Willaura Catchment Geochemistry

By Darren Bennetts

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ABSTRACT

Geochemical analysis, soil permeability, and salt profiling have revealed a complex water transport mechanism within the Willaura catchment. A fracture dominant basalt aquifer removes much water from Lake Muirhead and moves it southward to a series of terminal lakes at the foot of the Stavely Hills. Here it discharges in a series of relatively fresh seeps at rocky outcrops, evident at the edge of the basalt lithology. Low permeability solodic clays form on the Pleistocene basalt resulting in lateral water movement where significant salt is accrued before discharge at the break of slope, feeding Boggy Swamp and possible Gellerts Swamp. Rocky outcrops at these breaks of slope provide fresher water to generate flows up to 2ML/day into the swamps.

The Ordovician interbedded sandstone and shale, and Grampians sandstone lithologies forming the Stavely Hills, appear to be the dominant salt store in the area, with high permeability soil on cleared slopes, and excessively high concentrations of salt stored increasingly with depth through the profile. This unit is likely to be responsible for feeding the extremely saline terminal lakes low in the catchment. Revegetating the Stavely Hills is suggested to manage saline increases in the terminal lakes area.

INTRODUCTION

Willaura catchment is situated on the eastern side of the Grampians Ranges, and covers some 85,000 hectares in Western Victoria (Sibley, 1967). It is bordered by the Hopkins river in the east, and the Stavely Hills in the south. It is included in the north west of the Hopkins River catchment. The area has no external drainage which leads to water logging, and the presence of many swamps. This is caused by basalt flows cutting off drainage to the Hopkins River in the East. The area is generally flat except for the Stavely Hills in the South. The area is characterised by a series of terminal saline lakes in the southern end of the catchment that occur along the flanks of the Stavely Hills. These are readily observed by white precipitate of NaCl surrounding many of the lakes, and the presence of various salt tolerant succulents. Larger swamps (Lake Muirhead and Mt. William Swamp) are also prominent in the broad and flat expanses of the central catchment region.
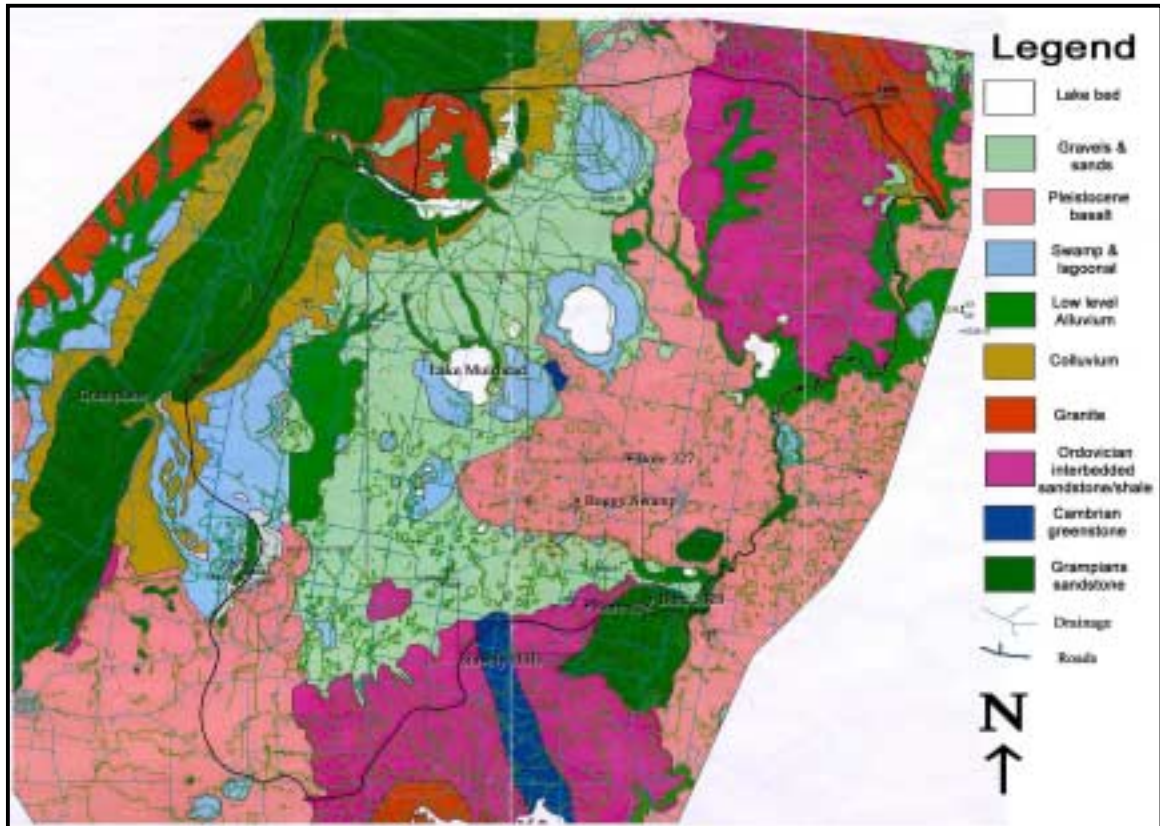
Figure 1 showing geology of Willaura catchment, bore locations and major geographic locations.

The geology of the area is quite complex, and generally reflects in the topography of the area (refer to figure 1). The area features the Grampians Sandstone unit on the Western boundary of the catchment, which features steep slopes that border the catchment. A small area of this lithology is also found in the South East of the catchment showing similar relief to the surrounding Ordovician geology. Alluvium and Colluvium geology overlies the lower slopes of the Grampians Sandstone to the West. A minor Cambrian Greenstone belt is featured in the south of the catchment, and is surrounded to the West and East by the prominent Ordovician interbedded sandstones and shales. These units maintain the integrity of the dipping planes, and hence form the slopes of the Stavely Hills, which show prominent relief at greater than 5% grade (Sibley, 1967). The east of the catchment is dominated by a Pleistocene basalt flow that covers the older sedimentary units. This Willaura basalt flow is relatively flat and undulating, and has been noted to have no stony rises and "an internal drainage system with swamps" (Sibley, 1967). This basalt flow appears to also form the basement of Lake Muirhead and Mt William Swamp in the centre of the catchment as shown by aeromagnetic data (refer to appendix VI). The basement of the terminal lakes is also shown to be from that of the interbedded sandstone and shale lithology. The basalt is covered in the centre of the catchment by sands and gravels of Pleistocene to recent age. The Cambrian and Ordovician units of the South are partially covered by the same sands and

gravels which meet the lower slopes of Stavely Hills. The site of Lake Muirhead and Mount William Swamp features a series of paleolake beds, covered by the current lakebeds in certain areas, and surrounded by the sands and gravels as mentioned above. The area also contains a series of Holocene lunettes that appear on the eastern edges of the paleolakes.

These geological units correlate with soil units described by Uren (2000) and Sibley (1967). Basalt lithology has been found to have formed heavy solodic clay soils with gravel throughout. Sedimentary units in general have formed sandy loam type soils with gravel and quartz being dominant. The soils are generally conducive to cropping, which features a rotational system of Canola and Wheat. Grazing of sheep is also a common use of the now persistent grasslands.

Salt accessions in the region as previously eluded are a major problem. The once prominently woodland vegetation has been removed for agriculture and now grasslands cover much of the southern catchment area. The northern extremities are not cleared due to the grade of slopes in the Grampians foothills. Evidence suggests there is more water in the catchment than anytime in history. This has increased the incidence of break of slope salinity in the Stavely Hills, the expansion of the saline terminal lakes, greater appearance of discharge areas, and salinisation of much of the surrounding pasture.

In this area movement of groundwater is not well known, and transport of salt through and within the bedrock and soil are also poorly understood. Bore and spring sampling and soil analysis is hoped to reveal the hydrological and geochemical mechanisms active in the catchment. The bores selected for investigation are chosen such to sample a range of lithologies in the Willaura catchment. Bore 5020 is located in the Stavely Hills in the locally known 'Walkers Bores'. This occurs on Grampians Sandstone lithology. Bore 328 is found in the interbedded sandstones and shales. Bore 327 is in the centre of the basalt unit northwest of Willaura Township. Boggy Swamp is also found on the basalt lithology but appears to be a groundwater fed surface flow. These processes are thought to source a series of springs in the area (Boggy Swamp and Gellerts Swamp) as well as Lake Muirhead and the terminal lake system in the South. The correlation with soil type and parent lithology makes soil sampling adjacent to bores adequate to provide representative soil analysis.

METHODS

A. Chemical analysis of water samples

Apparatus
pH meter, EC meter, thermometer, hand pump, 0.45micron filter paper, vials (100ml), 0.5 M NaOH, pipette (0.5ml), redox probe, gloves, baler, tape measure, and tissues.

Sampling
Bores were baled once before sample was taken. However, all bores were checked on a subsequent sampling exercise to ensure that condensate had not diluted surface bore water. EC's were checked after one, two and three balings respectively and EC did not change. EC's were very similar to those EC's gained after one baling before sample was taken. All apparatus was cleaned in the bore water to be sampled by rinsing thoroughly. Water was emptied into a large beaker for immediate pH, EC, redox and temperature measurement. Temperatures quoted are from the pre-calibrated pH meter which provided more accurate results (± 0.05 °C). Samples were immediately filtered in the field using a hand pump and 0.45 micron grade filter paper. Five samples were taken. One was acidified with 0.5ml of 0.5 M Nitric Acid solution before addition of the sample. This sample was filled up to the 100ml mark to ensure exact concentration. The other samples were filled to the lid of the vial to minimise air being trapped. Samples were stored in an esky.

Figure 2 showing field testing for pH and EC.

Testing
Bicarbonate titrations were completed within two days of taking the samples. Filtered samples were used. Titration was duplicated so that the difference between individual titres was not more than 0.1ml. The titre was the amount of HCl needed to bring the pH of the water to 4.5. pH was measured continuously using the pH probe and stirrer bead. Values quoted are average of duplicated values and can be seen in appendix I.

ICP (Inductively Coupled Plasma) analysis used the filtered samples treated with nitric acid. Various dilutions (1/10, 1/20) were performed to suit the range of the standards. Na, Mg, Ca and Si were analysed using this technique. Acidified samples were also used for the AAS method for potassium analysis. For further notes on standard analysis, refer to appendix I.

HPLC (High Pressure Liquid Chromatography) was also used to determine concentrations of Cl and SO_4. 1/10 diluted samples were also used here due to high concentrations of Cl. For further notes on standard analysis, refer to appendix I.

AAS was used to analyse for K and appendix I contains dilution and absorption results.

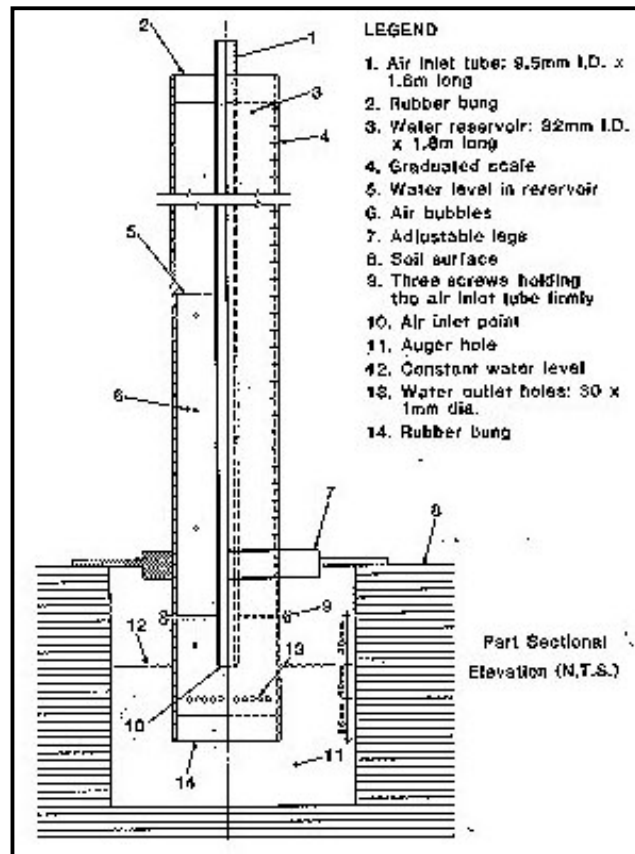*** Table 1 shows elements tested for and method used for each.***

Major Elements	Method for testing
Ca, Mg, Na, Si	ICP
HCO_3^-	Titration
Cl, SO_4	HPLC
K	AAS

Results were processed using PCWATEQ computer package which is compiled by the US Geological Survey.

B. Hydraulic conductivity of selected soils

Hydraulic conductivities were taken using Talsma-Hallam well permeameters for a range of selected soils within the area. Both unmodified tubes (as described by Talsma *et al*, 1980) and modified tubes (as amended by Nash *et al*, 1986) were used for *in situ* measurements (see figure 3). The tubes were allowed to equilibrate for approximately 45 minutes, or until such a time as steady state infiltration was observed to occur. A series of time and draw down measurements where then taken.

Several problems were noted with the operation of the Talsma tubes. In several cases, infiltration was extremely rapid indicating large voids in the soils, giving a false indication of the true infiltration rate. These were remedied by repetition until such a time that plausible infiltration was achieved. The tubes were also observed in one case to totally stop infiltrating water and the cause of this is not entirely known, needless to say that these results cannot be acceptable as we expect all soils to maintain some infiltration. Another problematic case showed the water actually rising in the tube, rather than dropping. This is probably due to a change in air pressure, which was particularly evident in the field by increases in wind, and a sudden drop in temperature. It is suggested that air pressure is monitored in future field measurements to ensure that it is stable and doesn't change significantly to alter results.

LEGEND

1. Air inlet tube: 9.5mm I.D. x 1.8m long
2. Rubber bung
3. Water reservoir: 92mm I.D. x 1.8m long
4. Graduated scale
5. Water level in reservoir
6. Air bubbles
7. Adjustable legs
8. Soil surface
9. Three screws holding the air inlet tube firmly
10. Air inlet point
11. Auger hole
12. Constant water level
13. Water outlet holes: 30 x 1mm dia.
14. Rubber bung

Part Sectional Elevation (N.T.S.)

* Figure 3 showing amended Talsma Tube setup (Talsma et al, 1980).

C.   Salt profiles

Soil samples were obtained through augering to approximately 80cm depth. Further depths were unattainable with heavy thick clays being encountered and the absence of a suitable auger extension. Salt profile measurements were undertaken in duplicate. The soil was sieved in a 2mm-grade sieve after being allowed to air dry until the soil was friable. Five grams of air-dry soil was added to 25ml of distilled water. This was shaken for one hour before EC of the suspension was measured using a probe as used in the field for EC measurements. Particular attention must be paid to ensure EC probes are correctly calibrated. Hand texture analysis was also undertaken.

RESULTS:

A. Chemical analysis of water samples

Table 2 showing results of chemical analysis on four water samples.

| SAMPLE	Boggy Swamp	5020	328	327
Lithology	Basalt	Sandstone	Sandstone/shale	Basalt
Ca (ppm)	277	384	221	99
Mg (ppm)	448	599	784	161
Na (ppm)	2008	3244	5236	883
Si (ppm)	13.7	12.1	5.6	18.4
Cl (ppm)	3949	6213	7687	1444
SO_4 (ppm)	551	753	1234	145
HCO_3 (ppm)	347	77.7	244	522
K (ppm)	79.9	104	70.0	26.3
pH	8.36	6.65	7.16	7.79
EC (mS/cm)	11.13	16.29	19.42	4.85
Temp. (°C)	17.3	16.0	15.6	16.7
TDS[#](mg/L)	7675	11388	15483	3300
TDS*(mg/L)	7624	11159	13303	3322
Log PCO_2	-3.06	-1.97	-2.01	-2.21
$SI_{calcite}$	1.26	-0.9	0.27	0.64
Redox (mV)	215	248	274	228
Charge balance error (%)	4.27	4.95	10.61	4.52

\# TDS as sum of major ions

* TDS as related to measured EC (TDS (mg/L) = EC (µS/cm) x 0.685)

Table 3 showing chemical analysis of four water samples standardised to Cl⁻ concentration in bore 328.

SAMPLE	Boggy Swamp	5020	328	327
Lithology	Basalt	Sandstone	Sandstone/shale	Basalt
Ca	539.71	475.20	221.41	527.94
Mg	872.25	742.14	784.52	859.49
Na	3908.39	4013.51	5236.18	4700.44
Si	26.74	14.97	5.62	97.98
Cl	7687.00	7687.00	7687.00	7687.00
SO4	1073.42	931.56	1234.00	773.81
HCO3	675.78	96.06	244.33	2778.05
K	155.52	128.66	70.00	139.97

For initial results, refer to appendix I. Results from PCWATEQ can be observed in Appendix II.
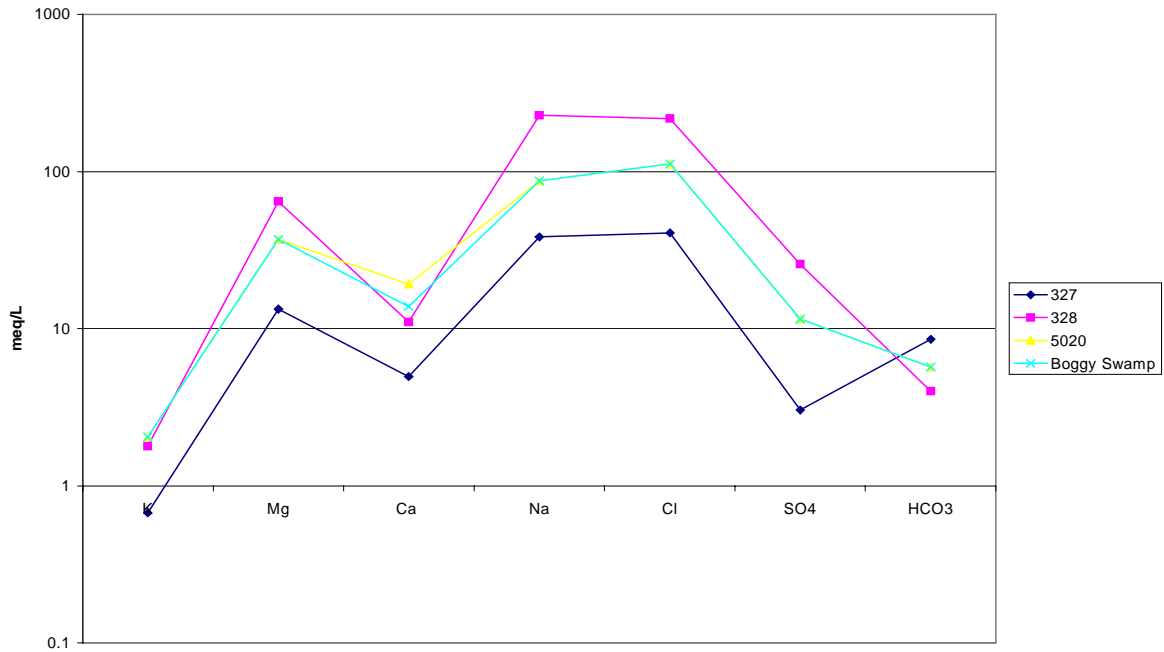
Figure 4 featuring Schoeller plot showing comparison of ion concentration.
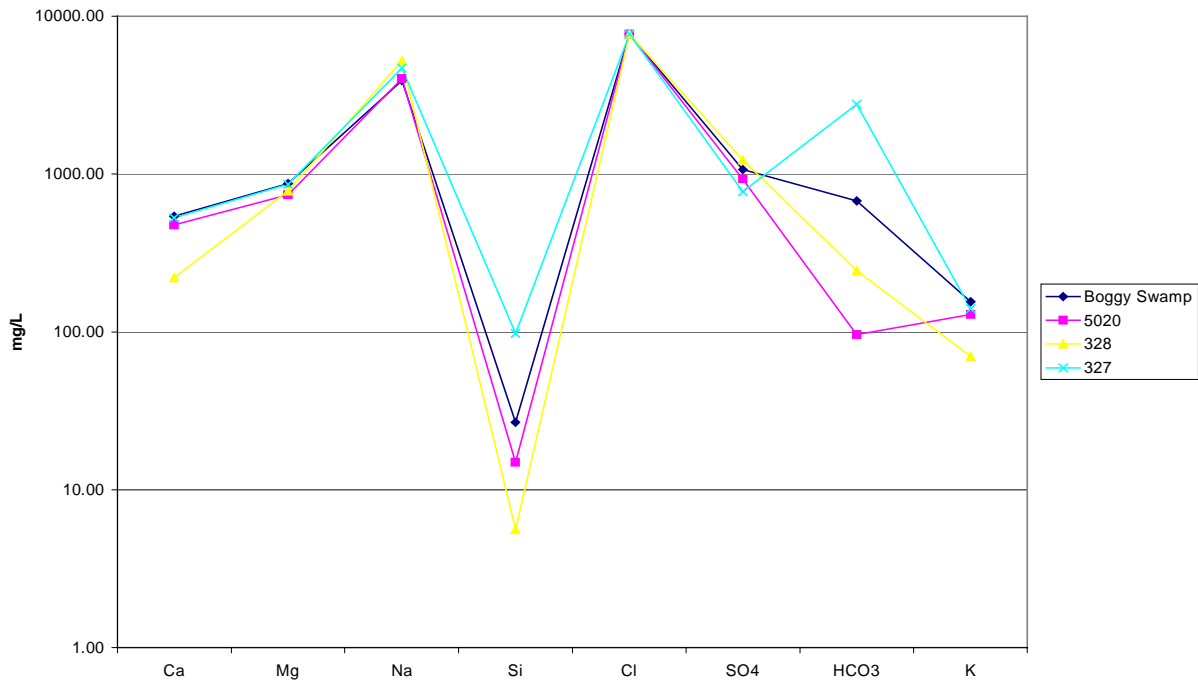
Figure 5 showing comparison of ion concentrations standardised to highest Cl⁻ concentration.
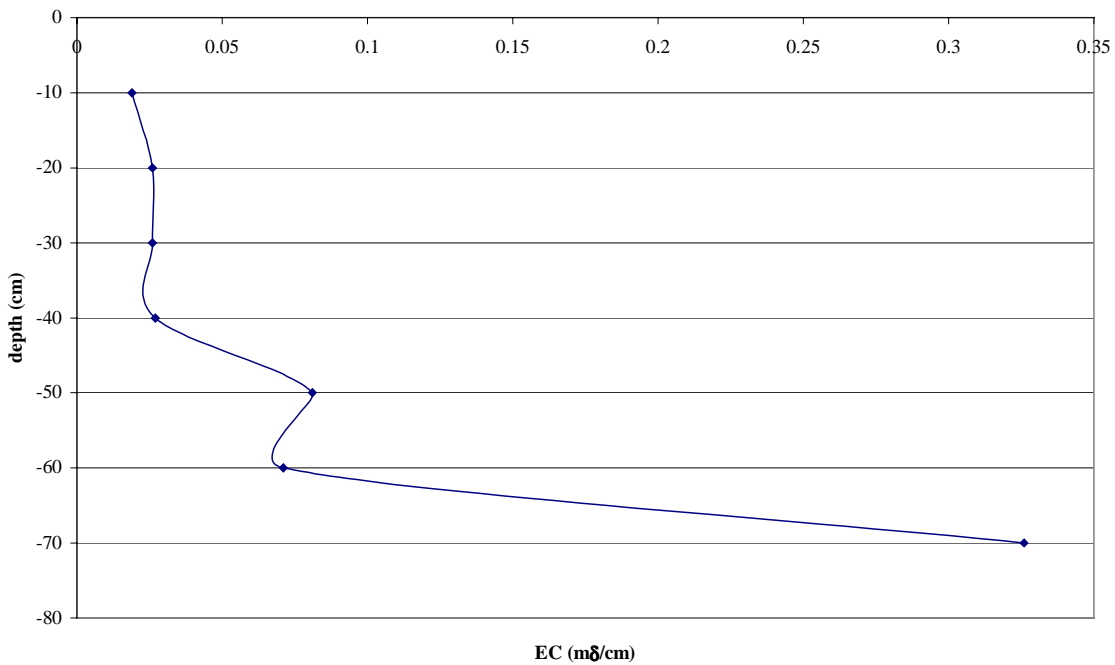
B. Hydraulic conductivity and texture of selected soils

Table 4 showing saturated hydraulic conductivity (K_s) for soils formed on varying lithology.
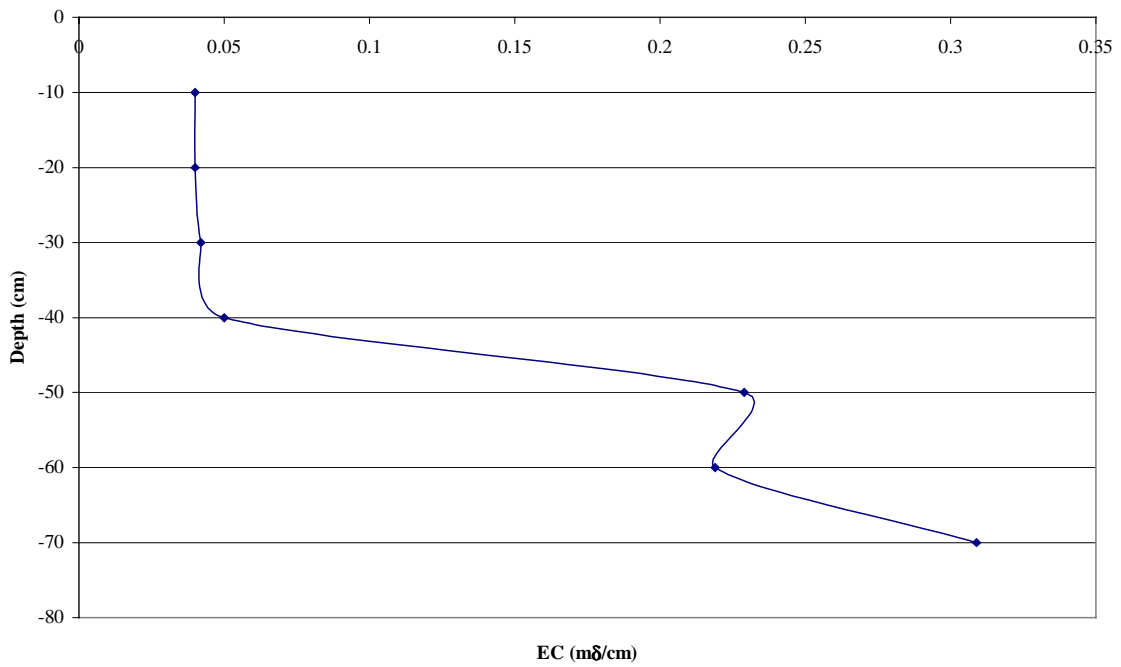
Soil Type	Lithology	K_s (m/s)
Clay	Basalt	8.75×10^{-5}
Sandy loam	Sandstone	9.09×10^{-4}

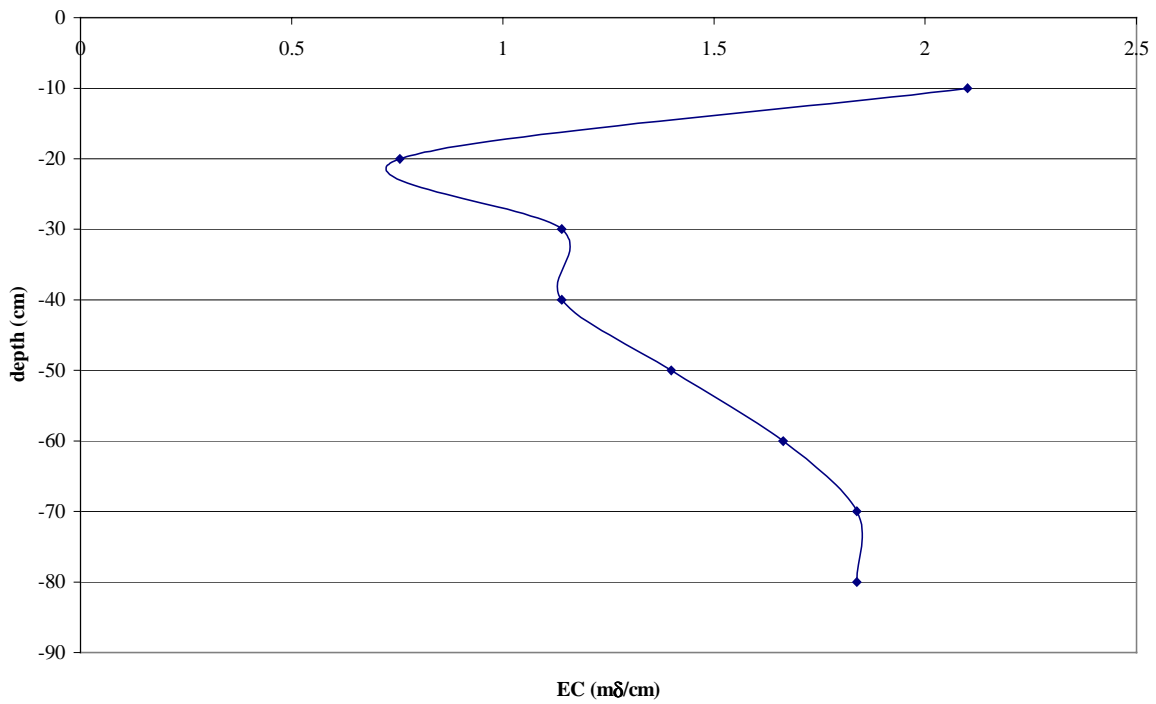Refer to appendix III for hydraulic conductivity measurements and calculations.

C.   Salt profiles

Figure 6 showing salt profile for bore 5020 (sandstone) soils

Figure 7 showing salt profile for bore 328 (sandstone/shale) soils

Figure 8 showing salt profile for Boggy Swamp (basalt) soils

Refer to Appendix IV for salt concentration data and texture descriptions.

DISCUSSION:

A. Chemical analysis

Charge Balance Errors

Charge balance errors are generally within acceptable bounds ($\pm$ 5%). We find with increases in electrical conductivity, the charge balance also increases. The most saline sample of bore 328 has a charge balance of 10.61%; suggesting result should be approached with caution.

TDS values have also been cross-checked against the measured EC, using the relationship described by the VIEPS hydrogeology guide (Weaver, 2000). These show results are all reliable (refer to table 2).

Chloride (Cl⁻)

Chloride is an unreactive ion so is used as a tracer. Cl concentrations are quite variable, ranging from 1400ppm to 7700ppm. The ion can come from weathering reactions or rainfall. Due to the fact that there are no major sources of Cl within the rock and sediments of the area (eg. evaporites), we can assume that Cl input will be from rainfall. High concentrations of Na in line with Cl concentrations also suggest this, and Uren (2000) also noted that salt accessions are from rainfall sources.

The high Cl⁻ concentrations are generally a result of evapo-transpiration over a long period of time. Aeolian input is also a prominent source during Gondwanan glacial history. Clay soils have an affect on inhibiting leaching of such salts (Marshall *et al*, 1995), so Cl⁻ will build up in the soil. The results have been standardised to the highest Cl concentration in the samples, (7687ppm) to highlight differences in ion source. (Refer to table 3, figure 5) This is due to differences in concentration caused by evapotranspiration that preside in samples. If all the ions in each sample were derived entirely from rainfall, then the standardised compositions of each sample will be the same. Therefore any differences in concentration of particular ions between samples must be due to other processes, and these will now be discussed for each ion in turn.

Sodium (Na⁺)

If Na is entirely derived from NaCl in rainfall, we expect Na to be in similar amounts to Cl that are found in seawater. The ratio of Na to Cl found in these samples are 0.5, 0.52, 0.68 and 0.61 for Boggy Swamp, bore 5020, 328 and 327 respectively. The ratio of Na to Cl in rainwater is 0.55 (Drever, 1988). This suggests that Boggy Swamp has a slight removal of Na, possibly due to leaching. Bore 5020 is quite close to the theoretical value and indicates possible slight leaching. These leaching processes are quite minimal compared to the input mechanisms of Na. Bore 328 has a higher amount of Na with reference to seawater, and this may be due to aeolian input as eluded previously. Bore 327 features this input to a lesser extent. The lower concentrations seen in the samples (refer to table 2) are due to dilution, perhaps associated with variations in porosity. Based on this bore 327 has higher porosity than bore 328 and 5020 for example.

Bicarbonate (HCO$_3^-$)

Bicarbonate tends to be quite variable in concentration, and this is particularly evident in the standardised results in graph 2. Normal results (table 2) shows highest concentrations in Boggy Swamp and bore 327 samples, which both occur in basalt lithology. This indicates that basalt contains a greater amount of reactive silicate minerals, which produce HCO$_3^-$ as a by-product of the following reaction

Silicates + H$_2$CO$_3$ → HCO$_3^-$ + H$_4$SiO$_4$ + ions in solution + clay minerals   (1)

Hence, it is also expected to see higher concentrations of Ca, Mg, and Si in accordance with HCO$_3^-$ concentrations. The production of HCO$_3^-$ is thus controlled by weathering reactions.

The sandstone and sandstone/shale lithologies of bore 5020 and 328 respectively exhibit lower HCO$_3^-$ concentrations. This will be due to respective high and medium quartz concentrations in each unit. Quartz is unreactive in reaction (1), so won't influence HCO$_3^-$ concentrations. The concentration in bore 328 is probably lower than expected due to the obvious Fe precipitation. During this precipitation pH is lowered and in doing so, the HCO$_3^-$ is also reduced. It is this discrepancy in HCO$_3^-$ that is likely to be causing the charge balance error for this sample.

The concentration for bore 327 in the standardised results shows an extremely elevated concentration in light of the results for the other samples. This can not be explained and suggests experimental error, although this cannot be substantiated.

pH

pH tends to reflect bicarbonate concentration as it reflects alkalinity. Bores 5020 and 328 show greater acidity than the other samples, and 5020 does have the greatest acidity (pH=6.65). This is obviously reflected in bicarbonate concentration, which is also lowest in 5020, and is due to high quartz concentrations in sandstone, which is unreactive as previously discussed. The pH of normal rainwater is slightly acidic (5.6) and is due to dissolved CO$_2$ in the atmosphere creating carbonic acid in a reaction with water. This acidity is then neutralised by silicate weathering in general. The Grampians Sandstone of bore 5020 hence has a low amount of silicates to neutralize acidity. Shale/sandstone lithology also shows low pH, although not to the same extent, due to the slightly lower quartz concentration to that in the sandstone. Hence it has a greater acid neutralising ability.

The correlation of high bicarbonate with high pH is fine for Boggy Swamp, as standardised results show the concentration is very similar to that of the other bores. This indicates basalt lithology has a high amount of reactive silicates to increase pH. We expect the highest pH to correlate with the highest HCO$_3^-$, however this is not the case. Bore 327 has a very high HCO$_3^-$ concentration, which is exemplified by standardised results, but it has the second highest pH which we do not expect. This either suggests that high bicarbonate in bore 327 is not reacting to increase pH which is not plausible, or secondly experimental error which cannot be identified. There hence appears to be an error in the HCO$_3^-$ concentration for bore 327.

pCO₂

pCO_2 values appear to be normal as expected through the carbonic acid system equation. Boggy Swamp has a low value very close to atmospheric ($10^{-3.5}$) pressure, showing that water is equilibrating very close to the surface with the atmosphere. The other samples are mentioned in order of depth from the surface. 5020 has a high pCO_2 due to microbial activity associated with respiration in the soil. Bores 328 and 327 show a gradual decrease as microbial activity is reduced with depth. All values lie within the equilibrium lines for the carbonate system (refer to Appendix V) and hence appear to be quite reasonable. These values will have a major control on bicarbonate production, and hence pH.

Calcium (Ca)

Ca is generally similar in all bores. All results tend to lie between 100ppm and 400ppm. Standardised results for Boggy Swamp, bore 5020 and 327, show very close results, indicating a similar source (refer to graph 2). This source is likely to be Ca bearing minerals such as pyroxene ($CaMgFeAlSi$) or plagioclase ($CaAl_2Si_2O_8$). Either of these minerals could be found in basalt and sandstone. Thin sections could certainly clarify this, although either mineral is plausible. The weathering of these minerals also supports the bicarbonate concentrations, as explained previously in terms of silicate weathering. The standardised results for 328 and 5020 are much lower because these minerals (plagioclase or pyroxene) are probably lacking in these rocks. Seawater contains 412ppm (Drever, 1988) so may be contributing some Ca as well in rainwater, although silicate weathering is the most likely factor.

Magnesium (Mg)

Mg shows similar trends to those observed in Ca, with a lower amount in bore 327, due to the dilution discussed earlier in terms of Na. Standardised results (see figure 4) show very similar compositions for both basalt units. Similarly, the sandstone and sandstone/shale units have similar concentrations to one another, but these are slightly lower than those observed for basalts, as indicated by less reactive silicates. Mg concentrations are higher than Ca, so this may perhaps indicate that Mg is coming from a different source than the Ca. This indicates that rather than coming from pyroxene, other sources may be biotite ($K(MgFe)_3(SiAlO_{10})(OH)_2$) which has a large Mg fraction, or even rainwater which contains 1290ppm of Mg (Drever, 1988)

Silica (Si)

Si is generally quite low in samples (5 to 18ppm) although it does tend to be highest in Boggy Swamp, and bore 327. These basalt bores have elevated Ca, Mg and HCO_3^- levels, indicating silicate mineral weathering is the dominant process for ion supply, and these Si results support that notion. Hence we expect Si to be resulting from weathering of plagioclase, biotite, or pyroxene. Si is not released by quartz weathering in sandstone, due to very low solubility. This also explains lower Ca, Mg, and Si concentrations seen in the sedimentary sequences, with quartz being the most common silicate in these rocks.

Sulphur (SO₄)

SO_4 results are quite variable, as seen in table 2. Bore 328 has a large amount at 1234ppm. Bore 327 again has a low concentration in normal results suggesting dilution. The other basalt lithology also has low SO_4. Standardised results seen in table 2 are relatively uniform and show similar sources for SO_4. This may be a result of SO_4 supply in rainwater. The SO_4 concentration in seawater is generally 2710ppm (Drever, 1988), and as with Na and Cl, is contributing to the total SO_4 concentration. Standardised results show a slightly elevated SO_4 concentration in bore 328. It was also noted that after sampling that oxidation of Fe tended to be evident in the bottom of the sample vials from bore 328. This observation coupled with the extra SO_4 content indicates that FeS_2 (pyrite) is the extra source of SO_4 in the interbedded sandstone and shale unit, which occurs as follows

$$FeS_2 + 7/2O_2 + H_2O \rightarrow Fe^{2+} + SO_4 + 2H^+ \qquad\qquad (2)$$
$$Fe^{2+} + H^+ + 1/2O_2 \rightarrow Fe^{3+} + 1/2H_2O \qquad\qquad (3)$$

Potassium (K)

K values are quite variable in normal results, indicating dilution differences in each respective aquifer. This fact is influenced by very similar standardised results in table 2 indicating similar sources. Likely sources of K are likely to be biotite, which may also be the dominant supply of Mg also. As expected from a biotite source, K is lower in concentration than Mg.

Electrical Conductivity (EC)

Electrical Conductivities are high in 5020 and 328. 5020 is slightly lower as a sandstone would have a higher hydraulic conductivity (K_s) than the shale of 328 would, which will increase EC due to low K_s and hence higher reaction time. Boggy Swamp and bore 327 have lower EC's but there is substantial difference in each of these. We expect them to have very similar concentrations as the basalt they move through is the same magma flow, which is further confirmed by the similarity of the standardised results. Consistent lower ion concentrations in bore 327 indicate dilution (at 30m depth) and fast travel times characterised by fracture porosity. A marked increase in EC in Boggy Swamp suggests an input of ions from shallower zones. The EC of the waters flowing out of Boggy Swamp was also taken and can be seen in appendix VII. This showed a higher EC than the Boggy Swamp seep, suggesting other seeps supplying salty water to Boggy Swamp.

As previously mentioned, Na and Cl are the dominant ions contributing to EC in this case. Hence we see a direct correlation with NaCl levels. Bore 328, 5020, Boggy Swamp and 327 (in order of high to low EC) have NaCl levels that correlate in exact order to EC values seen. Therefore we can suggest that the higher EC at Boggy Swamp is due to Na and Cl accumulation in soil. The dilute waters observed in 327 suggests deep flow paths in fracture porosity, and the shallow concentrated water at Boggy Swamp indicates flow through salt bearing soil. We can hence suggest that soils are the dominant source of NaCl, especially in basaltic aquifer systems.

Saturation Indices (SI)
Saturation indices are listed in table 2. These were calculated using the PCWATEQ geochemistry program. Calcite saturation indices are very similar for bores 5020, 328 and 327. The index for Boggy Swamp is extremely high. Generally calcite will precipitate at SI > 0.5, so we would expect calcite to be precipitating at Boggy Swamp. The saturation index for this was 1.26. This was not evident on visual inspection, though calcite may be precipitating in the soil. The other samples' saturation indexes were all below or just at precipitation values.

Indices for minerals such as aragonite, silgel, and gypsum are all undersaturated. Saturation indices indicate supersaturation with respect to quartz (ranging from 0.4 to 0.6) although quartz will not precipitate, as it is very insoluble.

Redox
Redox values were taken and show all bores were oxidising during measurement and appear to be all of a similar magnitude.

Implications
The results indicate that basalt lithologies have a greater amount of reactive silicates has shown by higher Ca, Mg, Si and HCO_3^-. However these do not contribute greatly to overall electrical conductivity, as the greater EC results are seen in bores 5020 and 328 which occur in sedimentary lithologies and have clearly dominant NaCl concentrations. These are likely to have greater NaCl concentrations, as these units are about 500 million years of age compared to basalt at 1 million years of age. The sedimentary units would obviously have a greater amount of time to accrue salt accessions. These units are likely to be dominant suppliers of salinity.

The differences in NaCl concentration could be attributed to differences in porosity between sedimentary and basaltic lithologies. The basalt appears to have dominant fracture porosity, while other lithologies are less permeable. The sandstone and interbedded sandstone and shale units are also likely to have fracture porosity but not to the same degree due to their age. High fracture porosity in basalt appears to be a dominant water carrying mechanism and is likely to supply much of the fresher water to seeps identified in the area. More saline seeps on basalt are likely to be soil derived, as indicated by progressive salinisation of Boggy Swamp. Deep flow paths appear evident in basalt, with major salt supply in these areas from the soil horizons, as dilution is occurring deeper. Sedimentary units of the Stavely Hills appear to be dominant salt stores, and with topographic information are likely to be supplying saline water to the terminal lakes at the foot of the Stavely Hills. Salt profiles of the soil and hydraulic conductivity information will reveal more information about water movement, recharge, and salt delivery through soils.

B. Hydraulic conductivity and textures of selected soils

Soils formed on basalt lithologies (Boggy Swamp and bore 327) tend to be high in clay. Water chemistry results indicate that these are likely to be Na and Ca Beidellite clays (refer to figure, appendix VIII). The soils are generally uniform grey and brown clays, with the clay getting much heavier into the B horizon. There is also a clear layer of gravel at the bottom of the A horizon, formed by periodic waterlogging events, illustrating the low permeability of the soil. This feature is also described by Uren (2000) and is evident in bore drilling data in Appendix IX.

Saturated hydraulic conductivity for this soil is based on only one permeameter. The conductivity is taken in the A horizon, although this value is likely to be fairly uniform for the B horizon. The value is 8.75×10^{-5} m/s and is classed by Marshall *et al* (1999) as soil generally suitable for general cropping. However, it was noted that at greater depth (50cm), a very thick clay became apparent which appears to be of low permeability. This horizon is likely to decrease downward flow through soil and hence decrease recharge to basaltic aquifer. It is also likely to cause dominant lateral flow through soil. It is this lateral flow that is likely to be supplying saline flows to Boggy Swamp and Gellerts Swamp. It is suggested that future studies incorporate multiple horizon conductivities to quantify this point.

The soils formed on the Interbedded Sandstone and Shale lithology, which includes bore 328, consist of a brown silty clay loam A horizon, with increasing gravel fraction with depth. The B horizon interestingly features a red/yellow clay loam with vibrant red iron oxide mottles. These are reflective of the water chemistry and support the high amount of iron oxides that are present in the waters of bore 328. This feature can be observed in the driller's log in Appendix IX. No hydraulic conductivity was measured for this soil due to air pressure problems as previously mentioned, although it is generally expected to be of the same magnitude as the Grampians Sandstone due to similarities in the soil profile.

Saturated hydraulic conductivities are an order of magnitude faster than those at Boggy Swamp (9.09×10^{-4} m/s) and are classed on the borderline of soils regarded as those with poor water retention (Marshall *et al,* 1999). This suggests that the soil is well drained, and likely to be the major supply of water to the underlying aquifer.

Soils found on the Grampians Sandstone lithology are similar to that mentioned above for the interbedded sandstone and shale unit. The major difference is the absence of the iron oxide mottles. This soil has a loamy appearance in the A horizon. A heavy silty clay is found in the B horizon. These soils are very similar to the soils described by Uren (2000) in the Edgarley area adjacent to the Willaura area. Water chemistry indicates Kaolinite will be the most dominant clay produced (refer to figures 12 and 15, appendix VIII). We expect soil to be dominant recharge source to the interbedded sandstone and shale unit, and also the Grampians Sandstone.

C. Salt Profiles

Salt profiles adjacent to bore 328 in interbedded sandstone and shale geology shows a very similar salt concentration from the surface to 40cm depth. There is then a notable increase in salt concentration marking the change from sandy clay loam to clay loam. The clay increase is expected to retain more salt from the leaching profile. From this point salt tends to increase markedly with each increment of depth. We would expect greater salt concentrations to be found with depth in the soil profile until bedrock was reached. The increase with depth indicates that the soil is very likely to be a source of salt for groundwater supplies in this lithology. The EC in groundwater here is in line with this soil salt concentration as compared with that as bore 5020.

Bore 5020 soils have an EC that is slightly lower than those in the neighbouring sandstone/shale of 328. These EC's illustrate the further influence of soils on groundwater accumulations. The coarse texture of the soil is likely to lower the exchange capacity of the soil and hence the cation retentiveness. There is a marked increase at 70cm depth, which corresponds with the appearance of a heavy clay. This corresponds to a change in profile and influences of regolith material. Again we would expect salt concentrations to increase with further depth, although the general salty nature of the soil reflects it influence on salts in groundwater supplies. We would not expect another further bulge type profile at depths greater than two metres as described by Jenkin *et al* (1983) as the subject soils do not have vegetation roots causing concentration increases due to adsorption of water. The texture does appear to dominate the salt storing ability of the soil, with clay containing the greatest amount of salts. However, the hydraulic conductivity of that soil will control the rate at which salts are leached into groundwater.

In line with the above trends, Boggy Swamp shows a much greater salt concentration all over, and increasing with depth. The maximum salt concentration observed at 80cm depth is 1.838 mS/cm. A study of salt levels in salt affected areas near Eppalock in central Victoria found salt levels at Kamarooka in a seriously salt affected area to be 2.8 mS/cm at the same depth (Jenkins *et al*, 1983). This shows that the Boggy Swamp salt levels are indeed very high, and comparable to extremely salt affected regions. There are elevated salt concentrations in the first 10cm, possibly due to shallow rooted vegetation taking up water leaving a concentration of salt behind. This area is extensively pastured with C*anola* and this may be the source of the high concentrations. The sample site was also prominently bare earth so may have experienced a greater influence from evapotranspiration than a vegetated site. The clays appear to be much heavier at this site, so are likely to hold more salt than a coarser soil fraction. This salt profile supports the idea postulated that the source of salt in the basalt lithology is from the soil, with salt in groundwater being diluted by fracture porosity.

Water and Salt Movement conclusions in the Willaura Catchment

The complex geology of the area tends to inherently influence a complex water movement regime. Ordovician interbedded sandstones and shales are the oldest lithology in the area and contain the greatest salt concentrations due to a greater amount of time being available for salt acquisition. They feature prominent infiltration recharge through soil. The Grampians sandstone lithology bears many of the same features, being the other dominant salt source. In both of these units, Na and Cl are the dominant ions, with the water being relatively low in major ions resulting from silicate weathering. Water flow through these units is believed to be high as the Stavely Hills they form are cleared of much native vegetation, and hence infiltration is increased. The topography of this range suggests that much of this water acquisition will be deflected northward to the terminal lakes that fall between the Stavely Hills and the basalt plain. Appendix X shows water table depths in the area and illustrates that water is fact moving from the Stavely Hills Northward qualifying water movement findings in this report.
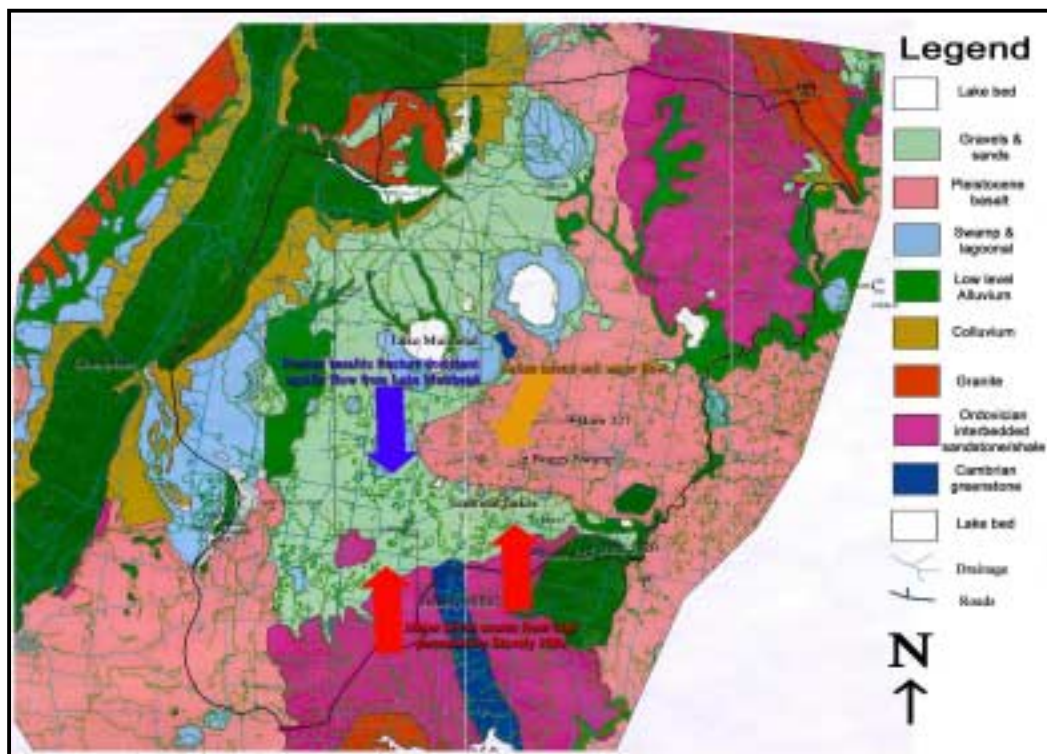

Figure 9 showing major water and salt movement pathways active in the Willaura Catchment.

The basalt lithology does appear to carry large volumes of water in its fracture system. These however are low in salt and appear to provide a source of relatively fresher water. The soil based on the basalt is solodic heavy clay, and reasonably impermeable to surface infiltration. As a result of this low permeability the soil has acquired large concentrations of salt since the Pleistocene. Recharge is also very limited to the underlying aquifer. Hence rainwater and

surface flow is believed to hold in the soil, leaving it saturated throughout the year. This is likely to be aided by localised stony outcrop around Boggy Swamp which discharge sufficient volumes of fresher water into the soil. Here the water flows laterally, and in doing so collects salt, which is subsequently discharging in the local swamps.

The basalt aquifer is fed with sufficient volumes of water from several sources. Supply is very minorly from soil and the few stony rises that appear in the area. The dominant supply of water is from Lake Muirhead. The lake has large volumes of water diverted into it from Mt William Swamp. These collect in the relatively depressed expanses of Lake Muirhead. Aeromagnetic data indicates that the basalt aquifer underlies the sands and gravel base of Muirhead, so the lake must lose its water to the underlying aquifer. The flow of water is then southward to the Stavely Hills. Freshwater (relatively fresh) seeps are observed along some of the terminal lakes and these are a result of discharge straight from the aquifer.

The terminal lakes area lies at the foot of the Stavely Hills to the south, and at the edge of the basalt to the north. These lakes are fed by saline flow from lateral soil movement (although this volume is very small), fresher seeps from the basalt aquifer (fed from Muirhead) and dominantly from the highly permeable and saline sandstone and interbedded sandstone and shale units.
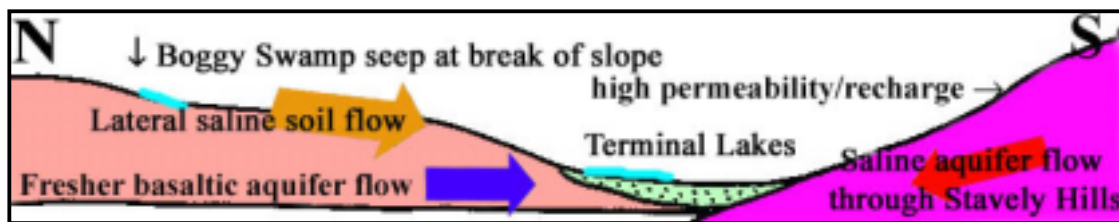
Figure 10 showing diagrammatic cross section of flows from major aquifers converging on the terminal lakes. Note exaggerated vertical scale. Lithological color representations are the same for those in figure 1 and 8.

It is suggested that the findings of this study be correlated with the existing hydrological conceptual model of Willaura catchment, to produce a consistent and robust model for water and salt movement within the catchment. Further work could be implemented to quantify the amount of water recharging through the Stavely Hills to see their overall influence on extra water volumes. The salt carrying capacity should also be quantified so best management practices can be implemented in particularly problem areas. Soil salt profiling to sufficient depth and variable soil horizon infiltration should also be studied, to enhance indications discussed in this report. Control of increasing salinity at the foot of the Stavely Hills is best managed by reducing recharge in the Stavely Hills. Revegetation is suggested throughout the hills so as to limit the amount of water moving to the foot of the hills.

ACKNOWLEDGMENTS

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