The hydrology of Wetlands in the Strathbogie Ranges

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EXECUTIVE SUMMARY

Background

In mid 2008, the Goulburn-Broken Catchment Management Authority (GBCMA) commissioned an investigation of peatlands and spring soak wetlands primarily in the Strathbogie Ranges, central Victoria. The investigation focused on wetland flora and hydrology with the primary aim of understanding the threats to wetland condition. An improved understanding of these wetlands is expected to inform future policy and management to protect wetland and downstream environmental values.

Coates et al. (2009) provide the primary report for this project including project background, general site description, details of the floristic investigation and management recommendations based on combined results of the floristic and hydrological investigations. This report describes the results of the hydrological components of the project and should be read with the Coates (2009) report to understand the full context of the project.

There has been no previous hydrological investigation of the Strathbogie wetlands. As such, this report documents an initial study on which future hydrological work might build. With only 12 months and a modest budget, the investigation relied wherever possible on easily collected or pre-existing data. This limits the extent to which conclusions can be made regarding hydrological processes, particularly those involving sub-surface flow pathways. There is a need for further work to understand the hydrogeology of this region.

The Strathbogie Ranges

The Strathbogie Range is a granite Batholith consisting of two plutons. A pluton is a large mass of intrusive igneous rock believed to have solidified as it cooled slowly below the earth's surface. Permeable rock fractures form around the pluton surface. The permeability of this fractured rock layer reduces deeper in the rock as fracture density (and hence connectivity through the rock) is reduced.

There is little known specifically about the hydrogeology of the Strathbogie Batholith. There have been no previous scientific hydrogeological investigations and no monitoring bores are located on the plateau. Groundwater is widely used to supply water for domestic, stock and horticultural irrigation uses. Water is usually pumped from shallow aquifers. Springs are found throughout the plateau. Farm dams are ubiquitous and frequently associated with Springs. In some cases, where groundwater discharge occurs across a broad front, small channels have been constructed to direct water into a farm dam.

In recent years there has been concern for reduced spring discharge rates (and complete cessation of discharge in some cases) and reduced bore water yields. Reduced spring discharge may adversely affect wetlands *dependent on reliable spring flows, reduce downstream baseflows and reduce availability of water for human use. It is uncertain to what extent reduced groundwater flows may be attributed to the recent drier climate and/or increased groundwater pumping for human uses and in particular horticulture. Other human impacts on the hydrological cycle include construction of farm dams, drainage and changes to vegetation cover.*

Hydrogeology Model

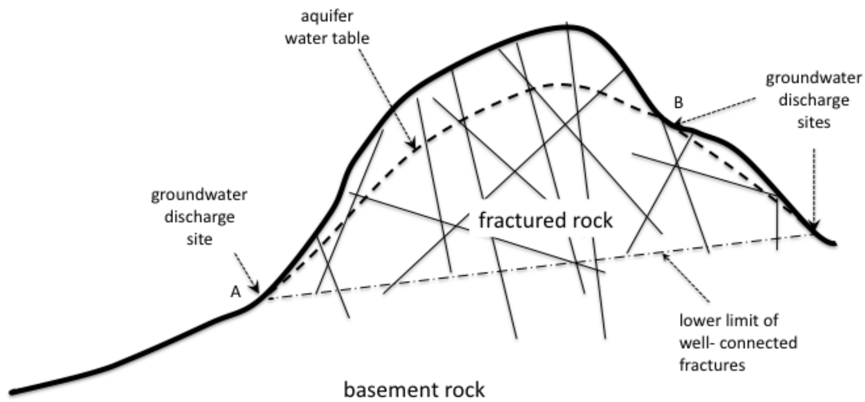

***Figure 1**: Conceptual model of fractured rock aquifers in the Strathbogie Batholith (adapted from Dewandel et al., 2006)*

Dewandal et al (2006) provides a conceptual hydrogeological model of hard rock aquifers which is consistent with observations in this preliminary study of the Strathbogie Ranges. The essential components of this model are a high porosity weathered surface layer (or saprolite) overlaying a fissured layer with lower porosity but through which the water stored within the saprolite can drain. The depth of the saprolite depends on the extent to which this layer as been eroded. This fissured layer sits on the fresh basement. In this model, the fractured rock aquifer is perched on this low permeability basement material. Groundwater is typically discharged from the aquifer at springs located where the ground surface intersects the basement surface, typically at valley margins. Aquifer drainage through fissures in the basement may also be possible.

Given this model, it is to be expected that springs will be mostly found along valley margins and not on the main surface water flow lines. Surface flow paths in creeks or depressions will align more centrally along valley floors with many of these channels flowing over the impermeable basement rock.

This groundwater model has been constructed with no direct observations of groundwater levels and few observations of groundwater discharge. It should be considered preliminary and is a useful basis for the design of further investigations and testing of this model.

Causes of Recent Wetland Drying

Groundwater recharge represents a small portion of total rainfall with base-level groundwater discharge rates equivalent to approximately 1% of rainfall. Annual minimum flows, which we presume are largely sourced from groundwater, vary from year to year in close association with variation in cumulative rainfall over the preceding year. This suggests that low annual rainfall leads to low groundwater recharge, lower groundwater levels and reduced groundwater discharge.

There appears to be a threshold annual rainfall of between 400 mm-600 mm when flow ceases entirely in Seven Creeks. Rainfall has been frequently within or close to this range since 2000. Lag correlation of rainfall and streamflow indicates there is a lag effect of reduced rainfall lasting up to 6 years. This suggests that persistently low annual rainfall over several years, like we have had recently, will have a cumulative effect. This will result in lower groundwater levels and discharge rates than would be experienced in an isolated low rainfall year.

The available evidence suggests that reduced spring discharge in recent years is primarily a consequence of the sequence of lower annual rainfall totals experienced in the Strathbogie Ranges over the last decade.

The extent to which groundwater extraction has contributed to reduced groundwater discharge is difficult to assess. There are 149 licensed private bores across the Strathbogie Ranges with the number of bores increasing steadily since 1970. This is equivalent to a bore density of approximately 1 per 6 km^2. Assuming 2 Ml/year rate of groundwater extraction from each bore, mean aerial average rate of groundwater extraction is 0.33 mm/year. This is less than 5% of a base-level groundwater discharge rate estimated in this study. On average the influence of groundwater extractions on spring discharge is likely to be small. However the distribution of groundwater bores across the Strathbogie Ranges is quite patchy and where there is a high density of bores (e.g. at Boho South) they may have a significant local effect on aquifer levels and groundwater discharge rates.

Whilst this analysis suggests the general effect of groundwater extraction on spring discharge is low, this advice should be verified with a more detailed assessment of groundwater discharge rates and both the distribution and pumping rates of groundwater bores.

Significance of Hydrological Threats

The single greatest threat to spring discharges and dependent wetland ecosystems is a drier climate as a consequence of anthropogenic greenhouse gas emissions. There appears to be a threshold rainfall below which baseflows cease entirely. While some springs may continue to flow in exceptionally dry years, persistent dry years are likely to reduce spring discharges across the Strathbogie Ranges.

The effect of groundwater extraction is likely to be restricted to areas where there is a high density of bores. The general effects of groundwater extraction at the current bore density in the Strathbogie Ranges is likely to be small. However locally high bore densities may have an effect on local groundwater levels and discharge rates.

Farm dams are unlikely to influence groundwater recharge or discharge. When dams are located on a spring-fed wetland, they may have localized effects on soil moisture distributions within the wetland. The effect of farm dams in surface water flows depends on their size relative to dam catchment area and can be large. Where spring-fed wetlands are not located on the main drainage lines they are unlikely to be affected by altered runoff due to dams.

Site-to-site Variation in Wetland Sensitivity to Hydrological Threats

The most persistent springs will be located at relatively low elevations to the southwest of the higher ridges on the Strathbogie Plateau. These sites are likely to be locations where the surface level intersects the basement rock and aquifer volumes are relatively large. These springs will be least affected by a drier climate. Springs in area of low relief or at higher elevations along these ridges will be considerably more sensitive to low rainfall.

Effects on Downstream Baseflows and Water Quality

The hydrological and water quality effect of wetlands will be largely insignificant during wetter times when streamflow is generated through surface runoff and soil drainage. Most of the wetlands appear to be located in very small tributaries or off the drainage lines.

During dry periods, groundwater discharges could be a significant contribution to stream flows. However wetland condition will not affect the rate of groundwater discharge and the quality of groundwater is unlikely to be a concern.

Coates et al. (2009) Mapped wetlands across the region and estimate that they represent 0.65% of the total ground area and a typical soil depth of around 1.0 m. If we assume a soil moisture storage capacity within the wetlands of 0.4 m, at the catchment scale, and the soil water in the wetlands when saturated is equivalent to 2.6 mm of water. This is relatively small compared to total runoff. It is possible that the wetland soil store may buffer baseflow variation to changes in groundwater discharge. However groundwater discharge variations are likely to be quite slow and any hydrological buffering effect will be small.

ACKNOWLEDGEMENTS

The Goulburn Broken Catchment Management Authority (GBCMA) funded this project. We thank Simon Casanelia (GBCMA) for his support and project management, and also members of the Project Steering Committee for their advice. In particular Bertram Lobert provided essential support for locating field sites, establishing contacts with landholders and reviewing the final report. The discharge monitoring sites were located on properties owned by Claude and Lindy Vasselet and Brian and Brenda Law and we greatfully acknowledge their support and interest in the project. Other landholders around Boundary Hill kindly allowed access to their properties for water sampling. Stephen Wealands undertook the terrain analysis described in Section 2.4. Fiona Coates and Arn Tolsma (Arthur Rylah Institute) undertook the concurrent study on floristic values.

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1 Introduction

In mid 2008, the Goulburn-Broken Catchment Management Authority (GBCMA) commissioned an investigation of peatlands and spring soak wetlands primarily in the Strathbogie Ranges, central Victoria. The investigation focused on wetland flora and hydrology with the primary aim of understanding the threats to wetland condition. An improved understanding of these wetlands is expected to inform future policy and management to protect wetland and downstream environmental values.

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The project brief and subsequent Steering Committee meetings have identified the following key hydrological questions of interest to the GBCMA in relation to these wetlands:

- *To what extent is wetland drying over the last decade attributable to increased groundwater extractions, farm dam construction, changes in vegetation cover and a drier climate?*
- *How significant is the threat is posed by farm dam construction, increased groundwater extraction, changes in vegetation cover and a drier climate for wetland hydrology?*
- *What are the primary factors influencing site-to-site variation in wetland hydrology and sensitivity to these hydrological threats?*
- *What is the cumulative effect of changes in wetland condition (and in particular water holding capacity and residence time) on baseflows and water quality in the downstream river network?*

In addition to providing initial information on the hydrology of these wetland systems, this report provides a preliminary response to these questions.

1.1 Study Area

The Strathbogie Range is a granite Batholith consisting of two plutons, one to the northeast and one to the southwest (we will call these the Boho and

Ruffy pluton respectively). A pluton is a large mass of intrusive igneous rock believed to have solidified as it cooled slowly below the earth's surface.

Granite has a crystalline structure, which is brittle and forms mostly course grained erosion products (Cook 2003). These two properties result in permeable rock fractures around the pluton surface. The crystalline rock matrix itself has extremely low permeability. However the fractures allow water to percolate through the rock causing deep weathering. The size of fractures will enlarge along preferential flow pathways. The permeability of this fractured rock layer reduces deeper in the rock as fracture density (and hence connectivity through the rock) is reduced. The depth of fractures and hence depth to the impermeable bedrock massive can be 10's of metres deep. It is common to find sheet fractures in granite intrusions, which are oriented parallel to the topographic surface with a typical vertical spacing of up to 10m and increasing with depth.

The upper surface of the Strathbogie Batholith forms a plateau with surface elevations mostly between 450 m and 650 m Australian Height Datum (AHD). The escarpment around the Batholith's perimeter falls to less than 200 m AHD. The surface of both plutons is heavily eroded as evidenced by river valleys incised across the Batholith's plateau and into the escarpment. Sevens Creek and Hughes Creek collect much of the surface drainage and groundwater discharge from the central portions of the Boho and Ruffy plutons respectively and both drain to the southwest. Other creeks drain surface water from around the Batholith perimeter.

Dewandal et al (2006) provides a conceptual hydrogeological model of hard rock aquifers. The essential components of this model are a high porosity weathered surface layer (or saprolite) overlaying a fissured layer with lower porosity but through which the water stored within the saprolite can drain. The depth of the saprolite depends on the extent to which this layer as been eroded. The fissured layer sits on the fresh basement. In this model, the fractured rock aquifer is perched on this low permeability basement material. Groundwater is typically discharged from the aquifer at springs located where the ground surface intersects the basement surface, typically at valley margins. Aquifer drainage through fissures in the basement may also be possible.

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In recent years there has been concern for reduced spring discharge rates (complete cessation of discharge in some cases) and reduced bore water *yields. Reduced spring discharge may adversely affect wetlands dependent on reliable spring flows, reduce downstream baseflows and reduce availability of water for human use. It is uncertain to what extent reduced groundwater flows may be attributed to the recent drier climate and/or increased groundwater pumping for human uses and in particular horticulture. Other human impacts on the hydrological cycle include construction of farm dams, drainage and changes to vegetation cover.*

Climate change projections produced by the CSIRO Murray-Darling Sustainable Yields Project consistently indicate that this region will be subject to reduced streamflows as a result of reduced rainfall and increased potential evapotranspiration associated with climate changes driven by greenhouse gas emissions. The rate of drying is uncertain with forecasted reductions in surface runoff for the entire Goulburn-Broken catchment of between 2% and 44% by 2030 (CSIRO 2008). There are no specific studies of the impact of projected climate changes on groundwater in the Strathbogie Ranges. The recent changes in precipitation and rate of drying (over the last two decades) is considerably greater than projected rates as a consequence of climate change.

2 Methods

This section of the report describes the existing data, field methods and analyses used in this hydrological investigation. Several investigations were used to understand the Strathbogies' hydrological system. Where possible we used existing data sources and this was augmented with fieldwork within this project. The 12-month field program commenced in early Spring 2008 and continued to the end of Winter 2009.

2.1 Climate

Gridded daily rainfall and potential evapotranspiration data are used for relating rainfall and streamflow in the larger gauged catchments. These data were obtained from the SILO database[1]. These are interpolated from the available climate stations in the region. In addition we use daily rainfall records observed at the Strathbogie rainfall gauge (082042).

Rainfall (recorded at Strathbogie) during the study period was generally low relative to long-term mean rainfall although higher rainfalls (at or above mean rainfall) were recorded in July, November and December of 2008 (Figure 2). Annual rainfall has been generally declining over the period 1990 to 2009 and annual rainfall for the study period was approximately the 12th percentile value for the 106 year record (Figure 3). The recent 10-year sequence of annual rainfalls is driest on record with a mean rainfall of 800 mm/year. The next driest decade on record commenced in 1906 and had a mean rainfall of 850 mm/year.

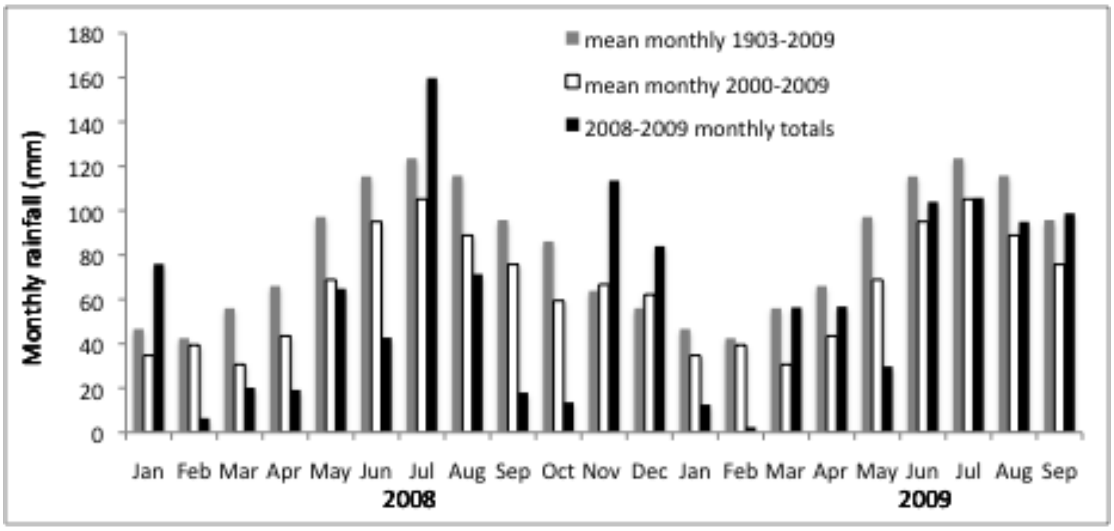

Figure 2: Monthly rainfall at Strathbogie showing observed monthly rainfall and mean monthly rainfall over the recent dry period (2000-2009) and the long-term mean (1903-2009)

[1] For more information on the SILO database see http://www.longpaddock.qld.gov.au/silo/

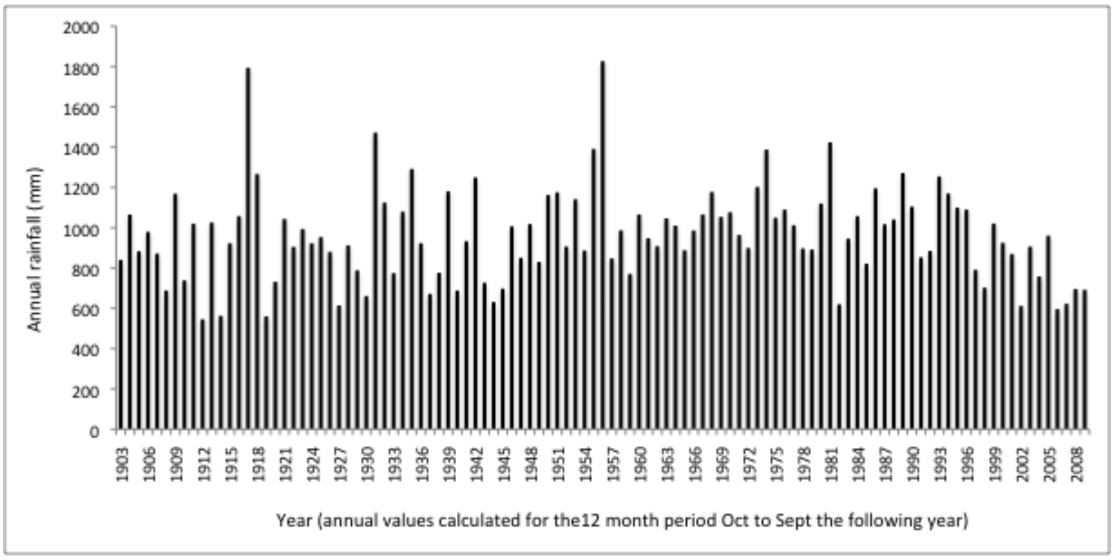

Figure 3: Annual rainfall series at Strathbogie

2.2 Streamflow

Two streamflow gauges have been operated since the mid 1970s on Seven Creeks: one downstream of Polly McQuinn Weir on the plateau and the other downstream of Eurora, which is located close to the base of the Strathbogie Batholith (Table 1). For a short period (Dec 1974 to Nov 1982) a streamflow gauge was operated on Spring Creeks at Strathbogie township, just upstream of its confluence with Seven Creeks. A streamflow gauge is also located on Hughes Creek at Tarcombe Road.

Table 1: Streamflow gauges used in this study.

Gauge Number	Stream	Site name	Catchment Area (km^2)	commenced operation	ceased operation
405228	Hughes Cr	Tarcombe Rd	471	May 1975	-
405237	Seven Cr	D/S Eurora	332	Nov 1973	-
205234	Seven Cr	D/S Poly McQuinn Weir	153	Dec 1973	-
205233	Spring Cr	Strathbogie	28	Dec 1974	Nov 1982

In addition to these longer-term streamflow observations, we installed modified V-notch weirs and stage recorders downstream of two springs in the Upper Seven Creeks catchment at properties belonging to Brian and Brenda Law and the Claude and Lindy Vasselet (Figure 4). Standard weir calculations are used to convert observed weir levels and discharge rates. The elevations of Law's and Vassalet's springs are 565 m and 605 m respectively. They are both located in the vicinity of Boho South on the Boho Pluton at the base of Boundary Hill. The weirs were operated from beginning of Spring 2008 to end of Winter 2009. A third weir was installed *at an additional Spring, but this ceased to flow soon after the weir was installed and did not recommence for the duration of the field program.*

An attempt was made to install additional weirs but there were no suitable sites in the region of interest. Measurement of discharge from springs is a technical challenge due to low flow rates, high loads of organic litter and shallow sheet flow unless an artificially channel has been constructed. Artificial channels existed at the two successful monitoring sites but netting had to be hung across the weirs and a filter installed upstream to prevent leaf litter blocking the weir notch. We used weir notches of 45 degrees. An orifice was also drilled below the V-notch to improve measurement precision at low flows. The weir at Vasselet's Spring was located on one of two artificial channels which drain Spring water. It appeared to be the major channel and flow patters will be representative of the total flow but the total flow will be under-estimated.

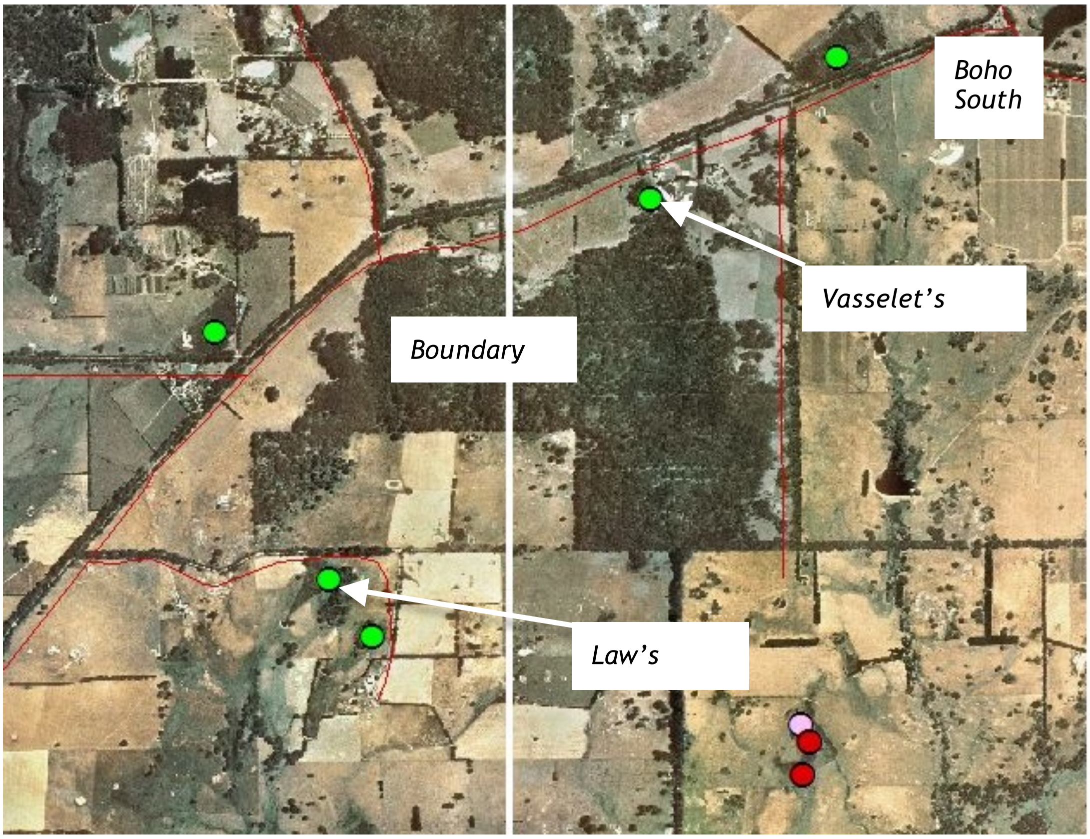

Figure 4: Location of V-Notch Weirs installed to monitor spring discharge

2.3 Water Isotopes

Water samples were collected from bores, spring discharges and streams in the vicinity of Strathbogie township and Boho South on 17/9/2008 and 4/5/2009. Samples were collected in 30 mm McCartney Bottles using standard protocols for isotope analysis. The samples were analysed at the CSIRO Isotope Analysis Service in Adelaide to detect levels of deuterium *and oxygen 18. Isotope concentrations are expressed relative to a global standard. Concentrations of these two isotopes have a linear relation in rainfall referred to as the local meteoric water line (MWL). The concentrations of both isotopes have been found to vary with rainfall intensity and are generally lower in heavier (less frequent) rainfall.*

When surface waters are evaporated, deuterium and oxygen 18 preferentially accumulate in the liquid phase because of their higher molecular weight (they don't evaporate as easily as "normal" water). However, this effect is greater for Oxygen 18 and evaporation leads to deuterium (Y axis) and oxygen 18 (x axis) plotting below the meteoric water line. This means we would expect groundwater that is not subject to evaporation to lie along the MWL and water which has a significant amount of time at or near the earth surface will lie below the MWL.

There is no published Local MWL for the Strathbogie Ranges. The nearest MWL available is from the MUNIP MWL developed for Melbourne.

2.4 Terrain Analysis

The location of known wetland sites was compiled by ARI as part of their component of the project. We used a selection of sites from the site inventory assembled by Ecology Australia (Carr et al. 2006) to examine the spatial distribution of wetlands across the Plateau. In total there were 194 wetlands in this list in relation the Plateau's terrain.

ARI conducted detailed field-based assessments of 68 "Quadrat" sites in the Strathbogie Ranges. We examined variation in the topographic position of these wetlands in relation to vegetation type, condition and soil moisture status at the time of the ARI field survey (i.e. Spring of 2008).

For both spatial investigations we derived terrain metrics for the wetland sites using the recently updated 1:25,000 DEM for Victoria. Terrain metrics were derived for the sites catchment area and a notional maximum volume from which groundwater might drain to the site. The later is difficult to define. Essentially we followed the contour of the wetland elevation to draw a polygon defining the contributing volume. However this area was constrained by the boundary of the pluton within which the site sat.

There are major difficulties in defining hydrogeologically meaningful terrain metrics for these sites, particularly with no information available on groundwater flow directions or connectivity. Because the DEM-derived flow network may not correctly align with the true flow paths, it was necessary to adjust the location of sites where they were clearly not on the correct flow path. This was a problematic task given some wetlands do not lie on obvious surface flow paths. This is complicated by the fact that many springs are not located on drainage lines.

2.5 Hydrological Modelling

Ideally we would like to develop a hydrological model that allows us to evaluate the contribution of groundwater pathways to baseflows in the region and evaluate sensitivity of groundwater flows to the various *hydrological threats in the region. A common approach would be to construct a rainfall-runoff model for the Strathbogie. However, such models are not appropriate tools for analyzing groundwater contributions to baseflows. Without direct observations of groundwater discharge these models can only be calibrated to observed total streamflow, making them unreliable for partitioning flow into surface and baseflow components.*

There are various statistical methods for analyzing streamflow series to separate baseflow and "quickflow" components but there remains a question over the proportions of groundwater and soil drainage in the resulting baseflow time series.

Our solution to this problem was to construct a linear regression model relating monthly streamflow to monthly rainfall in the current and antecedent months. Components of streamflow correlated with rainfall in previous months are likely to be baseflows with longer lag-times associated with groundwater pathways. The purpose of this analysis is to identify this lag effect and hence the time period over which groundwater stores drain and fill. This is particularly important when assessing the cumulative impact of the recent sequence of dry years. If groundwater stores drain and fill over periods of several years, a sequence of dry years is likely to have a particularly severe impact on baseflows.

Streamflow and rainfall have highly skewed distributions so were transformed by taking the natural logarithm prior to the lag-linear regression. The purpose of the transformation was to normalize the data. However the resulting regression model is not a "water balance" model (i.e. ln-transformed water balance components will not sum to zero) and cannot be used to estimate the volumetric contribution of baseflows.

3 Groundwater Discharge Rates

3.1 Rainfall-Runoff Response - Events

We observe quite different temporal patterns in discharge at the two Springs monitored in this project. The flow at Vasselet's Spring varies seasonally. There is complete cessation of flow between February and June 2009 at this Spring with the exception of some flow pulses associated with rainfall at Strathbogie gauge. Baseflow from the Spring steadily decreases between November 2008 and January 2009 and increases after the cease-to-flow period. Higher flow spells associated with rainfall throughout the year indicate that this site is receiving some surface runoff. The sustained baseflow following rainfall events in the later period indicate that the site is receiving water, either directly through lateral drainage of soil water stores or indirectly by recharging a groundwater system to the point where it discharges to the site, thereby extending the recession limb after cessation of rainfall. Given the seasonal nature of the baseflow here it is more likely to be related to soil water storage than deeper groundwater. The rapid recession during the cease-to-flow period indicates minimal or no drainage, presumably due to low soil moisture contents within the local catchment.

It is interesting to note that the decline of flows at Vasselet's Spring is not halted by the November-December 2008 rainfall. Rainfall for November and December 2008 exceeded the long-term average (at Strathbogie) but the rate of decline in Spring discharge seems slightly greater following this rainfall, if anything. This is probably due to the very low September and October rainfalls in 2008 (see Figure XXX), which would be resulted in quite large soil water deficits developing. These deficits appear to have been sufficient to absorb the rainfall resulting in minimal recharge to the saturated zones discharging to the spring. A short increase in flows at this weir in late January seems to coincide with a rainfall event, but again this rainfall does not appear to have slowed the rate at which the Spring flow declines or delayed flow cessation. It is not until there is sustained winter rainfall in June 2009 that sustained spring flow recommences.

An important question is "what is driving the seasonal fluctuation in spring flow at Vasselet's Spring given it seems unaffected by the late spring and summer rainfall events". A probable explanation for this is that sustained rainfall and low evapotranspiration rates are required for significant aquifer recharge. These conditions are more likely to occur in wetter months during the cooler seasons. There is also the possibility that groundwater extractions during the drier months have contributed to reduced groundwater levels. Interestingly, a bore located 450m upslope of this Vasselet's Spring shows a groundwater level 2m-3m higher than the Vasselet's Spring (Bertram Lobert, Pers. Comm.). This is consistent with the conceptual hydrogeology model of hard rock aquifers developed by Dewandal et al. (2006). Groundwater surface in fractured rock systems can be relatively steep because of low hydraulic conductivity. For example, Cook (2003, p 60) reports differences of up to 50 m in hydraulic head over

1 km in a fractured rock aquifer of the Clare Valley. Even when the Vasselet Spring ceases to flow, the Boundary Hill aquifer at Boho South will continue to drain at lower elevation Springs around the hill.

In contrast, the discharge from Law's Spring remains constant throughout the year with some flow pulses associated with rain events. The two extended periods of elevated flow in November and December 2008, are likely the result of the weir notch and orifices becoming blocked with twigs and leaves. In January 2010, an upstream filter and overhead shade cloth were installed to prevent this.

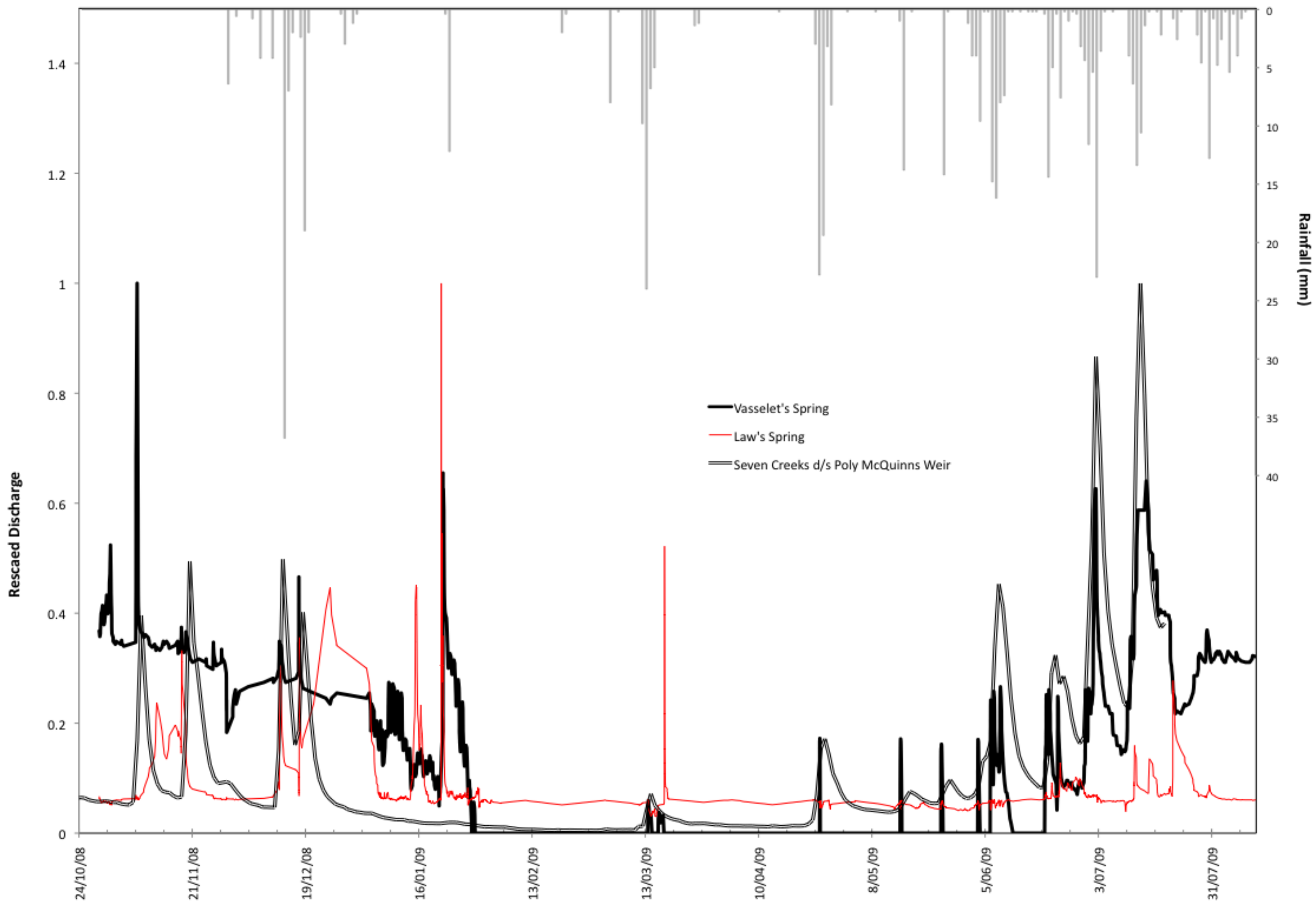

Figure 5: Discharge at two observation weir downstream of Springs and the Seven Creeks gauge at Polly McQuinn's Weir. Daily rainfall observed at Strathbogie is plotted as a bar graph (with labels on right hand axis). Note that discharge has been re-scaled to allow these to be plotted on the same axis. The value of 1.0 on the y-axis corresponds to 0.025, 0.95 and 120 Ml/d respectively for Vasselet's Spring, Law's Spring and the Seven Creeks gauge.

Both Vasselet's and Law's springs are located on the same hill. It would appear that rock aquifer discharging at the higher elevation Vasselet's Spring is either much smaller, draining considerably quicker, or more sensitive to seasonally varying influences than the aquifer discharging at Law's Spring. Indeed these two aquifers may be connected and the lower elevation of Law's Spring means that flow persists after the water level falls below Vasselet's Spring. It is easy to imagine a single fractured rock aquifer in this region, which drains at a relatively high rate and at multiple springs when the aquifer is high. As the aquifer drains, the water table drops and flow is reduced or ceases at the higher elevation aquifers. However, flow persists at the lower elevations. As the water table drops, the rate of aquifer discharge (accumulated across the region) is reduced and hence slowing the rate at which aquifer storage levels decline.

3.2 Rainfall-Runoff Response – Monthly Analysis

The lag regression coefficients (Figure 6) are provided for the two longer-term streamfow gauges operating on Seven Creeks and the Hughes Cr gauge. There is a lag correlation between streamflow and rainfall in the previous three months for all gauges. There is only weak correlation with rainfall lagged by 4-8 month, which is not unexpected given seasonal patterns in rainfall and runoff. Indeed this could be the results of limited influence of summer rainfall on groundwater recharge rates as indicated in observations of flow at Vasselet's spring (Section 3.1).

There is a positive lag correlation with rainfall of up to 5 years prior to the observed streamflow. Correlations for these longer lag periods are greatest for Seven Cr D/S Eurora, the gauge with the largest catchment and located lowest relative to the Strathbogie Batholith. The large lag correlation for these longer lag period compared to 1-3 month lag periods may seem odd, but rainfall is averaged over a longer period (12 months) for these longer lag periods and hence they represent a substantially larger volume of water (although expressed as an average of log transformed flows).

It is likely than the lag correlations for lags greater than 9 months are a result of groundwater storage effects. This would suggest that groundwater effects are greatest at the Eurora gauge, which is consistent with it being located at a lower elevation than the other sites. Lag correlations extend up to 6 years suggesting significant lag effects created by changes in ground water stores. This also suggests persistent low rainfall over several years will tend to have a cumulative affect on groundwater stores and discharge.

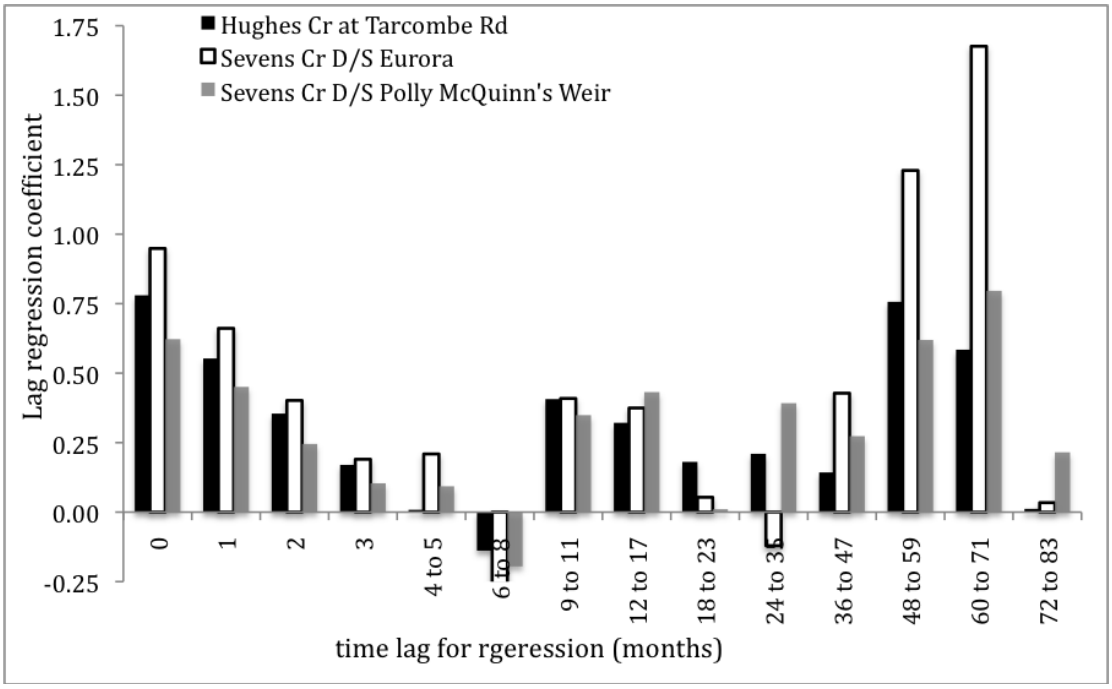

Figure 6: Coefficients for lag regression model relating ln-tranformed monthly rainfall and runoff (n.b. monthly rainfall was averaged over 2 or more months for longer lag periods as indicated by ranges in the x-axis labels)

3.3 Water Isotopes

The water isotope results for the two sampling periods show a generally linear trend, consistent with what would be expected in rainfall (Figure 7). The relative Deuterium concentrations are somewhat higher than is predicted from the Global Meteoric Waterline or the local Meteoric Waterline for Melbourne. However variations in the local meteoric waterline of this magnitude are within a normal range of variation, particularly given climate influences inland of the Great Dividing Range are likely to be quite different from influences on rainfall in coastal Melbourne.

There were two sample dates, one before and one after summer. Flow had ceased in many of the creeks in the post-summer sampling trip and conditions were generally drier. One would expect evaporative effects on isotope rations to be strongest in drier conditions and hence there would be lower Deuterium concentrations in surface water samples (for a given oxygen 18 concentration). A comparison of the pre-summer and post-summer results shows that that this is indeed the case (Figure 7).

Rainfall during larger rain events generally has lower relative deuterium and oxygen concentrations. Larger rain events are more likely to lead to groundwater recharge and hence groundwater generally has lower relative concentrations than is typical of surface runoff and soil water stores. Consistent with these expectations, we find that the lowest relative concentrations of deuterium and oxygen 18 are found in groundwater samples and obvious groundwater discharge sites (Figure 8).

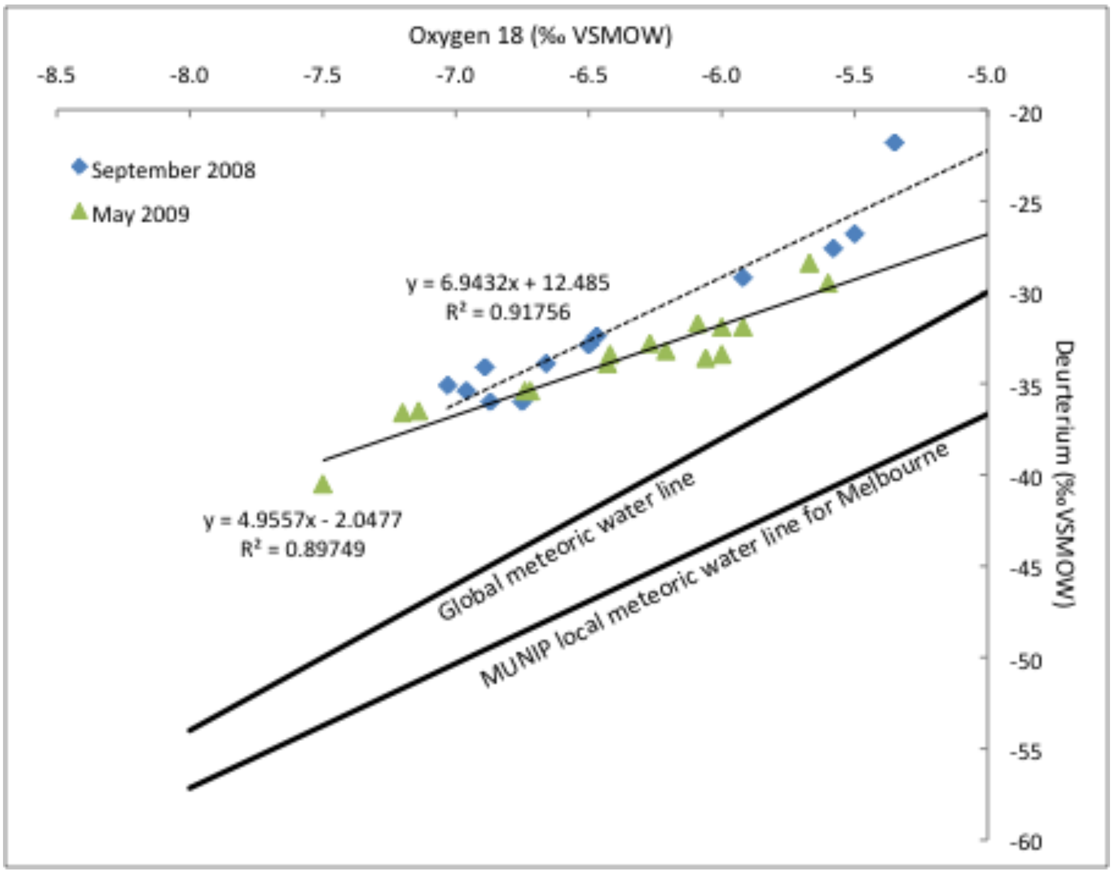

Figure 7: Comparison of Deuterium and oxygen 18 concentration for two sampling times

Focusing initially on the bore samples (red circles in Figure 8) we notice that oxygen 18 concentrations are at the lower end of the observed range and vary between -7.6 and -6.3 ‰VSMOV. The lowest relative concentration (-7.5%) was for the sample taken from Bert Lobert's bore to the east of Boundary Hill. This low concentration may be due to its location on Boundary Hill, which is likely to contain a substantial groundwater aquifer. The larger storage volume (and hence greater temporal persistence) would make it more likely that the large rainfall events in the past had contributed to groundwater at the bore site at the time it was sampled. The Vasselet and Macintosh Bore samples had similar concentrations -7.2‰. These are only slightly higher than at Bert Lobert's. Both of these bores are located on the periphery of boundary hill. Bores with higher relative isotope concentrations were to the south of the study region (at Colin Broughton's house and the house on the south-west corner of the intersection between Creek Junction Rd. and Boundary Hill Rd.). These bores are distant from Boundary Hill and their higher concentrations is indicative of smaller aquifers which respond to more recent and smaller rain events.

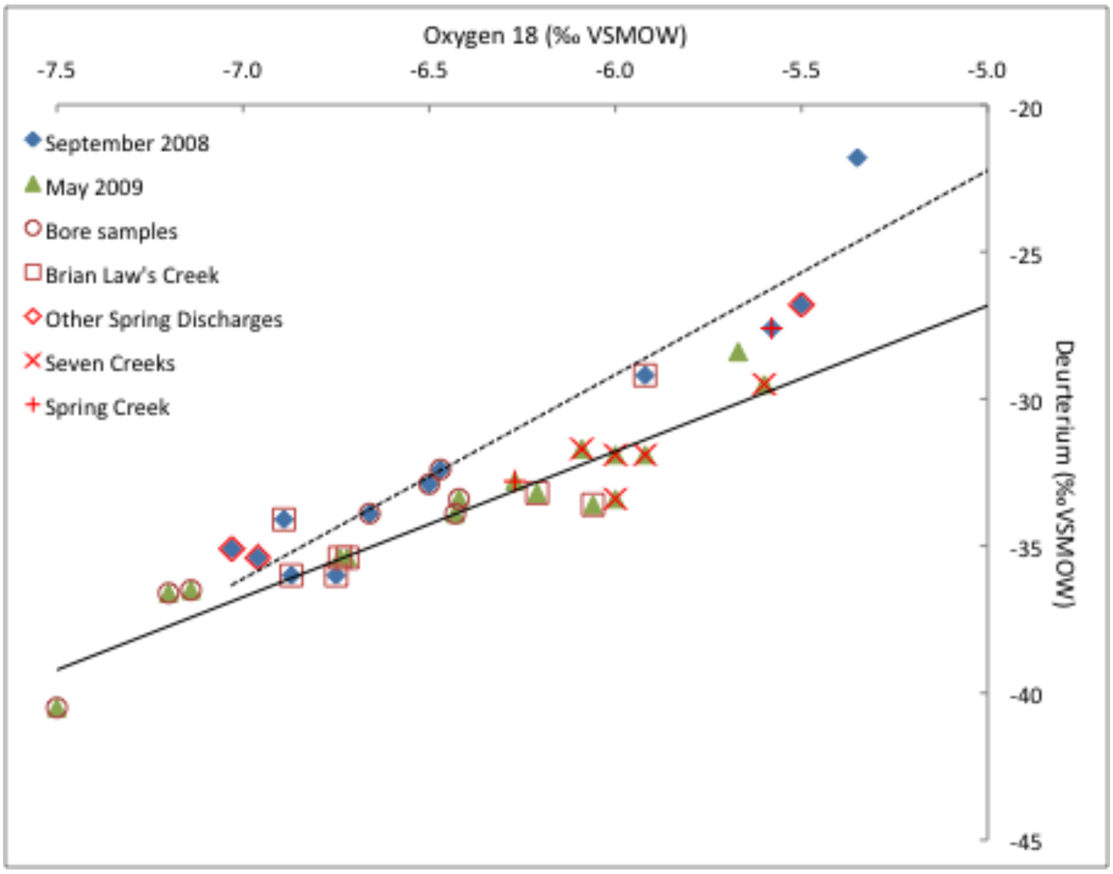

Figure 8: Comparison of Deuterium and oxygen 18 concentration for different site groups

A small unamaed creek drains Brian Law's property with a spring as its source in a gully at the base of the south face of Boundary Hill (we will refer to this as Brian Law's Cr). One of the two V-notch weirs was installed on this creek. We took water samples along Brian Law's Cr from its source to the Junction with Seven Creeks (red boxes in Figure 8). Samples taken near the source had oxygen 18 concentrations (6.7 to 6.8 ‰VSMOV) in the middle of the range for bore samples consistent with this being a groundwater fed creek. Further downstream, concentrations increased in both September and May indicating inputs of water from shallower storages. In May, low deuterium concentrations in sites further downstream indicate evaporation has occurred prior to water being sampled. This is not the case in September.

Two other Spring discharges (at Vasselet's and on Colin Broughton's property) have very similar isotope concentrations to Brian Law's spring. Again this is consistent with the source being a significant groundwater aquifer. A third Spring discharge had a much higher Oxygen 18 concentration (5.5‰). This site was located some distance from Boundary Hill on gently sloping ground where any groundwater store would be relatively shallow. Indeed, flow ceased very quickly after the September *visit. It is possible this was drainage from the soil rather than from groundwater.*

Isotope concentrations taken from Seven Creeks and Spring Creek are also reported but it is difficult to draw any conclusions from these on the importance of groundwater sources. Deuterium concentrations in the May sample were low relative to the September samples indicating evaporation had taken place and could have conceivably originated as Groundwater discharges despite relatively high Oxygen 18 levels.

3.4 Groundwater Discharge Rates

The groundwater flux through fractured rock aquifers is central to an assessment of hydrological risks in the Strathbogie Ranges. However it is a particularly difficult component of the hydrological cycle to measure. Discharge observations at two nearby springs show very different magnitudes and temporal patterns (Section 3.1). Recharge rates and groundwater flows will show a high spatial variability with flow concentrated along connected rock fractures.

It is likely that percolation of groundwater into deeper aquifers is low, assuming connected fractures do not penetrate vertically through the Batholith. Assuming this is the case, groundwater discharge and recharge rates must be more or less equal over the long-term. The logistics of continuously monitoring multiple springs is daunting given the number of springs, low flow and lack of flow concentration. Whilst the spatial and temporal variability of groundwater discharge will require a more intensive study of multiple Springs, it is possible to get an approximate estimate of minimum discharge rates by examining minimum flows in the available streamflow records and compare this with discharge monitored at the two monitored Springs.

The series of annual minimum daily flows at the 4 streamflow gauging stations show similar patterns (Figure 9). The downstream gauge on Seven Creeks at Euroa generally has the lowest minimum flows. Given these are lower than flows observed upstream at Polly McQuinn Weir, there must be losses between these two gauges either through private extractions, leakage or evaporation. Given these losses, the Euroa guage data is not useful for estimating groundwater discharges and is a reminder that observed streamflows may be lower than the cumulative upstream groundwater discharges.

It is rare for any of either the Hughes Cr or Polly McQuinn Weir gauges to have a minimum annual flow less 0.02 mm/day[2]. We will take this as a lower bound on our estimate of groundwater discharge in normal years. Lower minimum flows occur in dry years and this may be due either to

[2] The Streamflow gauges reports discharge in Ml/day but this can be converted to an aerial discharge (mm/day) if the volume flow rate is divided by the catchment area. This conversion is helpful when comparing streamflow data from gauges of different catchment area.

lower groundwater discharge or surface water losses upstream of the streamflow gauges.

This is an estimate of the areal average of groundwater discharge. The average observed flow recorded at Vasselet's and Brian Laws's springs was 0.004 Ml/day and 0.08 Ml/day respectively and the average across these two sites is 0.04 Ml/day. If we assume this is an average spring discharge across the Strathbogie Ranges, then 0.02 mm/day is achieved if we have 1 spring for every 2 km^2 area or 76 springs across the Seven Creeks catchment upstream of Poly McQuinn's Weir. This seems a reasonable estimate for the true density of Springs in the Strathbogie ranges and hence observations of Spring discharges is consistent with our estimate of the lower bound on groundwater discharge across the region.

This groundwater discharge rate is equivalent to 7.3 mm/year, which is slightly less than 1% of the mean annual rainfall at Strathbogie. However, the total volume of groundwater discharge will be greater than this as groundwater discharge rates from smaller groundwater storages will show seasonal variation as was observed at Vasselet's spring.

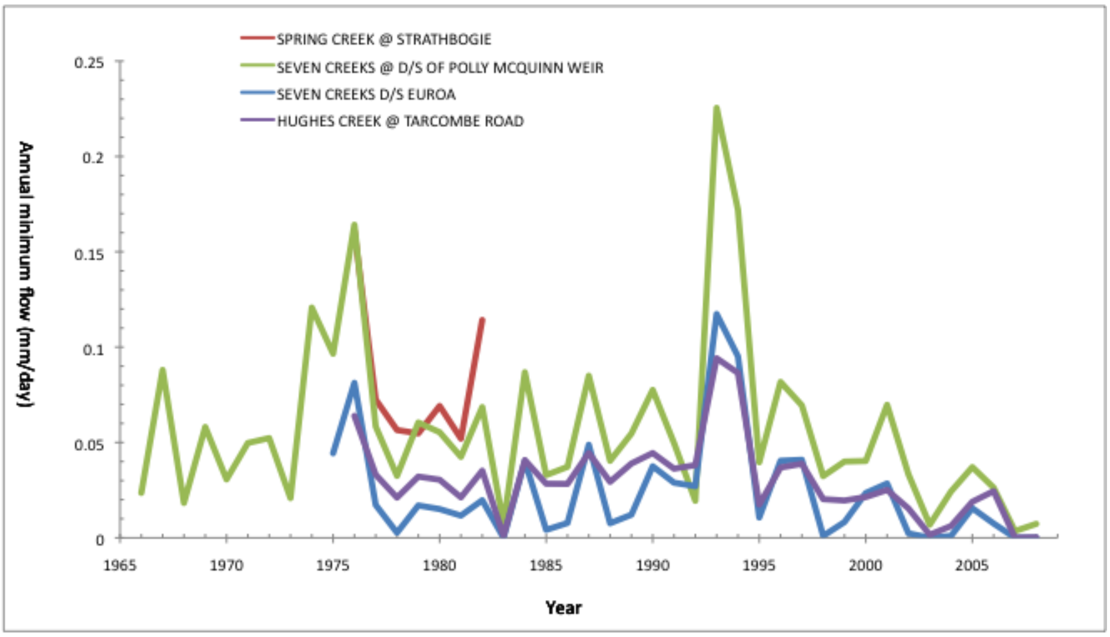

Figure 9: Minimum annual streamflow at the four Strathbogie Ranges streamflow gauges.

Annual minimum streamflows vary considerably from year to year. At Polly McQuinn Weir there is a strong correlation between the minimum summer flow and rainfall over the preceding year (Figure 10). There appears to be a threshold annual rainfall of between 400 mm and 600 mm below which flow may cease.

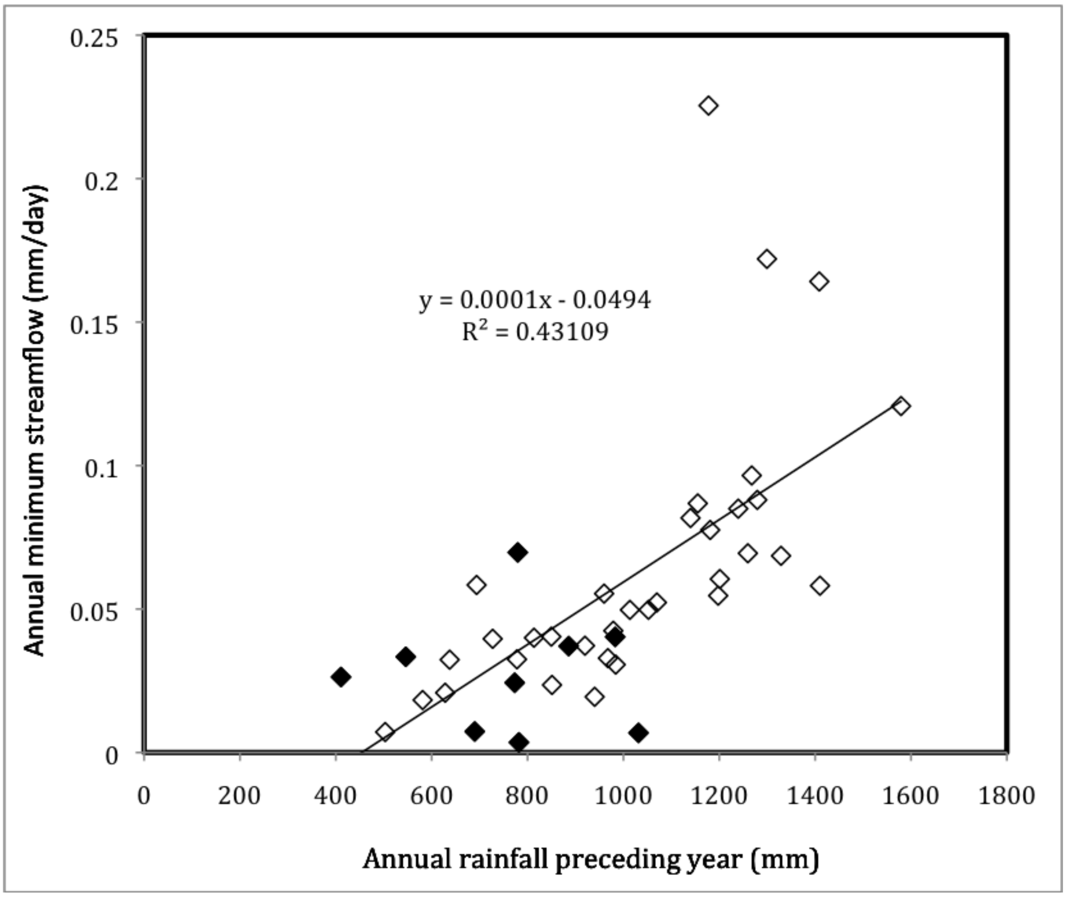

Figure 10: Minimum summer streamflow at Polly McQuinn Weir and rainfall over the preceding calendar year (years 2000 to 2008 shown as solid symbols).

4 Regional-Scale Analyses

4.1 Topographic Location of Wetlands

Ecology Australia (Carr et al. 2006) mapped wetlands across the Strathbogie Ranges (Figure 11). This map indicates some wetlands align approximately along an elevation contour. The two most obvious linear groups are labeled (A and B) in Figure 11. Examining elevations of these springs in profile (Figure 12 and Figure 13) we can see the alignment follows a gentle gradient with lower elevations to the west. This is evidence of a major fracture, or interface with impermeable bedrock along this feature producing the springs. Over the whole Batholith we see a reasonably coherent pattern in elevations for many of the Springs, forming a plain dipping generally in a west-north-west direction (Figure 14). An explanation for this is that this is the lower limit of the fractured aquifer and the interface with basement rock. A more comprehensive survey of springs is required to be certain that these patterns are not an artifact of a restricted survey program. For example, the state forest south of Group B was not surveyed (Bertram Lobert, Pers Comm..

If this alignment reflects the lower limit of connected fractures within the aquifer, it provides a useful model for predicting the flow patterns through the fractured rock with flow draining mostly in a west-southwesterly direction following the grade of the basement rock. This is consistent with the location of Brian Law's spring, the strongest and most reliable spring we encountered during the study, on the west-southwest face of Boundary Hill. It is also consistent with the dominant surface flow direction to the west-south-west on both pluton. It is quite likely that fluvial erosion of the fractured batholith surface was retarded when the basement rock was reached. If this more resistant basement rock slopes to the west-south-west then so to would the resulting valley floor. Indeed we do see a valley floor at around 500-550 m elevation AHD which is relatively flat and drains to the west-south west on both plutons (Figure 11).

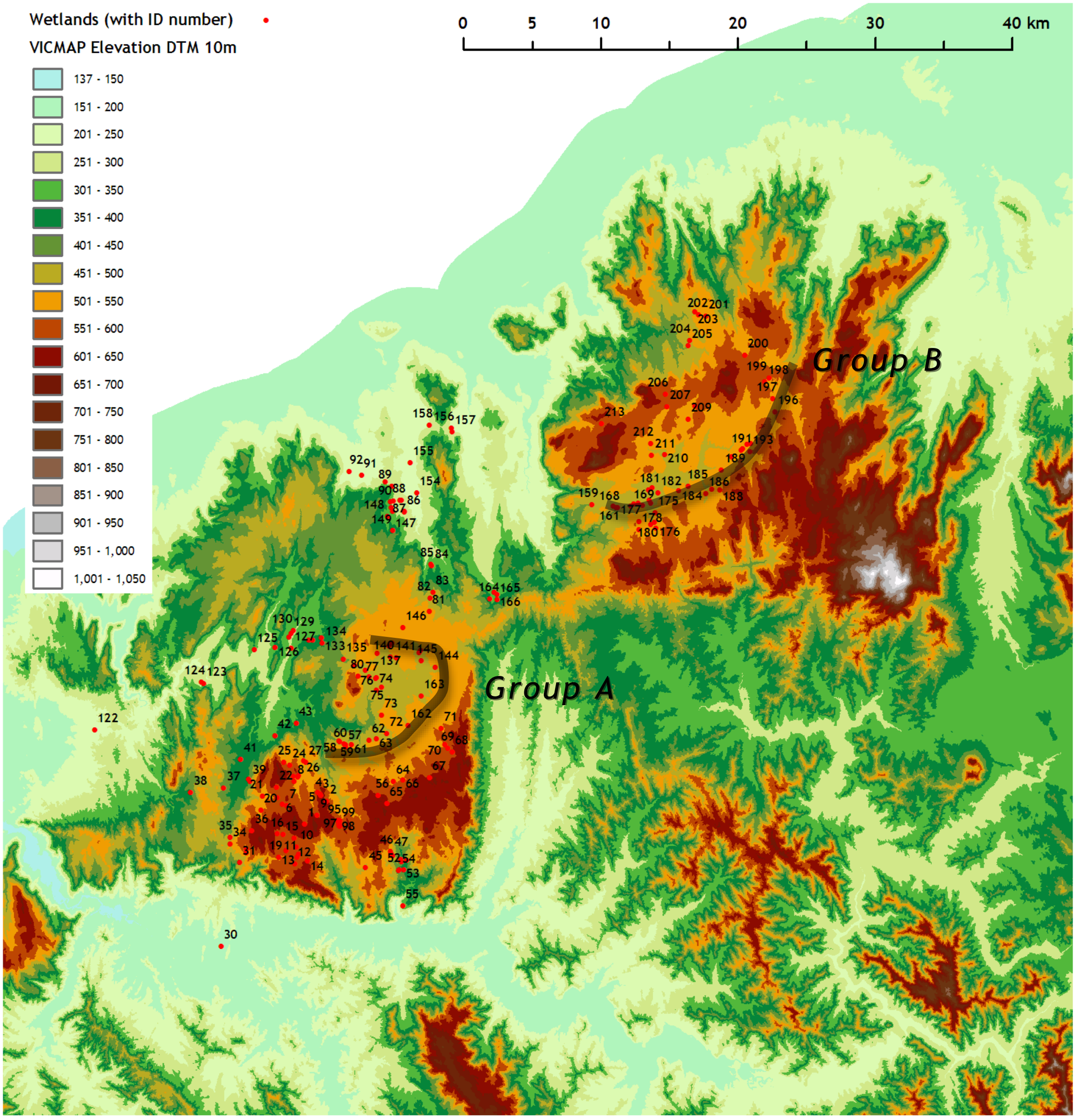

Figure 11: Distribution of Wetlands identified by Ecology Australia across the Strathbogie Batholith.

Elevation range

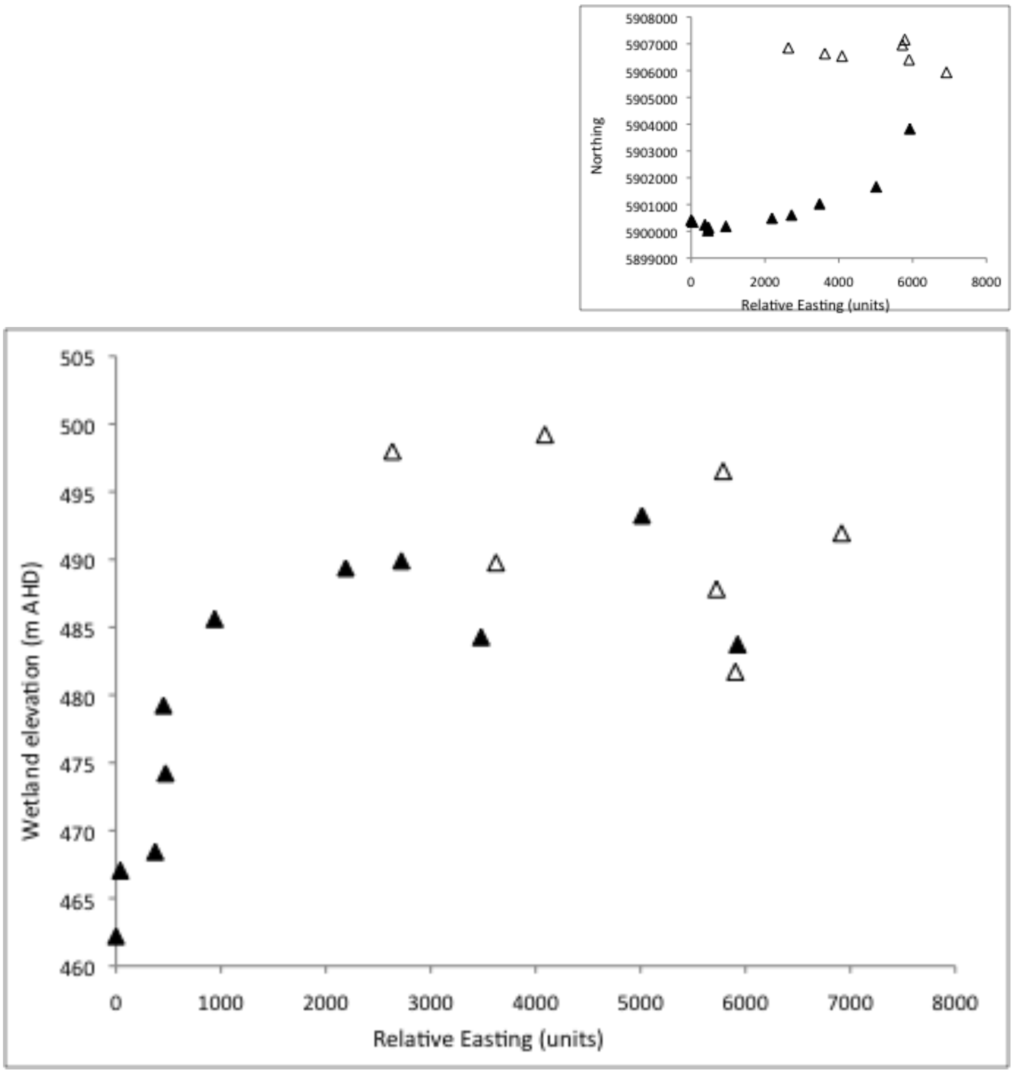

Figure 12: Elevation profile of Group A Wetlands

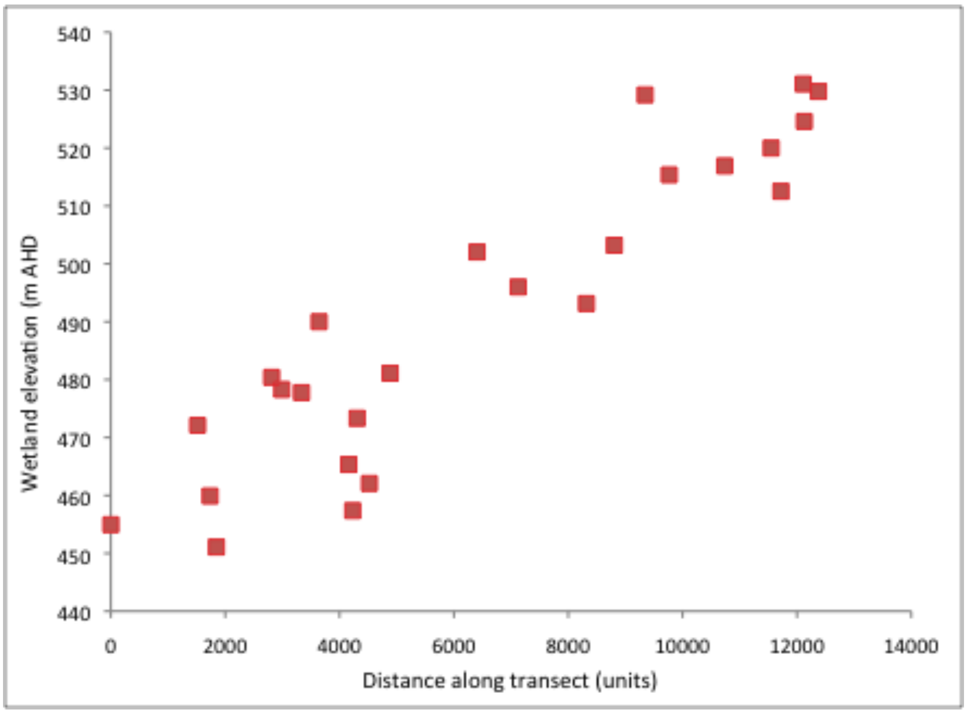

Figure 13: Elevation profile of Group B Wetlands

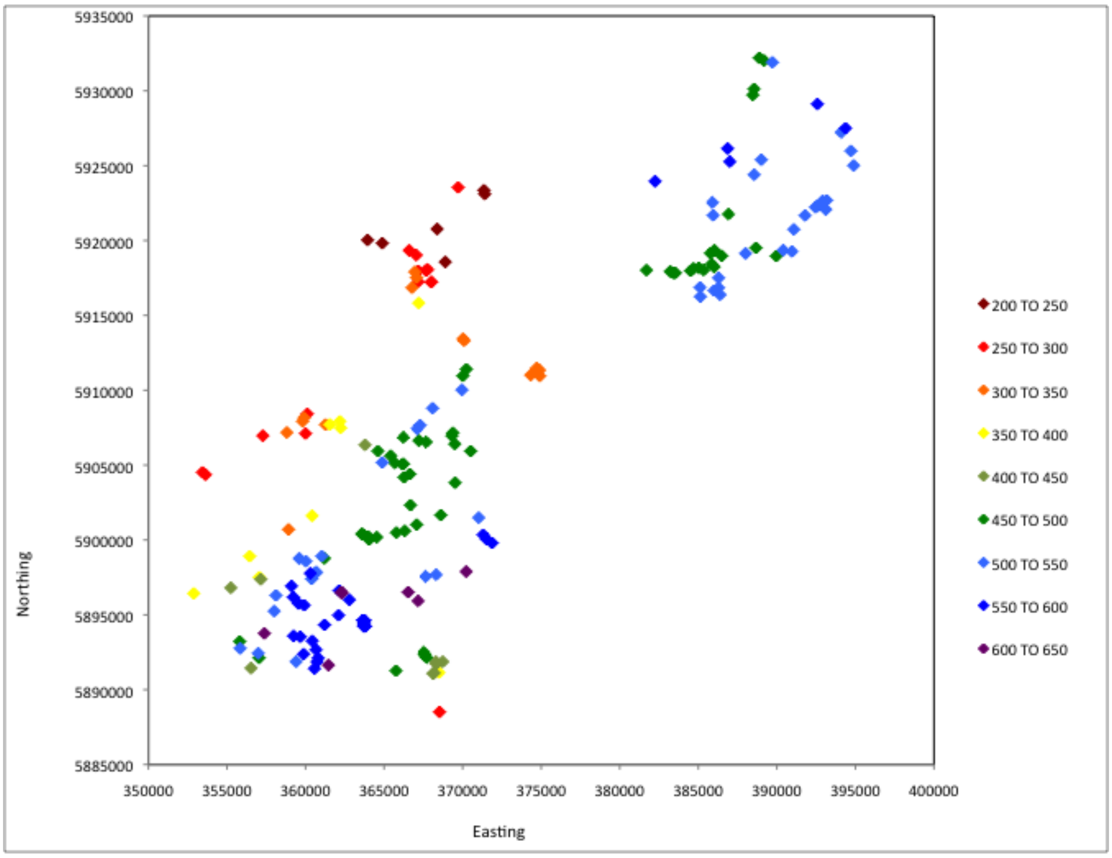

Figure 14: Elevation of known wetlands across the Strathbogie ranges.

4.2 Wetland Type and Wetland Terrain

The wetlands surveyed by ARI in their partner project were classified into vegetation types. In this section we cluster these types into three groups: woodland, shrubland and treeless. Of the wetlands surveyed, woodland wetland are mostly located to the east (Figure 15).

Assuming our model of west-south-westerly groundwater flow pathways is correct, the easterly wetlands will be draining the aquifers in the higher elevation areas along the eastern boundary of the Batholith. The ridge along the eastern boundary is likely to have the greatest depth of rock fractures and hence represent the largest and most persistent groundwater stores. Elsewhere, erosion of the fractured Batholith surface will result in shallower depths to basement rock and hence less aquifer storage. This is particularly likely along the valley floors where there may no aquifer storage at all. It is possible that these easterly wetlands have a more persistent flow, which has supported the woodland vegetation through dry periods. Wetlands supplied by shallower and more local (i.e. smaller contributing recharge area) aquifers will dry periodically and may not be well suited to supporting longer-lived woodland vegetation.

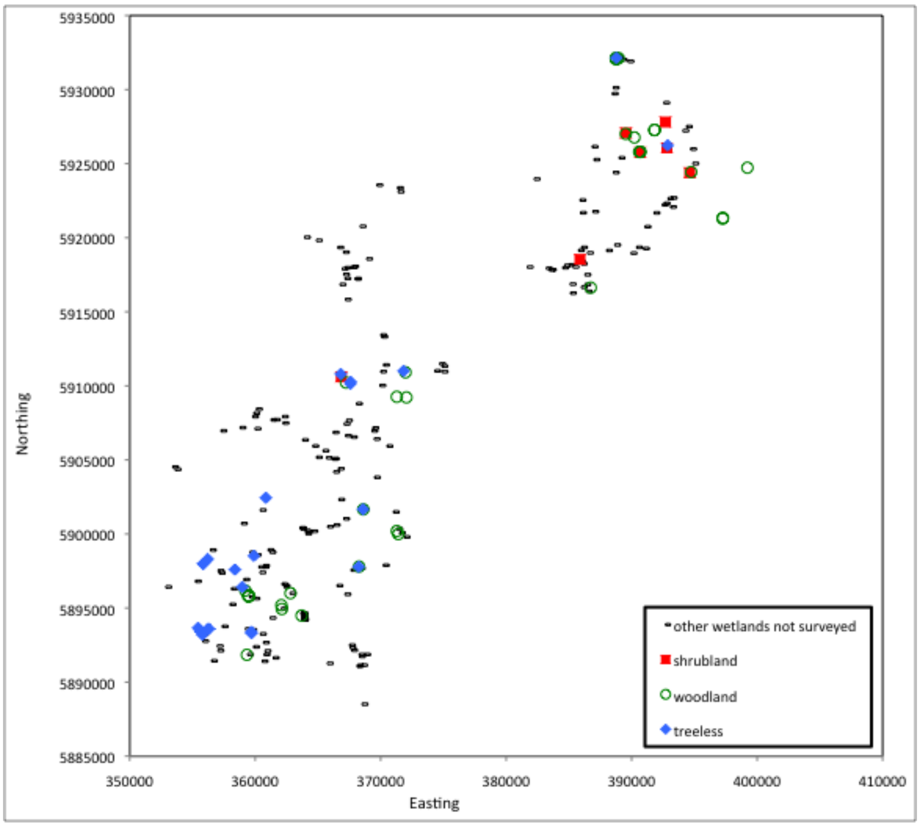

Figure 15: Distribution of Wetland types based on general vegetation class

4.3 Wetland Condition and Wetland Terrain

We undertook a multiple regression analysis comparing wetland condition (surveyed by ARI) with a range of terrain metrics, which might describe *the volume of the groundwater store contributing to the wetland. This comparison provided no significant results. One might expect sites with more persistent groundwater flows would generally be in better condition. A limitation of this analysis is the difficulty defining a terrain metric indicating the volume of the contributing aquifer. We attempted metrics related to the surface water catchment and also to the total volume above the elevation contour passing through wetland. Neither approach is entirely satisfactory. The surface water catchment is highly sensitive to the location of a wetland relative to the surface water drainage lines. The second approach tends to provide larger volumes for lower elevation wetlands which were generally to the west of the plutons, at some distance from the regions we propose produce the highest groundwater yields.*

5 Conclusions

5.1 Model of Groundwater System

The study results allow us to construct a model of the groundwater system in the Strathbogie Ranges. Observed patterns are remarkably consistent across both plutons suggesting this model is common to both plutons.

At the pluton scale, we propose that the weathered Batholith surface has been eroded through fluvial action to the point where valley floors have been established in the erosion-resistance basement rock (Figure 16). This basement surface appears to dip to the southwest. Consequently, valley floors penetrating this basement rock drain in the same direction and the main surfacewater of both plutons (i.e. Seven Creeks and Hughes Cr) drains to the southwest.

We suggest that the hills surrounding these valleys are largely fractured rock and represent the bulk of aquifer storage capacity. With the exception of the ridge along the eastern boundary of the Batholith, hills across the Strathbogie Ranges represent more or less isolated fractured rock aquifers. Where these hills are arranged in ridges, connection along the ridge is possible.

Many of the springs found in the Strathbogie Ranges will be located where the valley floors intersect the basement rock (Figure 16) and springs on the southwest side of hills will generally be at a lower elevation and have a more persistent flow. Groundwater discharge at higher elevations is also possible where the hill surface intersects the aquifer water table but these sites will have intermittent groundwater flows. Groundwater discharge at lower elevations may also be possible if isolated fissures extend below the main weathered zone and into the basement rock.

In areas of low relief, groundwater storage volumes and discharge rates will generally be low. The ridge on the eastern boundary of the batholith is likely to contain larger aquifers. Springs draining this ridge will be the most persistent, particularly on the western side of this ridge.

Given this model, it is to be expected that springs will be mostly found along valley margins and not on the main surface water flow lines. The surface flow paths will align more centrally along valley floors with many of these channels flowing over the impermeable basement rock.

This groundwater model has been constructed with no direct observations of groundwater levels and few observations of groundwater discharge. It should be considered preliminary and is a useful basis for the design of further investigations and testing of this model.

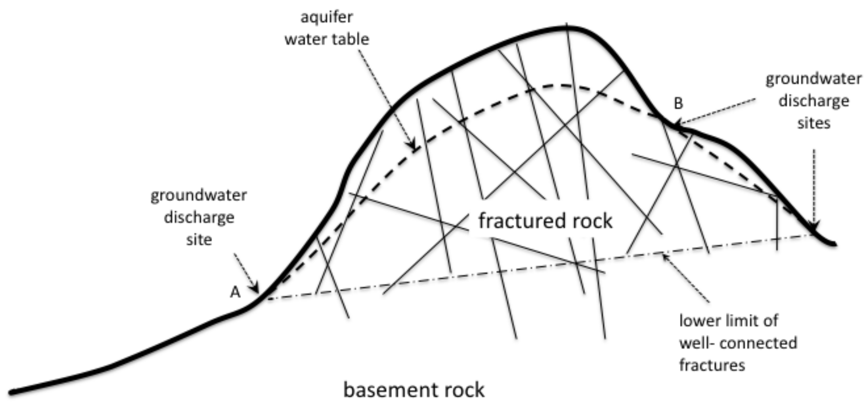

Figure 16: Conceptual model of fractured rock aquifers in the Strathbogie Batholith (modified from Dewandal et al., 2006)

5.2 Causes of Recent Wetland Drying

Groundwater recharge represents a small portion of total rainfall with base-level groundwater discharge rates equivalent to approximately 1% of rainfall. Annual minimum flows, which we presume are largely sourced from groundwater, vary from year to year in close association with rainfall over the preceding year. This suggests that low annual rainfall leads to low groundwater recharge, lower groundwater levels and reduced groundwater discharge.

There appears to be a threshold annual rainfall of between 400 mm-600 mm when flow ceases entirely at the Polly McQuinn Gauge on Seven Creeks. rainfall has been frequently within or close to this range since 2000. Lag correlation of rainfall and streamflow indicates there is a lag effect of reduced rainfall lasting up to 6 years. This suggests that persistently low annual rainfall over several years, like we have had recently, will have a cumulative effect. This will result in lower groundwater levels and discharge rates than would be experienced in an isolated low rainfall year.

The available evidence suggests that reduced spring discharge in recent years is a consequence of the sequence of lower annual rainfall totals experienced in the Strathbogie Ranges over the last decade.

The extent to which groundwater extraction has contributed to reduced groundwater discharge is difficult to assess. Certainly there is little evidence that the minimum flows at Polly McQuinn Weir are any lower than would be expected given the low rainfall (Figure 10). There are 112 and 137 licensed private bores across the Boho and Ruffy plutons respectively (based on information in the Victorian Water Resources Data Warehouse) with the number of bores increasing steadily since 1970 (Figure 17). Although the number of bores has increased over the last decade there no evidence of a sudden growth in their number.

The area of the Strathbogie Ranges is approximately 1500 km^2. Which means the density of licensed bores is approximately 1 per 6 km^2. The steering Committee for this project advises that 2 Ml/year is a realistic mean rate of groundwater extraction from each bore. At this rate, mean *aerial average rate[3] of groundwater extraction is 0.33 mm/year. We estimate the typical annual minimum groundwater discharge rate is 7.3 mm/year. This would suggest that groundwater extractions are less than 5% of the groundwater discharge rate. On average the influence of groundwater extractions is likely to be small. However the distribution of groundwater bores across the Strathbogie Ranges is quite patchy and where there is a high density of bores they may have a significant local effect on aquifer levels and groundwater discharge rates. For example, groundwater irrigation entitlements in the Boho South region are reported to be 300 ML/year compared to a total irrigation entitlement across the Strathbogies of 600 Ml/year (Bertram Lobert, Pers Comm)*

Whilst this analysis suggests the general effect of groundwater extraction on spring discharge is low, this advice should be verified with a more detailed assessment of groundwater discharge rates and both the distribution and pumping rates of groundwater bores.

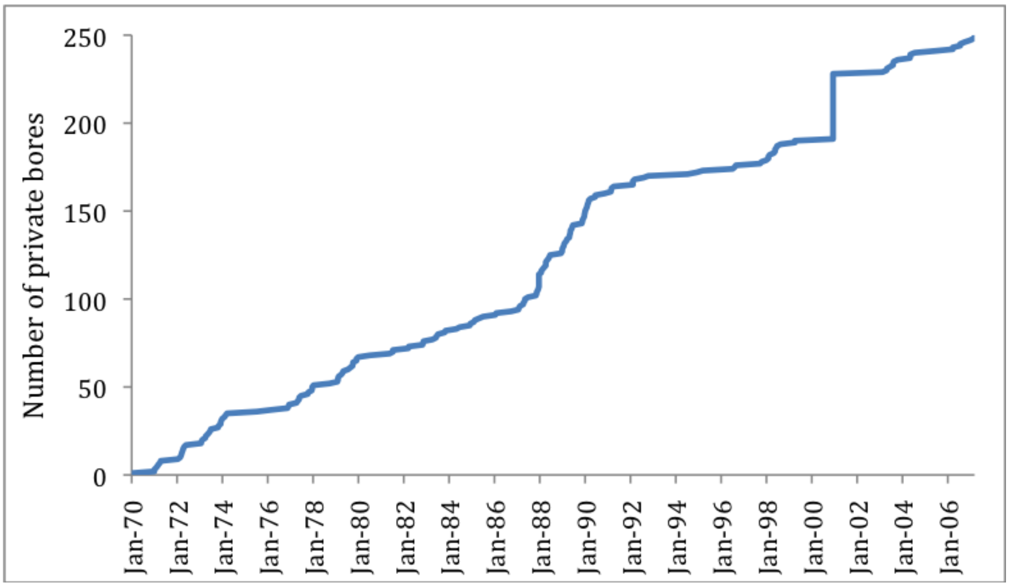

Figure 17: Cumuative number of locensed bores in the Strathbogie Ranges

5.3 Significance of Hydrological Threats

The single greatest threat to spring discharges and dependent wetland ecosystems is a drier climate as a consequence of anthropogenic greenhouse gas emissions. There appears to be a threshold rainfall below which baseflows cease entirely. While some springs may continue to flow in exceptionally dry years, persistent dry years are likely to reduce spring discharges across the Strathbogie Ranges. Under such a scenario, more

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[3] The aerial average rate of groundwater extraction refers the volume rate of extraction divided by the area over which the extraction is occurring. This can be calculated for the entire Batholith, one of the plutons or a region within the plutons.

Springs will flow intermittently and Spring discharges will generally decrease.

The effect of groundwater extraction is likely to be restricted to areas where there is a high density of bores. The general effect of groundwater extraction at the current bore density in the Strathbogie Ranges is likely to be small. However locally high bore densities may have an effect on local groundwater levels and discharge rates.

Farm dams are unlikely to influence groundwater recharge or discharge. When dams are located on a spring-fed wetland, they may have localized effects on soil moisture distributions within the wetland. The effect of farm dams in surface water flows depends on their size relative to dam catchment area and can be large. Where spring-fed wetlands are not located on the main drainage lines they are unlikely to be affected by altered runoff due to dams.

5.4 Variation in Sensitivity to Hydrological Threats

The most persistent springs will be located at relatively low elevations to the southwest of the higher ridges on the Strathbogie Plateau. These ridges generally align along the south and east on of the two plutons. These sites are likely to be locations where the surface level intersects the basement rock and aquifer volumes are relatively large. Law's spring is an example of this setting. These springs will be least affected by a drier climate. Springs in area of low relief or at higher elevations along these ridges will be more sensitive to low rainfall.

5.5 Effect of Wetland Condition Baseflows and Water Quality

The hydrological and water quality effect of wetlands will be largely insignificant during wetter times when streamflow is generated through surface runoff and soil drainage. Most of the wetlands appear to be located in very small tributaries or off the drainage lines.

During dry periods, groundwater discharges could be a significant contribution to stream flows. However wetland condition will not affect the rate of groundwater discharge and the quality of groundwater is unlikely to be a concern.

Coates et al. (2009) Mapped wetlands across the region and estimate that they represent 0.65% of the total ground area and a typical soil depth of around 1.0 m. If we assume a soil moisture storage capacity within the wetlands of 0.4 m, at the catchment scale, and the soil water in the wetlands when saturated is equivalent to 2.6 mm of water. This is relatively small compared to total runoff. It is possible that the wetland soil store may buffer baseflow variation to changes in groundwater discharge. However groundwater discharge variations are likely to be quite slow and any hydrological buffering effect will be small.

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