no flow. Some very high rainfall events caused high gully flow, but in general there was no

relationship between daily rainfall and daily flow over the three years of monitoring. This was because most flow in the gully was groundwater discharge, with some throughflow. There are time lags between rainfall and the groundwater discharge and throughflow entering the gully. On one occasion, gully flow was due mostly to runoff (overland flow and throughflow) as groundwater levels were very low. Total annual gully flow (catchment discharge) was similar each year (2.3%, 2.4% and 2.5% of rainfall) and reflected both the slight differences in annual rainfall and the annual change in groundwater levels.

Table 2. Average total salt concentrations in gully discharge.

| Chemical or nutrient | Average concentration (mg/L) | | |
|----------------------|------------------------------|--------------------|--------------------|
| | 1994 | 1995 | 1996 |
| Sodium | 2797.7 | 1985.6 | 2020.5 |
| Magnesium | 316.8 | 232.3 | 215.7 |
| Sulfur | 198.1 | 112.3 | 103.3 |
| Calcium | 102.9 | 90.9 | 91.9 |
| Potassium | 60.9 | 46.4 | 44.2 |
| Phosphorus | 0.94 | 0.59 | 0.53 |
| Boron | 0.61 | 0.65 | 0.44 |
| Nitrate | 0.57 | 0.30 | 0.11 |
| Iron | 0.15 | 0.09 | 0.11 |
| Zinc | 0.13 | <0.05 ^a | <0.05 ^a |
| Aluminium | <0.05 ^a | 0.26 | <0.05 ^a |
| Manganese | <0.05 ^a | <0.05 ^a | <0.05 ^a |

^a Level of detection

Table 3. Total chemical and nutrient loads in gully discharge.

| Chemical or nutrient | Total load (kg/ha/year) | | |
|----------------------|-------------------------|-------|-------|
| | 1994 | 1995 | 1996 |
| Sodium | 23.7 | 41.4 | 23.4 |
| Magnesium | 2.70 | 4.49 | 2.85 |
| Sulfur | 1.34 | 1.93 | 1.16 |
| Calcium | 1.32 | 1.22 | 1.35 |
| Potassium | 0.51 | 0.87 | 0.53 |
| Phosphorus | 0.005 | 0.007 | 0.005 |
| Boron | 0.006 | 0.011 | 0.007 |
| Nitrate | 0.010 | 0.009 | 0.002 |
| Iron | 0.008 | 0.013 | 0.03 |
| Zinc | 0.002 | 0.002 | 0.002 |
| Aluminium | 0.011 | 0.018 | 0.004 |
| Manganese | 0.0008 | 0.005 | 0.001 |

Table 4. Relationships between sodium (Na) and magnesium, sulfur and calcium loads in gully discharge (g/ha/year).

| Element | 1994 | 1995 | 1996 | All years |
|-----------|--|--|--|--|
| Magnesium | $0.116x\text{Na}-0.997$ $r^2=0.997$ | $0.107x\text{Na}+0.048$ $r^2=0.996$ | $0.126x\text{Na}-0.064$ $r^2=0.998$ | $0.120x\text{Na}-0.181$ $r^2=0.993$ |
| Sulfur | $0.056x\text{Na}-0.045$ $r^2=0.991$ | $0.044x\text{Na}+0.189$ $r^2=0.965$ | $0.051x\text{Na}+0.010$ $r^2=0.995$ | $0.049x\text{Na}+0.058$ $r^2=0.984$ |
| Calcium | $0.077x\text{Na}-0.570$ $r^2=0.697$ | $0.020x\text{Na}+0.408$ $r^2=0.548$ | $0.064x\text{Na}+0.001$ $r^2=0.989$ | $0.053x\text{Na}-0.185$ $r^2=0.804$ |

The gully drainage chemistry changed markedly over the three years of the study, partly due to the water pathways (groundwater recharge, throughflow and some overland flow) and water residence (lag) times. Changes in pH of the gully drainage were sometimes very rapid. In contrast, there was relatively little change in electrical conductivity of the gully drainage each winter. However, considerable changes were measured at the start of each winter season (probably due to the flushing and evaporation of salt) and at the end of winter (probably due to the concentration of salt).

Concentrations of Na, Mg, S and Ca were far higher than those of other contaminants. The loss of Na was one order of magnitude higher than the levels reported by Fleming and Cox (1998) for runoff from dairy catchments in the high-rainfall zone of the Mount Lofty Ranges, whereas Mg, S and Ca losses were similar. Mg, S and Ca behaved like Na; losses of these chemicals can be predicted with good accuracy from measurement of Na only.

P losses (5–7 g/ha/year) were two orders of magnitude lower than those reported by Fleming and Cox (1998) and Nelson et al. (1996) for grazed catchments in the high-rainfall zone of the Mount Lofty Ranges. The annual P losses were one order of magnitude lower than those reported in agricultural runoff in New South Wales by Costin (1980), or by Greenhill et al. (1983) in overland flow from perennial pastures in Victoria. P was always in the soluble form, probably because it does not enter the gullies as overland flow but moves through the soil (in both throughflow and recharge) into the gullies. Also, the hypersaline conditions probably cause flocculation of P, which attaches to colloids and is trapped in the gully (the gully sediments are high in P). P concentrations were about 100 times higher than those considered acceptable for the health of upland stream ecosystems (ANZECC and ARMCANZ 1999).

Conclusion

Gully discharge from the Keynes catchment in the Mount Lofty Ranges in low rainfall years was hypersaline and, just as importantly, had high levels of S, P, NO₃-N and other elements. It is expected that in higher rainfall years, when overland flow causes erosion and scouring of the gully, losses of some of these contaminants will be orders of magnitude higher. Thus, if drainage systems are installed in discharge areas, they must be designed to regularly filter fine (solutional) contaminants in low rainfall years as well as colloidal material during (the less frequent) erosive events.

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References

- ANZECC (Australian and New Zealand Environment and Conservation Council) and ARMCANZ (Agriculture and Resource Management Council of Australia and New Zealand). 1999. Australian and New Zealand Guidelines for Fresh and Marine Water Quality. National Water Quality Management Strategy. Public comment draft, July 1999. Canberra, ANZECC and ARMCANZ.
- Bos, E.G. 1976. Discharge Measurement Structures. International Institute for Land Reclamation and Improvements Publication 20. The Netherlands, International Institute for Land Reclamation and Improvements, 197–203.
- Brown, B. 1997. Transportation of the salts required in the formation of acid sulphate soils through a saline rocky micro-catchment. University of Adelaide, BSc Honours thesis.
- Chittleborough, D. 1992. Formation and pedology of duplex soils. *Australian Journal of Experimental Agriculture*, 32, 15–25.
- Costin, A.B. 1980. Runoff and soil and nutrient losses from an improved pasture at Gininderra, Southern Tablelands, New South Wales. *Australian Journal of Agricultural Research*, 31, 533–546.
- Cox, J.W. 1998. Land clearance changes on the hydrology of a toposequence as predicted by soil morphology. Proceedings of the 16th World Congress of Soil Science, Montpellier, France, 20–26 August 1998. (CD-ROM)

- Cox, J.W., Fritsch, E. and Fitzpatrick, R.W. 1996. Interpretation of soil features produced by modern and ancient processes in degraded landscapes: VII. Water duration. *Australian Journal of Soil Research*, 34, 803–824.
- Cox, J.W. and Ashley, R. 2000. Water quality of gully drainage from texture-contrast soils in the Adelaide Hills in low rainfall years. *Australian Journal of Soil Research* 38, 959–972.
- Cox, J.W. and Pitman, A. 2001. Chemical concentrations in drainage from perennials grown on sloping duplex soils. *Australian Journal of Agriculture Research*, 52, 211–220.
- Fitzpatrick, R.W., Fritsch, E. and Self, P. 1996. Interpretation of soil features produced by ancient and modern processes in degraded landscapes: V. Development of saline sulfidic features in non-tidal seepage areas. *Geoderma*, 69, 1–29.
- Fitzpatrick, R.W., Merry R.H. and Cox, J.W. 2000. What are saline soils and what happens when they are drained? *Journal of the Australian Association of Natural Resource Management*, June, 26–30.
- Fleming, N.K. and Cox, J.W. 1998. Chemical losses off dairy catchments located on a texture-contrast soil: carbon, phosphorus, sulfur and other chemicals. *Australian Journal of Soil Research*, 36, 979–995.
- Greenhill, N.B., Peverill, K.I. and Douglas, L.A. 1983. Nutrient loads in surface runoff from sloping perennial pastures in Victoria. *New Zealand Journal of Agricultural Research*, 26, 503–506.
- Haygarth, P.M. and Jarvis, S.C. 1996. Pathways and forms of phosphorus losses from grazed grassland hillslopes. In: Anderson, M.G. and Brooks, S.M., eds, *Advances in Hillslope Processes*. Vol 1. London, John Wiley and Sons Ltd., 283–294.
- Isbell, R.F. 1996. *The Australian Soil Classification*. Melbourne, CSIRO Publishing.
- Kirkby, C.A.K., Smythe, L.J., Cox, J.W. and Chittleborough, D.J. 1997. Phosphorus movement down a toposequence from a landscape with texture-contrast soils. *Australian Journal of Soil Research*, 35, 399–417.
- McMurray, L. 1994. Soil properties associated with waterlogging down concave and convex toposequences. Adelaide University, BSc Honours Thesis.
- McMurray, L.S. and Cox, J.W. 1995. Soil morphological features down a convex toposequence: Keyneton, South Australia. Adelaide, South Australia, CRC for Soil and Land Management, Technical Report 2/95, 22.
- Nash, D. and Murdoch, C. 1997. Phosphorus in runoff from a fertile dairy pasture. *Australian Journal of Soil Research*, 35, 419–429.
- Nelson, P.N., Costaris, E. and Oades, J.M. 1996. Nitrogen, phosphorus and organic carbon in streams draining two grazed catchments in the Mt. Lofty Ranges, South Australia. *Journal of Environmental Quality*, 25, 1221–1229.
- Northcote, K.H. 1960. *A factual key for the recognition of Australian soils*. Adelaide, CSIRO.
- Pitman, A., Cox, J.W. and Bellotti, W.D. 1998. Water usage and dry matter production of perennials down a duplex toposequence. *Proceedings of the 9th Australian Agronomy Conference*, Charles Sturt University, Wagga Wagga, 20–23 July 1998.
- Pritchard, J. 1998. *Modelling the water balance of duplex soils at Keyneton, Mt Lofty Ranges, SA*. Adelaide University, BSc Honours Thesis.
- Schofield, N.J., Ruprecht, J.K. and Loh, I.C. 1988. The impact of agricultural development on the salinity of surface water resources of south-western Australia. Perth, Water Authority of Western Australia, Report WS27, 69.
- Sharpley, A.N. and Syers, J.K. 1979. Phosphorus inputs into a stream draining an agricultural catchment. *Water Air and Soil Pollution*, 11, 417–428.
- Sharpley, A.N., Chapra, S.C., Wedepohl, R., Sims, J.T., Daniel, T.C. and Reddy, K.R. 1994. Managing agricultural phosphorus for protection of surface waters: Issues and options. *Journal of Environmental Quality*, 23, 437–451.
- Soil Survey Staff. 1996. *Keys to Soil Taxonomy*. 7th edition. Washington DC, United States Department of Agriculture, United States Government Printing Office.
- Stevens, D.P., Cox, J.W. and Chittleborough, D.J. 1999. Phosphorus, nitrogen and carbon movement over and through duplex soils in sub-catchments of the Adelaide Hills. *Australian Journal of Soil Research*, 37, 679–693.