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INTRODUCTION

The Wybong Creek catchment is located in central New South Wales, Australia, and has been identified as a priority catchment of the Hunter River for detailed study (Fig. 1). This is due to Wybong Creek delivering significant salt loads to the Goulburn River, which then flows into the Hunter River. Salts from Wybong Creek were also dominated by Na-Cl, which is anomalous with other Na-Mg-HCO_3 dominated rivers in the Hunter Catchment (Creelman, 1994). The 800 km^2 Wybong catchment is bordered in the north by the Liverpool Ranges, which are comprised of Triassic Narrabeen sandstones and conglomerates capped with Eocene Liverpool Range Volcanics. In the east, south and west of the catchment, the Narrabeen Sandstone group occur as gent out crops to extremely steep sandstone escarpments.

North of the Liverpool Ranges, salinisation in the Namoi River catchment and Liverpool Plains has been attributed to dryland salinity (Ringose-Voase et al., 2003). South of the Liverpool Ranges and in the Hunter catchment, conflicting opinions exist on the causes of soil and groundwater salinity, and include dryland salinity (Beale et al., 2000), irrigation salinity (Healthy Rivers Commission, 2002), and seepage from coal and associated formations (Creelman, 1994). Previous work shows that saline regolith (sodosols) occur within alluvial landforms in the mid-lower Wybong Creek catchment (Kovac, Lawrie, 1991). A field site containing showing clear evidence of salinity at the locality of Manobalai was selected for regolith sampling and piezometer installation, in order to assess sources of salinity to Wybong. Field investigations included soil (regolith) sampling at eight sites, and installation and sampling of groundwater from 12 bores and piezometers, and a single spring.

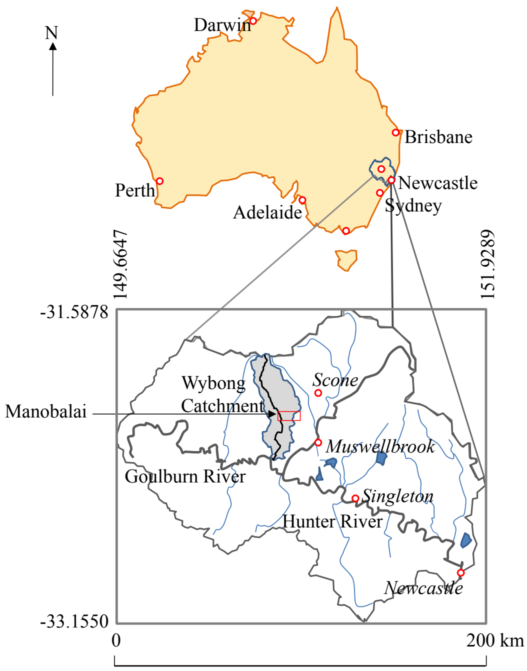

Figure 1. The location of the Hunter River catchment within Australia. The Hunter River, and the Goulburn River which flows into it, is shown in bold.. The Wybong Creek catchment is illustrated in grey.

METHODS

Regolith sampling

Regolith cores were collected on the 8th and 9th of January 2008 and the 25th and 26th of March 2009, from eight sites within the mid-catchment area of Manobalai (Fig. 2). Sites were selected according to landform, including at the breaks of slope (Sites One, Three and Five), in a drainage depression (Site Four) and within a salt scald (Site Two). The evolution of groundwater chemistry between the salt scald and Wybong Creek was study through the sampling of cores and installation of piezometers at sites Six – Eight. A total of 125 samples were collected every 0.25 – 1.00 m along the entire length of the cores, with sampling based on textural and colour changes.

Soil salinity in each of the samples was initially investigated by analysing 1:5 soil:water extracts for electrical conductivity (EC). A range of samples including the most saline, the least saline and a number with average salinity were selected for ion analyses according to the findings of $EC_{1:5}$ results. Samples were analysed for major cations using ICP-AES and ICP-MS, and IC was used for anions. Select samples from Site Two were analysed for minerals using XRD analyses.

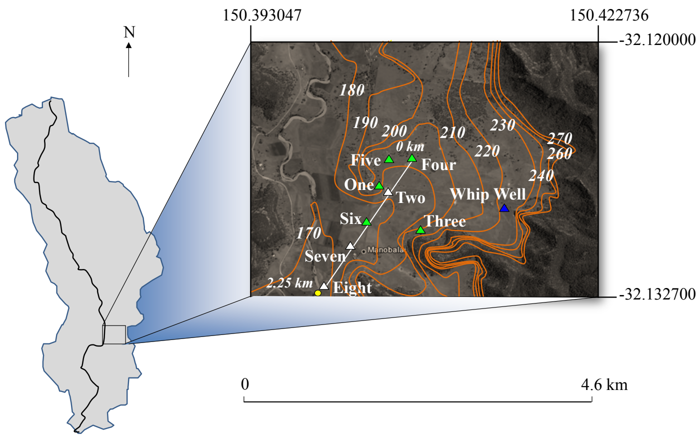

Figure 2. Location of regolith and groundwater sample sites within the Manobalai area of the Wybong Creek catchment. Single piezometers are indicated by (▲), while bore and/or piezometer nests are indicated by (△). The spring at the site is indicate by (▲). Numbers in italics indicate elevation as determined by Google Earth, with topographic contours also shown.

Water sampling

Groundwater was sampled from bores and piezometers at Manobalai, and from a well dug into a spring (Fig. 2). All water samples were filtered in the field. Samples for cation analyses were acidified using 2 mL 50% HNO_3, while anion samples were only filtered. Samples were analysed for major cations using ICP-AES and ICP-MS, and IC was used for anions. Electrical conductivity was measured on unfiltered water samples at the time of sampling using a calibrated Orion DuraProbe™ 4-electrode conductivity cell and conductivity meter. Alkalinity was measured in the field by titration, using filtered water, a Hach digital titrator, HCl and methyl orange.

RESULTS AND DISCUSSION

Regolith in the northern reaches of the study area, is largely composed of interbedded alluvium in the valley floor, though no water course is obvious in the area. The footslopes of the Narrabeen Group escarpments and outcrops overlying the local regolith are instead composed of colluvium, with cores collected from these footslopes showing pedological development. Three hundred metres south of the Manobalai salt scald, regolith cores changed in composition from the alluvium seen at Sites Two and Four, to black – chocolate brown smectitic clay. Little horizonal development was seen in cores collected from this area, which included Sites Six, Seven, and Eight Shallow.

Salinity within the regolith cores collected from the valley floor in the study area varied according to texture. None of the soil samples in the area were saline on an $EC_{1:5}$ basis, however, with saline soils defined as having $EC_{1:5}$ >1500 µS cm^{-1} (Northcote, Skene, 1972). The regolith beneath the salt scald at Site Two, for example, was comprised of sandy clays and clayey sands, with maximum salinities of up to 1200 µS cm^{-1}. Increases and decreases in salinity in the Site Two cores occurred according to texture. Sodium and Cl were the dominant salts in all samples. Salinity in the Site Four core further up-gradient of the salt scald varied similarly to the salinity seen in the Site Two Deep and Shallow cores, and solutes were also dominated by Na and Cl. The salinity in the Site Six core was higher than any of the other samples collected from Manobalai. Though regolith was not saline on an $EC_{1:5}$ basis with a maximum salinity of 1225 µS cm^{-1}, Na and Cl concentrations in two samples were over 0.2 % on a per weight basis, indicating that Na and Cl concentrations in these samples could be problematic to soil health (Northcote, Skene, 1972). Pedologically developed cores from the footslopes of the escarpments and outcrops instead increased from 15 µS cm^{-1} in the upper-most samples, to 313 µS cm^{-1} at the interception of hard-rock.

The solutes in the soil and regolith of many catchments within Australia are thought to arrive with rain and/or dust, with solute concentrations building up over geological time due to inadequate flushing through of salts by precipitation. Rainwater is dominated by SO_4 and HCO_3 when it arrives in catchments and evolves to Na and Cl dominated water as a result of carbonate and sulfate precipitation (Eugster & Hardie, 1975; Jankowski & Jacobson, 1989). Water is increasingly saturated with carbonate and sulfate minerals as it is evaporated (Eugster & Hardie, 1975). Precipitation and/or evaporation would be expected to result in sulfate and carbonate minerals within the shallower layers of the regolith profile, with increasing proportions and dominance of Na and Cl with increasing depth. This is not thought to give rise to salinity at Manobalai, however, with carbonate minerals not identified in any of the four samples from Site Two using XRD analysis and sulfate minerals only tentatively identified in the sample from 0.5 – 1.0 m below the ground surface. The $pH_{1:5}$ of soil:water extracts were below 8.3 within all samples from Sites One – Five, indicating that the conditions for carbonate precipitation do not occur (Charman & Murphy, 2000). Potential for the formation of pedogenic carbonate does exist further downslope at Sites Six – Eight, where $pH_{1:5}$s were as high as 9.6. No clear correlation between Na and Cl and depth occurred at any site, however, with increases expected to occur if Na and Cl dominance was caused by the precipitation of carbonate and sulfate minerals in the uppermost layers of the soil profile and/or evapoconcentration of fresher water. Because meteoric accession of salts would result in sulfate and carbonate dominated soil samples in the uppermost layers, and these did not occur at Manobalai, the Na and Cl dominated soil solutions at

Manobalai indicate salinity occurs as a result of processes not related to direct meteoric accession or evapoconcentration.

The highest soil moistures occurred at depths where groundwater was intercepted, though soil salinity and soil moisture were sometimes inversely at different sites. Total soil moisture was highest at the depth of groundwater interception, at Site Two and Four, with groundwater occurring beneath confining clay layers and within clayey sand layers. Groundwater instead occurred within the saprolitic material at the bottom of cores at the breaks of slope and within the smectitic regolith. The highest regolith salinities in the alluvium at Site Two (1200 μS cm^{-1}), and at the breaks of slope occurred just above the layers where groundwater was intercepted and where soil moisture was highest. Lower salinity regolith layers were instead correlated with the interception of groundwater at Sites Four and Six. The variation in soil salinity was not related to the type of regolith, with similar regolith at Sites Two, Four and Whip Well, but instead the occurrence of groundwater.

Groundwater salinity at the Manobalai site was highly variable, and varied independent of regolith type. Groundwater was fresh at Site Four and Whip Well, for example, where freshwater is defined as having salinities less than 400 mg L^{-1} (Rhoades et al. 1992). Although the bore and piezometer at Site Two had lower hydraulic heads, and were located within alluvium 600 m topographically down-gradient of Site Four, groundwater at Site Two was moderately – highly saline with salinities in excess of 5000 mg L^{-1}. Groundwater salinity again dropped 300 m topographically down-gradient at Site Six, where salinities of 1721 mg L^{-1} occurred. Groundwater at the break of slope was as variable as on the valley floor, with up to 1418 mg L^{-1} occurring at Site One, 4570 mg L^{-1} at Site Three, and no groundwater at all occurring at Site Five.

The occurrence of the highest Na and Cl concentrations in sandy layers at the same depth where saline groundwater occurs indicates that saline groundwater transports solutes to the regolith at Site Two. Groundwater was as little as two metres below the surface at this site, with the depth to water decreasing as drought conditions eased throughout the length of the study. The opposite instead occurs at Site Four and Site Six, where groundwater contains much lower solute concentrations, with groundwater removing solutes from the coarsest layers of regolith through which it flows, in turn giving rise to regolith with much lower salinities. The variability of groundwater salinity at the study site indicates the occurrence of a number of water bodies, with discharge of saline regional systems at Site Two, and the occurrence of fresher, more localised systems at Sites Four and Site Six. The regional and saline groundwater system discharging into the site is likely from the Permian Coal Measures, which cause abrupt increases in salinity elsewhere in the Hunter Catchment (Creelman, 1994). The results presented here are therefore evidence that groundwater is an important means of transporting solutes at Manobalai, bringing solutes to the sandy layers at salt scald (Site Two) and removing solutes from the regolith at Sites Four and Six.

CONCLUSIONS

Saline groundwater did not occur at all sites within the Manobalai area. The occurrence of similar saline water in specific bores and piezometers at the break of slope, and in the valley bottom suggests point source groundwater discharge via fractures and/or faults connected to a saline and regional aquifer, with saline and regional groundwater from the Permian Coal Measures identified as a potential source in research from elsewhere within the Hunter catchment. Saline and discharging water appears to be diluted by fresher local systems in places, such as at Site Four and Whip Well.

These findings have important ramifications in the context of salinity research within Australia, whereby a model of dryland salinity is often assumed and related to salt stores within the regolith, accession of meteoric water, and/or evapoconcentration. The discharge of regional groundwater implies that salinity is sourced from the deeper Permian Coal Measures, and as such, is a naturally occurring processes. This means that the sustainability of agriculture in the catchment necessarily requires the limitation of irrigation using surface and groundwater, including fresher water which can be used to dilute the more saline groundwater which occurs. Further research is required in order to ascertain that human changes to the hydrological cycle have not caused the discharge of regional groundwater into the catchment.

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