Slope Hydrology, Karst Drainage and Water Quality Related to Land Use: Great Western Tiers, Tasmania

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Abstract

In the Mole Creek fluviokarst in north-western Tasmania, conduit dye tracing experiments since 1966 failed to show any discrete source of Parsons Spring. Further, since 2001, this previously perennial spring has become intermittent in discharge. This change follows the establishment of 636 ha of eucalypt plantations since 1995 above the spring, including where Quaternary slope deposits obscure the limestone geological contact with overlying rocks.

In this 2008 study, evidence of a zone of diffuse recharge of Parsons Spring was sought. Water quality was compared and contrasted between Parsons Spring and other sites in the study catchment and a resurgence in a nearby reference catchment over different flow conditions and in response to a rainstorm. Results show that the study spring has a mixed recharge regime and complex discharge controls, including diffuse and conduit hydrological components. Parsons Spring is probably the main wet season overflow spring of a distributary system connected to the phreatic aquifer underlying the area. Apparent chemical "signatures" in the study spring's waters indicating soil disturbance implied the presence of an epikarst reservoir beneath the slope deposits cultivated for plantation establishment. Given their location, extent and growth stage, the plantations should substantially reduce aquifer recharge by 2013-2018 as interception of recharge increases. The consequent reduction of available aquifer yield implies economic stress for the rural community and compromise of karst ecosystems.

Keywords: Epikarst hydrology, chemical signatures, aquifer recharge, catchment land use, Northern Tasmania, Great Western Tiers.

Introduction

The recognition of different compartments to karst aquifers and research into their relative proportion and characteristics and behaviour of waters of those compartments has been carried out over the last few decades. Since the 1970s, research has been conducted on epikarst and vadose water percolation. Prestor and Veselic (1993) and Aley (1997) reported complex controls on temporal spring response to precipitation events, related to aquifer compartments. In the context of the dependence on groundwater of communities living on karst, Kranjc (2000) and Aley (2000) suggested there remains the need for more research on karst hydrology, water quality and measures for its protection.

In the Mole Creek karst of north-western Tasmania (Fig. 1), the principal settlements are the towns of Mole Creek, population 223, and Chudleigh, population 400

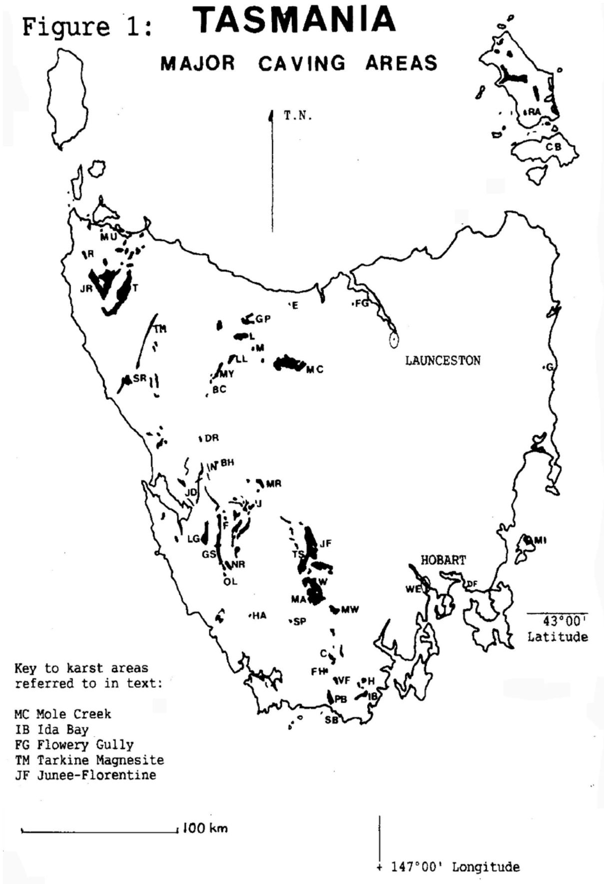


***Figure 1:** Locality of the Mole Creek karst study area, from Lichon, 1993*

(at census, 2006, Australian Bureau of Statistics, 2008). Intensive rural enterprise including mixed farming, forestry, limestone mining and tourism coexists with well-documented, heritage-listed and outstanding karst landforms (Meander Valley Council, 2005). Limestone crops out over approximately 10 km (north-south) by 26 km (east-west), between approximately 200 and 600 m in elevation (Kiernan, 1989 & 1995). However, much of the catchment lies above the limestone on the Great Western Tiers (GWT) escarpment (Fig. 2). Permanent surface water is scarce in the valley, but several subsurface drainage systems are known (Kiernan, 1989).

In the Lobster Rivulet drainage system, Parsons' behaviour changed from perennial to intermittent, following the conversion of 636 ha of mainly native forest to forestry plantations over the adjacent escarpment since 1995 (Fig. 2). This provided the impetus to investigate the spring's hydrology. Since decades of conduit dye tracing failed to identify any discrete source(s) for this major spring, the present study sought evidence of

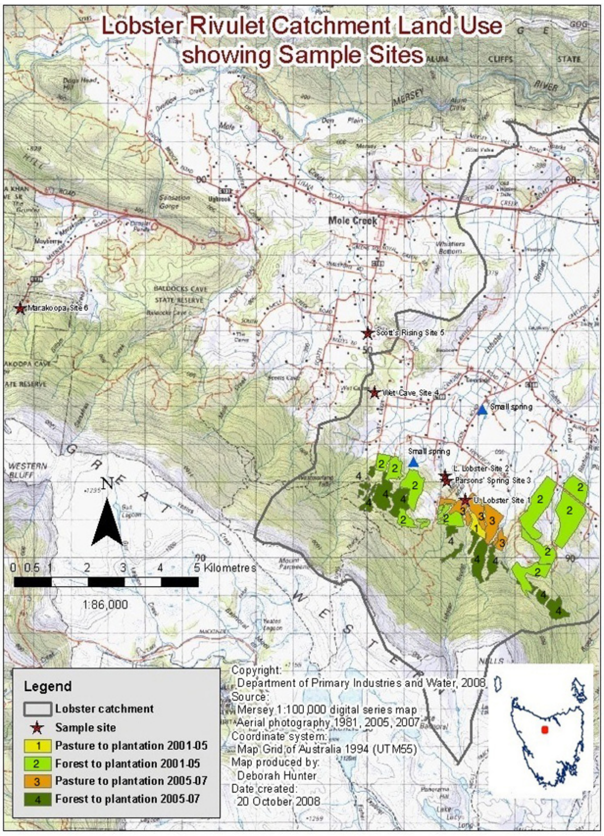


Figure 2: *The study setting, including the Great Western Tiers escarpment, Lobster Rivulet catchment (outlined), the four sample sites of the study catchment, the phreatic spring Scotts Rising (Site 5), the reference spring Marakoopa Cave, to the west (Site 6) and two small episodic springs. Land use change on the lower escarpment is shown ("Forest to plantation 2001-05" includes a minor conversion in 1995).*

diffuse recharge through the Quaternary slope deposits by identifying any land use "signal" associated with forest clearance, burning and cultivation. The objectives included to determine the nature of the Parsons Spring's aquifer and its likely recharge zone from analyses of the chemical and physical properties of its waters and a spring discharge hydrograph in comparison to similar analyses from a "reference" spring and in contrast to analyses of other nearby waters. The reference spring was Marakoopa Cave's resurgence about 13 km to the west (sample site 6). The small, permanent cave stream originates on slopes that remain cloaked by native forest. The other sample sites were the Lobster Rivulet 700 m and 50 m above the confluence with Parsons Spring water (sites 1 and 2), Parsons Spring (site 3), Wet Cave resurgence (a vadose cave) and Scotts Rising (a phreatic resurgence) (sites 4 and 5) (Fig. 2).

Climate, geology and geomorphology of the Mole Creek karst and its catchment

Up to 1320 m in altitude, the Great Western Tiers (GWT) form the northern escarpment of the Central Plateau above the Mole Creek valley (Fig. 2). The climato-geomorphic system is currently fluvial, however, in the past it has been glacial, glaciofluvial and periglacial (Kiernan, 1995). The annual precipitation ranges from 1111 mm in the valley (Bureau of Meteorology, 2007) to >1600 mm in the upper catchments due to orographic effects, and has a Mediterranean, seasonal distribution. Annual average daily temperatures range from minima of 3-6 ^{o}C to maxima of 12-15 ^{o}C (Bureau of Meteorology, 2008). Drought prevailed in the region at the commencement of this study.

Ordovician age, dark grey, fossiliferous and coralline Gordon limestone, of over 90% purity $CaCO_3$, occupies the Mole Creek syncline (Jennings, 1963; Fig. 3). Permian-Triassic Parmeener Supergroup (PSG) sediments (slate, mudstone, shale, sandstone, tillitic conglomerates and siltstone) up to 600 m thick lie unconformably upon the older rocks. A 200-300 m thick Jurassic dolerite intrudes into the PSG sequence, with block faulting, epirogeny and warping. Further Tertiary epirogeny and block faulting of the combined block resulted in the substantial elevated Central Plateau mass. Subsequent erosion down to the resistant dolerite has left the cap of the Central Plateau, with a northern scarp of about 1000 m elevation over the valley floor (Jennings, 1963). The Lobster Rivulet follows a perpendicular fault over the Plateau margin.

Quaternary periglacial processes resulted in extensive solifluction of saturated regolith, mantling or extending "tongues" of dolerite-derived taluvium over surfaces peripheral to ice sheets. Below the altitude of the Triassic geological contact, Quaternary mantles include sandstone fragments. Periglacial activity occurred to about 600 m elevation, although talus and solifluctate are found to about 450 m (Jennings, 1963; Davies, 1965; Burrett & Martin, 1989). Glacio-fluvial mantles extend over the limestone contact in the vicinity of the study spring (Calver et al., 1995; Fig. 3). Therefore, waters from the sample sites may be expected to yield weathering products of the limestone, dolerite and PSG sediments in their catchments.

Mid-Pleistocene glacial ice likely extended very close to, or overrode, the present sites of caves (Jennings & Ahman, 1957 and Jennings, 1967, in Kiernan, 1989). Younger gravels overlie some glacial deposits. The overall result is that glacial outwash and piedmont fans of gravels in a sandy matrix have diverted drainage to some of the valley margins, facilitating solutional processes in adjoining limestone outcrops (Kiernan, 1989). Part of the generally northerly course of the Lobster Rivulet is deflected along the hill-flank toward the north-west, proximal to Parsons Spring.

The maximum limestone topographical relief is about 350 m. It is intensively karstified, with complex hydrogeological systems (Kiernan, 1995). New cave discoveries still occur and knowledge of the hydrology remains incomplete. About 400 caves are currently known (Stephen Blanden, pers. comm., October, 2008). A wide range of surface and subsurface landforms is present, including hums and the Loatta and Mayberry poljes (Kiernan, 1989). The terrane is consistent with the classification "fluviokarst" (Jackson, 1997).

Water tracing experiments have shown the courses of underground streams frequently bear little relationship to the surface topography. The Mole Creek itself "double-breaches" the divide between the Lobster and Mole valleys. Two or more separate streams may share some catchment areas and groundwater conduit routes commonly vary with flow stage, periods of high discharge

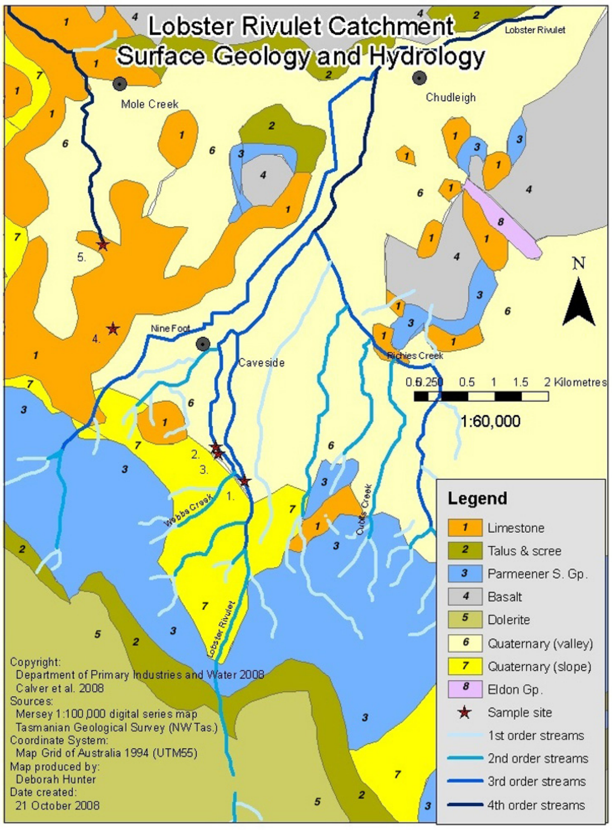
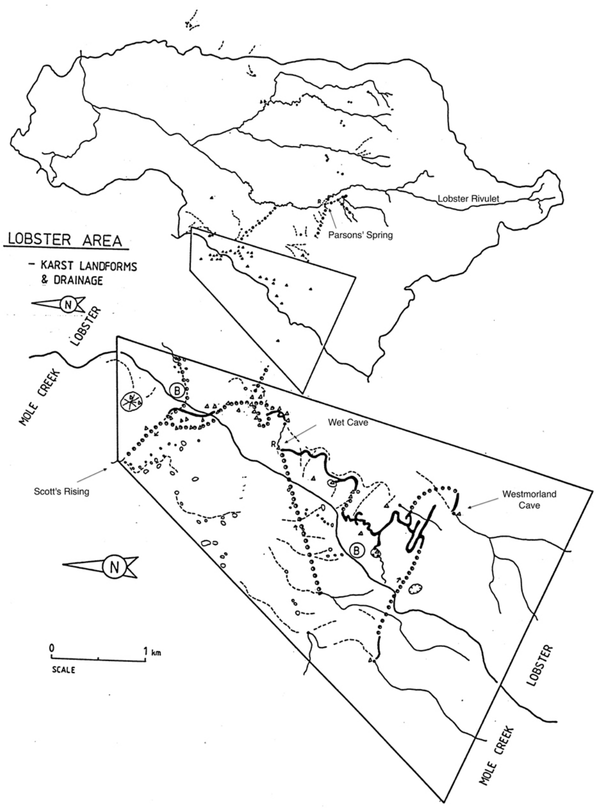


Figure 3: *A simplified surface geology and hydrology of the eastern extent of the Mole Creek karst. Parsons Spring is sample site 3. The reference spring (not shown) lies to the west.*

activating older, higher routes (Kiernan, 1989 and 1995: Fig. 4).

The results of previous conduit dye tracing experiments involving possible tributaries to Parsons Spring are shown in Table 1. No diffuse traces have been attempted.



Water resources, land management issues and karst conservation

The intimate relationship between karst (its environmental processes and integrity) and water, results in the susceptibility of karst aquifers to adverse impacts of land use in the recharge zone (Kiernan et al., 1993; Aley, 2000; Sharples, 2006). White (1988) suggested the most important problem in karst terranes is tillage and soil loss. Karst conduits transmit and store sediments, and may become blocked by sediments (Kiernan et al., 1993). Karst catchment disturbance can release metal ions from adsorption on clays and from complexation by organic acids (Lichon, 1993).

Recently, recurring drought and the prospect of anthropogenic climate change have added impetus to Australian research into catchment water yields and the role of catchment land management. Regarding stream flow reduction risks, Van Dijk et al. (2006) suggest climate change poses the greatest risk, followed by afforestation and groundwater pumping. In the TasLUCaS model demonstrated in small Tasmanian catchments, Brown et al. (2006) considered the age of regrowth forests and

Table 1: *Results of dye tracing experiments using stream sinks, Lobster/Mole karst systems.*

Origin	Date/ stage	Path	Destination	Reference	Notes
Lobster above sink	1966 low flow	Bypassed Wet-Honeycomb window?	Lobster downstream in 3-4 days (lingered for 6 days) and Scotts Rising	Gleeson (SCS), 1976, in Kiernan (1984 & 1989b)	Trace at Scotts Rising may be attributable to tracing in Wet system two weeks previously
Kelly's Pot	July 1976	Direct then upper Wet system	Herbert's Pot and Wet	Gleeson, (SCS), 1976, in Kiernan, 1984	Fluorescein 220g
West-morland	Nov 1976	Direct then upper Wet system	Herbert's Pot and Wet	Gleeson (SCS), 1976, in Kiernan, 1984	Fluorescein 670g
Stream downslope of Kelly's	1974	Direct	Upstream Wet	Gleeson (SCS), 1976, in Kiernan, 1984	Fluorescein 115g
Kelly's	1974	Direct	Shishkebab	SCS, in Kiernan, 1984	Fluorescein 900g
Sink near Herbert's entrance	1964	Unknown	"Wet cave stream"	Jennings and James (TCC), 1967, in Kiernan, 1984	
Prohibition	1984	Not Cobbler Cooler, Cycops, Glow-worm, Baldocks, Baldocks Spring, Sassafras Spring E or Sassafras Creek below Spring E.	Unknown	Kiernan, 1984 (p 133), 1989a & 1989b	Prohibition dye tracing was unsuccessful; may flow to Sassafras or Mayberry, although deflection along the strike to Mole is suggested (Kiernan, 1995)
Flower's Pot and Gimli's Grotto			Unknown	Kiernan, 1995	Waters may join Prohibition; the combined waters may flow to Scotts Rising
Waterworks Caves			Unknown	Kiernan, 1984 (p 171), 1989a & 1989b	Waterworks may flow to one of the springs below Scott's Cave or Scott's Rising

Figure 4 (left): *The Mole and Lobster drainage systems of the Mole Creek karst (Kiernan, 1989). Thick dark lines represent known caves, rows of dots proven hydrological connections and dots with dashes presumed hydrological connections.*

Water sinking in the bed of the Lobster Rivulet is presumed to pass north-west along the strike to join the Mole system, emerging at Scotts Rising at the left on the inset. Two proven breaches (B) of the surface divide are shown.

plantations was a major influence on their water use. Stream flows increase while stands are young, however a progressive decrease follows when such land use change is compared to a no-change scenario. Sustained reductions in catchment flow yield were predicted with 95% confidence over the 35 year model. Kuczera (1987) and Watson et al. (1999) found that in Victorian mountain ash forests regenerated after major disturbance, catchment yield reduced by 500 - 600 mm at 20 - 25 years of forest age, in a 2000 mm annual rainfall regime. However, no Australian models reviewed during the present study accounted for karst. The evaluation of karst aquifers to enable appropriate water resource management requires identification of aquifer characteristics including dynamic storage, rates of recharge and specific and sustained yield (White, 1988). Considering the unavoidable predicted impacts of anthropogenic climate change on effective precipitation, hence aquifer recharge, other human-induced stresses could seriously reduce the capacity of karst systems to adapt (Sharples, 2006).

Most surface streams of the Mole Creek karst either travel underground for much of their courses or are intermittent in nature, seasonally disappearing into their beds (Kiernan, 1989). Water sinking along the middle reaches of the Lobster Rivulet has been assumed to travel north-west with the limestone strike beneath the plain to join the Mole Creek in its underground course (Kiernan, 1995; Fig. 4). Summer and autumn flow has been diverted into a braid of the Rivulet (the Little Lobster) to bypass the streamsinks and maintain flows in the lower reaches. No permanent hill-flank springs exist in the study catchment, although for several generations until 2001, Parsons Spring maintained flow into the middle reaches of the Lobster Rivulet on the family farm through the summer-autumn season (Desley Parsons and Joe Parsons, pers. comms., September 2008). Episodic springs rise nearby after prolonged rain. Several farm and local community scale water schemes reticulate water from above the limestone geological contact and an unknown number of bores draw upon the valley aquifer. Bore sinking requires no permission and no records are kept of bores by the Department of Primary Industry and Water (D. Rockliff, DPIW, pers. comm., October 2008).

Much of the Mole Creek karst and its catchment is used for forestry and agriculture. Formal conservation reserves include a western portion of the GWT escarpment and several small, discrete reserves, including land parcels recently purchased or placed under Nature Covenants under the Mole Creek Karst Forest Program (Parks and Wildlife Service, 2004; Department of the Environment and Water Resources, 2007). This tenure mosaic remains intrinsically problematic for the effective conservation management of karst features, processes and resources that commonly extend across tenures (Kiernan, 1989, 1995; Parks and Wildlife Service, 2004; Eberhard, 2007). While the sensitivity of karst hydrogeological processes are now better recognised, much is still to be realised in actual land management practices (Kiernan et al., 1993; Eberhard and Houshold, 2002; Kiernan, 2002a; 2002b; Gray, 2004).

Concurrently with new sensitivity classifications and development constraints being incorporated into the redrafted municipal Planning Scheme, land classed in 2008 as high sensitivity karst in the study catchment has been undergoing plantation establishment. However, forestry is exempted from municipal development planning and approvals processes (Meander Valley Council, 2005; 2008).

Karst hydrogeology considered in the study setting context

The vadose hydrologic zone in mantled karst like the Lobster Rivulet catchment includes the epikarst (weathering zone), where water moves mainly by gravity or capillary action, equivalent to the subcutaneous zone elsewhere (Williams, 2008). Initial solutional processes may widen the fissures, but due to chemical saturation, the solutional aggressiveness of percolation water is limited with depth. Porosity and permeability reduce vertically, and leakage to the conduits below is slow (Klimchouk, 2000). Epikarst in pure crystalline limestone like that of the study setting typically develops to about 10 m depth, delaying recharge over extended dry periods. Meteoric and up-slope throughflow water typically ponds in an under-drained perched aquifer that sustains distal tributaries of caves and small perennial hill-flank springs (Williams, 2008). Vadose water movement can be anisotropic and travel substantial distances (Palmer, 2007), pathways varying between storms and seasons (Toran et al., 2006).

In contrast to vadose flow, conduits in the phreatic zone may rise and fall along an undulating reach, generally at shallow depths at or just below the water table. Smaller passages tend to feed into major trunks where the water table is lower than in the spaces surrounding them. Surrounding spaces can store and later return flood water to the main trunk in the same way bank storage functions in rivers. Downstream branching is rare except where sedimentation of the spring outlet forces diversion to overflow springs (Palmer, 2007; Fig. 5). River water may intrude in a flood pulse into an estavelle conduit that operates as a spring in wetter seasons (Ford and Williams, 2007).

An epikarst aquifer may sustain the phreatic aquifer of the Lobster Rivulet valley during periods of low aquifer recharge. Parsons Spring, which is partly blocked by sediments, could be the main outlet of a distributary

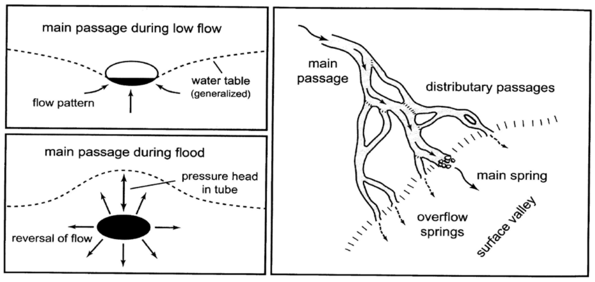


***Figure 5:** Conduits of distributary springs, from Palmer (2007, pub. Cave Books). At the top left, the trunk conduit under low flow conditions drains the surrounding aquifer, in the same way that streams drain bank storage. However, during a flood pulse (from the feeder system or an intruding river surge), the flow reverses (lower left). The hill-flank distributary system shown on the right illustrates the trunk conduits of a main spring and overflow springs. Such conduits may operate as estavelles, allowing incursion of surface river flood pulses.*

conduit system subject to river invasion during flood pulses of the Lobster Rivulet and/or to discharge related to exceeded storage capacity in the phreatic aquifer (Fig. 5). The spring discharges at the hill-flank 4 m higher and 100 m distant from the Lobster Rivulet and at least two episodic springs discharge nearby (Fig. 2).

Methods

Rainfall records for Caveside 1.5 kms east of Parsons Spring were collected using a Nylex cylindrical rain gauge. Rainfall records for Marakoopa were collected by Parks and Wildlife Service staff at the office 400 m north of the cave entrance from 1989 to 2005 and from 2nd August to 27th September 2008 using the same model gauge. Marakoopa rainfall records from 18th March 2005 to 25th September 2008 were collected from a DPIW automatic station (Eberhard, 2008, unpublished), although the data were incomplete. Interpolation covered the gaps, using means from earlier rain gauge data for Marakoopa and adjusting for percentage of the mean as recorded at Caveside for that day or month. Rainfall statistics for each catchment were based upon the same period of record for consistency.

A temporal sequence of aerial photography (1953-2007) was examined using a Wild ST4 stereoscope for evidence of karst surface features in the Lobster Rivulet catchment about the geological contact of the limestone. A limited ground search for karst features was made. GIS analysis (ESRI ArcGIS v9.2) of the aerial photography tracked and quantified catchment disturbance and related it to the hydrogeology. Plantations (<20 ha) currently under development proximal to the lowest point in the catchment were ignored. Ground control points used in georeferencing aerial photography and feature locations were fixed using a Garmin GPSmap76CSx. A photographic record was made of each site at the time of each sampling.

The community's utilisation of local water resources was documented from oral and published history.

The six sites sampled during 2008 were "upper" Lobster Rivulet (site 1), "lower" Lobster Rivulet (site 2), Parsons Spring (site 3), Wet Cave (site 4), Scotts Rising (site 5) and Marakoopa Cave (site 6). A total of four flow stages was sampled: "drought" (21st March), "first flush" (6th April), "base flow" (27th July) and "post-peak" (26th September). At the time of the first sample set, Parsons Spring was dry. The last sample set was taken after the rainstorm response discharge peak recorded at the study and reference springs.

Water samples for inorganic analyses were collected in acid-washed polyethylene containers. Samples were placed in cool storage within 0.5 hours and transferred to refrigeration pending analysis as rapidly as possible. Samples were collected mid-flow at the stream sites and 80 cm beneath the surface at the springs, avoiding sediment mobilisation. Temperature was measured at the time of each sampling at the depth of sampling, excepting for the drought set.

Discharge was calculated for the study and reference springs during the storm response from velocity, cross-sectional area and stage (depth) measurements. Stream velocity gauging was by OTT Current Meter No. 46051 Type 10.002, using propeller No. 1-45430, propriety propeller housing oil and a mechanical revolution counter. Velocity was calculated using the manufacturer's equation for this propeller and range of revolutions: $v=25.52n+0.4$ (cm s^{-1}), where n= number of revolutions per second (>0.76) and v= velocity (cm s^{-1}). Stage was measured using a metre staff for the larger Parsons Spring flows and a plastic ruler for smaller Marakoopa Cave flows. Gauging was limited to five velocity measurements at the less variable and larger study spring. Several intermediate stage measurements were taken at the reference spring in addition to velocity gauging. Calibration was by use of a rating curve of discharge versus stage and the regression equation enabled stage conversion to discharge (Goede, 2008, unpublished). Storm response was sampled over about 22 hours on 26th and 27th September at Parsons Spring (5 samples) and Marakoopa Cave (8 samples); 5 Marakoopa samples were selected for ICP-MS analysis.. Wet chemistry was performed for all samples. Samples L (Parsons Spring) and G (Marakoopa Cave) were selected to represent "post-peak" flow stage.

Wet chemistry analyses were conducted at the Newnham campus laboratory (University of Tasmania). Alkalinity >20 mg $CaCO_3$ L^{-1} was determined by titration to total alkalinity endpoint using screened methyl orange (Method 2320, Greenberg et al., 1992). Dissolved solids were analysed by Method 2540C and suspended solids by Method 2540D (Greenberg et al., 1992). Chloride determinations were carried out for a rainwater sample at the request of DPIW and sample G using a Waters ion chromatograph with M-45 pump, model 430 conductivity detector and IC-Pak anion column (4.6 mm x 5 cm). Determinations were by external standard and the detection limit of 0.10 ppb or 1.03x10-4 mg L^{-1} was calculated from the manufacturer's stated "area reject" (5,000,000).

Inductively coupled plasma mass spectrometry (ICP-MS) for cations was carried out at the Central Science Laboratory of the Hobart campus of the University. Measurements were carried out using an ELEMENT High Resolution ICP-MS (Finnigan-MAT, Bremen, Germany). Prior to analysis an Indium internal standard was added at a final concentration of 100ppb, and unfiltered samples were acidified with a small amount of ultra-pure nitric acid (final concentration ~0.2%). Solids were then settled overnight. The samples were usually analysed within 1-2 days of receipt (A. Townsend, pers. comm., October 2008). Samples were not analysed for organic materials, anions including Cl^- or $Si4^+$ cations, and a proportion of analysed cations probably remained adsorbed on settled clays and organic matter in ICP samples.

Approximate charge balances were calculated for all samples excluding the drought sample set by converting ppb concentrations to molarity and assigning charge. Given the limited ICP analyses, some assumptions were made within reason, including the maximum oxidation number assumed for multivalent metals, that the presence of S represented a net negative charge of $^{2-}$ due to speciation as $SO4^{2-}$, that similarly, P represented $H2PO^{4-}$ and that measured alkalinity was effectively wholly due to HCO^{3-}. Trace metals detected at concentrations of <1.00 ppb were disregarded. Cl^- was included in sample G.

Hydrographs and chemographs were constructed for the springs' storm response.

Relationships in the proportions of elements in possible "tracer/signature" groups representative of limestone (Ca, Na, Mg, S, Sr, Ba, Mn, Ti and Rb; Hughes, 1957; Burrett & Goede, 1987; Lichon, 1993; Jackson, 1997), dolerite (Ca, Na, Mg, S, K, Al, Fe, P and V; Leaman, 2002), a metals group (Al, Fe, Mn, Ti, P and Zr) and highly variable elements (Ca, Mg, S, Sr, B and Sc) were tested between sample sites (155 tests per element group). Alkaline earth/alkali ratios were calculated from molar concentrations. Concentrations of the highly insoluble Al, Ti and Zr were compared and contrasted between the springs.

Data was collated and handled using Excel spreadsheets (Microsoft Office 2008).

Results and discussion

Precipitation recorded for Caveside (ASL 319 m) and Marakoopa (ASL 444 m) for the three years to the date of the storm response monitoring, was 75% of the long term mean. This suggests drought alone was unlikely to have caused the change in discharge behaviour of the spring. Demand on the aquifer by bores requires further research.

No surface karst features could be identified from aerial photography in the study catchment. Access restrictions prevented a ground search for features on the slopes west of the Lobster Rivulet. No features were found on the eastern slopes upon inspection on 24th August 2008. However, epikarst may be present with or without such evidence.

In addition to upslope recharge, efficient autogenic recharge of the phreatic aquifer underlying the valley is suggested by the presence of a series of 120-150 mm diameter soil pipes in 2 m high banks of layered gravels and fines cut into by the Lobster Rivulet between sample sites 1 and 2. However, the efficiency of any aquifer drainage over about 5 km and 30-40 m altitudinal range to Scotts Rising (if such a connection exists) is dependent on the capacity of any connecting conduits, and the fall of the surface topography to Chudleigh is only 50 m over 8 km. Although confirmation by flow gauging over a series of water years is recommended, observations suggest that the discharge of Parsons Spring and any associated distributaries is probably limited to periods when the recharge rate exceeds the drainage capacity of the phreatic aquifer and/or the pumping from bores. Parsons Spring is probably the main overflow spring to the phreatic aquifer. In March, months of the Spring's inactivity concluded as if a threshold was reached, upon which the Spring represented the majority of flow in the middle reaches of the Rivulet until a winter surface base flow from upstream was established. A small episodic spring at 320 m elevation was flowing on 24th September, while another at 280 m elevation was inactive on 4th October (Fig. 2). The possibility of further episodic springs requires investigation. Sample site elevation differences are shown in Figure 6.

Although the 1995 plantation on the western flanks of the Lobster Rivulet, proximal to Parsons Spring, is of an age where substantial water interception is to be reasonably expected (Van Dijk et al., 2006), it represents

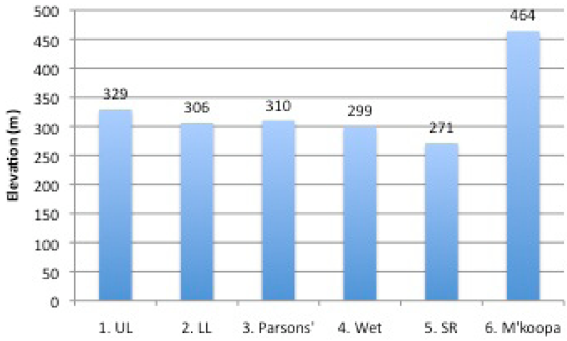


***Figure 6:** Sample site elevations.*

a small fraction of the total areal extent of plantations, most of which were established since 2001. Younger plantations intercepting less water than the forest they replaced, and remnant native forest under which the hydrology should not have changed, surround the 1995 plantation. However, given the total extent of newly established plantation and its location, upslope karst aquifer recharge should reduce substantially by 2013-2018 (Brown et al., 2006).

Temperatures and wet chemistry results are given below for the four flow stages (Table 2).

The presence of travertine on the stream bed and the low range in temperature of the water at Parsons Spring over the course of the project with respect to other karst sites supports a karst aquifer residence time generally sufficient to equilibrate the tested parameters with the host rock. Generally, the karst sites varied less in water temperature than the two fluvial sites, Upper and Lower Lobster. Parsons and Wet Cave varied the least and Scotts Rising had the warmest water throughout. Marakoopa's lower temperatures reflect fast vadose flow associated with the steep gradient of this cave.

The two river sites differed in pH, with Lower Lobster having the greater range and the higher readings in drought and flush. Of the karst sites, Scotts Rising had higher pH values than Parsons Spring throughout the study, Lower Lobster and Wet had very similar pH throughout the study and Marakoopa varied the least.

***Table 2:** Results from wet chemistry for flow stages. Alkalinity is expressed in mg $CaCO_3$ L^{-1} (bracketed entries should be regarded as <20) and suspended, dissolved and total solids are expressed in mg L^{-1}.*

UL	Temp (°C)	pH	Alkalinity	S. solids	D. solids	Tot S
Drought		6.31	(5)	0	11	11
First flush	11	7.44	(18)	0	0	0
Base flow	7	5.67	21	0	494	494
Postpeak	7.6	7.07	(14)	0	88	88
LL	Temp (°C)	pH	Alkalinity	S. solids	D. solids	Tot S
Drought		6.92	(13)	4	47	51
First flush	12.5	7.55	30	0	4	4
Base flow	8	5.56	20	0	45	45
Postpeak	7.6	7.04	(15)	5	73	78
Parsons	Temp (°C)	pH	Alkalinity	S. solids	D. solids	Tot S
Drought N/A						
First flush	9.5	7.67	56	6	40	46
Base flow	8	5.27	36	0	72	72
Postpeak	9	6.88	33	0	67	67
Wet	Temp (°C)	pH	Alkalinity	S. solids	D. solids	Tot S
Drought		6.91	64	29	2	31
First flush	9.5	7.62	56	0	42	42
Base flow	8	5.47	33	0	66	66
Postpeak	7.9	7.01	28	0	22	22
SR	Temp (°C)	pH	Alkalinity	S. solids	D. solids	Tot S
Drought		6.80	26	8	337	345
First flush	13	7.94	126	2	102	104
Base flow	10	5.59	84	2	115	116
Postpeak	9.3	6.89	70	4	143	147
Mara	Temp (°C)	pH	Alkalinity	S. solids	D. solids	Tot S
Drought		6.80	54	12	54	65
First flush	9.5	7.63	40	0	29	29
Base flow	7	5.68	41	2	73	75
Postpeak	7.6	6.82	28	0	93	93

Uncertainty in alkalinity determinations per sample set (relative standard deviation):
Drought: +/-11%
First flush: +/-0.69%
Base flow: +/-0.46%
Post-peak and chemographs: +/-0.57%
Glassware and analytical balance tolerances: +/- 0.18%

The lowest pH values for all sites were recorded in base flow, with Parsons Spring the lowest (5.27), while the highest pH values were recorded in flush, the highest and second highest being Scotts Rising and Parsons (7.94; 7.67) (Table 2).

In alkalinity, Upper and Lower Lobster varied little, from lowest in drought to highest in base flow, except Lower Lobster's alkalinity rose notably in first flush. Parsons Spring's flush-high alkalinity declined through the season. Wet Cave's alkalinity was drought-high, declining through sampling. Scotts Rising had higher alkalinity throughout than the other sites. However, its lowest reading, in drought, contrasting with the other karst sites was probably due to the precipitation of colloidal carbonate. Marakoopa's alkalinity varied little and was lower than Wet Cave's in drought. Parsons' values were higher than Marakoopa's in flush and post-peak flows.

Suspended solids throughout the study were generally low. The highest values, at Wet Cave (29 mg L^{-1}) and Marakoopa (12 mg L^{-1}) in drought were probably due to streambed sediment disturbance and/or colloidal calcite. Parsons was highest in suspended solids in first flush, when dissolved solids were lowest. The highest reading for dissolved solids, at Upper Lobster in base flow (494 mg L^{-1}), was probably due to analytical error. Scotts Rising otherwise carried the highest dissolved solids throughout, its drought reading being the second highest (337 mg L^{-1}). Charge balance calculations were of little utility in data evaluation. Metals, particularly silicon, and anions untested by ICP-MS resulted in substantial negative and positive imbalances. The inclusion of Cl^- in one of the equations was of little effect.

The ICP-MS results for the flow stages are shown in Table 3 (See Appendix 1 & Table 2). Alkali metals and alkali/alkaline earth metals ratios for flow stages are shown in Figure 7.

Ca/Mg and (Ca+Mg)/(Na+ K) ratios are important in helping distinguish karst ground water from other sources. The large phreatic spring, Scotts Rising, consistently had higher values than other sites in both ratios,

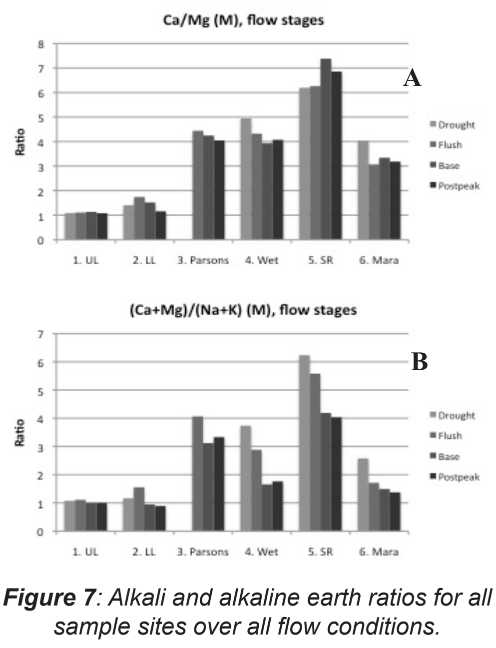


***Figure 7**: Alkali and alkaline earth ratios for all sample sites over all flow conditions.*

explained by long residence time in the aquatic $CaCO_3$/H_2O/CO_2 system. Fluctuating ratios at the other sites are consistent with origins of the water. Upper Lobster varies little, the karst sites Parsons Spring, Wet Cave and Scotts Rising are consistently high, and Marakoopa, with its steep hydraulic gradient and short throughflow time, has the lowest values of the karst water sources. Lower and Upper Lobster had similarly low drought (Ca+Mg)/(Na+K) ratios. The ratio was higher at Lower Lobster in the flush but higher at Upper Lobster in base and post-peak flows. All Ca/Mg ratios at Lower Lobster were higher than for the corresponding period at Upper Lobster.

All sites were highest in major limestone element concentrations in drought, declining with each sampling, excepting for Lower Lobster, highest in flush. Given the corresponding relatively high alkalinity and pH, inconsistent with that of Upper Lobster, it is suggested that a karst aquifer outlet discharges into the Lower Lobster stream bed with the first seasonal rains until winter surface flow is established from upstream.

Substantial epikarst storage is inferred for Parsons Spring and Wet Cave, whose (Ca+Mg)/(Na+K) ratios increase again with post-peak conditions. Wet Cave's Ca/Mg ratio also increases, however calcium was probably precipitating in the system at Parsons and upon efflux, either due to supersaturation with calcite or common ion effect from high solute load in the epikarst.

It is reasonable that the relatively immobile multivalent metals and phosphorus should be lowest in concentration during drought. Conduits store sediments, which can adsorb cations, particularly the more immobile elements. The substantially higher concentrations at Lower Lobster and Parsons in post-peak flow than other sites suggest a land use signal as recharge arrives from the cultivated wider catchment. Parsons' particularly strong signal in these metals in flush flow adds support for the presence of a substantial subcutaneous aquifer.

Parsons Spring's and Marakoopa Cave's storm response discharge, temperatures, wet chemistry results, alkali and alkali/alkaline earth metals ratios, ICP-MS results and Al, Ti and Zr chemographs are shown in Tables 4 and 5 and Figures 8 and 9. Light rain showers fell across the escarpment from 9.30 and cleared by noon, before heavier rain set in at 1.30 pm. Skies cleared across the escarpment by 4.20 pm and remained clear. Note that measurements and sampling commenced after Marakoopa's response began.

A pulsating discharge can be observed in the storm response at Marakoopa, from response to the earlier showers, the break in the precipitation, then the heavier rainstorm, with little lag in peak and recession. The discharge response is reflected in the dissolved solids load peaking with the recession of the first discharge peak. Little epikarst storage is evident. In contrast, Parsons Spring's dissolved and suspended solids load is still increasing, and following the recession of the distinct peak, the discharge is sustained. The initial temperature and alkalinity decline at Parsons ahead of the discharge peak suggests an initial invasion of a pulse from the Lobster, displacing water that had equilibrated with the host rock. Temperature and wet chemistry measurements suggest the spring's discharge towards the peak was then replaced by karst aquifer water. Following the heavier rain, Ti, Al and Zr concentrations rose, probably released from adsorption on sediments stored in the Spring's trunk aquifer conduits, then these concentrations decline again as pH rises substantially and discharge rises modestly, probably representing the arrival of epikarst water. Ti, Al and Zr concentrations are much lower and less variable at Marakoopa. In the chemographs of Ca/Mg and (Ca+Mg)/(Na+K) ratios, Parsons Spring has higher values overall, indicating a substantial karst aquifer influence. Marakoopa's ratios decline until the rapid vadose storm flow subsides, while the increasing contribution of epikarst water at Parsons is apparent from the rising Ca/Mg. Further, compared to Marakoopa, the sustained discharge at Parsons indicates the relatively large areal extent of the recharge zone. Suspended solids continue to increase at Parsons while declining at Marakoopa. It is suggested the 1.30 pm rainstorm activated the distal reaches of Parsons recharge zone, sending sediments through the system, lowering temperature and raising pH and Ca/Mg, accompanied by a sustained, modestly increased discharge, limited by epikarst porosity.

Coefficients of determination were calculated from linear regressions of ppb concentrations in the selected element groups (metals and P, limestone, dolerite and "highly variable" elements) between the reference and study springs and other sites. These relationships were examined for any indications of vadose quickflow and flushed aquifer storage water (similar to base flow) (Table 5). Being chemically aggressive, as the water has little time in contact with limestone, quickflow can potentially mobilize metals and phosphorus. Marakoopa's apparent lack of any substantial storage aquifer, indicated by rapid discharge response and subsequent recession behaviour with showers, provided useful contrast in identifying possible compartments of Parsons Spring's aquifer. Of the most significant of these relationships (R2>0.950; p<0.001), the storm response/post-peak relationships were the most informative.

For Marakoopa, the relative proportions of elements in all the tested groups were strongly related to those of the other vadose cave site, Wet Cave. Results were inconclusive for relationships with the waters of other sites.

Parsons Spring had strong relationships with Lower Lobster for the metals and P group, with Scotts Rising for the limestone and dolerite groups and with Wet Cave for the highly variable element group (Ca, Mg, S, Sr, B and Sc). It is suggested Parsons and Lower Lobster share a recharge zone or system that mobilises elements of the metals and P group; Parsons and Scotts share the signs of limestone and dolerite weathering in their systems, while Parsons relationship with Wet Cave for the variable element group suggests their recharge zone overlaps.

Throughout the storm response, Marakoopa most strongly related with the first sample from Parsons' storm response, excepting for the metals and P group, for which Parsons' discharge peak sample best relates with

Table 4: *Results from wet chemistry for the two springs' storm response. Alkalinity is expressed in mg $CaCO_3$ L^{-1} and suspended and dissolved solids are expressed in mg L^{-1}.*

Parsons'						
Time	Sample	pH	Temp °C	Alk	DS	SS
11.37 am	I	6.94	9	34	85	8
1.55 pm	J	6.9	8	32	56	2
3.5 pm	K	6.9	8.5	34	49	0
6.05 pm	L	6.88	9	33	67	0
7.52 am	3	6.93	8	36	80	41
Marakoopa						
Time	Sample	pH	Temp °C	Alk	DS	SS
10.15 am	B	6.68	7.7	34	104	0
10.39 am	C	6.7	7.7	35	63	0
11.43 am	D	6.74	7.6	34	85	0
12.45 pm	E	6.78	7.7	32	173	0
2.43 pm	F	6.77	7.7	33	104	5
4.25 pm	G	6.82	7.5	28	93	0
5.25 pm	H	6.85	7.6	32	66	36
8.50 am	6	6.86	7.1	31	71	5

Table 5: *Results of ICP-MS analyses for the two springs' storm response (ppb).*

Marakoopa	B	D	E	G	6
	10.15 am	11.43 am	12.45 pm	4.25 pm	8.50 am
Ca	10044	10093	8874	8581	9153
Na	4487	4513	4415	4412	4411
Mg	1699	1686	1658	1634	1679
S	984	954	916	916	972
K	388	420	373	494	354
Al	61	61	55	62	45
Fe	36	34	33	37	30
Sr	33	33	31	30	31
Ba	10	10	9	9	9
B	4	4	4	4	4
Mn	1	1	1	1	0
Zn	1	2	1	4	1
Ti	1	1	1	1	1
P	2	1	2	2	2
Rb	0	0	0	0	0
Ni	0	1	0	1	0
V	0	0	0	0	0
Cr	1	1	0	0	0
Cu	0	1	0	2	1
As	0	0	0	0	0
Sc	0	0	0	0	0
Co	0	0	0	0	0
Zr	0	0	0	0	0
Parsons	**I**	**J**	**K**	**L**	**3**
	11.37 am	1.55 pm	3.50 pm	6.05 pm	7.52 am
Ca	9139	9030	9164	9282	10090
Na	1929	1857	1873	1841	2003
Mg	1392	1374	1378	1390	1445
S	333	315	321	307	342
K	240	183	209	255	271
Al	290	257	288	322	220
Fe	212	194	210	249	174
Sr	15	15	15	15	16
Ba	5	5	5	6	5
B	2	2	2	2	2
Mn	9	8	9	10	7
Zn	5	2	2	4	2
Ti	9	5	6	8	5
P	4	3	4	5	2
Rb	1	1	1	1	1
Ni	1	0	0	1	1
V	1	1	1	1	1
Cr	1	1	1	1	1
Cu	1	1	1	1	1
As	0	0	0	0	0
Sc	0	0	0	0	0
Co	0	0	0	0	0
Zr	0	0	0	0	0

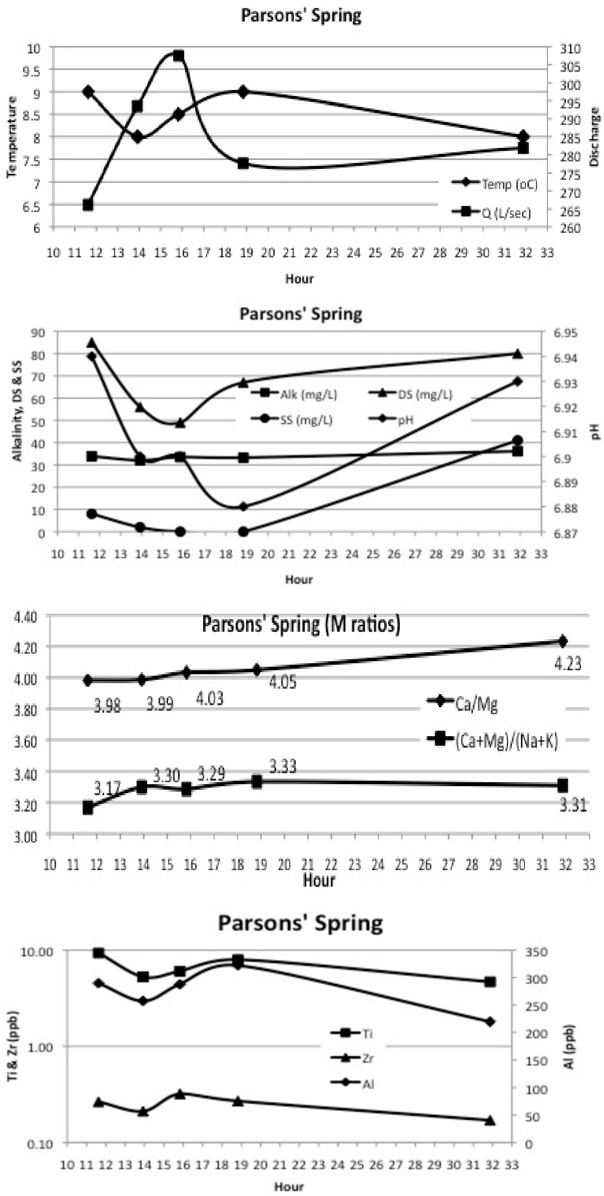


***Figure 8:** Parsons Spring storm response hydrograph and chemographs.*

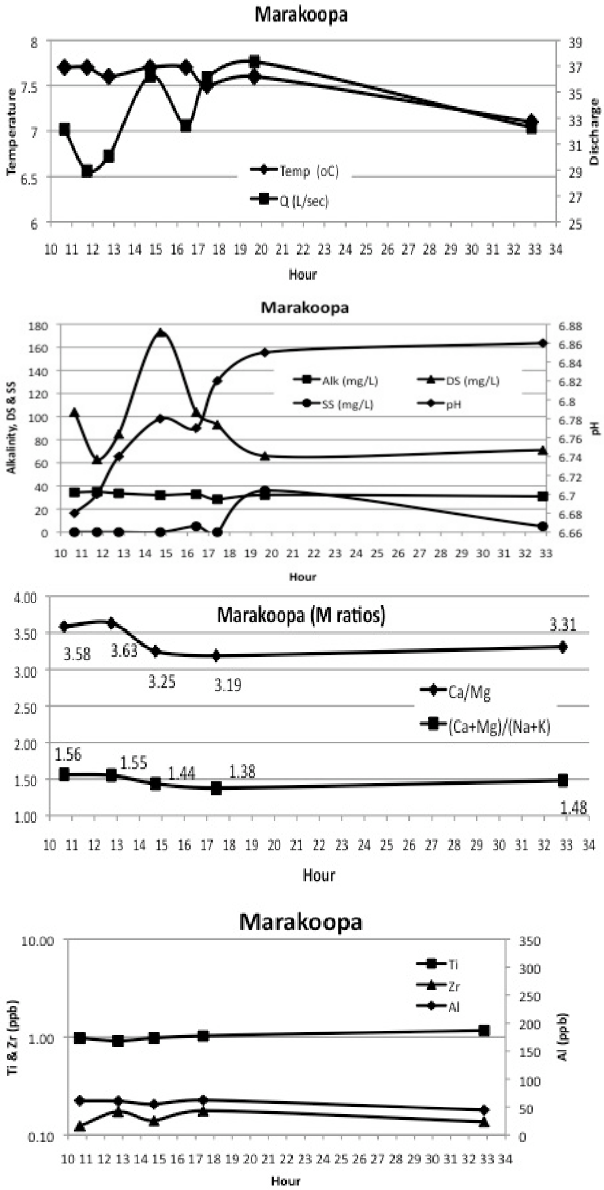


***Figure 9:** Marakoopa Cave storm response hydrograph and chemographs.*

Marakoopa's samples. The data set suggests Parsons Spring does not initially transmit water of long residence time during a rainstorm. The implication is that at least one quickflow route operates at Parsons during storms, flushing the relatively easily mobilized elements from the soluble, crystalline aquifer host rock and weathering allogenic sediments. Marakoopa's first pulse discharge is most like Parsons' waters with respect to the host rock and escarpment sediments. As suggested by the sustained post-peak discharge and alkalinity, falling temperature and rising pH, dissolved solids and suspended solids, Parsons sustained recharge is largely drawn from a subcutaneous aquifer farther afield (Figs 8 and 9).

Conclusions

Measurements of chemical and physical parameters across flow conditions and through spring storm responses provide valuable information on the nature of karst aquifers and their recharge zones. Long term familiarity with the local hydrology and local residency allowed best use of limited research time and resources. Further sampling and statistical analyses over a period of years would give more reliable information.

Parsons Spring probably drains a complex mixed recharge karst aquifer. It is considered that catchment extent across the escarpment and recharge regimes are variable, and flow routes and direction are anisotropic, varying between rainstorms and seasons. It is considered a perched epikarst reservoir maintains base flow in Parsons Spring, and a shallow valley water table in proximity to the hillslopes invokes an overflow threshold behaviour in the Spring. The existence of other small episodic springs suggests a distributary spring system exists, of which Parsons Spring is the main outlet. The Spring appears to operate as an estavelle, with invasion of water from the Lobster Rivulet during initial storm response.

Parsons Spring's recharge and hydrology may be compromised by anthropogenic influence. The recent change from perennial to intermittent discharge of Parsons Spring may be due to blockage of vadose conduits of the epikarst and/or conduits beneath it, changed flow routes and increased pumping from the phreatic aquifer. Reductions in aquifer recharge are reasonably expected by 2023 as plantations age. Compromise of sensitive hydrological processes coupled with climate change probably pose economic risks for the rural community and risks to aquatic ecosystems.

In order to enable improved management of the available resource, it is recommended that further research defining the recharge zones and flow regimes of the aquifer be conducted so that an investigation of the sustainable yield of the Lobster Rivulet basin karst aquifer can be carried out. It is essential appropriate modeling be applied, for example in the 2009 formal assessment of the Mersey-Forth catchment in the Tasmanian Sustainable Yields (TasSY) Project (CSIRO, 2008).

In order to optimize aquifer resilience in the face of likely climate change, catchment management prescriptions could be revised. This work could form the basis of a solution, the aim of which is the sustainable water supply for both the community and the karst ecology.

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Debbie Hunter at Karstaway Konference. Photo: B. Downes

Appendix 1 Table 3: *Results from ICP-MS analyses for flow stages (ppb).*

Drought

	1. UL	2. LL	3. Parsons	4. Wet	5. SR	6. Mara
Ca	2962	3739		22523	44711	16265
Na	2885	2932		3863	4425	4240
Mg	1652	1612		2760	4377	2443
S	516	538		1053	1370	722
K	254	364		494	595	472
Al	8	25		10	3	24
Fe	22	63		7	3	14
Sr	10	12		48	85	42
Ba	2	2		14	22	10
B	3	3		4	5	4
Mn	0	1		0	0	0
Zn	1	0		0	2	1
Ti	0	0		0	0	1
P	1	2		2	1	1
Rb	0	0		1	1	0
Ni	0	0		0	0	0
V	0	0		0	0	0
Cr	0	0		0	0	0
Cu	0	1		0	0	0
As	0	0		0	0	0
Sc	0	0		0	0	0
Co	0	0		0	0	0
Zr	0	0		0	0	0

Flush

	1. UL	2. LL	3. Parsons	4. Wet	5. SR	6. Mara
Ca	2620	6257	15460	16780	39523	10121
Na	2416	3428	2471	3839	4357	4243
Mg	1435	2175	2111	2354	3827	1999
S	344	1095	510	1045	1310	670
K	273	350	341	469	603	424
Al	47	48	370	51	133	87
Fe	52	73	232	64	97	56
Sr	9	17	21	39	76	27
Ba	2	3	7	12	20	7
B	3	4	4	6	5	5
Mn	2	9	8	2	5	51
Zn	1	1	4	1	4	1
Ti	1	1	8	2	58	2
P	1	50	8	7	5	4
Rb	0	1	1	1	1	0
Ni	1	1	1	1	1	1
V	0	1	1	0	0	0
Cr	1	0	1	0	1	1
Cu	0	1	1	0	1	0
As	0	0	0	0	0	0
Sc	0	0	0	0	2	0
Co	0	0	0	0	0	0
Zr	0	0	0	0	0	0

Base

	1. UL	2. LL	3. Parsons	4. Wet	5. SR	6. Mara
Ca	908	3886	11154	10352	31423	11447
Na	2978	3725	2399	4287	4467	5477
Mg1	560	1553	1592	1597	2582	2077
S	501	786	392	1018	1176	1072
K	269	310	228	353	712	409
Al	93	118	96	89	59	67
Fe	61	76	52	52	39	36
Sr	14	21	21	35	79	43
Ba	3	5	5	11	19	12
B	4	5	4	6	6	6
Mn	1	3	2	1	3	1
Zn	3	2	4	3	15	5
Ti	2	2	1	2	3	1
P	1	2	3	4	10	3
Rb	1	1	0	1	1	1
Ni	2	1	3	4	15	5
V	1	1	0	0	0	0
Cr	1	0	1	0	0	1
Cu	1	1	1	1	3	1
As	0	0	0	0	0	0
Sc	0	0	0	0	0	0
Co	0	0	0	0	0	0
Zr	0	0	0	0	0	0

Post peak

	1. UL	2. LL	3. Parsons	4. Wet	5. SR	6. Mara
Ca	2036	2187	9282	8186	21911	8581
Na	2123	2436	1841	3079	3310	4412
Mg	1143	1145	1390	1218	1938	1634
S	294	372	307	762	884	916
K	213	314	255	399	439	494
Al	87	132	322	51	50	62
Fe	65	96	249	37	61	37
Sr	8	10	15	24	48	30
Ba	2	3	6	7	12	9
B	2	3	2	3	4	4
Mn	1	2	10	1	3	1
Zn	1	2	4	1	3	4
Ti	1	3	8	2	1	1
P	23	3	5	2	2	2
Rb	0	0	1	0	1	0
Ni	0	1	1	0	1	1
V	0	1	1	0	0	0
Cr	0	1	1	0	0	0
Cu	0	1	1	0	1	2
As	0	0	0	0	0	0
Sc	0	0	0	0	0	0
Co	0	0	0	0	0	0
Zr	0	0	0	0	0	0