Waterways
Centre for Freshwater Management

Fluctuations in the flow of artesian springs in Christchurch

Summer Scholarship Report

WCFM Report 2016-003

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REPORT: WCFM Report 2016-003

TITLE: **Fluctuations in the flow of artesian springs in Christchurch**

Research Report

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Executive Summary

The purpose of this study was to conduct a preliminary investigation of flow and water quality variability in a number of artesian springs around Christchurch City. Spring dynamics provide an important insight into the nature and state of the shallow aquifer beneath and immediately to the west of Christchurch city. The flow and quality of these springs also affects that of spring-fed streams and rivers flowing through urban Christchurch.

This research was initially designed to monitor springs only over the months of summer (November to February) in 2014/15. However, flow monitoring for some springs was extended through to August 2015, and even to July 2016 for the Ilam Garden springs, after it became apparent that low rainfall in 2015 could be having significant consequences for spring flow.

Initially, flow and water quality measurements were taken weekly from six springs, from 18th November 2014 until the 13th February 2015. The springs were at;

- Redwoods in Belfast (mean summer flow = 14.5 L/sec)
- Ngaio Marsh in Papanui (0.81 L/sec)
- Jellie Park in Ilam (0.03 L/sec)
- Ilam Gardens (2 springs) in Ilam (spring A =5.0 L/sec, spring B = 2.8 L/sec)
- Knights Reserve in Halswell (0.59 L/sec)

All except Redwood Springs and Ngaio March springs stopped flowing over summer; Knights Reserve spring in mid-December, Jellie Park spring in mid-January and both Ilam Garden springs in early February. The (lack of) flow in these springs was then monitored weekly until the 26th of August 2015, and during this time none of the springs resumed flow. Thereafter Ilam Garden Springs were monitored fortnightly through to 13 July 2016, and remained dry throughout this period. This was in contrast to the previous 4 years, when university fieldtrips to the Ilam Garden Springs had consistently observed flows resuming late August/early September.

The relationships between spring flow, water quality and groundwater levels in local wells, (as monitored by Environment Canterbury) have been analysed. Loss of spring flow during summer in springs in the central and south urban area appears to be a regular response to seasonal loss of artesian pressure in the shallow confined aquifer (20-35m depth) likely to be feeding the springs. In the north of the urban area, closer to the Waimakariri River and the recharge this provides to the shallow aquifer in this area, artesian pressure did not drop significantly over summer. Consequently, spring flow was maintained throughout the summer monitoring period.

The most unusual event captured in this monitoring was that spring flow failed to resume at Ilam Garden springs in August/September 2015, or at any time while monitoring continued (until July 2016). Lack of spring flow in the headwaters of the urban streams and rivers led

to pronounced dry reaches and lower than normal stream flows throughout summer and autumn of 2015/16. In a groundwater well close to Ilam Garden springs, the water level had dropped to a level at or near the lowest ever recorded by winter 2015. We conclude that there was insufficient winter rainfall recharge in 2015 to recharge the aquifer where it is unconfined to the west of the urban area. This reduced the artesian pressure in the confined aquifer feeding the urban springs, leading to low groundwater well levels that have persisted through to winter 2016 and lack of spring flow.

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Section 1 Introduction

Since its inception in 2010, the Waterways Centre for Freshwater Management has been including visits to Christchurch artesian springs as part of a fieldtrip for a 2nd year undergraduate class in water resource management. The fieldtrips normally fall in late August or early September of each year, and highly variable flows conditions in some springs had been observed, both between the months of August and September, and from year-to-year. In particular, two springs in Ilam Gardens (on the south side of the University of Canterbury's sports fields), were consistently observed to be dry in mid-August but flowing strongly in September, when visited throughout 2011 – 2014. There appeared to be little information available on when such springs commenced and ceased flowing each year, and how their flow and water quality might be affected by climate and urban development.

A summer scholarship research project was therefore set up to determine the degree of short term variability in flow and water quality in artesian springs located in the Christchurch area, and whether this was related to fluctuations in groundwater well levels, water use in the wider Canterbury region and/or urban construction projects. This project was planned as an initial 3 month investigation, but was extended when it became apparent that unusually dry climate conditions (beyond normal seasonal variability) may also be affecting spring flow.

1.1 Christchurch Geomorphology

The Canterbury plains are one of New Zealand's largest regions of flat land, around 160km long and 60km wide, extending from the foothills of the Southern Alps to the Pacific Ocean. The plains formed as a result of overlapping gravel-based alluvial fans from glacier-fed rivers, during the late Quaternary when rapid uplift in the Southern Alps resulted in an inundation of alluvial and fluvial deposits and extension of the land mass to the east (Brown, 2001). During the latest Pleistocene and Holocene, the sea level rose to its current level, from approximately 150 m lower than present. The current sea level has remained constant for around 6,500 years, but at one point was located 14km west of its present location. Swamp, estuarine, lagoon and beach deposits are therefore interlayered with the alluvial gravel deposits. Christchurch city is located on this floodplain, atop old river channels of the Waimakariri River, and hosts two spring-fed rivers, the Avon and Heathcote River (Cubrinovski et al., 2011).

The original source of the groundwater beneath Christchurch city is mainly rainfall in the Southern Alps, which recharges both the Waimakariri River and the deep groundwater system beneath the Canterbury plains. The groundwater system developed within the permeable gravel stratigraphy of the plains is mainly comprised unconfined aquifers.

However, between the western edge of Christchurch city and the coast, confining, impermeable, marine and swamp sediments are interlayered with the alluvial gravels forming a layered structure of confined aquifers. Artesian springs occur near the unconfined/confined aquifer boundary, are likely sourced from the shallowest confined aquifer and contribute to the headwaters of the Avon, Heathcote, Styx and Halswell Rivers (Brown, 2001).

Environment Canterbury (Canterbury's regional council, or "ECan") maintains an online spring database (http://canterburymaps.govt.nz), which provides the location of over 1500 springs in the region; approximately 50 within the urban area of Christchurch (Fig 1). These urban springs fall mainly near, or to the east of, a line drawn between Belfast and Lincoln. Many also occur around the northern and western base of the Port Hills where aquifers encounter the less permeable volcanic rocks and rise to the surface (Earl, 1998). However, many urban springs are now capped, or flows diverted via underground pipes and culverts into urban waterways, and so are not visible or accessible.

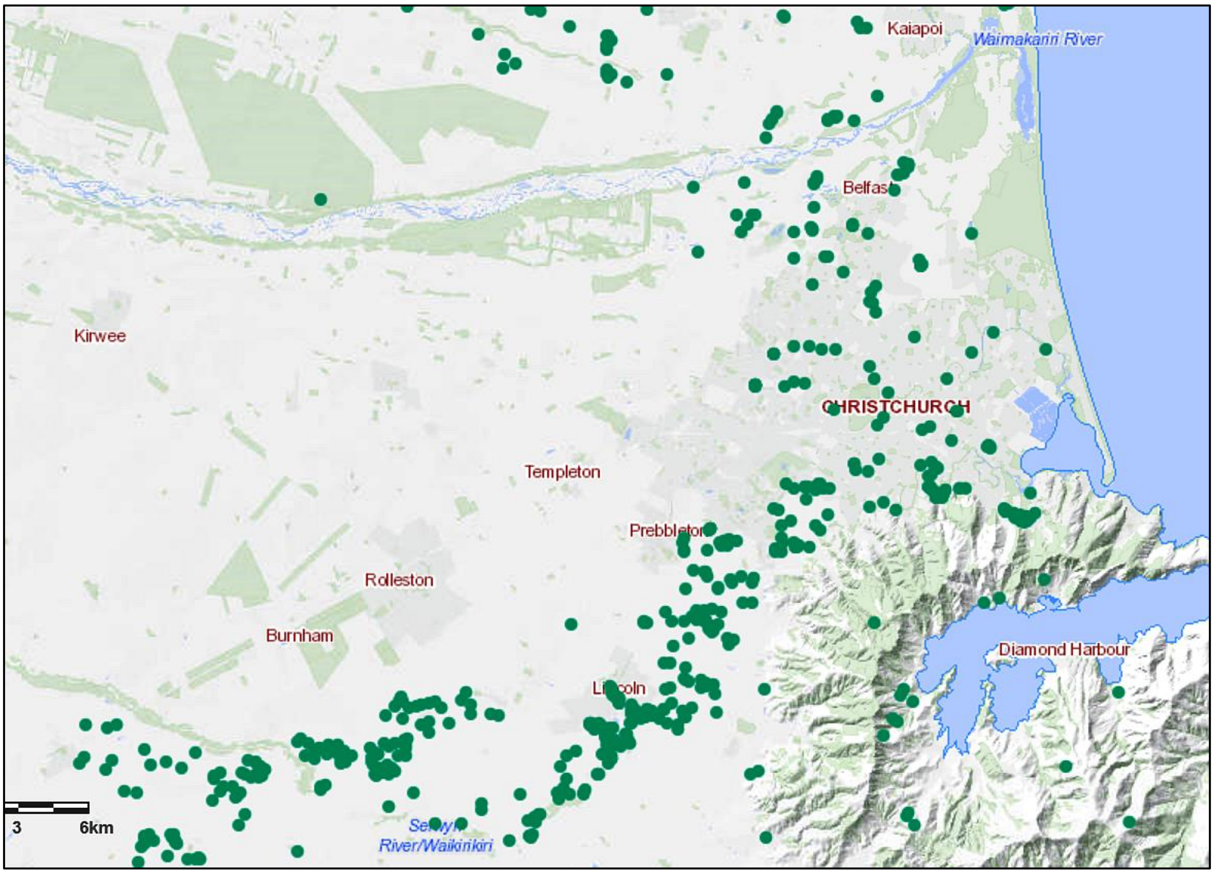


Figure 1. Known spring locations in Christchurch and the surrounding areas (from ECan data, provided at http://canterburymaps.govt.nz).

1.2 Urban aquifer characteristics

Recharge to the confined aquifers beneath Christchurch comes via seepage through the base of the Waimakariri River, from deeply circulating groundwaters and, in the shallowest aquifer, from rainfall immediately to the west of the city where the aquifer is unconfined (Hayward, 2002; Stewart et al., 2012). The proportion of each source of recharge varies for different regions of the city, and different depths in the aquifer system (Fig 2). Low rates of rainfall recharge or the construction of impermeable surfaces over the unconfined aquifer, or excessive water extraction from shallow wells, all have the potential to reduce the volume of the shallowest aquifer. This in turn reduces the artesian pressure and the force of the water moving upwards to form a spring (Cameron, 1992).

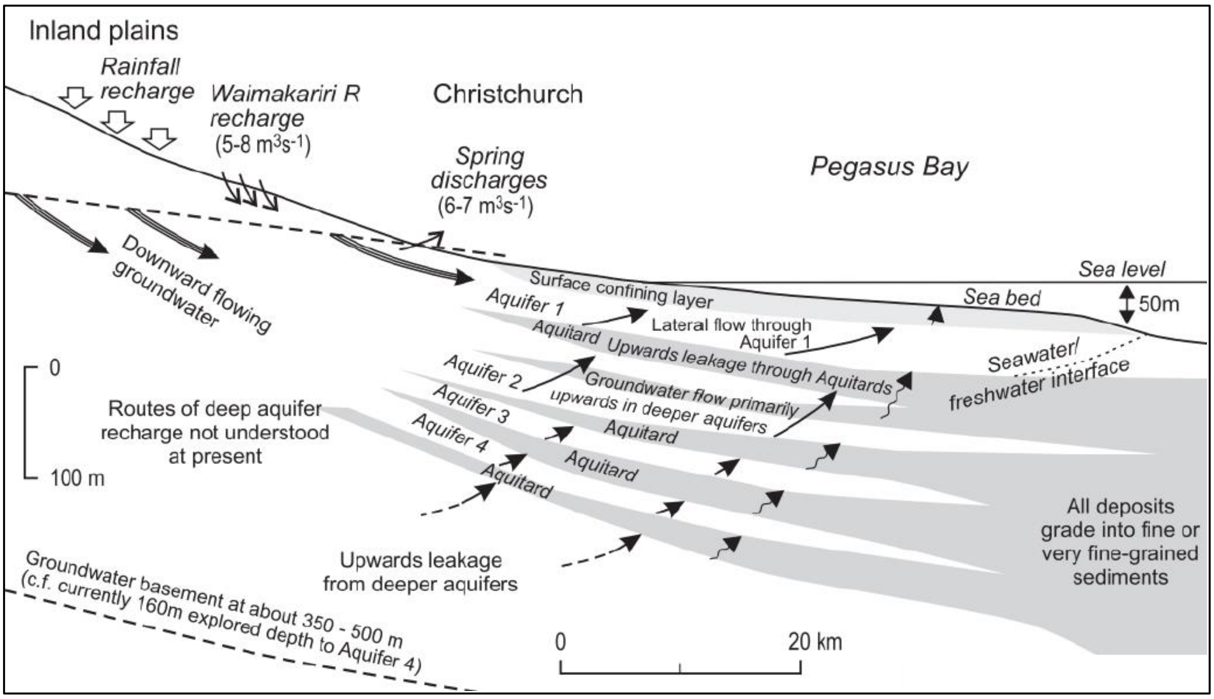


Figure 2. Recharge of the aquifers beneath Christchurch City, after Stewart et al., 2012.

Groundwater is pumped directly from wells that tap (mainly deep) confined aquifers beneath the city and is used (untreated) for drinking water and domestic use, as well as for municipal and industrial purposes. Deep groundwater has passed through an extensive geological "sieve" of alluvial gravels, which can retard and retain sediment and many contaminants, and is largely protected from contamination by confining marine sediment layers, and an upward water movement.

The quality of artesian spring water, sourced from the shallow aquifers in the city can shed light on aquifer and spring dynamics. Basic parameters such as conductivity and temperature, for example, can be used to track changes in water sources and identify pathways by which contaminants could enter the shallow aquifer system. These may include

infiltration into the unconfined aquifer to the west of the main urban area of Christchurch, or even surface water flowing back down spring vents when they are not flowing (as observed for a spring in this study).

1.3 Research Aims

The aim of this research project was to quantify short term flow patterns for selected artesian springs in Christchurch, and to make an initial assessment of the relationship with rainfall recharge, shallow aquifer well levels and water use in the wider Canterbury region.

Section 2 Methods

Table 1 Spring location and monitoring periods in 2014 - 2016.

Location	Monitoring period
Redwoods Springs, Belfast	November 2014 – February 2015
Ngaio Marsh spring, Papanui	November 2014 – February 2015
Jellie Park spring, Ilam	November 2014 – August 2015
Knights Reserve spring, Halswell	November 2014 – August 2015
Ilam A spring, Ilam Gardens	November 2014 – July 2016
Ilam B spring, Ilam Gardens	November 2014 – July 2016

2.1 Sampling Sites

Spring flow and water quality samples were collected from six springs in Christchurch city (as described in Table 1, located on Fig 3 and shown in Fig 4). The springs sites were chosen to be representative and accessible examples of the urban springs, with a reliable flow based on Environment Canterbury's spring database and (at least) anecdotal evidence of past flow conditions. A number of sites were visited before sampling began to check accessibility and to ensure that the springs selected for the study were not directly influenced by human activity (e.g., engineering projects and storm water interactions). Redwood Springs and Ngaio Marsh springs were monitored for a 10 week period, from December to February, while the remainder of the springs were continually monitored until mid-August 2015, with the Ilam Garden springs continually monitored until July 2016.

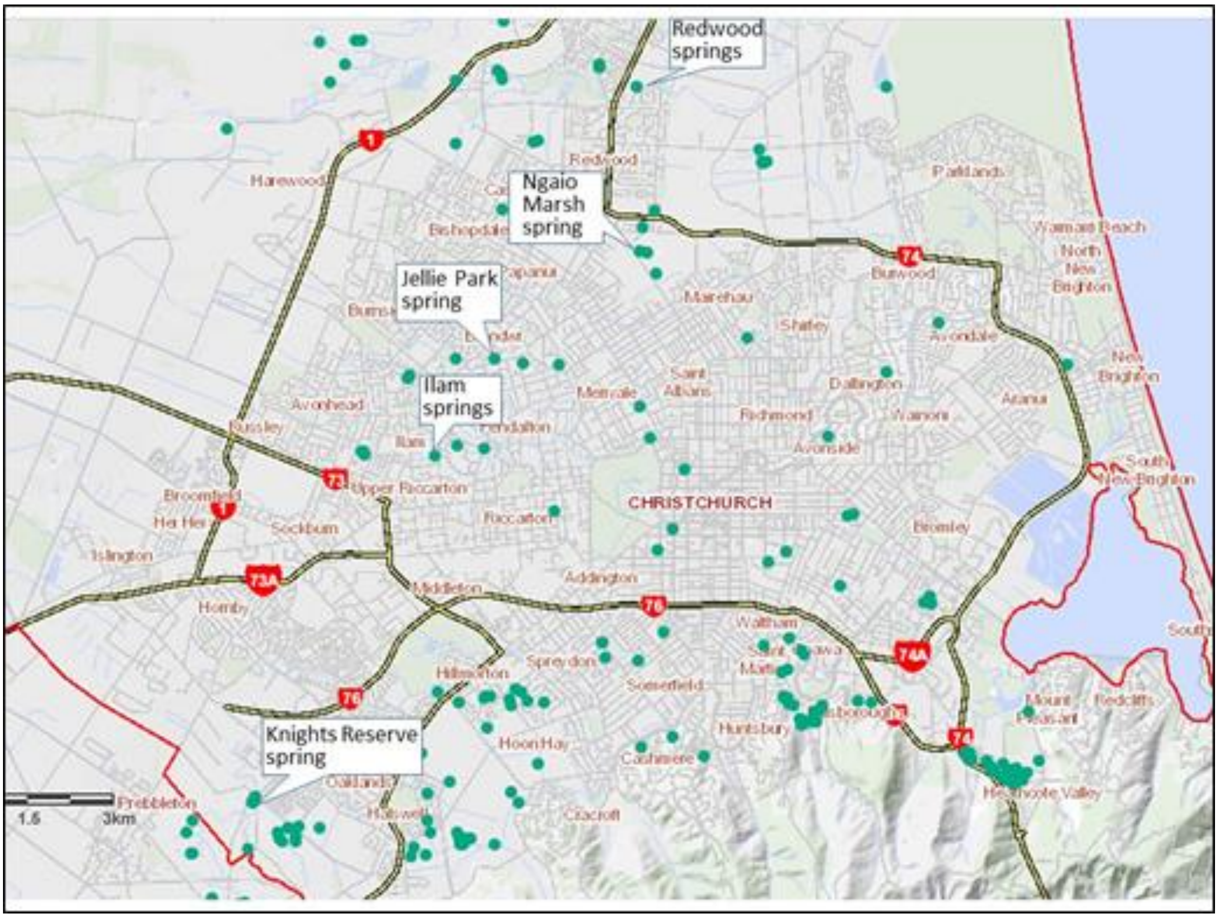


Figure 3. Locations of springs sampled in Christchurch city (refer also Table 1).

2.2 Flow Monitoring

Flow monitoring began at the two Ilam springs on the 18th of November, then at the four other sites on the 2nd of December, and was undertaken weekly or fortnightly until 13th February. Knights Reserve spring, both of the Ilam springs, and Jellie Park spring were then visited weekly from the end of the summer monitoring programme on the 13th of February until the 25th of August 2015, and Ilam springs monthly until July 2016.

Spring flow is difficult to measure using standard stream flow measurement techniques, due to low water velocity and shallow water depth. Often there is also no well-defined channel draining the spring. Therefore, two alternative flow measurement techniques were used;

- For those springs where spring water poured as if from a spout (i.e., all except Redwood Springs), the water was captured in suitable guttering and pipes and collected in a container of known volume. The time taken to fill the container was recorded, with container volumes ranging from a 9 L bucket for Ilam Garden springs, to a 1.25 L flask for the smaller flow from Ngaio Marsh springs. This method was modified slightly at Jellie Park where the volume from this small spring was measured over a 20 second period.

a)

b)

c)

d)

e)

Figure 4. Spring images taken while flowing; a) Redwoods Springs, b) Ngaio Marsh spring, c) Jellie Park spring , d) Ilam Garden A spring and e) Ilam Garden B spring.

- For Redwood Springs, where the springs had ponded and were underwater, the outflow of the pond was guided into a plastic channel of known volume, the flow timed along the length of the channel.

In all cases, a stop watch was used to record the time, and each flow measurement was repeated three times and an average taken.

2.3 Water Quality Measurement

Water quality measurements were conducted *in situ* using a HACH water meter. Dissolved oxygen (DO), pH, conductivity (µS/cm), and temperature were recorded for each site. Water samples were collected in a clean flask and then immediately tested using the HACH water meter's probes. DO was recorded immediately (and if possible directly in the spring) before oxygenation of the water in the air could occur. Each variable was measured three times. No samples were taken for later laboratory analysis.

2.4 Additional data used during analysis

Data was obtained from Environment Canterbury (ECan 2015, 2016a) for monthly aquifer water level levels in wells strategically located near to the study springs, and for daily Waimakariri river flow measurements. Daily and monthly average rainfall data for Christchurch Airport (identified as "Christchurch Aero", station 4843) was accessed from the NIWA CliFlo database (http://cliflo.niwa.co.nz/).

With Shane Orchard, a PhD candidate at the University of Canterbury, a spring system in Belfast was also investigated as part of this study. The system consists of a series of springs issuing from vents on a farm, and flows into box drains, making it simple to measure flow. This spring data is not reported here, but has been used by Shane Orchard in a report on the use of wetlands in land resource management.

Section 3 Results

The amount of flow data collected for the six spring sites depended on the duration of flow over the summer monitoring period. Some springs ceased to flow in January or February, and no further data was collected from these sites.

3.1 Water Flow

Flow range and mean data for the summer period during which a flow occurred at the spring, are shown in Table 2. Flow variation with time for the same period is shown in Figure 5, where considerable variability in flow is evident.

Table 2. Mean and range of summer flow (L/sec) in springs, for the period between 18 November 2014 and 13 February 2015 for which flow was present for the spring.

Spring	*n*	Mean Flow	Flow range	Flow had ceased by …
Redwood Springs	*10*	14.5	8.4-20.6	Ongoing at 13 Feb 2015
Ngaio Marsh	*10*	0.81	0.50-1.20	Ongoing at 13 Feb 2015
Jellie Park	*5*	0.03	0.004-0.04	23 Jan 2015
Ilam Garden A	*10*	5.0	3.1-8.7	13 Feb 2015
Ilam Garden B	*10*	2.8	1.6-3.3	13 Feb 2015
Knights Reserve	*3*	0.59	0.31-1.1	19 Dec 2014

The highest flow was observed at the northern most springs, Redwood Springs, with a mean flow more than twice that of the next largest springs (Ilam A and Ilam B). Mean flows of < 1 L/sec were observed in the other springs. The last monitoring date for the main study was 13th of February 2015, and both Redwoods and Ngaio Marsh springs were still flowing strongly at this time. Both springs had increased flow from mid-January through to early February

The other springs, however, ceased to flow prior to the 13th of February 2015. In the two Ilam Garden springs, flow rates decreased until the end of December, after which they increased from mid-January until the 2nd February. The springs then stopped flowing altogether sometime before the 13thFebruary. Knights Reserve spring showed a similar decline in December, and stopped flowing before the 19th December. The small flow at Jellie Park spring also ceased in the week before 19th December, but resumed briefly in January, at approximately half of the previous flow rate, before ceasing in the week before 23rd January. Thereafter, none of these springs resumed flow during the extended period of monitoring up to 26 August 2015.

Interestingly, after Knights Reserve spring had ceased to flow, a reverse flow of surface water into the spring was observed. This was observed in January and after a brief rainfall event (significant enough to form a stormwater flow) in April.

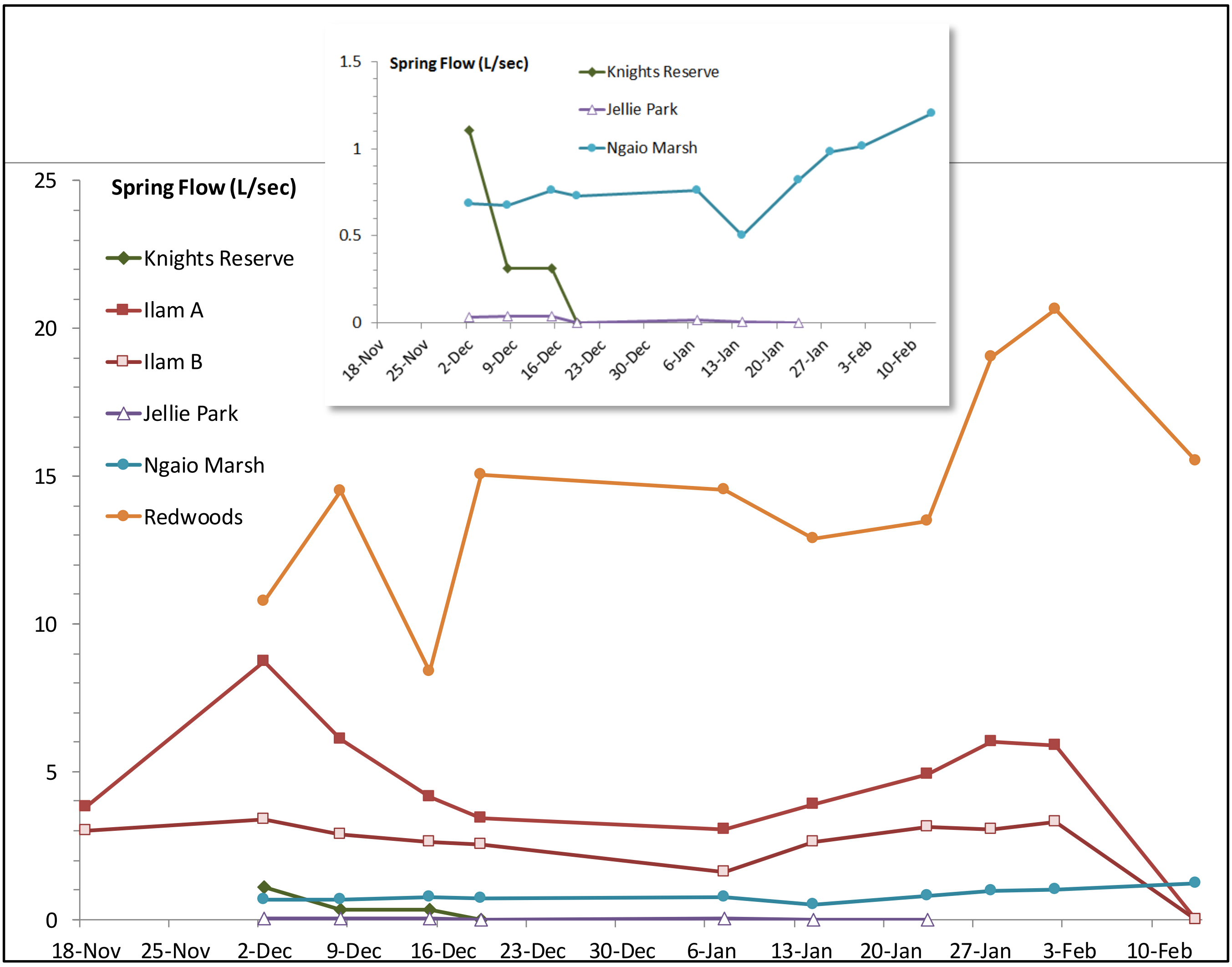


Figure 5. Summer flow rates for each spring from the 18th of November 2014 to the 13th of February 2015. Inset shows flows for smaller springs in greater detail.

3.2 Water Quality

3.2.1 Temperature

Figure 6 shows temperatures for each spring over the summer monitoring programme. Mean spring water temperatures ranged from 13.0°C at Knights Reserve to 14.6°C at Jellie Park. Redwood Springs had the most consistent temperature profile, likely reflecting the ponding of water at the spring, which allows time for mixing and for air temperature to

affect the spring water. All of the persistent springs appeared to show temperature minima in mid-December, and in mid-January, recording their highest temperatures in late December- early January.

All spring data was used to test for a correlation between flow and water quality variables. No relationship was observed between flow and temperature.

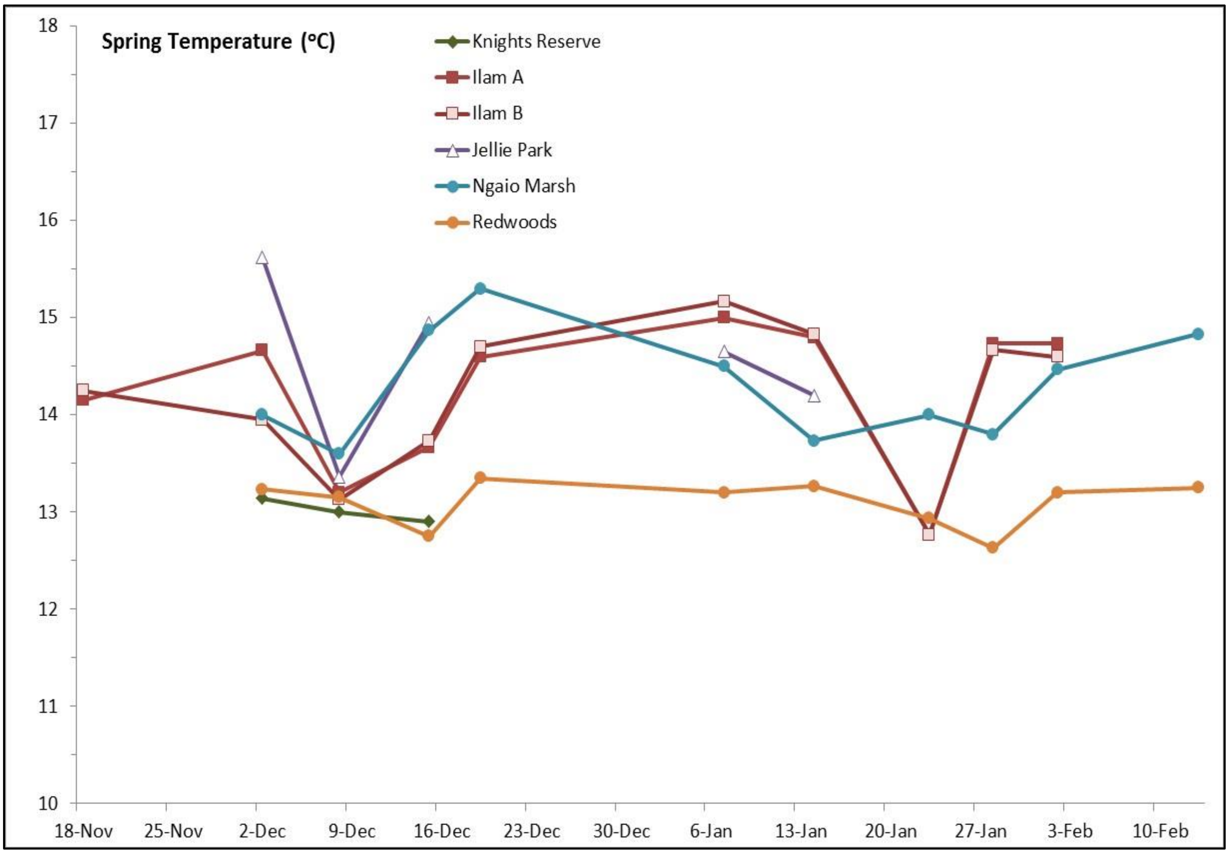


Figure 6 Spring temperatures from the 18th November 2014 to the 13th February 2015.

3.2.2 Conductivity

Conductivity decreased relatively consistently over most of the summer monitoring period (Fig 7a), with the exception of a mid-January spike of higher conductivity observed at all flowing springs, except Redwood Springs. The northern-most springs (Redwood Springs and Ngaio Marsh), which kept flowing after mid-February, showed an increase in conductivity in this later period.

Conductivity increased to the south; from a mean of 85.70 µS/cm at Redwood Springs, to a mean of 253.4 µS/cm at Knights Reserve spring. The very similar conductivities of Ilam Garden A and B springs confirm a common source of groundwater; the springs are less than 20m apart. A weak correlation between flow and conductivity was observed in the combined data from all springs with a significant flow (>1L/sec), as shown in Fig 7b. As flows increased, conductivity declined.

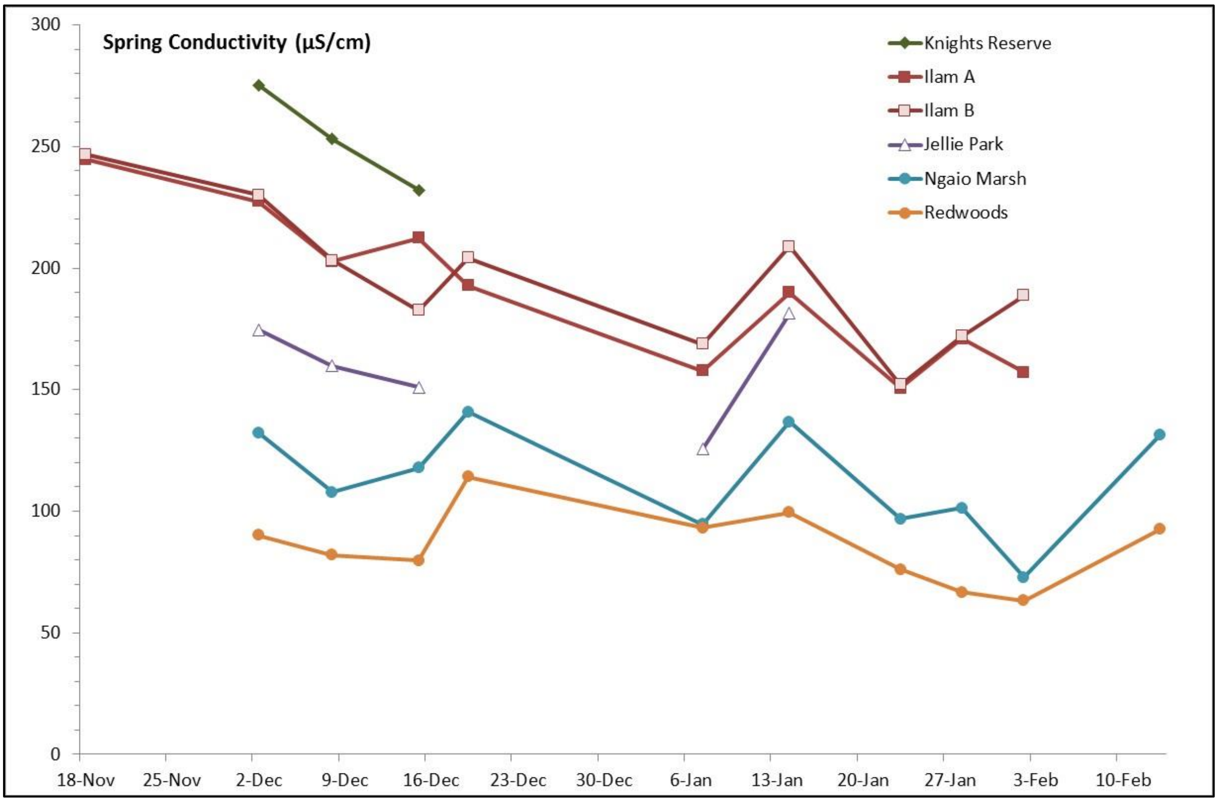


Figure 7a Spring conductivity from the 18th November 2014 to the 13th February 2015.

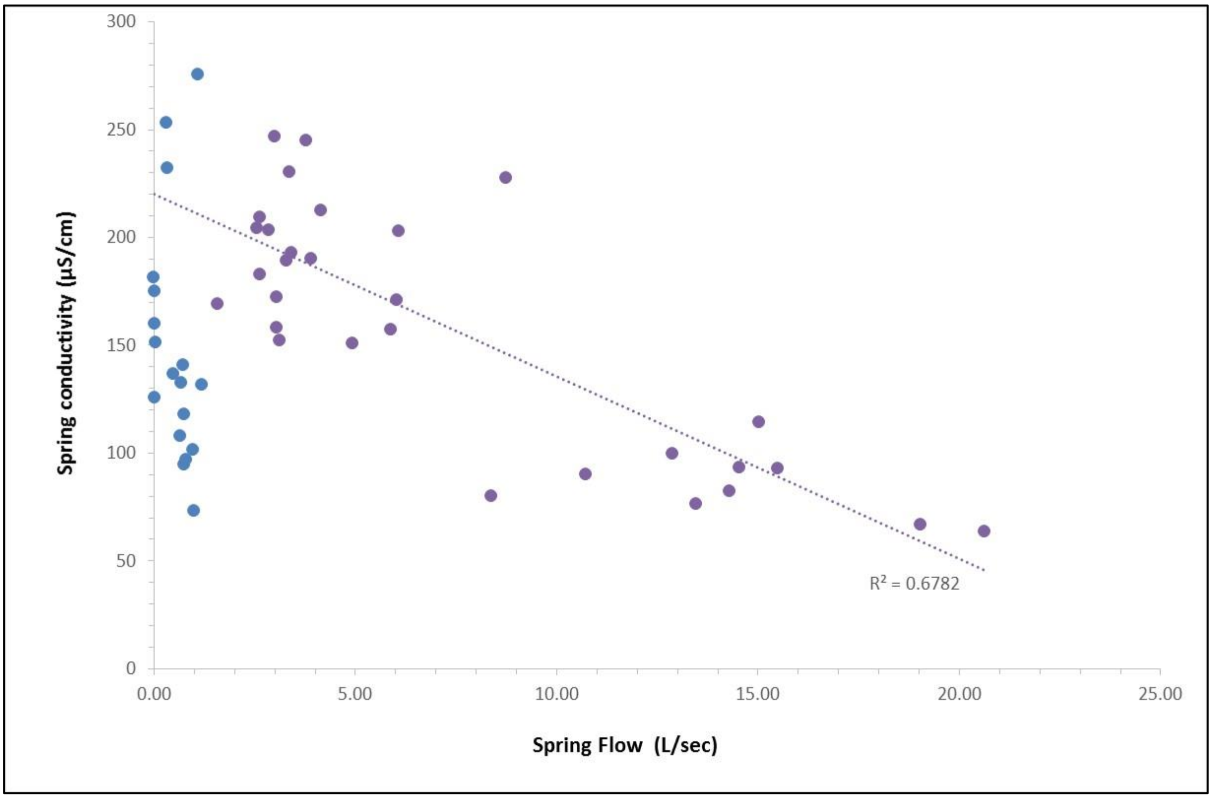


Figure 7b Correlation between conductivity and springs flow. All high flow spring data has been combined; low flow springs (mean <1 L/sec) at Ngaio Marsh, Jellie Park and Knights Reserve are shown in blue, and not included in the correlation.

3.2.3 Dissolved Oxygen

Dissolved oxygen levels remained relatively consistent over the summer monitoring period for each spring (Fig 8). The Ilam springs were fully saturated with oxygen, and Redwood springs, Knights Reserve and Jellie Park spring water also had a high oxygen content. However, Ngaio Marsh had depleted oxygen levels, possibly indicative of a deeper source of the groundwater feeding this spring.

There was no correlation between DO and spring flow evident in the summer monitoring data.

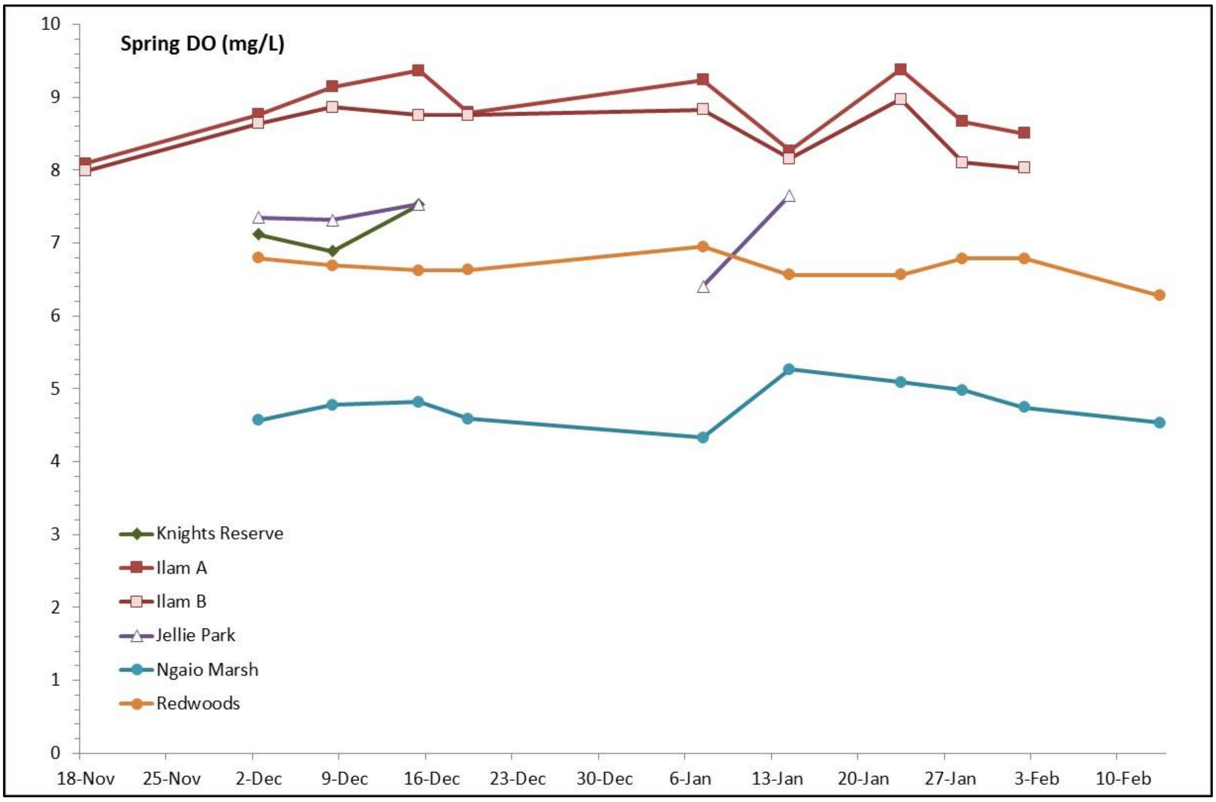


Figure 8. Spring dissolved oxygen concentrations from the 18th November 2014 to the 13th February 2015.

3.2.4 pH

The pH remained near neutral at the springs throughout the monitoring period (Fig 9). The main springs showed a general decrease to 19th December, then varied little until late January, when they began to increase again (except for Ngaio Marsh spring). The late February increase in Redwood Springs pH (to 7.92) may not be an accurate reflection of spring conditions given that the springs had ponded and may host photosynthetic algal with the ability to affect pH levels. No correlation was evident between pH and flow in the spring data.

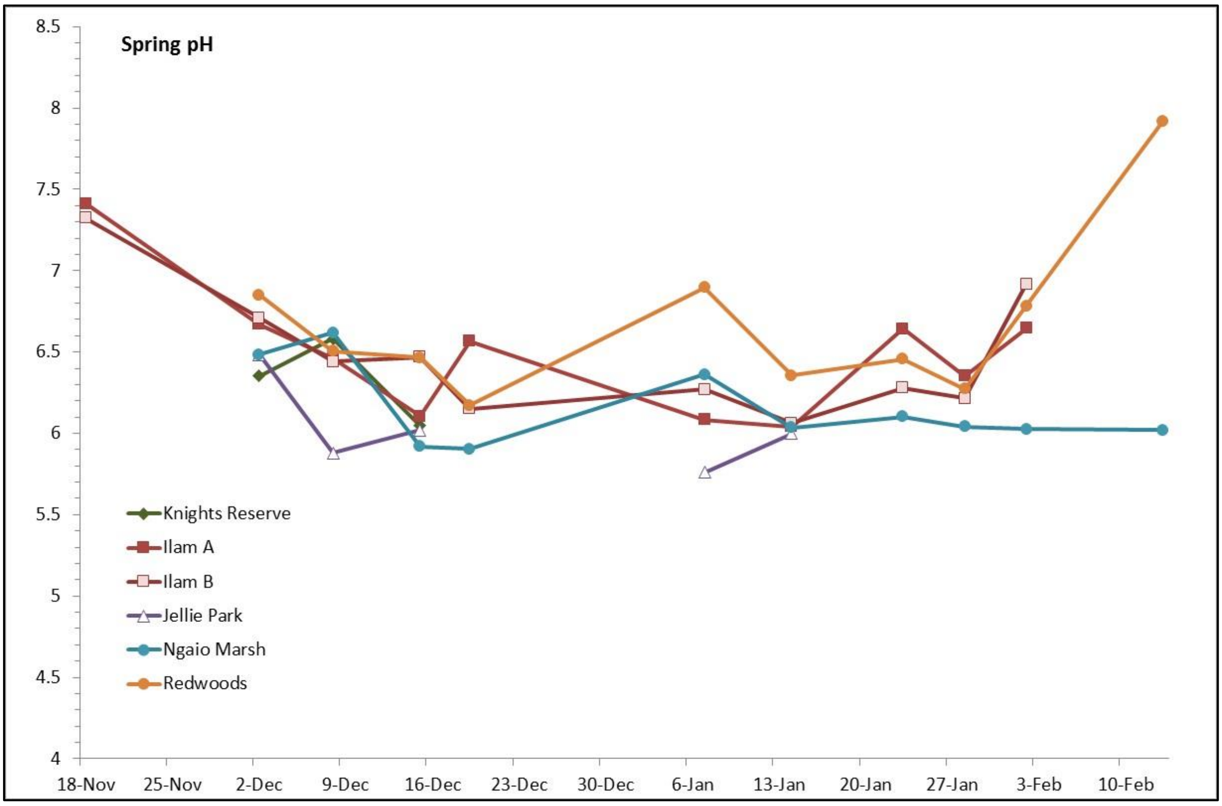
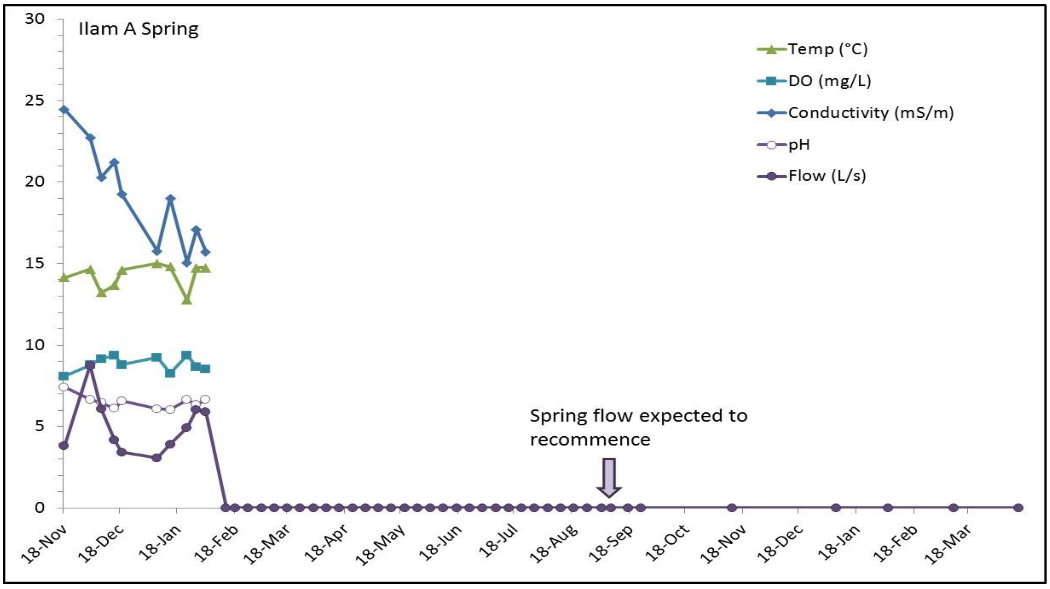


Figure 9. Spring pH from the 18th November 2014 to the 13th February 2015.

Section 4 Discussion

4.1 Flow variability

Highly variable flow was observed in all of the monitored artesian springs, with those to the south of Ngaio Marsh Spring (i.e., south of Papanui) ceasing to flow in mid-summer. None of these springs resumed flowing within the monitoring period (up to 25 August, 2015) and those at Ilam Gardens which were monitored for longer, had still not resumed flow by July 2016 (Fig 10). In 2015 the lack of flow had persisted through the late August/early September period in which flow at Ilam Garden springs has previously been observed to resume (Fig 9).



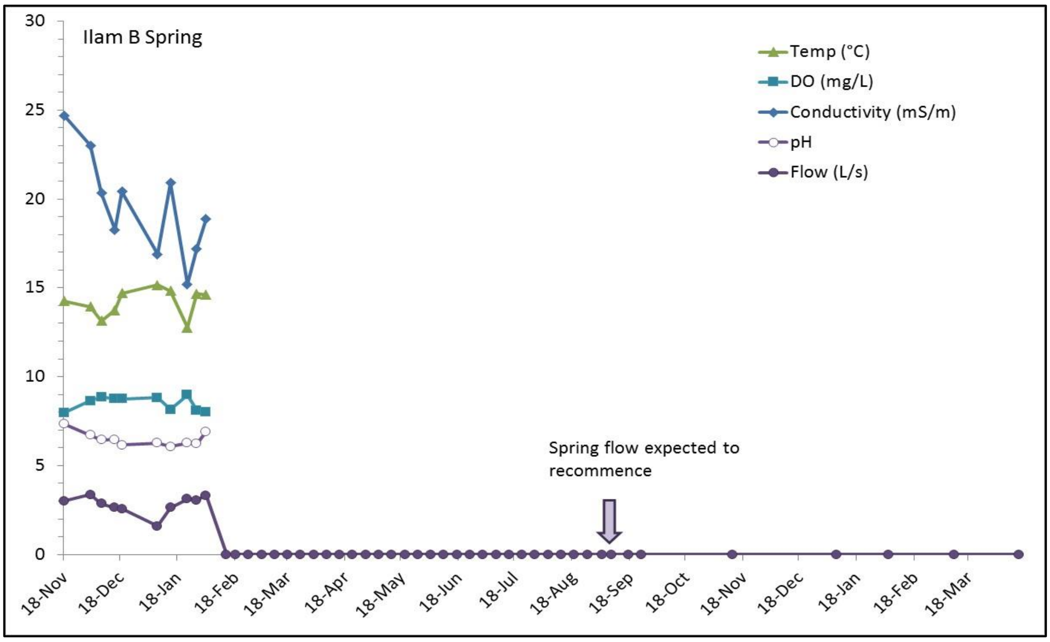


Figure 10. The full flow record (November 2014 to July 2016) for Ilam Gardens spring (A & B) showing the time at which flow was expected to resume, based on previous experience.

This was clearly unusual, as there was growing concern expressed by the residents of Christchurch at the lack of flow in the inner city streams, conveyed via letters to the editor of *The Press* and in articles in local newspapers (e.g., "Christchurch's vanishing streams worry residents", *http://www.stuff.co.nz,* 10 March 2016). The lack of water was particularly evident in the upper tributaries of the Avon and Heathcote rivers, such as the Waimari (Fig 11) and Wai-iti streams which flow through Fendalton and feed the Avon River. Environment Canterbury's monitoring data for Waimari Stream records that it had been dry on almost all visits (6 per year) between January 2015 and March 2016, as had nearby Wai-iti Stream (ECan, 2016b). Although summer dry conditions have been observed in these tributaries previously, this is the longest period of dry conditions since monitoring spring-fed streams began in 1997. ECan attribute the lack of flow to low rainfall in 2015 and specifically to lack of winter rainfall to recharge the groundwater aquifers that feed the springs. In order to interpret our spring flow data, we therefore accessed information on local groundwater levels.

Figure 11. A dry Waimari Stream bed, near Fendalton Reserve, Ilam. Waimari Stream is a tributary of the Avon River, which usually flows year round.

4.1.1 Fluctuations in local groundwater well levels

Groundwater level data from Environment Canterbury was analysed from 5 shallow groundwater wells (20m – 35m depth) close to the line of springs sampled (Fig. 12), specifically (from north to south) M35/1205, M35/1380, M35/5560, M35/1878 and M36/4010. Three additional wells to the west of the urban area (M35/1451, M35/3614 and M35/1110) were also investigated to provide context for this study (records are in Appendix B).

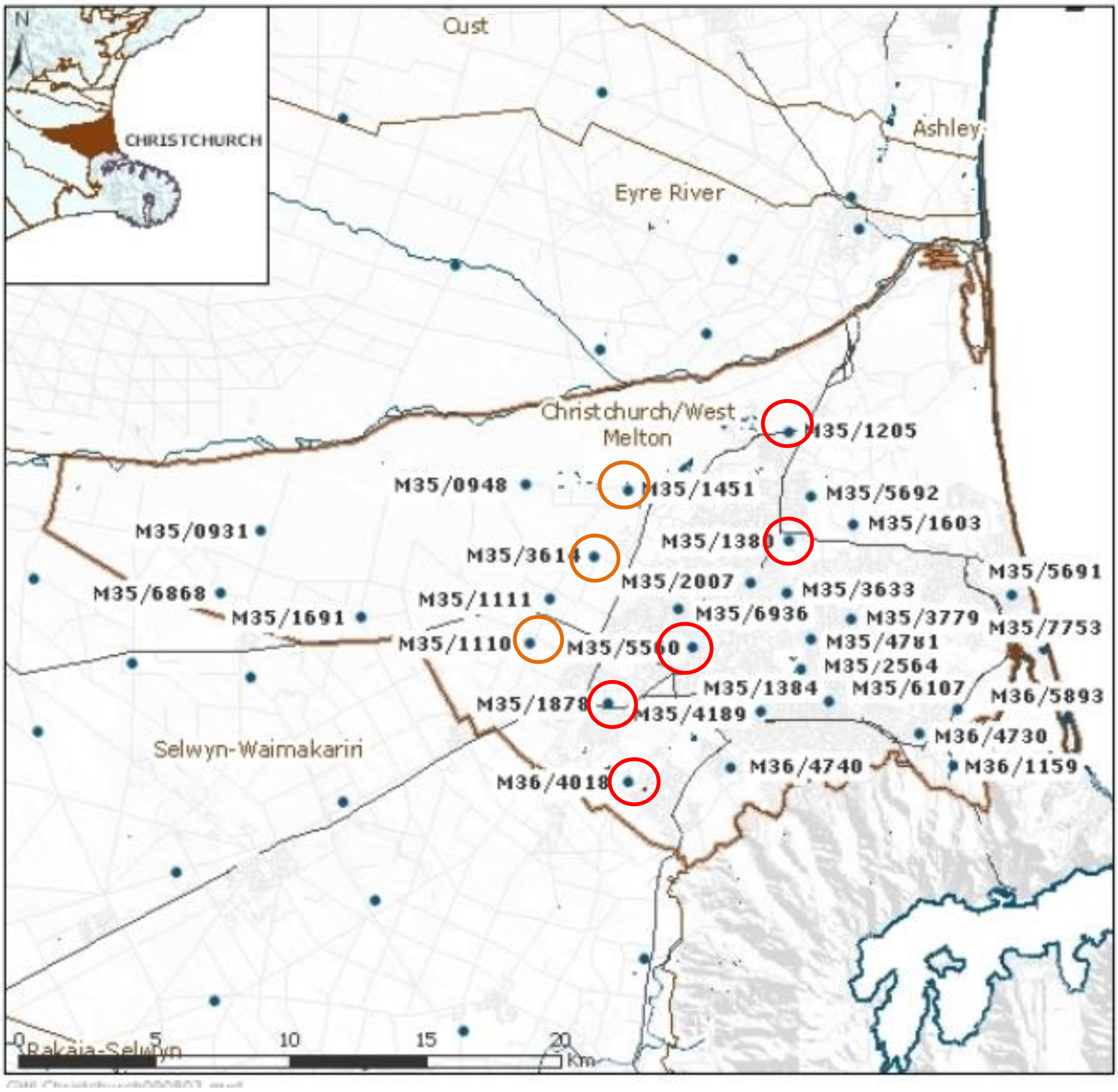
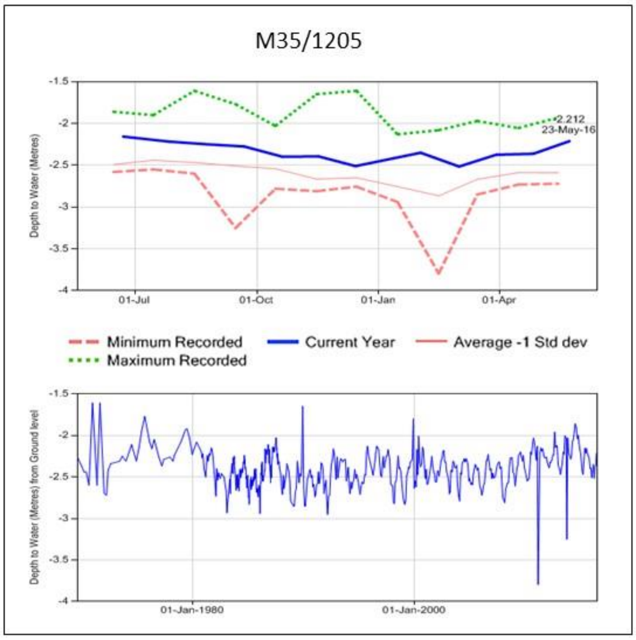
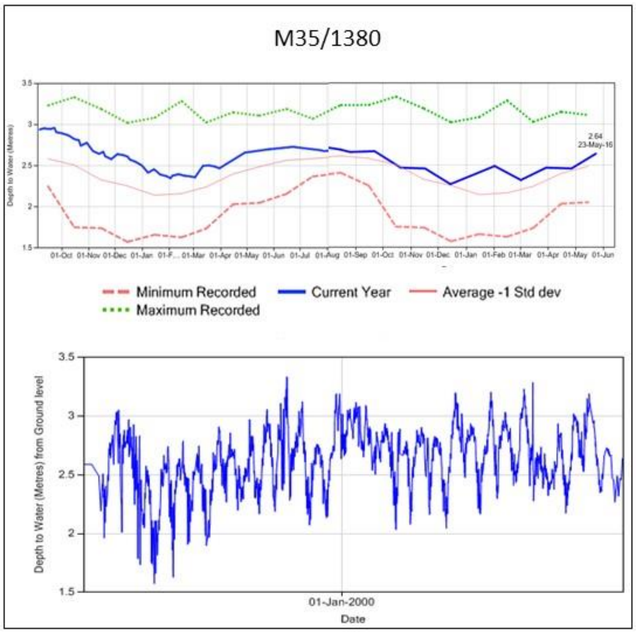
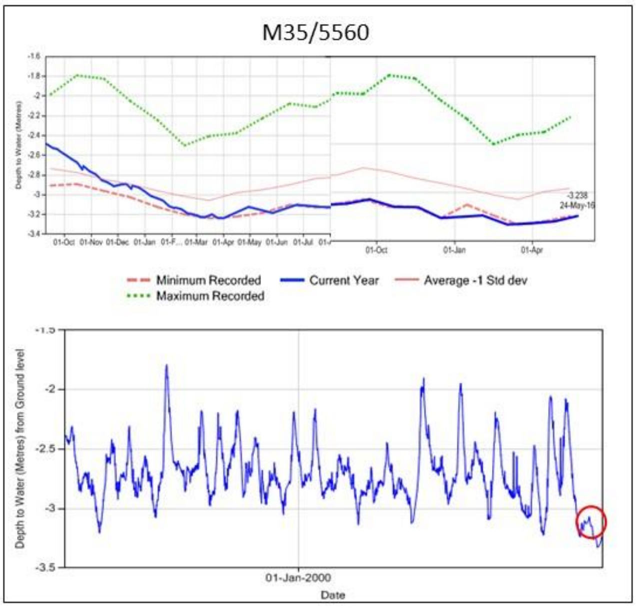


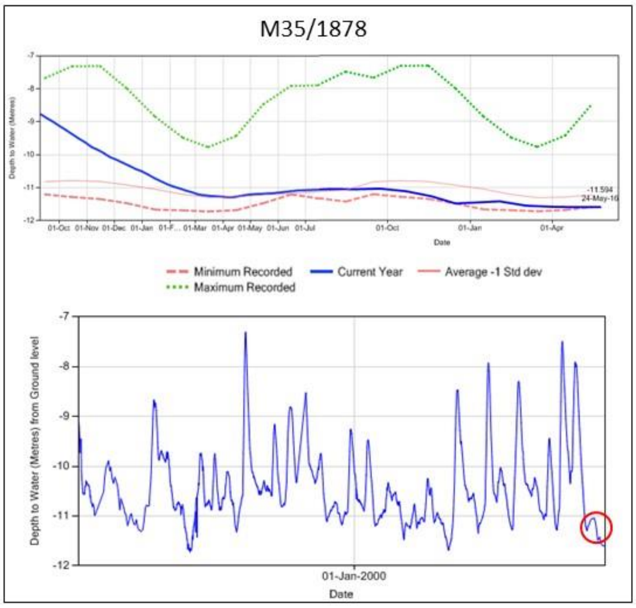
Figure 12. Locations of groundwater wells for which groundwater level monitoring data from ECan (2015 & 2016a) has been used in this report. Those highlighted in red fall closest to the line of artesian springs, from Redwood Springs in the north to Knights Reserve spring in the south. Those highlighted in orange lie to the west and have been examined to provide context (refer Appendix B).

In the vicinity of the two northern springs (Redwood Springs and Ngaio Marsh), groundwater levels in M35/1205 (25.6m) and M35/1380 (21.7m) were consistently close to "normal" levels throughout the study period (Fig. 13). The "normal" level is the monthly average calculated over the 45 and 30 yr periods that these two wells have been monitored, respectively. Seasonal fluctuation in the water level is relatively small; approximately 50cm for M35/1205, which is closer to the Waimakariri River, and approximately 75cm for M35/1380. This can be explained by a high and relatively constant contribution from Waimakariri River recharge to the urban aquifer in this area (Hayward, 2002; see Fig. 14). This contribution does not vary greatly with river flow (White et al, 2012). Consequently groundwater levels here typically remain high, and local artesian spring flows continue, throughout the summer period.









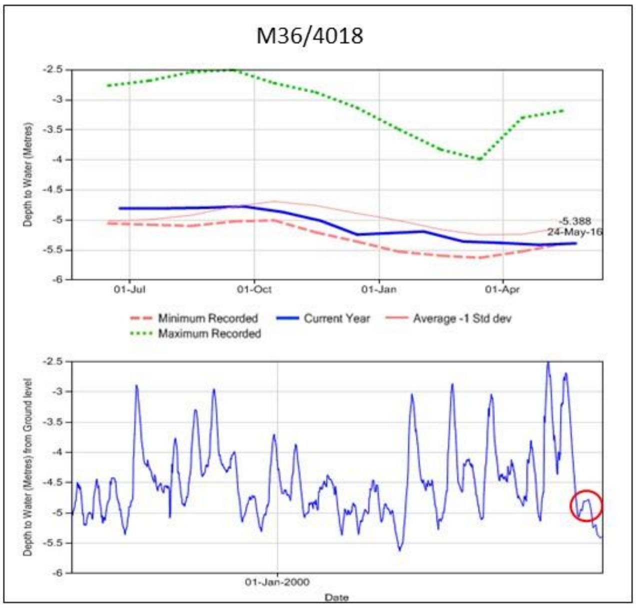


Figure 13. Groundwater levels in the urban Christchurch wells closest to the line of springs sampled in this study. The top graph for each well shows monitoring data for 12 or 20 months preceding June 2016. The lower graph shows the complete record, up to June 2016. Original images were downloaded from the ECan website in February 2015 and June 2016 (ECan, 2015 & 2016a). Those for the 20 month datasets have been manually merged after download, by the authors (hence axis discontinuity). Red circles identify the winter period for 2015.

In contrast, groundwater levels in the main urban area in wells immediately to the south, had dropped significantly below "normal" levels by January (M35/5560, 21m) or September 2015 (M35 1878, 34m and M36/4018, 30m), and have not recovered since. The groundwater levels are now at or near the lowest level recorded over the 25-30 year monitoring period for these wells. The magnitude of seasonal fluctuation in the groundwater level also increases to the south, with up to 2.5-3.5m of seasonal variability in M35/1878 and M36/4018. While this degree of seasonal fluctuation could explain the routine loss of flow observed in Ilam Gardens springs and other urban springs in summer, it is the persistently low water level over the last 18 months that appears responsible for the longer term loss of flow from these artesian springs.

Further investigation of these groundwater level records reveals that the current low level, like other particularly low summer levels before, is immediately preceded by a lack of recharge during the previous winter period (highlighted in red on Fig 13). The seasonally high groundwater levels that occur in response to winter rainfall recharge of unconfined aquifer systems to the west (evident in the regular high groundwater levels in Fig 13), are typically absent or very subdued in the winter months preceding an anomalously low summer groundwater level. In the central and southern areas of Christchurch, the aquifers do not receive as much recharge from the Waimakariri River seepage as those to the north (Fig 14) so are more vulnerable to variability in rainfall recharge of the unconfined aquifer.

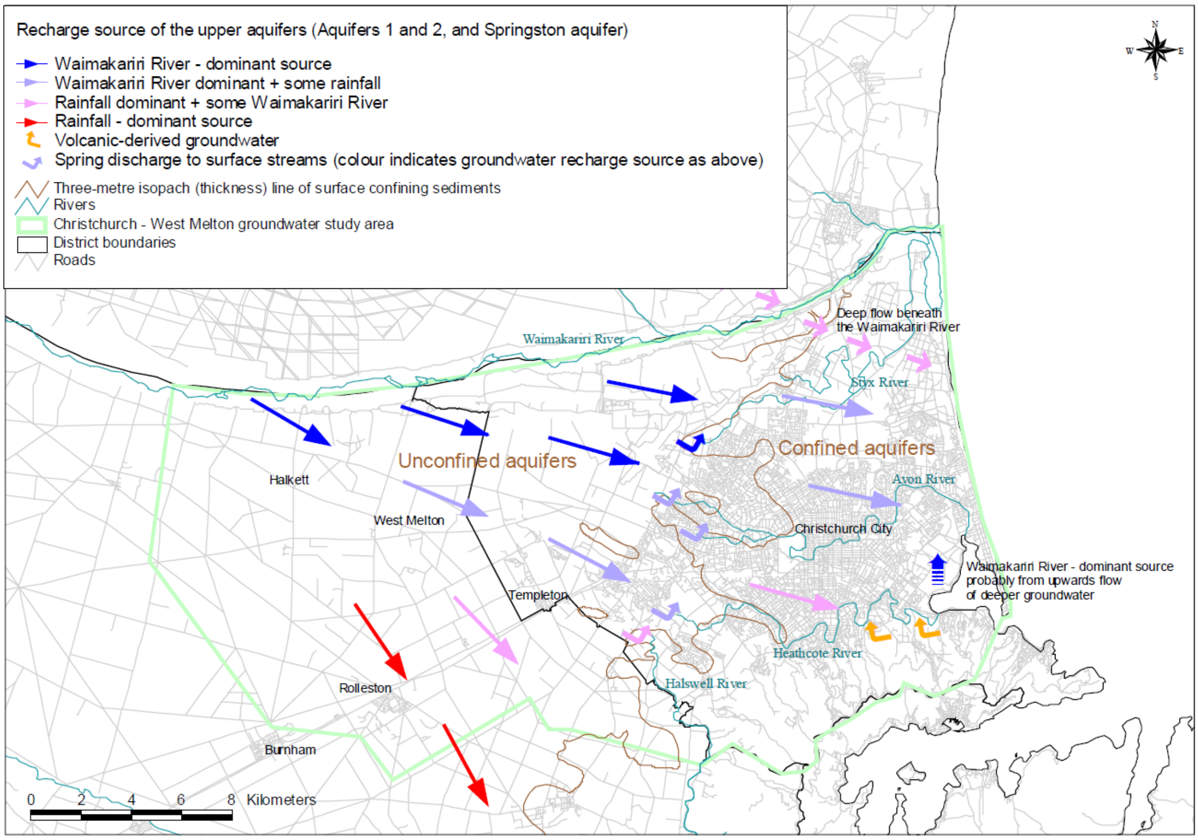


Figure 14. Conceptual model of recharge sources for the Christchurch urban aquifer system, from Hayward (2002).

Records were also examined for wells further to the west in the unconfined aquifers; M35/1451 (11m), M35/3614 (24.5m) and M35/1110 (32.6m) (Fig. 12; see graphs in Appendix B). These wells all show levels dropping below "normal" in August/September 2015, and a lack of significant winter recharge. Seasonal groundwater level variability is higher to the west (up to 4.5 – 6m in M35/3614 and M35/1110), a trend which continues further west resulting in seasonal changes of up to 12m in the West Melton region. Again, less variability is evident in wells closer to the Waimakariri River. The similar response of these western wells to those in the urban area confirms the role of rainfall recharge in initiating and/or maintaining spring flow.

These groundwater monitoring data do not appear to support the premise that there has been an increase in urban water extraction and that this is responsible for the current loss of spring flow. Summer low water levels do not appear to be showing a decreasing trend with time in any of the wells examined in the course of this study. However, Harrington (2016) has observed such a declining trend in a shallow groundwater well at Roydvale Ave in Burnside (near the airport), indicating that the water level here has been consistently drawn down over time by local water extraction. It is safe to assume that the water level over summer throughout the urban region is lower than it would be without extraction. Marshall (1973) reported that urban development around the Ilam area had caused the Avon river's source springs to shift downstream. Also, very few of the Avon springs listed in detail by Daglish (1985), could be found during this study.

ECan's groundwater level monitoring data in Figure 13 also do not show evidence of reduced recharge due to urbanisation and increased impermeable surfaces to the west of the confined aquifer system. However, these data extend back only to the 1980s, and the main development of older urban areas to the west of the springs occurred long before this monitoring began. The direct effects of urban development on springs, such as capping and diversion of spring flow will also have an inevitable effect on springs and the habitats they support (Barquin and Scarsbrook, 2008).

The reverse flow observed in the dry artesian spring at Knights Reserve appears quite unusual. There are reports in the international literature of lowland springs draining water away during flooding, e.g., from low lying regions of Florida, USA (Stamm, 2008), but it does not appear to have been observed previously in New Zealand springs. In the weeks following the two periods of observed reverse flow, the entire spring bed dried up. Such an occurrence could be of concern if contaminated surface waters can access the confined aquifer systems via this route. This particular spring is located in an area where water abstraction for drinking and domestic water is substantial.

4.1.2 Variability in local rainfall

Rainfall data from the weather station at Christchurch airport to the west of the main urban area, has been accessed from the NIWA CliFlo database (Fig. 15). There was low rainfall in 2015 (only 72% of the mean for 2003-2013), with particularly low rainfall in spring and summer. Winter rainfall was only moderately low (82% of the 2003-2013 mean), but is likely to have had a disproportionate effect on aquifer recharge which occurs mainly in winter when low temperatures and evapotranspiration rates enable the overcome the soil moisture deficit to be overcome. This enables rainfall to become recharge. Such low rainfall years have occurred before, for example most recently between 2000 and 2005 (Fig 15), and even lower rainfall occurred in 1988.

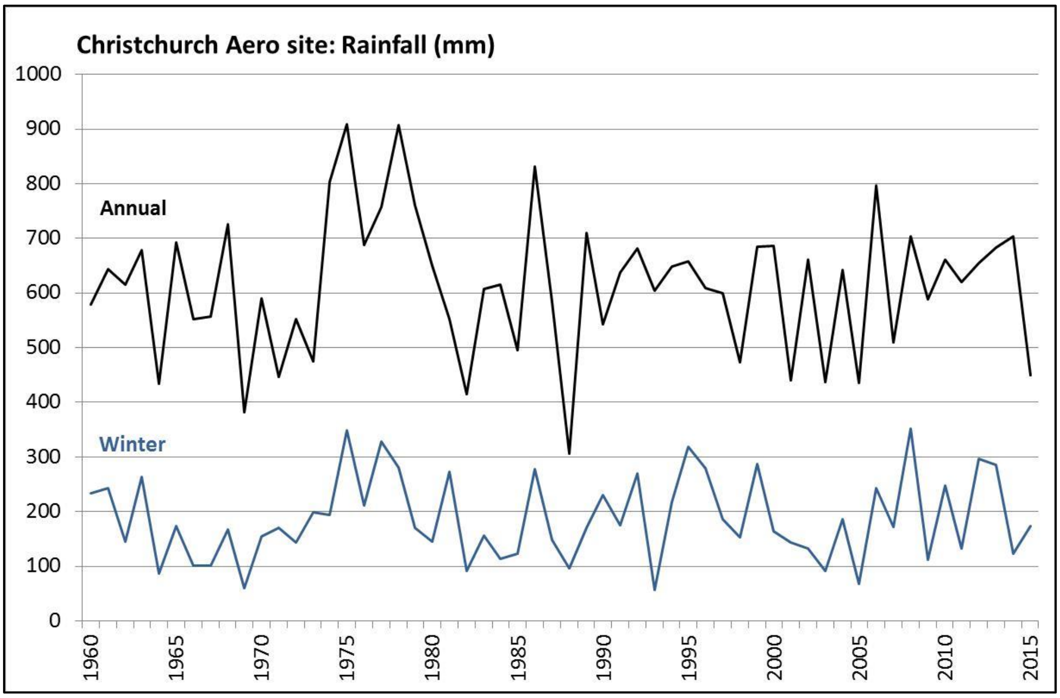


Figure 15. Average rainfall at Christchurch Airport (NIWA, 2016), and rainfall over the winter months (June, July and August).

Despite the fact that summer rainfall in 2014/15 (58mm) was less than half the average summer rainfall for the preceding 10 years (2003-2013: average 132mm), daily rainfall data indicates that there were 18 days with rain between 2 Dec 2014 and 13 February 2015, though only 5 with >5mm and none over 10mm. These discrete periods of rain do not appear to correlate directly with any increase in spring flow. However, without knowing the time taken for rainwater to percolate through to the shallow confined aquifer system, it is not possible to eliminate this as the cause of the short term, minor flow increases observed (e.g., in mid-late January).

4.1.3 River Levels

ECan monitoring data for the river stage height of the Waimakariri River, from September 2014 to June 2016, is shown in Fig 16 (ECan, 2015, 2016a). There was no evidence of a decrease in the base flow of the Waimakariri River over the study period, and the frequency of high flow events is as expected; more frequent during winter and early spring, with fewer during summer. Given the assertion that flow variability in the river does not significantly affect recharge rates (White et al., 2012), and the "normal" water level levels maintained in the northern urban area where the Waimakariri River contributes the most to groundwater recharge (Fig 13), it is unlikely that variability in spring flow discharge is related to Waimakariri River flow.

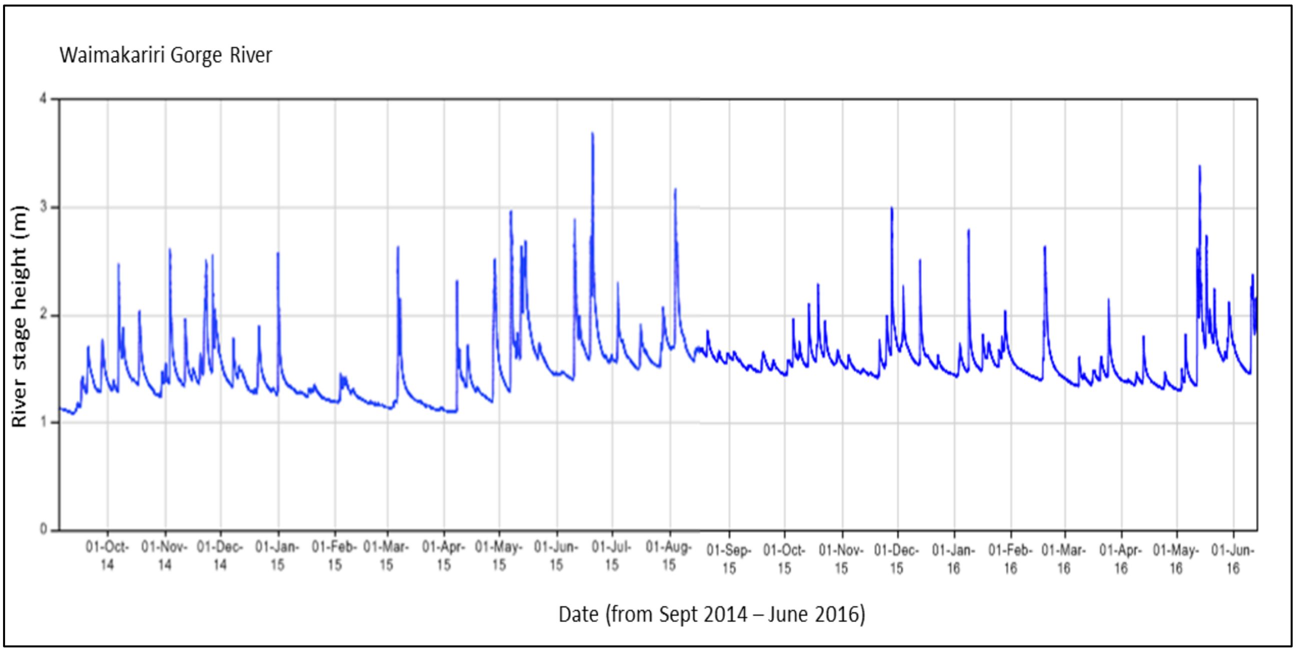


Figure 16. Waimakariri River stage height, recorded from September 2014 to June 2016 (ECan, 2015, 2016a).

4.2 Water quality variability

Conductivity was the only water quality parameter measured which showed a significant variation during the summer spring flow measurements. There was an overall decrease in conductivity with time through summer, punctuated by short-term increased conductivity in late December and mid-January. The higher flow springs at Redwood Springs consistently had the lowest conductivity, due to a significant component of Waimakariri River seepage in the aquifer feeding the springs at this site. Given the lower conductivity of the northern springs, and the tentative relationship between conductivity and flow (Fig 7b), we propose that the trend towards lower conductivity in the springs as summer progresses reflects the increased proportion of dilute Waimakariri River seepage in the aquifer recharge. Shorter

term fluctuations in conductivity, as with the short term fluctuations in flow, may relate to discrete rainfall events. However, without knowing the time taken for rainwater to percolate through to the shallow confined aquifer, this cannot be ascertained.

Otherwise, the water quality of the springs showed little variation while the springs were flowing;

- All springs appeared well-oxygenated throughout the summer period of 2014/15, except for Ngaio Marsh which had a depleted DO (< 6) possibly indicating a deeper source of artesian spring water. Ilam Gardens springs had the highest DO, consistent with a shallow aquifer source.

- All springs had a near neutral pH. Slight elevation of the pH in Redwood springs in late summer may reflect photosynthesis in the spring ponds in the sunny conditions and hot weather.

- Temperature varied <3^{o}C within and between springs, throughout the sampling period.

Section 5 Conclusions

Before this investigation, little was known about when or why some of the artesian springs in urban Christchurch suddenly ceased and resumed their flow during the year. Our investigation of spring flow and basic water quality over the summer months of 2014/15 revealed the following:

- There were minor variations in flow and conductivity while springs were active. Other water quality parameters were relatively constant.
- Springs in the north of the urban area (Redwood Springs and Ngaio Marsh spring), closer to the Waimakariri River, remained flowing throughout this summer period and had a lower conductivity than springs further south. The water level in nearby shallow wells remained at a “normal” seasonal level throughout the summer period (and thereafter). We surmise that these springs are fed by shallow confined aquifers receiving a high proportion of dilute river seepage recharge. The depleted oxygen concentration in Ngaio Marsh spring may suggest a slightly deeper groundwater source.
- In contrast, springs to the south (at Jellie Park, Ilam Gardens and Knights Reserve) ceased flowing during the summer monitoring period, as the water levels in nearby shallow wells fell to a low summer level. Prior to running dry, springs showed decreasing conductivity with time, which we interpret as dilute Waimakariri River recharge making up an increasing proportion of the source aquifer. Drying out is reputedly a regular summer occurrence in these springs, at least in recent years, and low or occasionally no flow, is evident in many spring-fed streams at this time.

These four dry springs were continuously monitored until August 2015, and the two Ilam Gardens springs until July 2016. None of the springs resumed flow during this period, even in August/September when Ilam Gardens springs have been observed to restart in the last 4 years. Monitoring data from nearby shallow wells showed that water levels failed to rise significantly during the winter of 2015, due to lack of rainfall. There was therefore little winter recharge of the unconfined aquifer to the west, reporting to the shallow confined aquifer feeding Ilam Garden springs. Shallow groundwater wells in the central and south of the urban area are currently at or near their lowest levels since monitoring began.

5.1 Recommendations for further study

It would be beneficial to have a longer dataset for spring flow and water quality in the urban area in order to better understand the relationship between precipitation events, water level and aquifer recharge/spring flow. We intend to maintain a monthly monitoring programme for Ilam Gardens springs, but a more detailed record for more springs would

generate better information. The frequency of reverse flow events during dry periods, and implications for groundwater quality, also need to be explored further.

Acknowledgements

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References

Barquin, J. and Scarsbrook, M. (2008). Management and conservation strategies for coldwater springs. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 18, 580-591.

Brown, L.J. (2001). Groundwater research in New Zealand: Canterbury. In *Groundwaters of New Zealand*. NZ Hydrological Society, Claxton Press, Christchurch, NZ.

Cameron, S. (1992). A hydrological study of the interaction between Avon River baseflow and shallow groundwater, Christchurch, New Zealand. *University of Canterbury Masters Thesis (unpublished)*, Christchurch, NZ.

Cubrinovski, M., Green, R., & Wotherspoon, L. (2011). Geotechnical Reconnaissance of the 2011 Christchurch, New Zealand Earthquake. *Report for Web Dissemination, GEER Association Report No. GEER-027.*

Daglish, W. (1985). Flow Regimes and Spring Locations in the Styx and Avon River Streams, *North Canterbury Catchment Board Document Number IN06/4847.*

Earl, P. (1998). Groundwater Springs: A literature review of existing classification schemes and studies, and proposal for a Canterbury Spring Classification System. *ECan Technical Report U98/7.*

ECan (2015 & 2016a) Environment Canterbury monitoring data for rainfall, groundwater level and river flow was accessed from http://ecan.govt.nz/services/online-services/monitoring/ in August 2015 and again in June 2016.

ECan (2016b) Summary of the state of Christchurch spring-fed streams. Short report for the Christchurch-West Melton Zone Committee, 18 March 2016.

Harrington G (2016) Waimairi Stream 2016 Summer Low Flows. Christchurch City Council memo, provided to the authors by Mr Harrington.

Hayward S.A. (2002) Christchurch –West Melton Groundwater Quality: A review of monitoring data from January 1986 to March 2002. *ECan Technical Report* U02/47, 141 pp.

Marshall J. (1973). A benthic study of the Avon spring stream, Christchurch. *Mauri Ora* 1, 79-90.

NIWA (2016). http://cliflo.niwa.co.nz/

Stamm D. (2008) The Springs of Florida (2nd ed). Pineapple Press Inc, Sarasota, Florida, USA.

Stewart M., Trompetter V., & van der Raaij R. (2002). Age and source of Canterbury plains groundwater. *ECan Technical Report* U02/30.

Stewart M. (2012). A 40-year record of carbon-14 and tritium in the Christchurch groundwater system, New Zealand. *Journal of Hydrology* 430-431, 50-68.

White P., Kovacova E., Zemansky G., Jebbour N., Moreau-Fournier M. (2012) Groundwater - surface water interaction in the Waimakariri River, New Zealand, and groundwater outflow from the river bed. *Journal of Hydrology* 51, 1-24.

APPENDICES:

Appendix A: Raw water quality and flow data for springs.

a) Redwood Springs

Date	Temp (°C)	DO (mg/L)	DO (%)	Conductivity (µS/cm)	pH	Flow (L/s)
2-Dec	13.23	6.79	64.27	90.07	6.85	10.74
8-Dec	13.15	6.69	63.43	82.00	6.51	14.32
15-Dec	12.75	6.62	64.37	79.80	6.47	8.39
19-Dec	13.35	6.63	64.17	114.20	6.17	15.03
7-Jan	13.20	6.95	67.37	93.10	6.90	14.56
14-Jan	13.27	6.56	65.20	99.47	6.36	12.90
23-Jan	12.93	6.56	63.60	76.03	6.46	13.46
28-Jan	12.63	6.79	64.53	66.60	6.27	19.04
2-Feb	13.20	6.79	66.33	63.30	6.78	20.64
13-Feb	13.25	6.28	60.70	92.48	7.92	15.51

b) Ngaio Marsh

Date	Temp (°C)	DO (mg/L)	DO (%)	Conductivity (µS/cm)	pH	Flow (L/s)
2-Dec	14.00	4.57	43.77	132.23	6.48	0.68
8-Dec	13.60	4.78	46.03	107.80	6.62	0.67
15-Dec	14.87	4.82	64.37	117.73	5.92	0.76
19-Dec	15.30	4.59	48.60	140.80	5.90	0.73
7-Jan	14.50	4.33	43.83	94.50	6.36	0.76
14-Jan	13.73	5.27	51.37	136.67	6.04	0.50
23-Jan	14.00	5.09	48.90	96.87	6.10	0.82
28-Jan	13.80	4.98	49.07	101.37	6.04	0.98
2-Feb	14.47	4.75	49.60	72.80	6.03	1.01
13-Feb	14.83	4.54	45.40	131.27	6.02	1.20

c) Jellie Park

Date	Temp (°C)	DO (mg/L)	DO (%)	Conductivity (µS/cm)	pH	Flow (L/s)
2-Dec	15.62	7.35	73.97	174.7	6.48	0.0336
8-Dec	13.37	7.32	70.20	159.8	5.88	0.0375
15-Dec	14.95	7.54	74.03	151.1	6.02	0.0393
19-Dec						0
7-Jan	14.65	6.41	65.97	125.5	5.76	0.0168
14-Jan	14.20	7.65	76.20	181.4	6.00	0.0038
23 Jan						0

Zero flow measured every week between 28th January and 26 August 2015

d) Ilam Springs

Ilam A:

Date	Temp (°C)	DO (mg/L)	DO (%)	Conductivity (µS/cm)	pH	Flow (L/s)
18-Nov	14.15	8.09	81.60	244.67	7.41	3.80
2-Dec	14.66	8.76	86.40	227.33	6.67	8.74
8-Dec	13.20	9.14	87.17	202.83	6.46	6.09
15-Dec	13.67	9.37	90.17	212.30	6.11	4.16
19-Dec	14.60	8.79	89.13	192.73	6.57	3.43
7-Jan	15.00	9.24	92.47	157.73	6.08	3.06
14-Jan	14.80	8.27	83.90	189.93	6.04	3.91
23-Jan	12.77	9.38	87.53	150.63	6.64	4.93
28-Jan	14.73	8.67	86.67	170.97	6.35	6.03
2-Feb	14.73	8.50	86.47	157.20	6.65	5.89
13-Feb						0

Ilam B**:**

Date	Temp (°C)	DO (mg/L)	DO (%)	Conductivity (µS/cm)	pH	Flow (L/s)
18-Nov	14.25	7.99	80.00	246.67	7.32	3.00
2-Dec	13.95	8.64	83.27	230.00	6.71	3.37
8-Dec	13.13	8.86	84.13	203.17	6.44	2.86
15-Dec	13.73	8.75	86.43	182.63	6.47	2.64
19-Dec	14.70	8.76	87.80	204.17	6.15	2.56
7-Jan	15.17	8.83	88.60	168.80	6.27	1.59
14-Jan	14.83	8.16	80.67	208.93	6.06	2.64
23-Jan	12.77	8.97	83.73	152.00	6.28	3.13
28-Jan	14.67	8.11	80.53	172.03	6.22	3.06
2-Feb	14.60	8.03	81.77	188.80	6.92	3.31
13-Feb						0

Zero flow measured every week between 18th February and 26 August 2015, and in monthly observations between then and 11 July 2016.

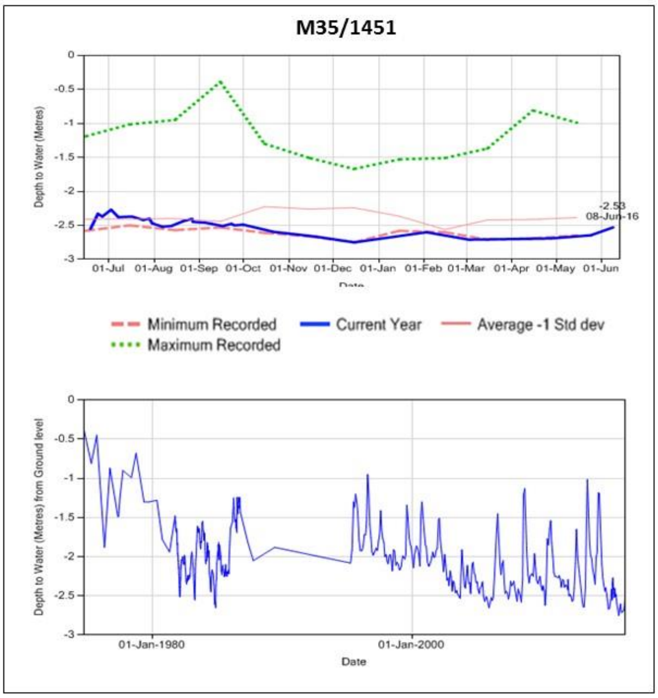
e) Knights Reserve

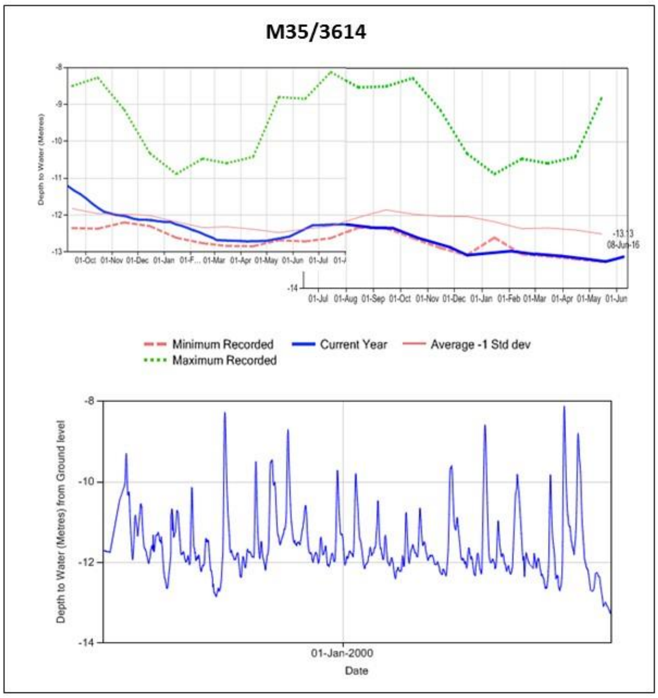
Date	Temp (°C)	DO (mg/L)	DO (%)	Conductivity (µS/cm)	pH	Flow (L/s)
2-Dec	13.14	7.12	67.5	275	6.35	1.10
8-Dec	13	6.89	68	253	6.58	0.314
15-Dec	12.9	7.53	71	232	6.05	0.345
19-Dec						0

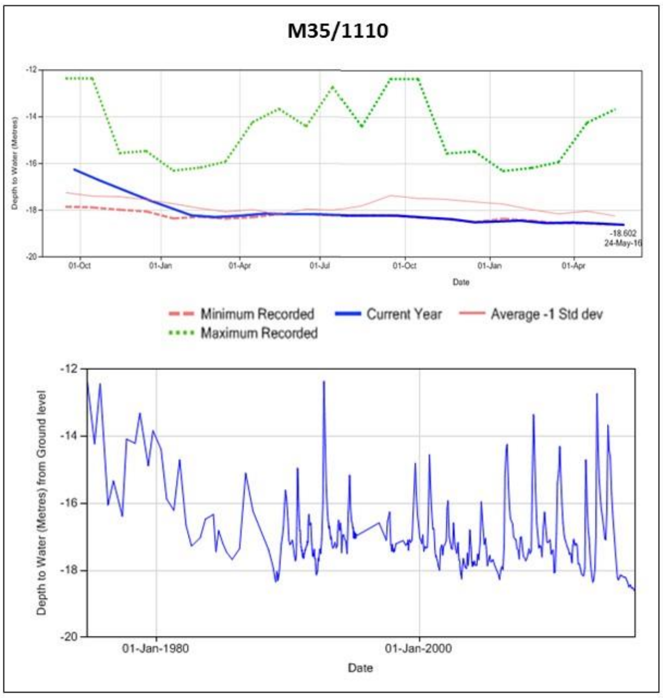
Zero flow measured every week between 7th January and 26 August 2015,

Appendix B: Monitoring data for wells to the west of the study area.

(caption as for Figure 13)







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