Rotorua Geothermal Bore Water Level Assessment – 2014

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BIBLIOGRAPHIC REFERENCE

Kissling, W. 2014. Rotorua Geothermal Bore Water Level Assessment – 2014, *GNS Science Consultancy Report* 2014/199. 39 p.

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EXECUTIVE SUMMARY

This report presents data from the Rotorua Geothermal Aquifer Monitoring Programme, with new, previously unreported data included from 2007 to 2014. The data comprises water levels for geothermal monitor wells (M-wells) M1, M12, M16, M24, M25, M26, M27 and M28 and the shallow groundwater wells (G-wells) G2, G11, G12, G13 and G14. For older wells (M1, M12, M16 and M24) the available data spans a period from the early 1980s, while for the newest wells (M25, M26, M27 and M28) data taking started in 2009.

The raw M-well data have been processed and appended to existing historical records. Analysis of the M-well data entailed removing the barometric pressure effects from the water levels. Consequently, the processed data for the M-wells now show short term (a few months or less) responses to rainfall events which are strongly correlated between all of the M-wells which penetrate the Rotorua Rhyolite aquifers. The longer term ‘underlying’ water level variations since 2010 in some of these wells are correlated. The recent data from the M-wells in the ignimbrite aquifers show no correlations to rainfall.

The temperature profiles of the M-wells can be divided into two groups. M1, M16, M25 and M27 show little or no variation in temperature over time while M12, M24, M26 and M28 show slow heating or cooling on timescales of a few years to decades. Both groups exhibit strong variations in water level and contain both ‘old’ wells dating from the 1980s and more recent ‘new’ wells. Wells in both groups are located throughout Rotorua City.

M12 and M24 are the only two wells remaining in the Monitoring Programme which have assigned Minimum Aquifer Geothermal Water Levels (MAGWLs) – M6 and M16 having ceased operation in 2004 and 2014 respectively. As the MAGWLs were set in the early 1990s, part of the current work programme involved a review of options for setting new MAGWLs. A methodology has been proposed to establish new MAGWLs for all M-wells in the programme. The method determines MAGWLs by relating current water levels in the M-wells to water levels in selected intervals during the recovery of the Rotorua Geothermal Field following the Bore Closure Programme that started in the 1980s.

The M-wells M1, M12 and M16 are being replaced by M27, M28 and M26 respectively. With strong correlations now being seen between the short term water level variations in these M-wells it is expected that the replacement wells will continue to provide useful data which can be linked back to the older records. The end of data recording at M16 in January 2014 means that M25 will be the only monitor well penetrating the Rotorua Ignimbrite aquifer. While its water level record is very different from the wells in the rhyolite aquifers, its location at Ngapuna means it is uniquely placed to monitor conditions there, and is useful for this reason.

The G-wells have generally continued to behave as in the past. However, since 2004 the water levels in all of these wells (except for G14) have shown two broad peaks, each about five years long. This is the first time that common behaviour of this type has been seen in the G-well data. Moreover, the deeper M-wells M24 and M26 seem to both show the second of these peaks, providing tentative evidence for a link between the shallow groundwater and the deeper geothermal aquifers.

1.0 INTRODUCTION

This report presents water level data from the Rotorua Geothermal Aquifer Monitoring Programme (hereafter 'The Monitoring Programme') for the period from 1982 until mid-2014. New data in this report cover the period from early-mid 2007 to May 2014. In this document water levels are presented for both monitor wells (henceforth M-wells) and shallow groundwater wells (G-wells). Temperature profiles for the M-wells covering the period 1991 to 2014 are also presented. The locations of these wells are shown in Figure 1.1 and Table 1.1. To aid the analysis, daily-averaged rainfall data and barometric pressures have also been received from the National Institute of Water and Atmospheric Research (NIWA) Rotorua. Data from April 2007 to May 2014 has been appended to the existing historical records which spanned the period from 1982 to April 2007.

Since the last report on the Monitoring Programme data (Kissling, 2007), there have been some changes to the M-well series at Rotorua. In particular, data was no longer collected from M17 from July 2009, and two new wells, M27 and M28, have come on-line to replace M1 and M12. At present data continues to be collected from all four wells (M27, M28, M1 and M12) so that some overlap in coverage exists between the old and new datasets. Also of note is that, in 2007, the records covering M25 and M26 were of too short duration to be of much value for long-term analysis. Now, with the addition of a further seven years of daily records for both wells and more than five years of recording at M27 and M28, the current data coverage is once again long enough and there are sufficient new (reliable) wells to serve as a good basis for the Monitoring Programme for the next decade.

The main objectives covered by this report are:

- Adjustment of the M-well water levels to remove the response to barometric pressure and assessment of the long term trends in these water levels and possible influences from rainfall and other effects.
- To comment on options for setting the Minimum Aquifer Geothermal Water Levels (MAGWLs) in the light of the most recent data.
- Assessment of the long term trends in the M-well temperature profiles and the relation of those trends to the M-well water levels.

Secondary objectives are:

- To assess any long term changes in the G-well water levels.
- To update and maintain the historical M-well, G-well, barometric and rainfall data records held at GNS Science, and formerly at Industrial Research Limited (IRL).

This report begins with a review of the rainfall data for Rotorua, as this is one of the main potential drivers of changes in both the shallow groundwater and deeper geothermal systems. Then, in the next section various aspects of the M-well data are discussed – the issue of data overlap (between old and new datasets), the 'historical' water levels, brief reviews of the MAGWLs and replacement wells, and finally the relationship between relative water levels and temperature profiles over time. Lastly the water levels for the G-wells are reviewed.

Figure 1.1 Location map showing the positions of monitor wells and shallow groundwater wells at Rotorua. Figure courtesy of Bay of Plenty Regional Council.

Table 1.1 Details of the wells in the Monitoring Programme. For M16 and G14, data recording ended on the dates indicated by the asterisks.

Well	Location	Depth (m)	Geology	Location	Data Span
M1	Fenton St, Info. Centre	64	Rhyolite	E2795308 N6335681	16/11/1982-16/3/2014
M12	Hospital	75	Rhyolite	E2794769 N6335972	18/11/1982-2/4/2014
M16	Sala St, Alpin Motel	157	Ignimbrite	E2795582 N6333166	26/9/1982-6/1/2014*
M24	Carlton St, Retirement Village	133	Rhyolite	E2794555 N6333537	31/3/1993-2/4/2014
M25	Sewage Plant	241	Ignimbrite	E2796180 N6334563	1/3/2003-2/4/2014
M26	Ward Ave, Rose Gardens	186	Rhyolite	E2795461 N6333482	7/9/2006-2/4/2014
M27	Haupapa St ROC car park	78	Rhyolite	E2795262 N6335602	16/9/2009-2/4/2014
M28	Hospital	75	Rhyolite	E2794733 N6336009	16/9/2009-2/4/2014
G2	Kuirau Park	6	Alluvial sediments	E2794500 N6336100	17/9/85-3/4/2014
G11	Whakarewarewa	6	Alluvial sediments	E2795700 N6332400	17/9/85-3/4/2014
G12	Arikikapakapa	8	Alluvial sediments	E2795200 N6333200	17/9/85-3/4/2014
G13	Sewage Plant	6	Alluvial sediments	E2796100 N6334400	19/12/83-3/4/2014
G14	Racecourse	10	Alluvial sediments	E2795300 N6334300	17/9/85-16/10/2012*

2.0 ROTORUA RAINFALL

Figure 2.1 shows the total annual rainfall for Rotorua for the period 1979-2013. Since the time of the last report in 2007 (Kissling, 2007) the rainfall has been typical in the sense that the long term annual average has remained close to that reported in 2007 of 1380 mm/year. However, Figure 2.1 shows that in 2011 over 2000 mm of rain fell, the highest recorded total in the 34 year dataset. The total daily rainfall for 2011 is shown Figure 2.2. There were three days in 2011 when over 100 mm of rain fell. These were January 23rd (203 mm), January 29th (113 mm) and December 31st (108 mm). To put this in perspective, during the 14 year period from 2000 to 2013, only four other days had more than 100 mm of rain. These occurred in 2002, 2004, 2006 and 2008, and there was no instance of this occurring twice in any year.

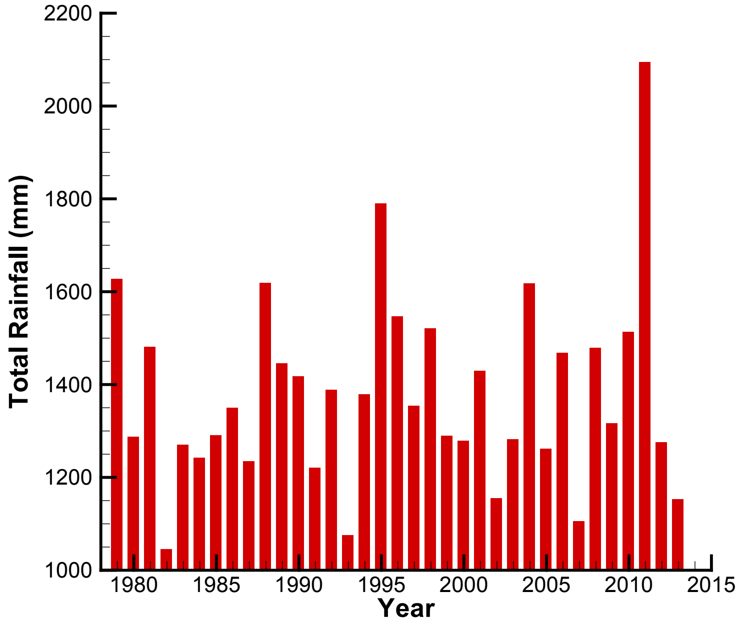

Figure 2.1 Total yearly rainfall at Rotorua. The long-term average annual rainfall is 1380 mm/year. The total annual rainfall in 2011 was the highest recorded since the programme began.

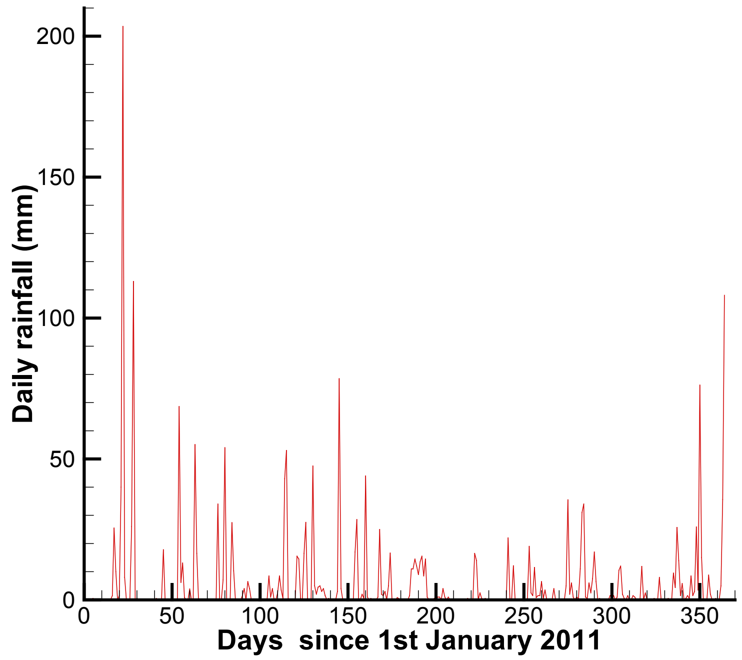

Figure 2.2 Daily rainfall at Rotorua for 2011. The year was unusual for its high total rainfall (2095 mm) and that there were three rainfall events of > 100 mm/day.

3.0 MONITOR WELLS

3.1 DATA

For this work, new daily-averaged water levels were obtained from NIWA Rotorua for the monitor wells M12, M16, M24, M25, M26, M27 and M28. For M1, ‘spot’ measurements of the water level occur at approximately two week intervals – daily recording at this well ceased in June 2004, but has continued at this reduced rate since then. The periods covered by the new data received from NIWA are shown in Table 3.1.

Table 3.1 Summary of periods of new M-well daily water levels received from NIWA.

Well	Span of new data
M1	10/5/2007-19/3/2014
M12	1/5/2007-2/4/2014
M16	1/5/2007-6/1/2014
M24	1/3/2007-2/4/2014
M25	1/3/2007-2/4/2014
M26	1/5/2007-2/4/2014
M27	16/9/2009-2/4/2014
M28	16/9/2009-2/4/2014

3.2 DATA OVERLAP

The new data from NIWA were provided with some time overlap with the existing historical datasets. This provided a means of checking the consistency of the datasets, and potentially identifying any problems before the new data are appended to the historical records. The periods of overlap range from 33 days (M24, M25), 55 days (M12) and 615 days (M16 and M26).

Figures 3.1 to 3.5 show comparisons of the water levels from the ‘historical’ and ‘new’ data sets for the period of overlap, for M12, M16, M24, M25 and M26 respectively. These plots show that apart from M12, there is no significant difference (as determined by a visual comparison) between any of the historical and new sets of data where they overlap. For M12, between early April and the end of May, 2007 there is a small difference between the two sets of water levels. The reason for this was traced (by G. Timpany, pers. comm.) to a small adjustment made to the data to correct for calcite precipitation in the sensor tubing. The magnitude of the difference changes with time, but is consistent with a 34 mm offset observed in the measuring apparatus on a visit to the site in April 2007. The offset is small and has not been corrected in the data prior to processing. It has no effect on any of the conclusions presented in this report.

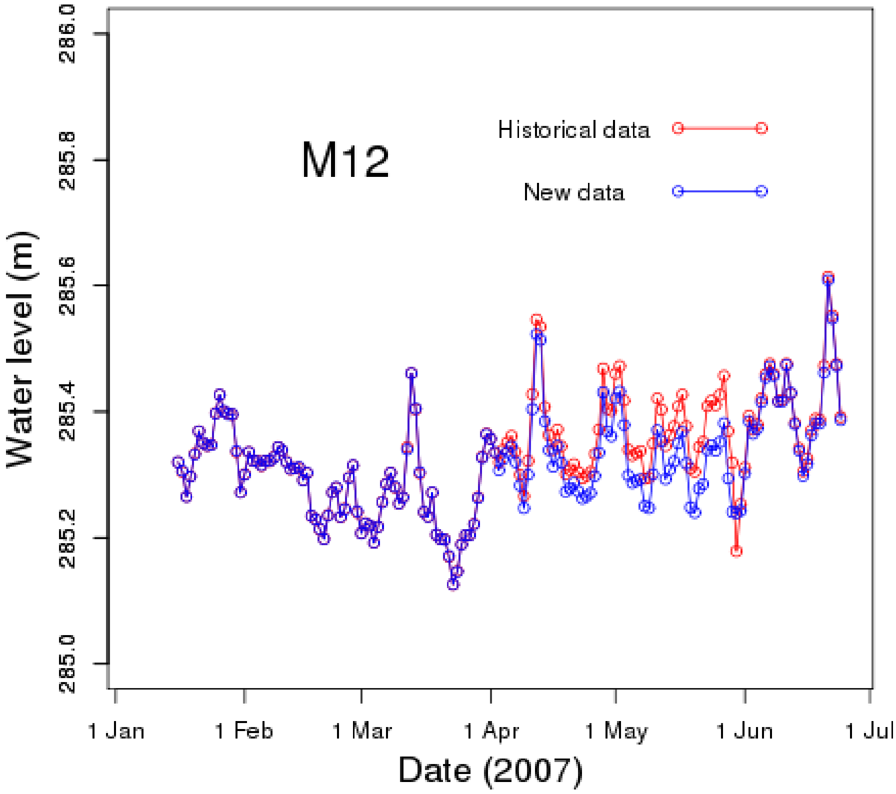

Figure 3.1 Data overlap for M12. The two sets of data show a difference of up to about 0.03 m between early April and late May 2007.

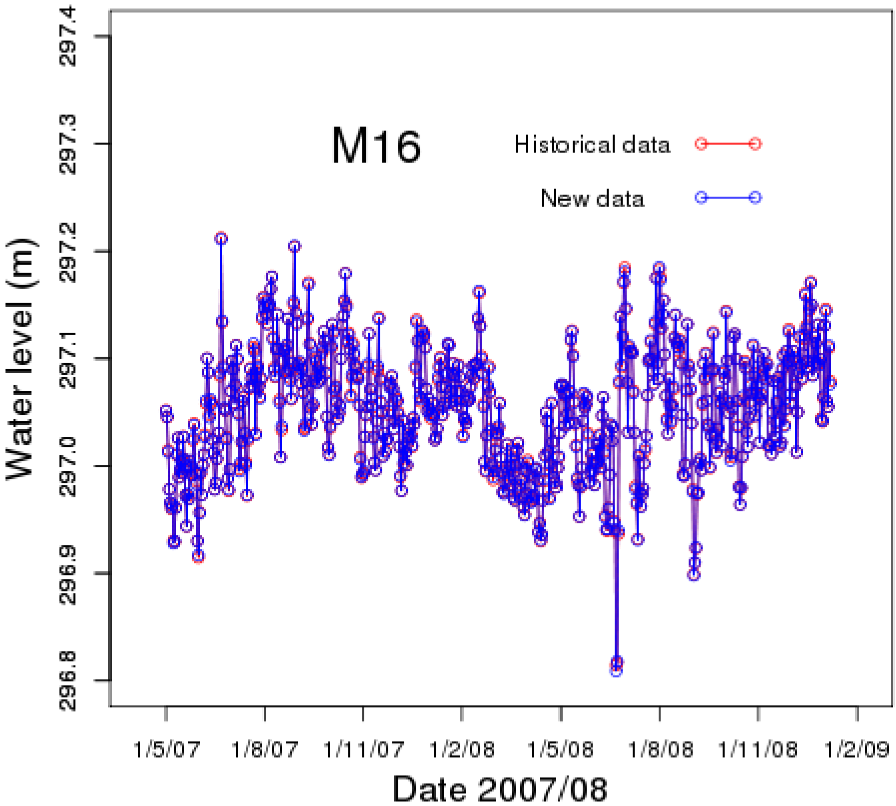

Figure 3.2 Data overlap for M16. The two sets of data show no significant difference over the period of overlap.

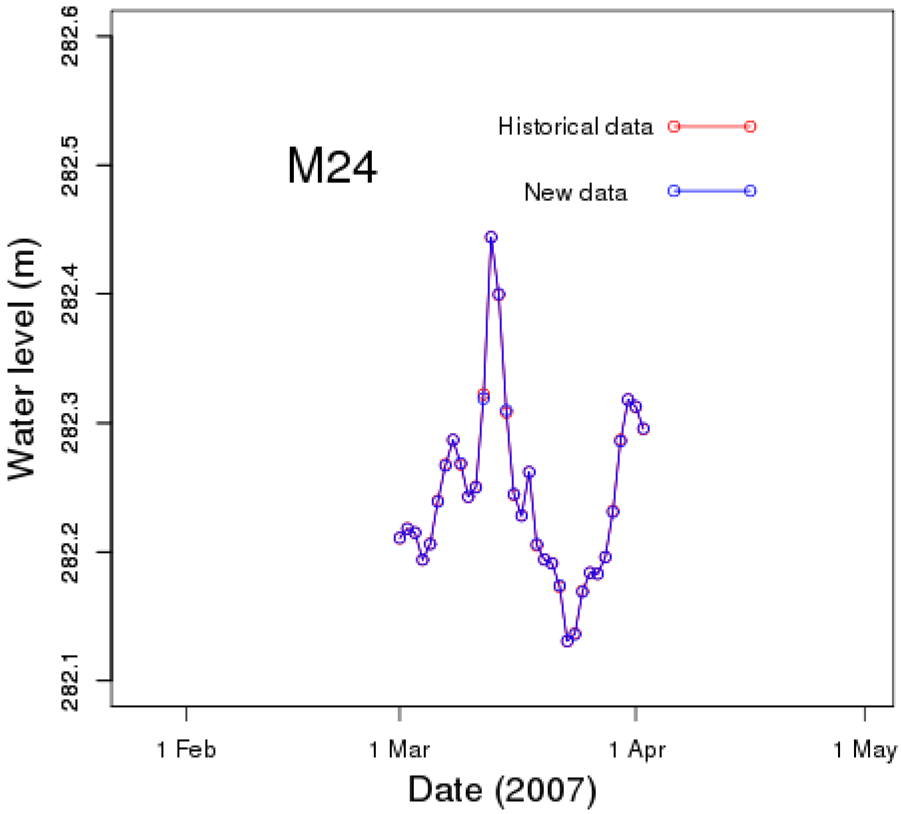

Figure 3.3 Data overlap for M24. The two sets of data show no significant difference over the period of overlap.

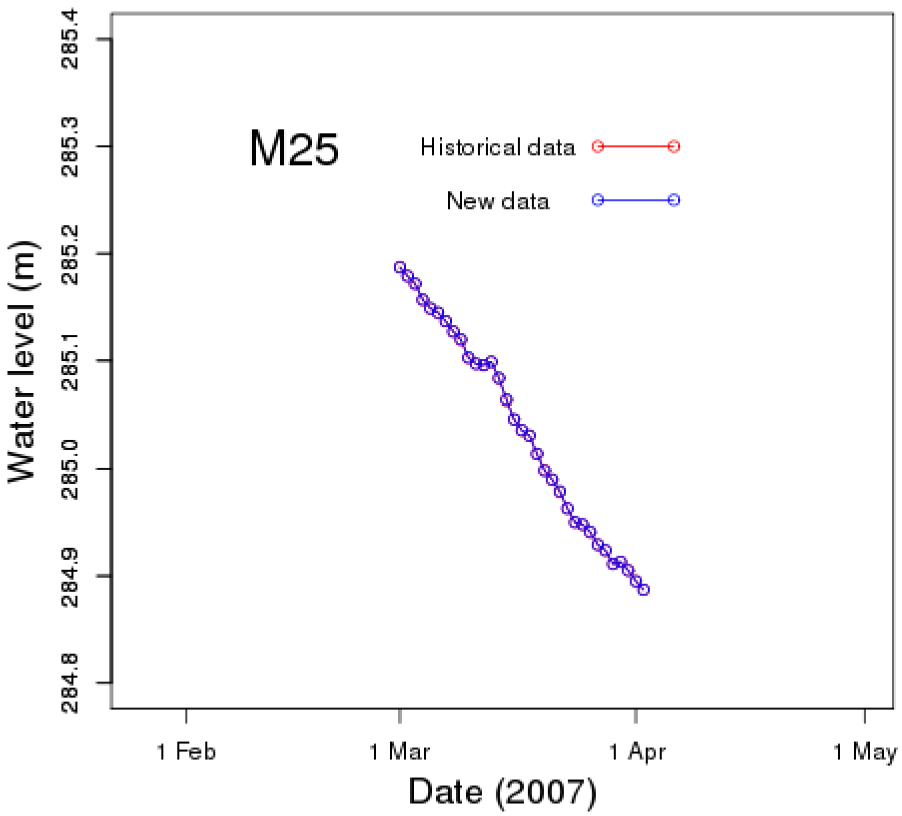

Figure 3.4 Data overlap for M25. The two sets of data show no significant difference over the period of overlap.

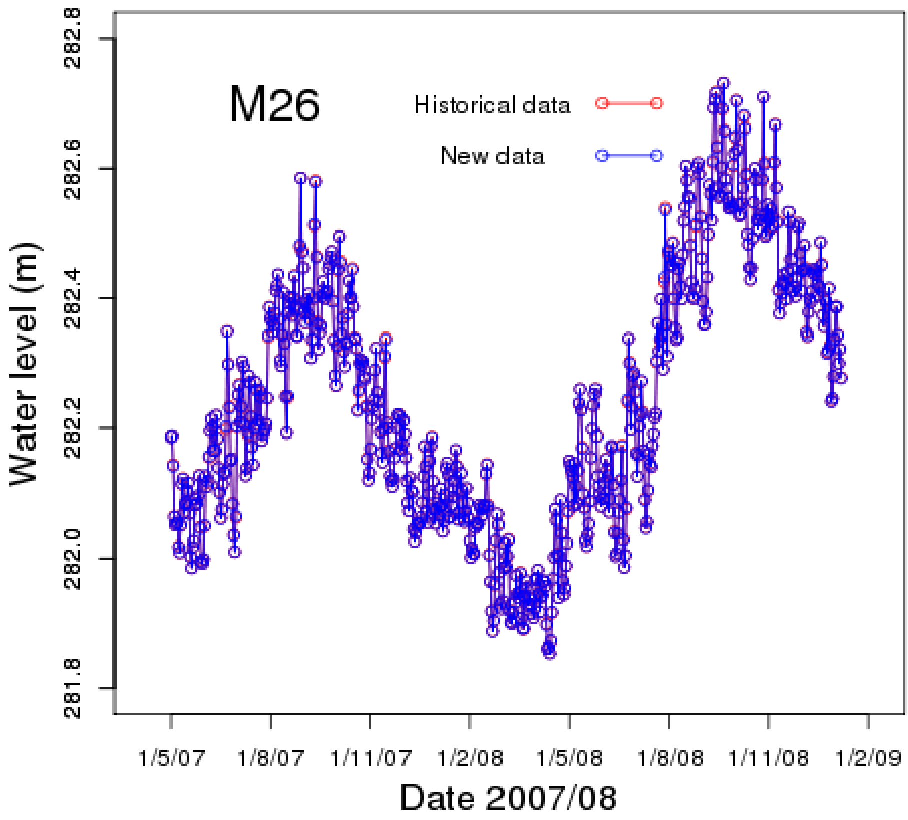

Figure 3.5 Data overlap for M26. The two sets of data show no significant difference over the period of overlap.

3.3 M-WELL WATER LEVELS WITH BAROMETRIC RESPONSE REMOVED

All of the M-wells show some response to barometric pressure variations, and to best analyse the water level data these must be removed. The statistical technique for doing this is described in Appendix 1 of Kissling (1998), and consists of regressing the *differenced* daily water levels and barometric pressures against one another. The differenced data is formed by taking the difference between each daily data value and the corresponding one for the day before. The method is robust against missing values in the data, and makes no assumptions about the reservoir response. This process effectively cleans the data of the unwanted barometric responses and reduces the apparent noise.

For this analysis the wells have been divided into two groups, based on the length of data recorded at each well. The Group A wells, comprising M1, M12, M16 and M24 (Figures 3.6 to 3.11) have the longest records, with M1, M12 and M16 dating from the early-mid 1980s and M24 the mid-1990s. The Group B wells (Figures 3.12 to 3.16) are more recent, with the first data recorded at M25 in 2003, followed by M26 (2006) and M27 and M28 (2009). To aid comparison, the two groups are each plotted with separate scales – Group A from 1980 to 2015 with a vertical range of 4 m, and Group B from 2000 to 2015 with a vertical range of 2 m.

Of the wells in Group A, M1, M12 and M24 all penetrate the shallower Rotorua Rhyolite aquifers, while M16 is in the deeper Rotorua Ignimbrite. They are geographically widespread, with M1 and M12 near to each other in the north of the city, while M16 and M24 are both within the 1.5 km Exclusion Zone centred on Pohutu Geyser.

Of these wells, M1, M12 and M16 showed increases in water level on the order of 1 m or more immediately following the Bore Closure Programme in 1986 but following this initial recovery, all wells (including M24) have continued to vary by up to about 0.5 m over periods of several years. This is perhaps surprising, given the controls placed on net withdrawal of fluid from the Rotorua Geothermal Field put in place by the Rotorua Management Plan. It seems probable that these are largely *natural* variations in the water levels. The nature of these variations is important for understanding the behaviour of the Rotorua geothermal reservoir.

Despite the clear differences between the longer term water level histories of these wells, they do show some common features. The most obvious one is the broad minimum in the water levels of M1, M12 and M24 which occurs between 2005 and 2010 (Figure 3.10). This suggests that there are some field-wide trends in the water levels. This signal is absent from M16, which shows instead a small downward trend over this period, with a weak yearly seasonal modulation. Another common feature of these wells (also on Figure 3.10) is a broad declining 'plateau' in the water levels from 2005-2007 and a large spike just prior to 2000. Again, M16 does not show this feature.

The heavy rainfall events in 2011 shown in Figure 2.2 offer a good opportunity to assess the effect of rainfall on the water levels. Figure 3.11 shows barometric-corrected water level data for M1, M12 and M24 from 2010 to 2012, together with the rainfall for the same period. We first note that the three water levels are quite similar, indicating (as Figure 3.10 does) that there is a common field-wide influence in all of these wells. The changes in all water levels corresponding to the heaviest rainfall events suggest that rainfall does have an immediate impact on the geothermal aquifers.

The largest changes occur at the beginning and end of 2011, and less pronounced ones in response to clusters of smaller rainfall events, for example in mid-late May 2010 and July/August 2012. Evidently, rainfall is responsible for much of the short-period variation in the water levels. The responses generally grow very quickly, but decay more slowly – for example, the high water levels persist for several months following the large rainfall events in early/late 2011. For the smaller responses, the growth is slower and water levels drop to 'ambient' in one or two months. It is clear that the rainfall plays an important role in the short to medium term water level variations. The longer timescale (several years), large amplitude variations (on the order of 1 m, as shown in Figures 3.6 to 3.9) show no obvious correlation with the yearly-averaged rainfall and are more likely to be associated with changes in the geothermal field.

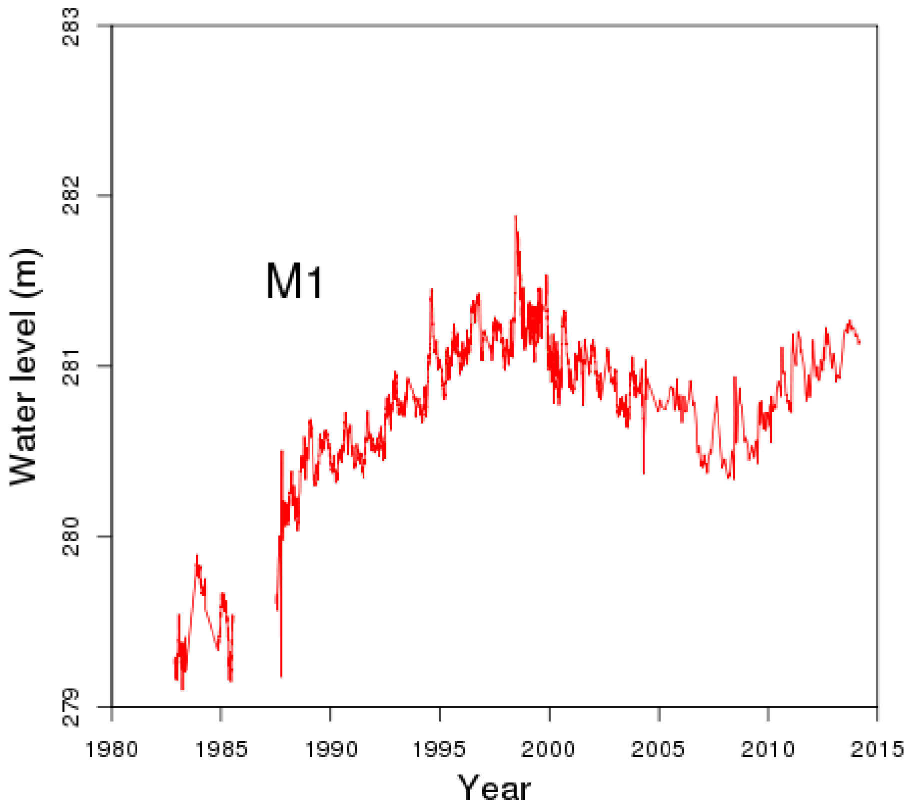

Figure 3.6 Water level in M1, with barometric response removed.

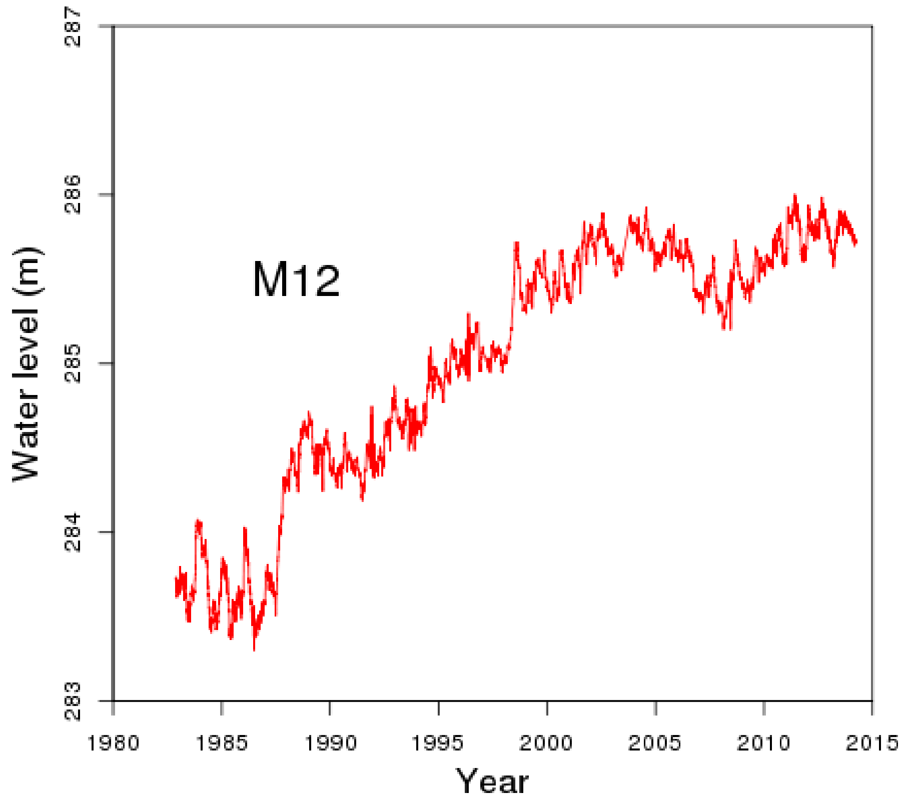

Figure 3.7 Water level for M12, with barometric response removed.

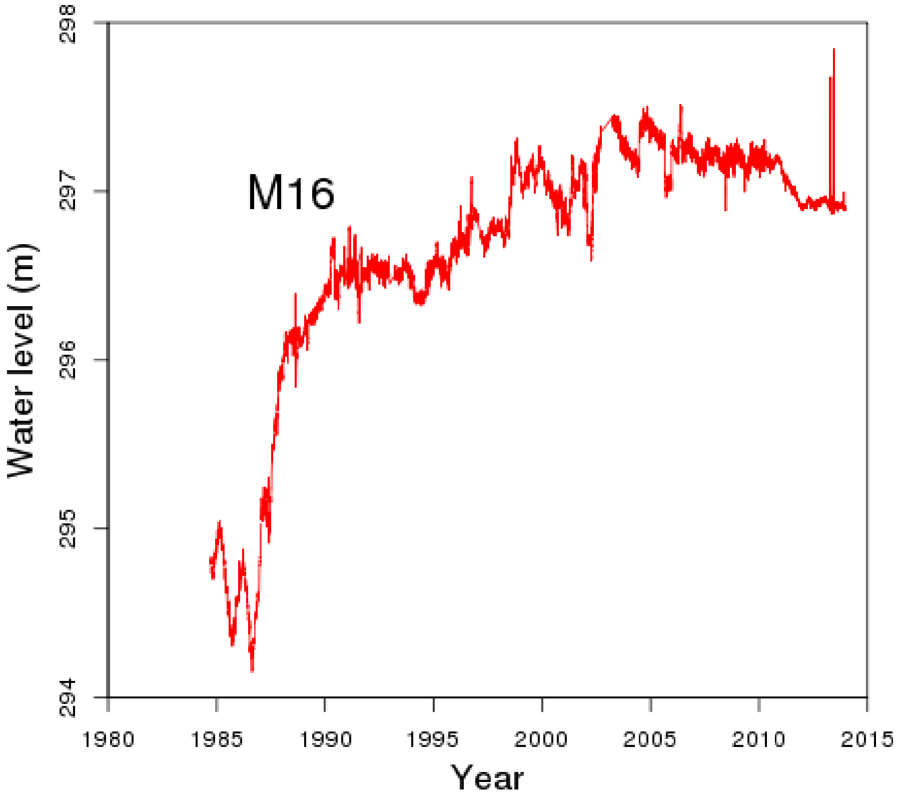

Figure 3.8 Water level for M16, with barometric response removed.

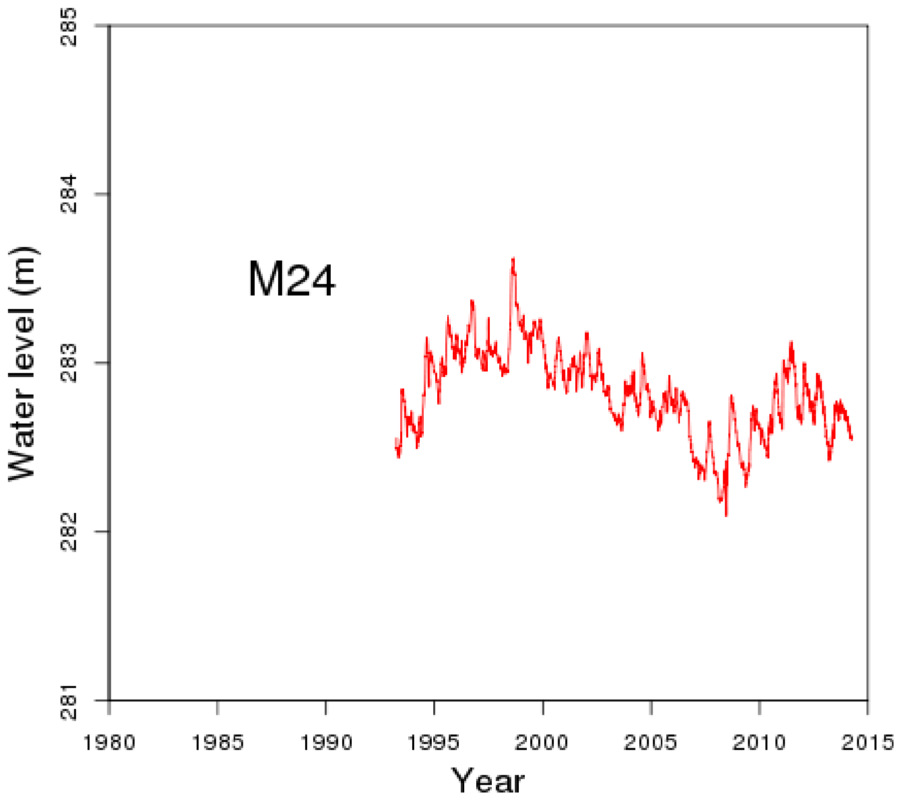

Figure 3.9 Water level for M24, with barometric response removed.

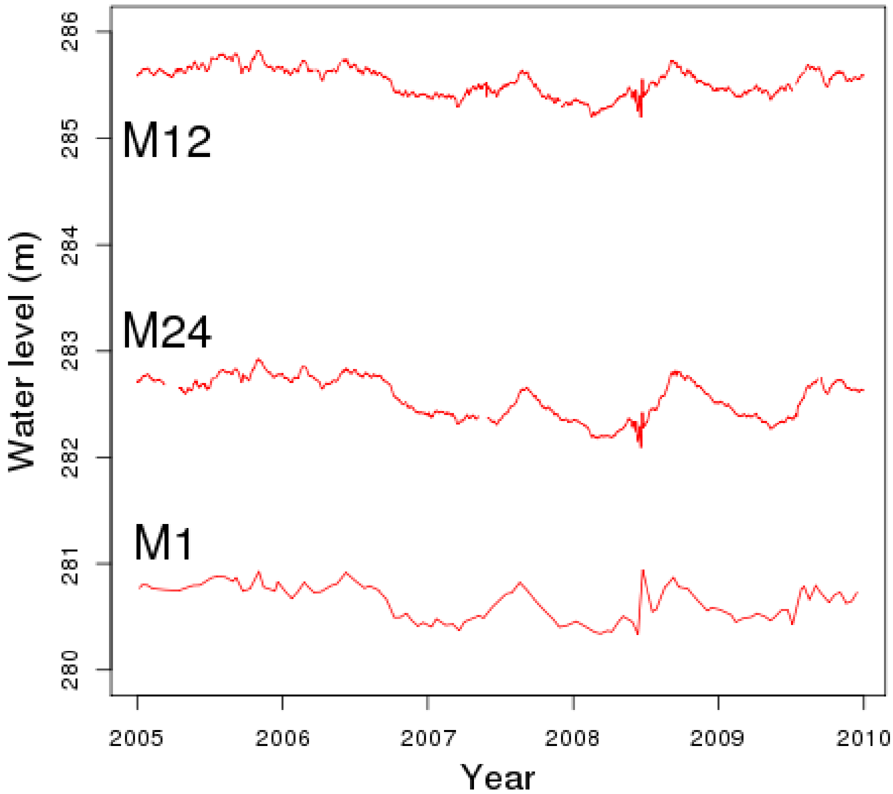

Figure 3.10 Water levels for M1, M12 and M24 showing the common behaviour between 2007 and 2009.

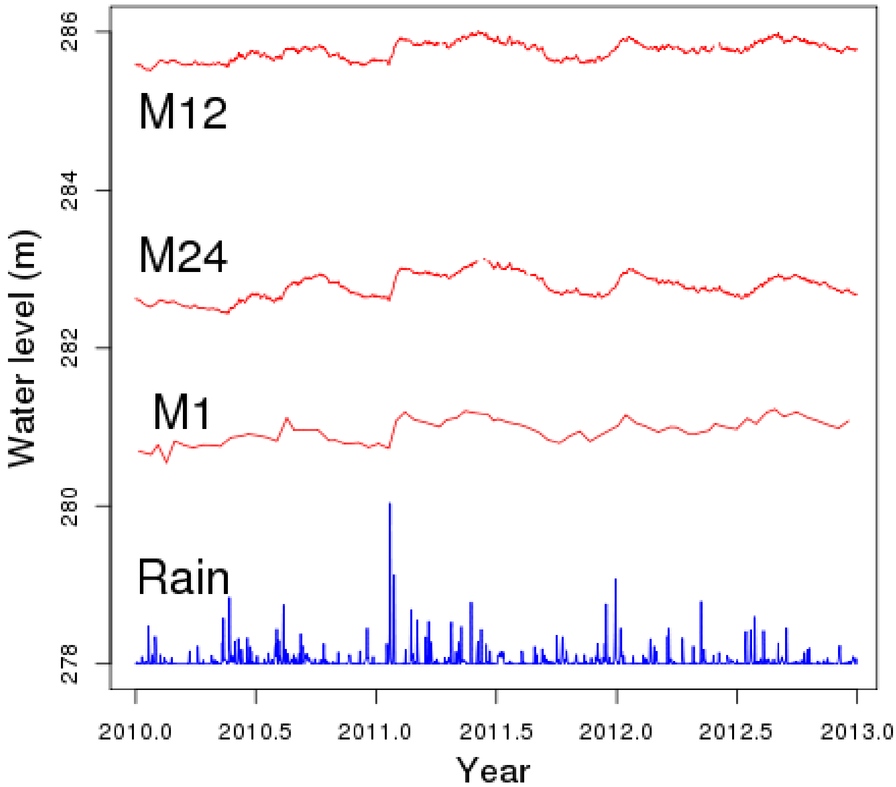

Figure 3.11 Comparison of water levels in M1, M12 and M24 and rainfall for the period 2010 to 2012. The heaviest rainfall event, in early 2011, is coincident with a step change in the water levels of all three wells. The rainfall is scaled to fit onto the figure, but for reference, the highest peak in early 2011 corresponds to 200 mm/day.

In Group B the wells M26, M27 and M28 penetrate into the rhyolite aquifer, while M25 is completed in deeper ignimbrite. Like the Group A wells, they are distributed throughout the city – M26 lies within the Exclusion Zone about 900 m from Pohutu Geyser, M25 is in the Ngapuna area and M27 and M28 are to the north and close to M1 and M12 respectively – they are the intended replacements for these wells.

Figures 3.12 to 3.15 show the water level histories for the Group B wells, M25, M26, M27 and M28. These wells sample a more recent period during which the Rotorua geothermal field has been in a more stable state – net fluid withdrawal was smaller and more regulated, and the field itself mostly recovered from transient effects caused by the bore closures in the 1980s.

M25 (Figure 3.12) has a water level record which is unlike that of any other monitor well. Data for this well was not collected for approximately one month starting 31st January 2012 and on resumption of data collection (March 6th 2012) the water levels showed an initial transient lasting about two weeks (visible on Figure 3.12) before finally settling at about 0.6 m above the previous readings. The data shown on the plot following this stoppage have been corrected by this amount. In recent years M25 has had a stable level with variations of the order of 0.1 m or less, but the water level shows none of the short period variations of the other monitor wells. M25 is the deepest well in the Monitoring Programme (241 m), and the ignimbrite aquifer it taps is not affected by near-surface effects as much as the rhyolite wells.

Despite the short periods of data coverage, it is useful to look for common behaviour and the influence of heavy rainfall events in the water levels for the Group B wells. Figure 3.16 shows the water levels for M26, M27 and M28 for the period 2010 to 2012, together with the rainfall record for the same time. This figure reveals a common behaviour between the wells, and also that they have similar responses to high rainfall events – an immediate rise in level, which persists for a period of a few months before decaying and being lost in the background water level variations. As with the Group A wells, this signal is clouded by the presence of irregular, quasi-annual variations in water level.

It has been noted that the water levels for wells within each of Groups A and B have a strong similarity, but until now (Figure 3.17) no comparison has been made between these groups. Due to the very different behaviour of the two Ignimbrite wells M16 and M25 they are excluded from Figure 3.17 and the figure shows data only for the wells which penetrate the rhyolite aquifers. The vertical scale has been removed and the individual records spaced for clarity. The figure shows that much of the short term (less than a few months) water level variation is common to all of these wells, regardless of their location, and that heavy rainfall events have a large impact on the variations.

This is the first time since the start of the Rotorua Monitoring Programme that such clear correlations have been observed between water levels in so many of the rhyolite monitor wells. This suggests that the water levels in the Rotorua Geothermal Field have entered a state where the natural variations are more apparent.

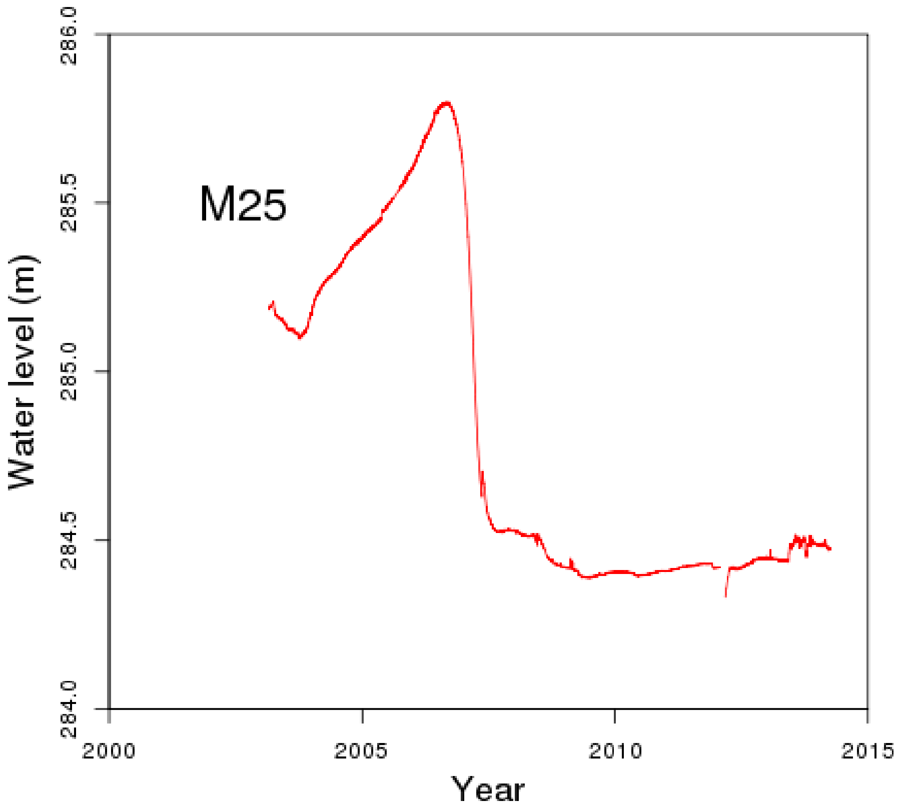

Figure 3.12 Water level for M25, with barometric response removed. The water levels after March 2012 have been adjusted downward by 0.6 m to account for changes in the data following remedial work on the well.

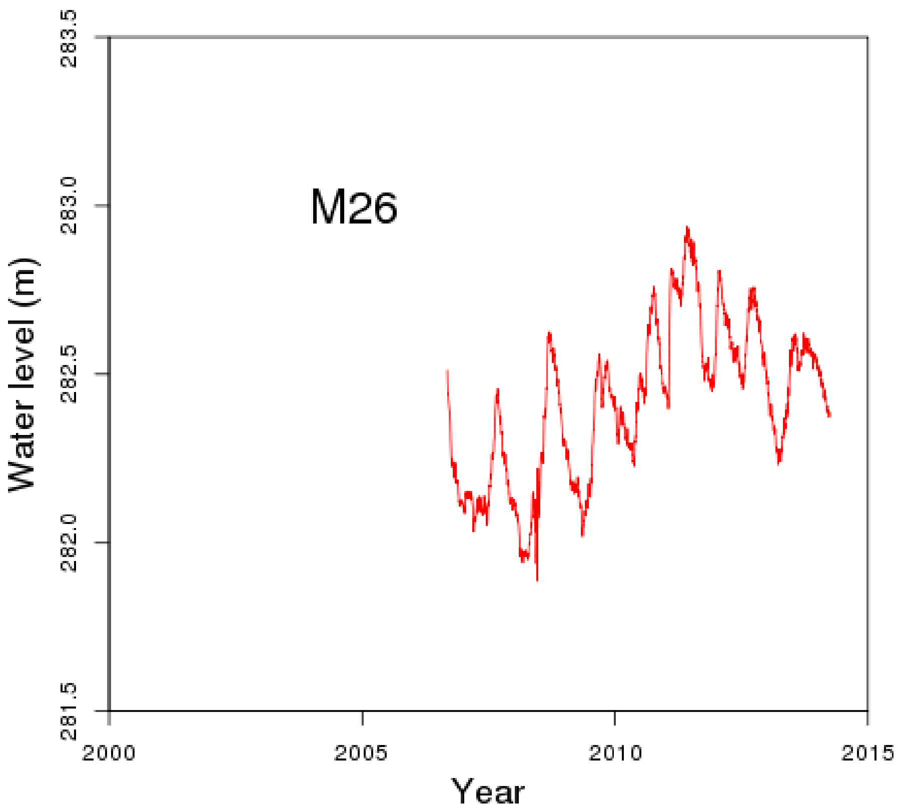

Figure 3.13 Water level in M26, with barometric response removed.

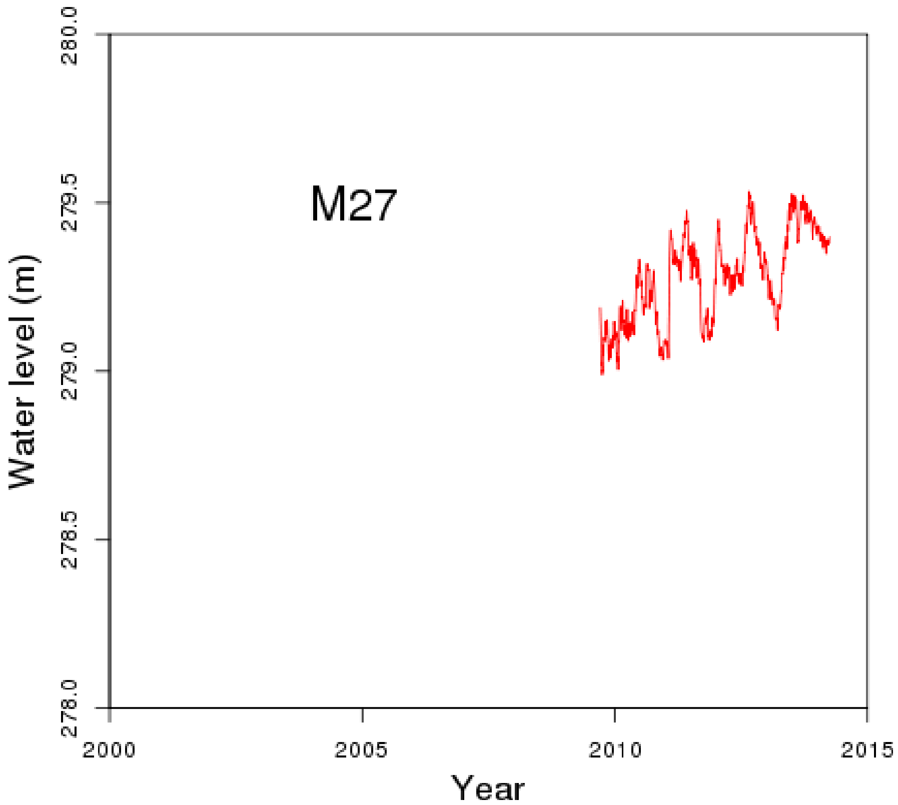

Figure 3.14 Water level in M27, with barometric response removed.

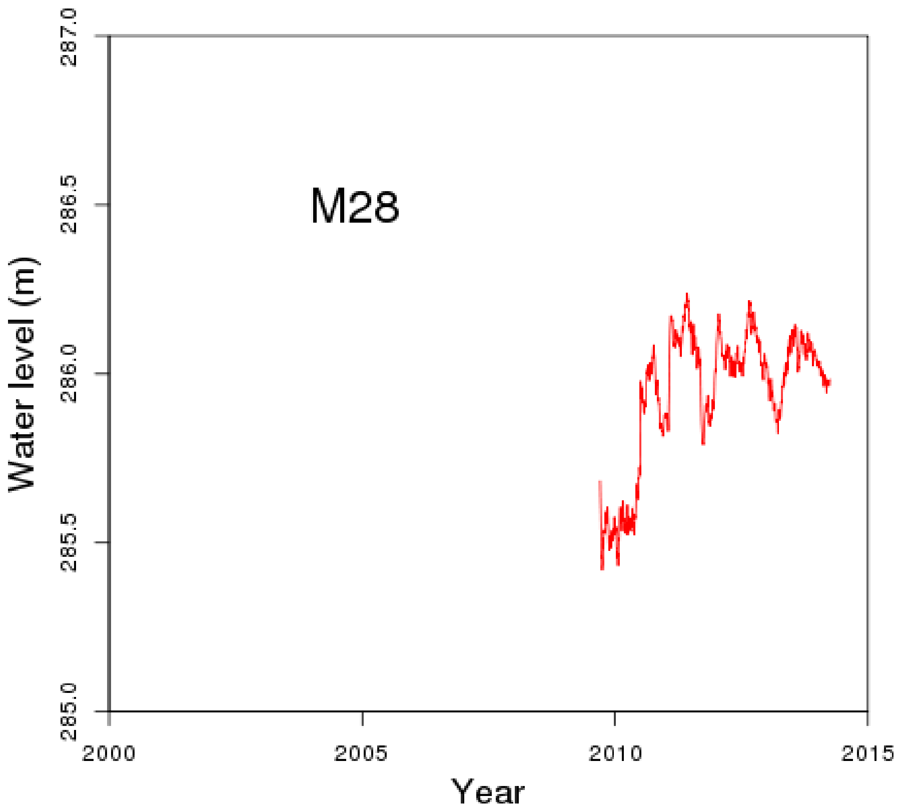

Figure 3.15 Water level in M28, with barometric response removed.

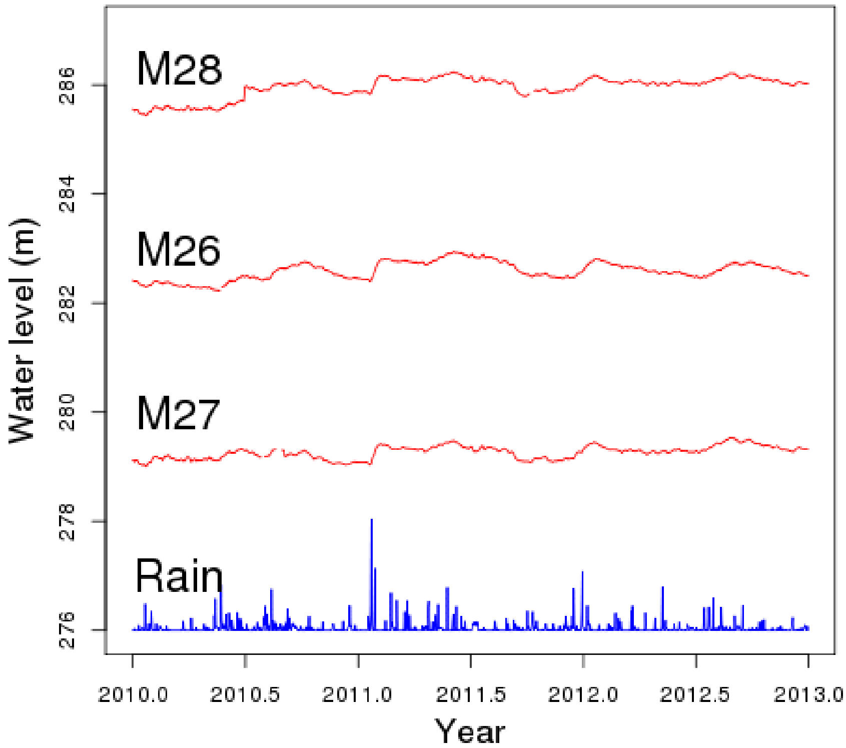

Figure 3.16 Comparison of water levels in M26, M27 and M28 and rainfall for the period 2010 to 2012. The heaviest rainfall event, in early 2011, produces a noticeable change in the water levels of all three wells. The rainfall is scaled to fit onto the figure, but for reference, the highest peak in early 2011 corresponds to 200 mm/day.

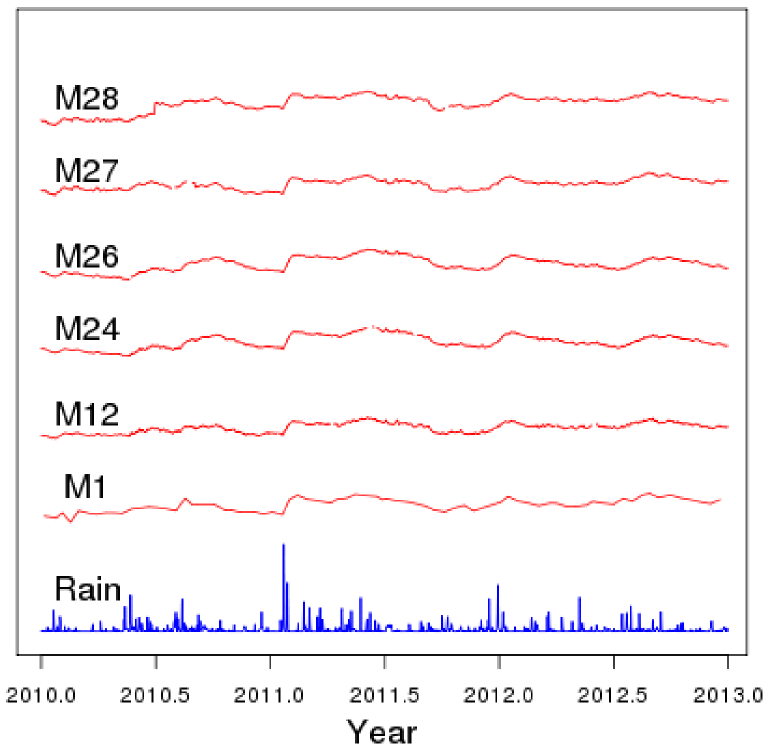

Figure 3.17 Comparison of water levels in the monitor wells M1, M12, M24, M26, M27 and M28 for the period 2010 to 2013. All of these wells penetrate the Rotorua Rhyolite aquifers. The water level variations show clear correlations, despite the wells being widely distributed throughout Rotorua City. The rainfall is scaled to fit onto the figure, but for reference, the highest peak in early 2011 corresponds to 200 mm/day.

3.4 M-WELL TEMPERATURE PROFILES

One of the possible causes of water level variations in the monitor wells is temperature changes within the wells. The temperature profiles are measured at approximately yearly intervals, together with spot measures of the *relative* water levels at the same time. These are made manually and refer to the distance down to the water level from a datum near the wellhead (G. Timpany, pers. comm). For the Group A wells (M1, M12, M16 and M24) there were between 21 (M24) and 30 (M12) profiles available, and for the Group B wells between 5 (M27 and M28) and 11 (M25).

Due to the large number of profiles available for most wells, it was decided to not show plots of all of them in this report. Past experience has shown that there is very little variation between the temperature profiles for a given well, and showing them all on the same plot is confusing and makes it difficult to see any changes that have occurred. Instead, three plots are shown for each well (e.g. Figures 3.18, 3.19 and 3.20 for M1). The first shows only the first and last temperature profiles, the second the variation of water level with time and the third the temperature history at some selected depths within each well.

The reason for doing this is twofold. Choosing the first and last profiles is useful in that the largest possible time interval can be used to identify the longer term changes in the temperature profiles. Conversely, a short-lived temperature deviation in a well may not be detected in the profile plots, but will be seen in the corresponding temperature history plot. Of course this relies on the duration of the temperature deviation being greater than the sampling interval, which is typically about one year here. For convenience, wells are again classified into two groups, A and B.

The relative water levels for Group A wells M1, M12, M16 and M24 are shown in Figure 3.19, 3.22, 3.25 and 3.28 respectively. In this group, both M1 and M16 show large drops in relative water level (2 m and 4 m respectively) in the early-mid 1990s. These are not seen in the daily ‘automatic’ water level data shown in Figures 3.6 and 3.8 and so must be viewed with some scepticism. Similar large but short-lived excursions in the relative water levels, e.g., in M24 in 2000 and in M12 in 2000 and 2003, also do not appear in the daily data. Unlike the automatic data, the relative water levels are single spot measurements which are isolated in time and cannot be verified against other, nearby data. In addition, it is possible that the act of measuring the relative water level somehow disturbs the water level itself, potentially leading to an unreliable result.

Disregarding these apparently discordant data, the relative water levels in all of the Group A M-wells show a reasonable *inverse* correlation with the daily data. This is because the relative levels are measured downward from a datum in each well. Thus, the relative levels for M1 after 1996 show a broad peak reaching a maximum in 2007, whereas the daily data show a broad trough of similar magnitude (0.5 m) over the same interval. Similarly, for M24 the relative water levels exhibit the same general (but opposite) trends as the daily levels. For M12 and M16, the relative levels show general declines of about 1 m from the early 1990s to the present, while simultaneously the daily data for both increases by a similar amount. It is concluded that the relative water levels are generally consistent with the automatic daily data, apart from a small number of discordant points which appear to be in error.

Since 1991, the M1 temperature profiles (Figure 3.18) show only small differences and the temperature histories (Figure 3.20) remain quite steady. Over the same period, the relative water levels (Figure 3.19) vary by order of 0.5 m (disregarding the large drop prior to 1996).

M12 (Figure 3.21) shows heating of about 10°C below 20 m, and this is confirmed by the continuously upward trending temperatures (Figure 3.23) over the same depth range.

Figure 3.23 also shows two short-lived heating ‘events’ in 2003 and 2008 which temporarily raised the temperatures in those years. A steady decline in relative water level (Figure 3.22) has occurred, with two large (2 m) downward excursions in the early 2000s.

The M16 temperature profiles (Figure 3.24) show slight cooling between 1991 and 2013, but the temperature histories (Figure 3.26) reveal that some changes occurred in this period. In particular, another heating event raised the temperatures between 1992 and 1996, and cooling at 100 m depth by ~10°C is seen between 2011 and 2013. The relative water level in M16 (Figure 3.25) shows a general decline from 1992 to 2013, with variations about this trend of up to ~0.2 m.

The M24 temperature profiles (Figure 3.27) show a cooling of about 5°C between 1992 and 2013, and this seems to be confirmed as a long term trend by the temperature histories (Figure 3.29). The relative water level (Figure 3.28) shows variations up to 0.5 m, apart from one large drop in 2000 which may be an erroneous measurement.

The Group B wells (M25, M26, M27 and M28) behave no more consistently. Although the records for these wells are of much shorter duration, all show significant changes in relative water levels (Figures 3.31, 3.34, 3.37 and 3.40) of between 0.5 m and 2 m. For M25 the relative water levels correlate quite well with the daily water level data, but for the other wells the span of the data is too short and the sampling interval too large to see this clearly.

The temperature profiles for M25 (Figure 3.30) apparently show some heating (typically ~10°C) at depths above about 100 m and below 150 m, but the presence of long term trends is not borne out by Figure 3.32, which shows fluctuating but overall steady temperature histories.

The M26 temperature profiles (Figure 3.33) exhibit a rather complex change with a combination of heating and cooling at different depths between 2007 and 2013. In particular the heating almost causes the temperature inversion below 140 m depth to disappear. This is seen clearly in Figure 3.35, where the temperature histories at 120 m and 180 m in this well switch places in 2011.

The profiles for M27 (Figure 3.36) show little change, although the temperature histories (Figure 3.38) show that heating of about 4°C occurred throughout the well between 2009 and 2010. This has subsequently diminished again, although the water column remains slightly warmer on average than it was in 2009.

The M28 profiles (Figure 3.39) show that it has been progressively heating toward the surface by up to 10°C between 2009 and 2013. The temperature histories (Figure 3.41) confirm this, but show the temperatures peaked in 2011/2012 and fell again in 2013. M28 seems to have been subject to the same heating event as M27 between 2009 and 2010.

The temperature profile data, in combination with temperature histories and relative water level measurements over the same time periods, show a plethora of different and apparently inconsistent behaviours. All of the wells show variations of between 0.5 and 2 m in relative water level and temperatures which fluctuate over periods of (say) up to a few years. Underlying these fluctuations, four of the wells (M1, M16, M25 and M27) show approximately steady temperature histories while the others (M12, M24, M26 and M28) exhibit longer term trends of both heating and cooling in their temperature histories.

This shows that temperature changes are occurring across the geothermal field, perhaps on timescales of a few years to a decade. The two groups of wells are equally widely distributed around Rotorua City so their locations offer no clue to this behaviour. There is also no clear correlation between temperature changes and the relative water levels.

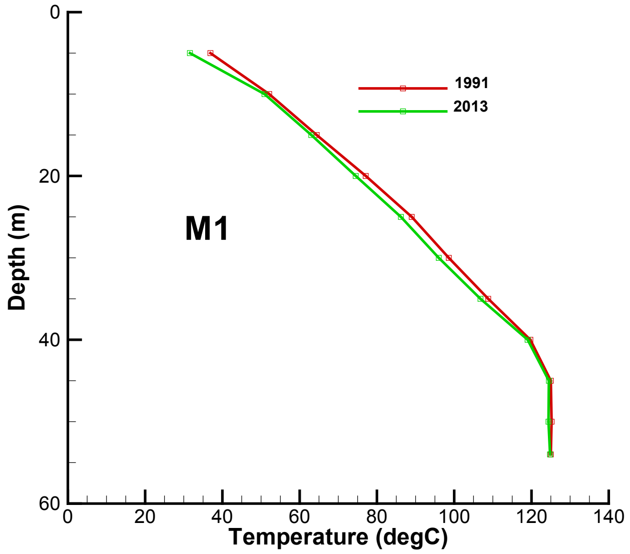

Figure 3.18 Temperature profiles for M1, from 1991 and 2013.

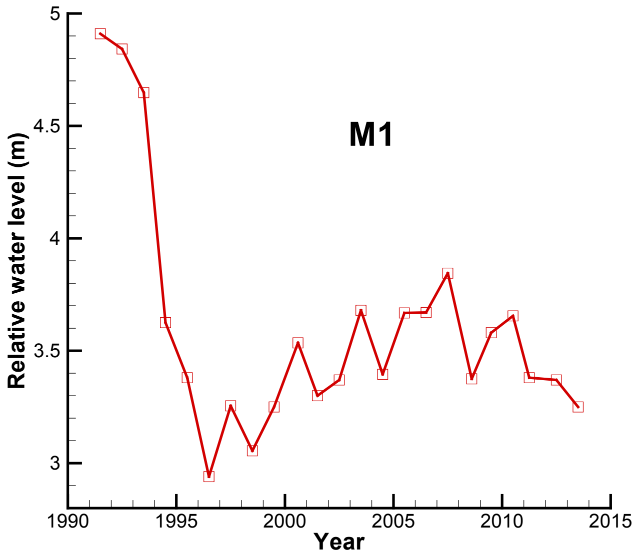

Figure 3.19 Variations in relative water level measurements in M1.

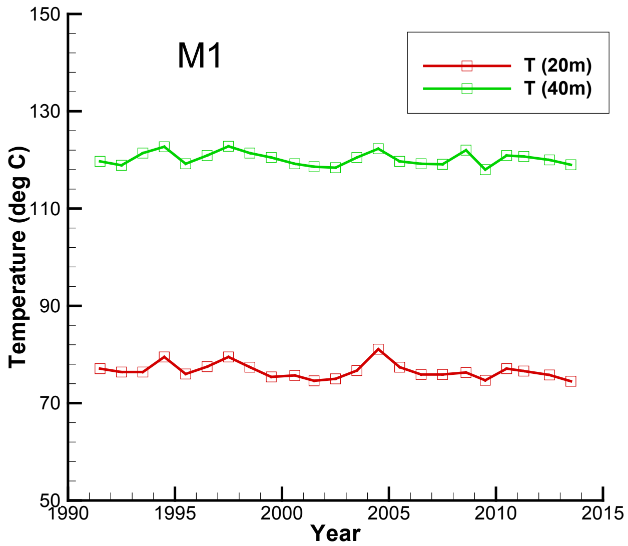

Figure 3.20 M1 temperatures at 20 and 40 m depth versus time.

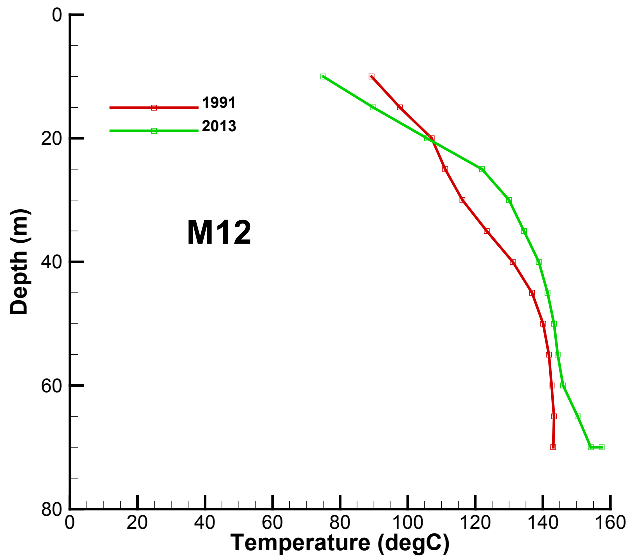

Figure 3.21 Temperature profiles for M12, from 1991 and 2013.

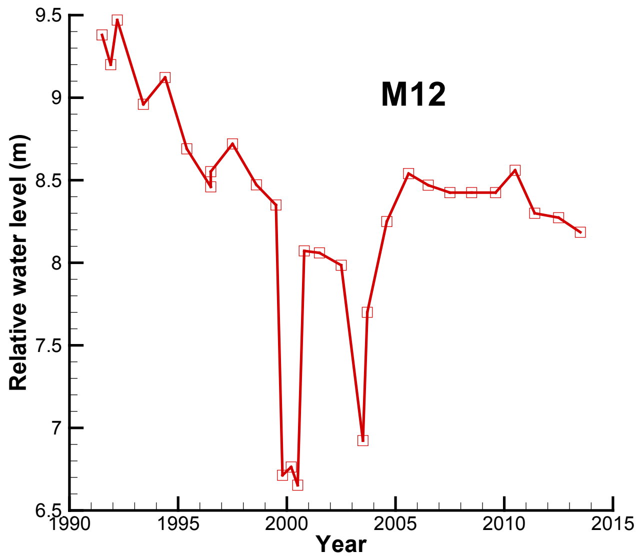

Figure 3.22 Variations in relative water level measurements in M12.

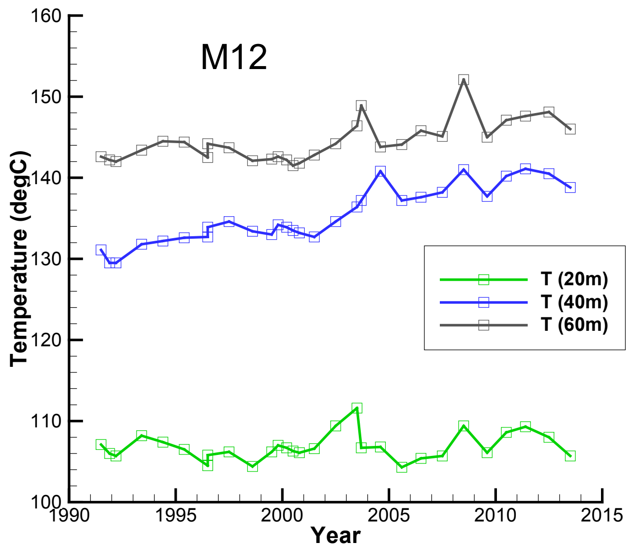

Figure 3.23 M12 temperatures at 20, 40 and 60 m versus time.

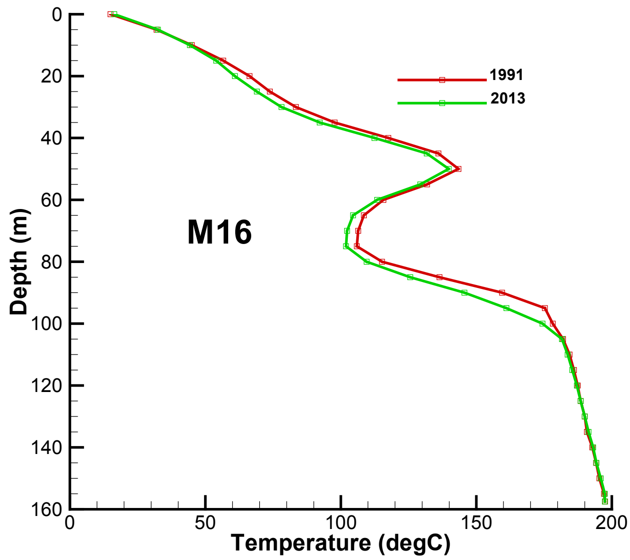

Figure 3.24 Temperature profiles for M16, from 1991 and 2013.

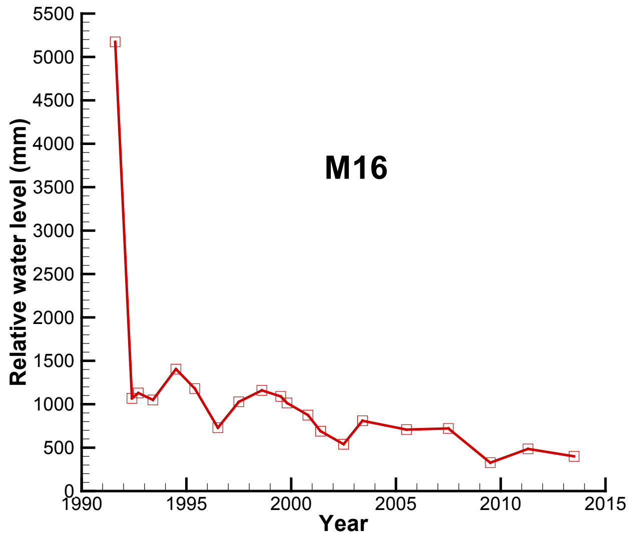

Figure 3.25 Variations in relative water level measurements in M16.

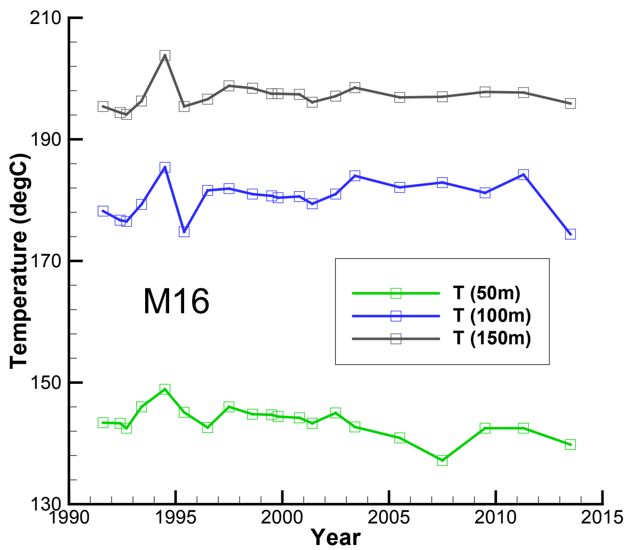

Figure 3.26 M16 temperatures at 50, 100 and 150 m versus time.

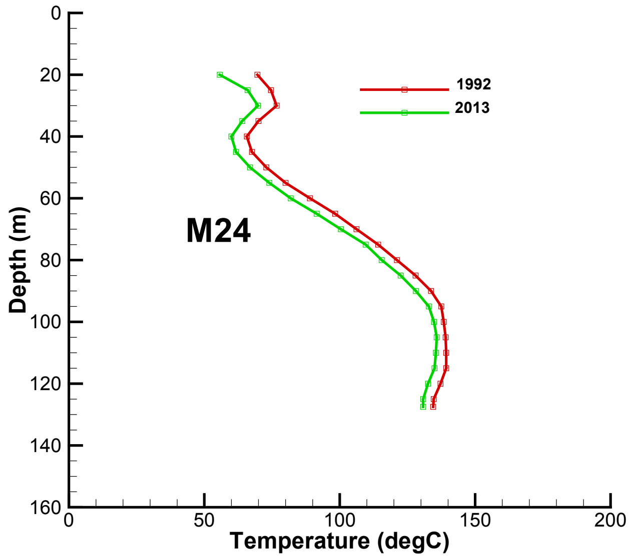

Figure 3.27 Temperature profiles for M24, from 1992 and 2013.

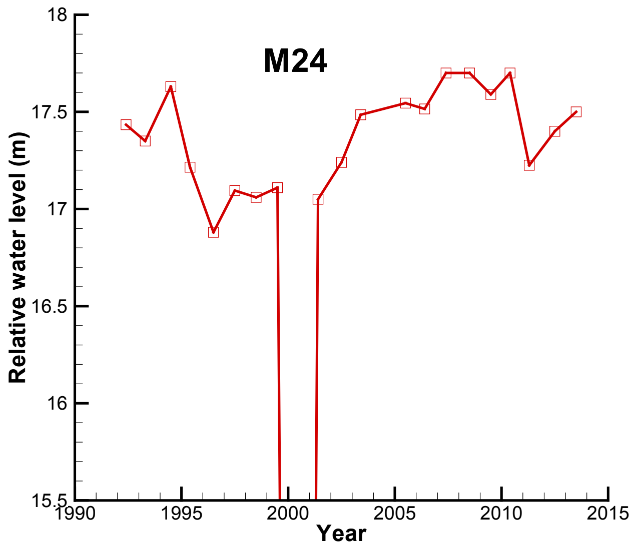

Figure 3.28 Variations in relative water level measurements in M24.

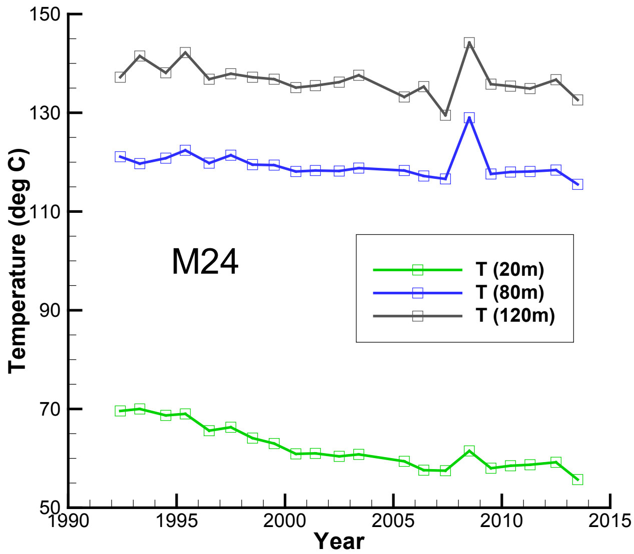

Figure 3.29 M24 temperatures at 20, 80 and 120 m versus time.

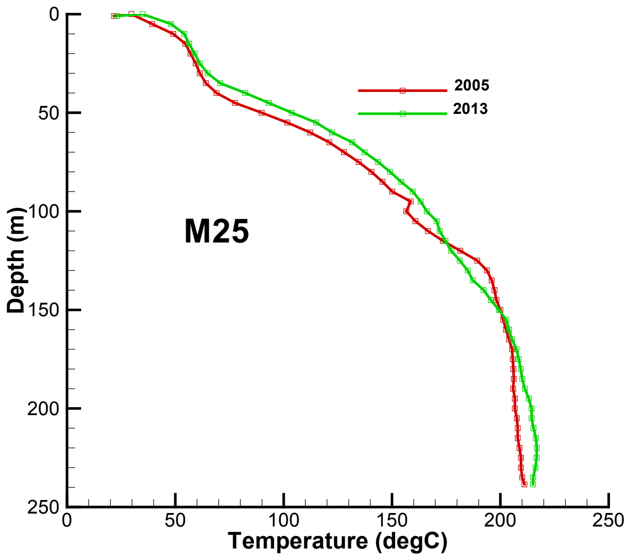

Figure 3.30 Temperature profiles for M25, from 2003 and 2013.

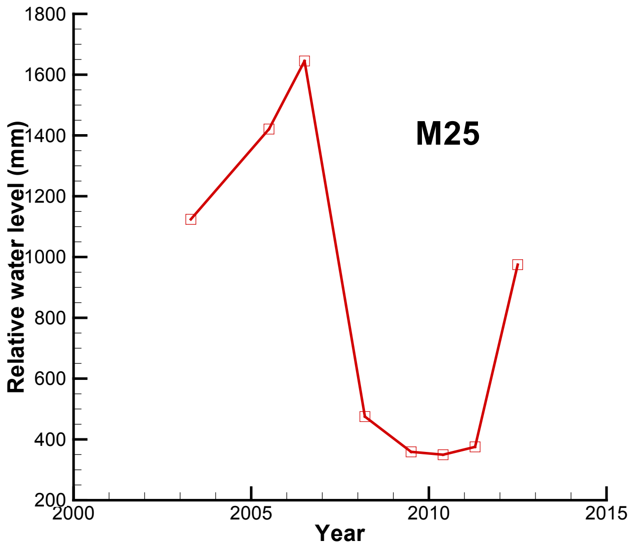

Figure 3.31 Variations in relative water level measurements in M25.

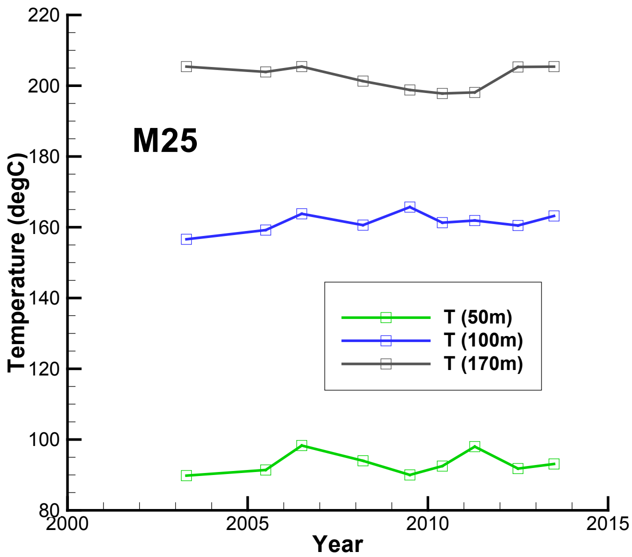

Figure 3.32 M25 temperatures at 50, 100 and 170 m versus time.

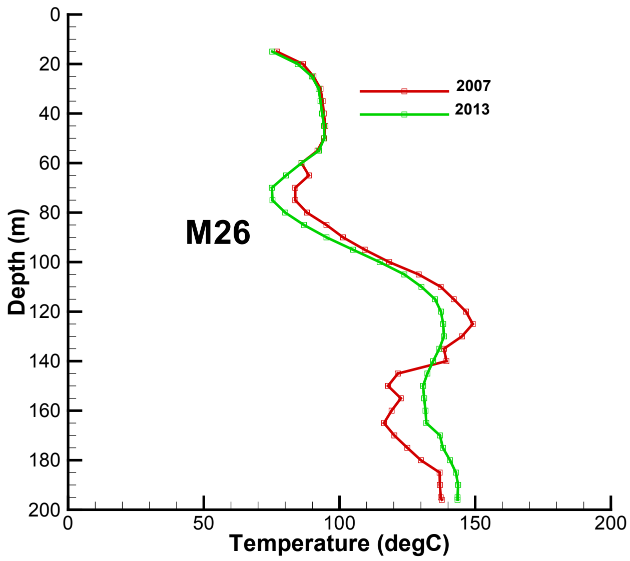

Figure 3.33 Temperature profiles for M26, from 2007 and 2013.

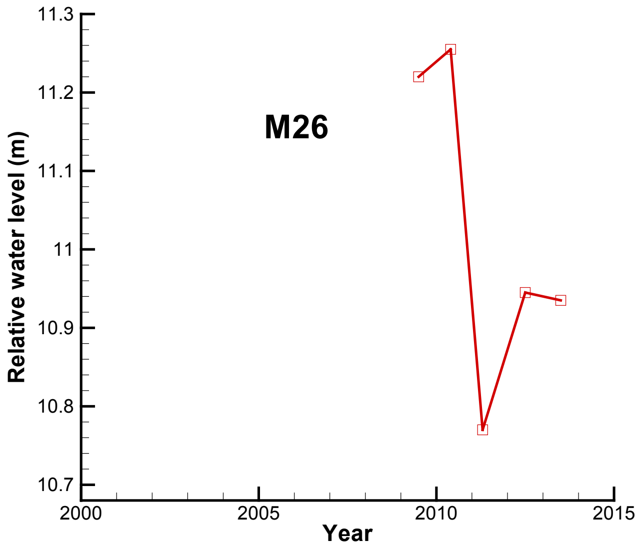

Figure 3.34 Variations in relative water level measurements in M26.

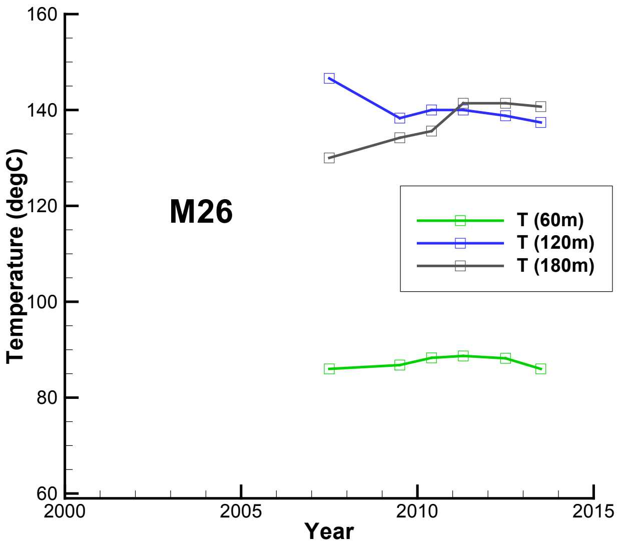

Figure 3.35 M26 temperatures at 40, 120 and 170 m versus time.

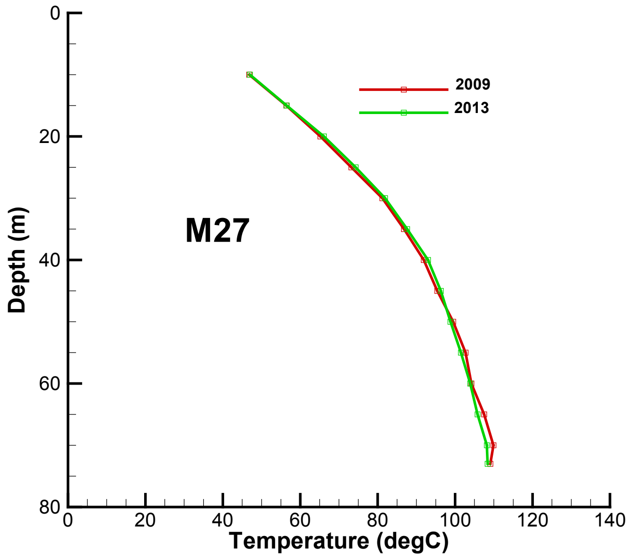

Figure 3.36 Temperature profiles for M27, from 2009 and 2013.

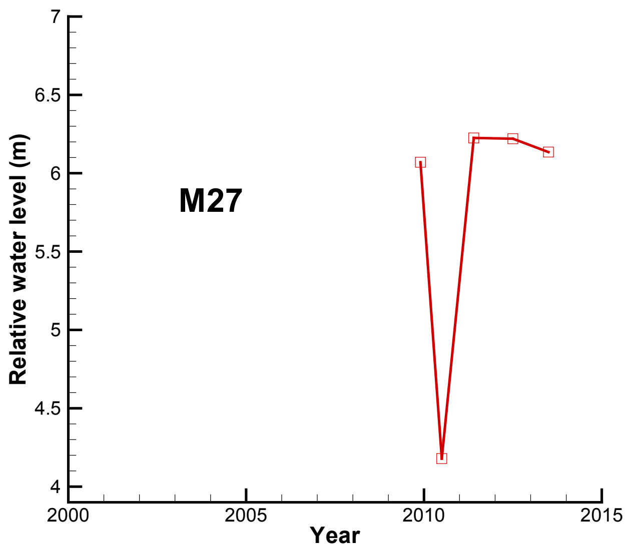

Figure 3.37 Variations in relative water level measurements in M27.

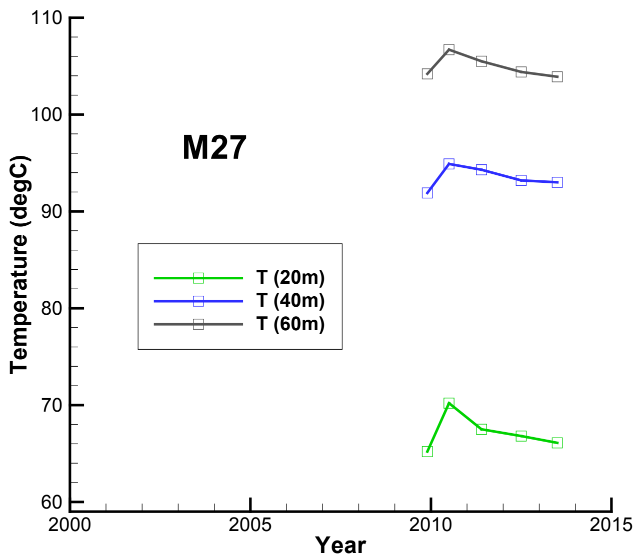

Figure 3.38 M27 temperatures at 20, 40 and 60 m versus time.

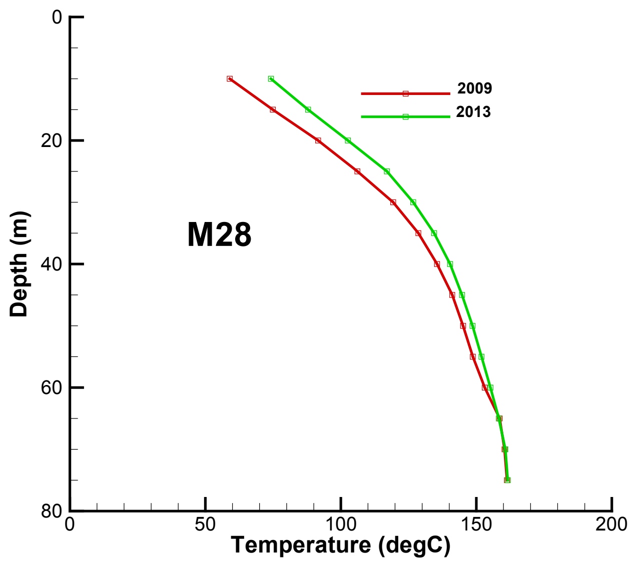

Figure 3.39 Temperature profiles for M28, from 2009 and 2013.

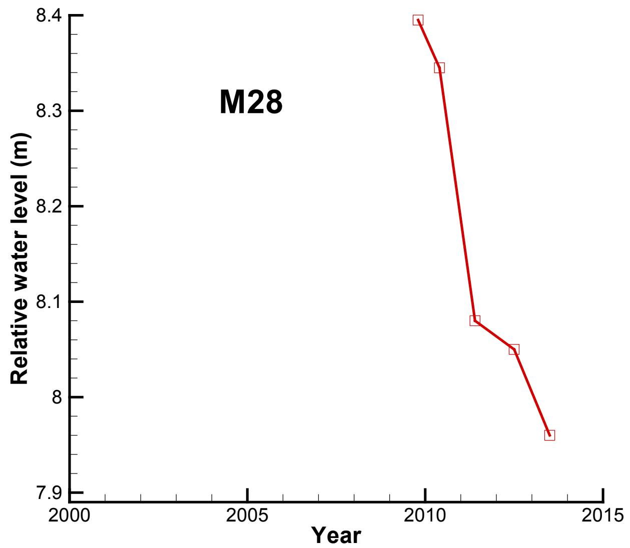

Figure 3.40 Variations in relative water level measurements in M28.

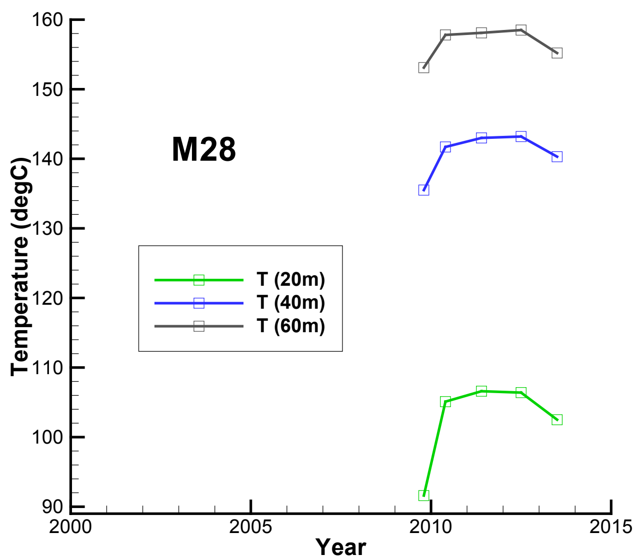

Figure 3.41 M28 temperatures at 20, 40 and 60 m versus time.

3.5 MAGWLs

The Rotorua Geothermal Management Plan describes the setting of Minimum Aquifer Geothermal Water Levels (MAGWLs) for some wells. These provide triggers so that some action will be taken if the water level in a monitor well drops below its MAGWL. As part of this update of the monitoring data we are reviewing the definition and applicability of the MAGWLs. In this section a methodology is provided by which new MAGWLs can be set for the new and existing wells in the Monitoring Programme.

The key assumption in defining the MAGWLs is that the geothermal surface activity is related to the reservoir pressure or water level. That is, if the reservoir pressures are reduced, there will be a corresponding reduction in surface activity. Thus, the MAGWL should represent a state of the geothermal field that corresponds to the minimal level of surface activity that is acceptable to the community.

Since the MAGWLs were originally set, surface activity in the Rotorua Geothermal Field has shown some recovery with respect to the early 1980s (Gordon *et al*., 2005). Furthermore, there is good evidence that the level of human-induced changes in the geothermal pressures is now much reduced when compared to the 1980s. The setting of new MAGWLs, if appropriate, can be anticipated to take both of these factors into account. In this section some options for setting new MAGWLs are discussed.

3.5.1 Coverage

Of the four M-wells which were originally assigned MAGWLs only M12 and M24 remain in the Monitoring Programme. This raises an important issue as to what constitutes adequate coverage of MAGWLs across Rotorua City.

Historically there were four MAGWLs assigned, of which three (M6, M16 and M24) were within the 1.5 km exclusion zone surrounding Whakarewarewa, with the fourth (M12) in Kuirau Park. Of these wells, M16 was located in the Rotorua Ignimbrite, while the others were in the shallower Rotorua Rhyolite. These wells provided good spatial coverage across the city, and sampled both of the important aquifers within the Rotorua Geothermal Field.

To maintain the original level of MAGWL coverage is feasible with the network of new and existing M-wells. MAGWLs could be assigned as follows:

- To M27 and M28, as replacements for M1 and M12 respectively, in the north of the city.
- To M24 and M26 within the exclusion zone and close to Whakarewarewa.
- To M25 at Ngapuna, and in the Rotorua Ignimbrite.

The selection of these M-wells offers excellent coverage over the city and provides some redundancy in the event of any well failing. The assignment of a MAGWL to M25 would provide a new and independent indicator of unusual and potentially significant water level fluctuations in the Rotorua geothermal reservoir.

3.5.2 Options for redefining MAGWLs for old wells

The methodology described in this section applies only to M12 and M24 – the only M-wells remaining have both long water level histories and assigned MAGWLs.

Originally the MAGWLs were defined as the minimum water level observed in each of the nominated wells during the five year period between 1989 and 1993. This definition led to

MAGWLs that were above the pre-bore closure water levels by some margin, typically between 0.5 and 1 m. This ensured that the water levels remained comfortably above the point where the surface features were known to be at risk.

An extension of this approach is proposed here for setting new MAGWLs – they can be set to ensure that water levels never fall below the levels in some selected time interval of the post-bore closure recovery of the Rotorua Geothermal Field. It should be emphasised that selecting an appropriate interval during the recovery is a subjective decision to be made by the Bay of Plenty Regional Council.

Examples of how time intervals for defining the MAGWLs might be selected are given in Table 3.2. This shows the advantages and disadvantages associated with each time interval. In the table the five year interval in the original MAGWL definition has been retained but there is no compelling reason to do this. The most important consideration is that the time interval selected contains a meaningful minimum water level which will act as a reliable trigger in the event that any unusual fall in water level occurs.

Lastly, it is worth noting that selecting a time interval starting in 2003 would mean that M25 could be assigned a MAGWL using this method.

Table 3.2 Examples of how time intervals for defining MAGWLs might be selected.

Interval	Advantages	Disadvantages
1989-1993 (original definition)	• No change required.	• Represents a period with surface activity that is less than today. • Unlikely that with current (2014) variations water levels will reach 1989-1993 levels.
2000-2005	• More than 10 years elapsed since the initial rapid recovery of geothermal pressures following the bore closures. • Recovery of surface features becoming evident but still uncertain.	• Insufficient water level history in many wells to be certain of long term behaviour.
2009-2014	• More than 25 years since the bore closures. • Better understanding of natural variations in water levels in the Rotorua Geothermal Field. • Anecdotal evidence for continuing surface feature recovery.	• Possible false triggers due to ‘normal’ variations in water level.

3.5.3 Transferring MAGWLs to new wells

Several of the new monitor wells (M25, M26, M27 and M28) have comparatively short datasets, and do not probe very far back into the history of pressure recovery in the Rotorua Geothermal Field. For these wells the suggested approach to defining a new MAGWL is to apply a simple transformation to relate the water levels from one of the existing wells with those from the new well. This can be done using data from both wells where they overlap in time. There is no unique way of doing this, but the average water level over some time interval or some other measure (such as the minimum level) might be used to calculate the transformation.

As an example of this consider M28, the replacement well for M12. This well has recorded data from 2009 to 2014, and the average water level over this interval is approximately 0.4 m higher than in M12. Then, the water level in M12 prior to 2009, if increased by 0.4 m, will be a proxy for the early water level data in M28, and can be used to derive a new MAGWL as described above. This procedure assumes that the histories of the two wells were similar before 2009. This assumption cannot be verified, but in practice any of the historical water level records could be used to create the proxy, and the most conservative resulting MAGWL adopted.

3.6 REPLACEMENT M-WELLS

The three newest M-wells in the Monitoring Programme, M26, M27 and M28 are intended as replacements for older wells, M16, M1 and M12 respectively. All three pairs of wells are located sufficiently close together to be sampling the same regions of the geothermal field, although M16 and M26 penetrate different aquifers – M16 is in the ignimbrite aquifer and M26 in the rhyolite. Figure 3.42 shows a comparison of the M16 and M26 water levels (with barometric response removed) on an arbitrary vertical scale. The plot shows data only for the period where it is available for both wells – M16 closed in January 2014 (G. Timpany, pers. comm.). These wells show very different short and long term behaviour, and for this reason it is not possible to directly compare the data from M16 with that from M26. M26 should be regarded as new and separate monitor well in that region of the Rotorua Geothermal Field.

M25 is the sole remaining ignimbrite well. Although this has historically shown quite different behaviour compared to the rhyolite M-wells, it will remain useful because it is the only M-well at Ngapuna and serves as an important indicator of changes in that area.

The correlations between the M-well data in Figure 3.17 show that all of the M-wells in the rhyolite are measuring the same short term variations in water level. This gives confidence that the replacement wells are providing useful data. While these wells do show some differences in their underlying long term (smoothed) water level variations no information is ‘lost’ here because, as shown earlier, strong correlations between these long term trends are not so well established.

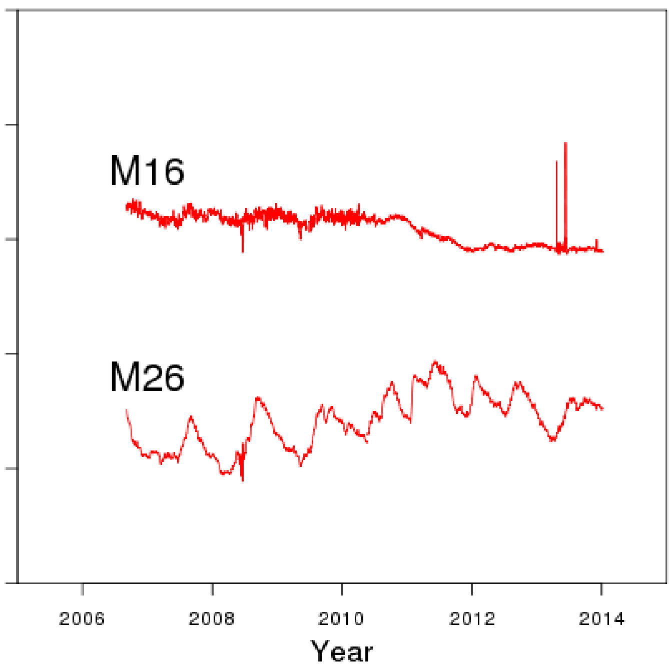

Figure 3.42 Comparison of water levels in M16 and M26. For scale, the tick marks on the vertical axis are 1 m apart.

4.0 SHALLOW GROUNDWATER WELLS

4.1 DATA

New water level data for the G-wells G2, G11, G12, G13 and G14 were obtained from NIWA Rotorua covering the period from 2007 to the present, as shown in Table 4.1. The record for G14 ended in October 2012. These data are recorded at approximately two week intervals.

Table 4.1 Summary of periods of new G-well daily water levels received from NIWA. The asterisk indicated that data recording in G14 ceased on this date.

Well	Span of new data
G2	10/5/2007-3/4/2014
G11	10/5/2007-3/4/2014
G12	10/5/2007-3/4/2014
G13	10/5/2007-3/4/2014
G14	20/8/2007-16/10/2012*

The relative paucity of the data compared to the M-wells means that the correlation with barometric pressures is very poorly determined, and so this correction is not applied. The data shown in Figures 4.1 to 4.6 are therefore raw, uncorrected data. There are two figures for G12. This well shows large spikes in its water level – Figure 4.3 shows clipped data on the same vertical scale as the other G-wells, and Figure 4.4 shows the unclipped data.

There have been no obvious changes in behaviour in any of the G-wells. For the first time however, some correlations between their water levels are apparent. While most of the G-wells have quite noisy records, G11 is the 'cleanest' and shows two broad peaks in water level have occurred in the recent data, each about five years long (2003-2008 and 2010-14) and separated by about three years (2008-2010). Despite the noise, similar features are also evident in G12 and G13 and more indistinctly in G2, where the (approximately annual) deep minima in the water levels (down to about 282.5 m) are suppressed during the peaks. The peaks are indicated on Figures 4.2, 4.3 and 4.5 by arrows. The data for G14 in this period are too sparse, and end too soon to either confirm or reject the presence of these features in that well.

Of greater interest is that the second of these peaks can also be seen in the deeper monitor wells M24 and M26. Both of these are close to Whakarewarewa, and the amplitudes of the water level peak are similar to that observed in the G-wells. If this correlation is confirmed with future data it will be the first evidence of a link between the shallow groundwater and deep geothermal aquifers revealed by the monitoring programme.

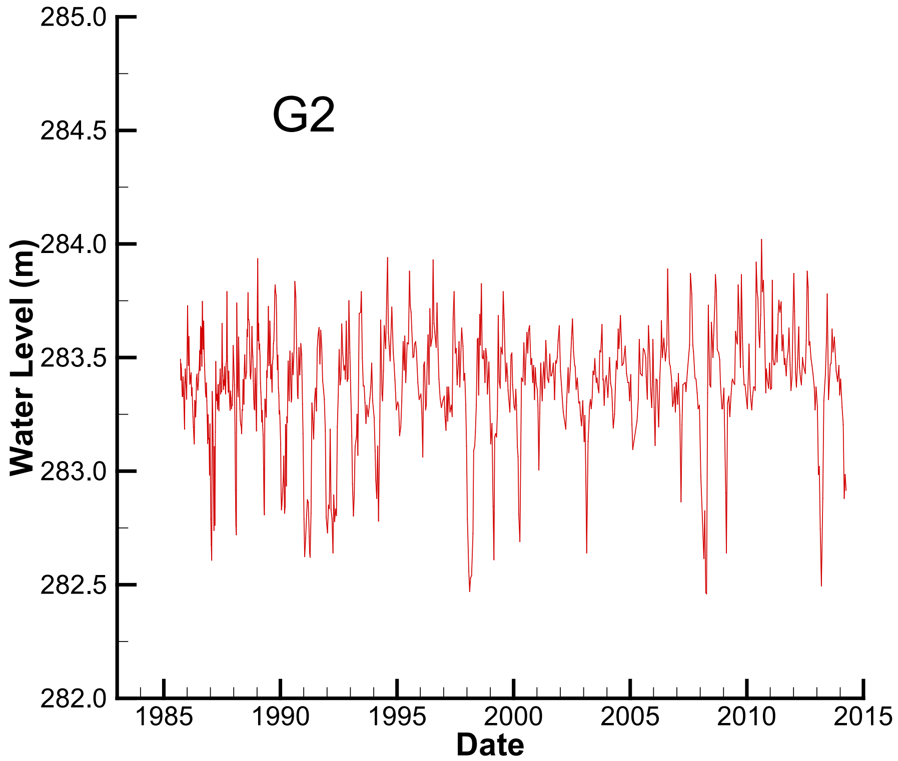

Figure 4.1 Water level in G2.

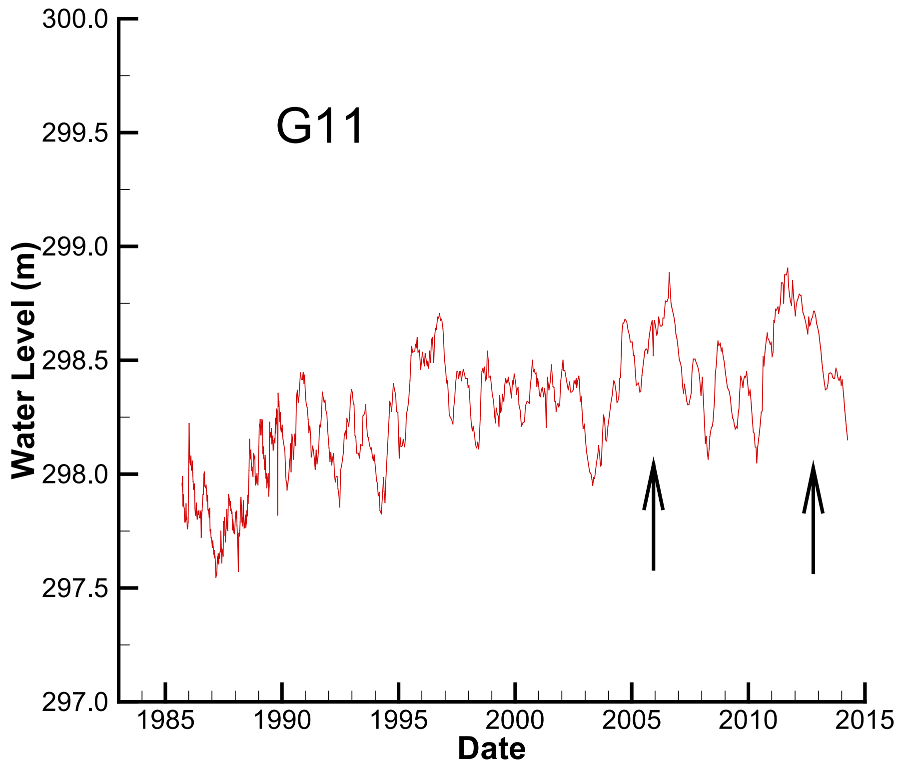

Figure 4.2 Water level in G11. The arrows indicate two broad peaks which also occur in G12 and G13.

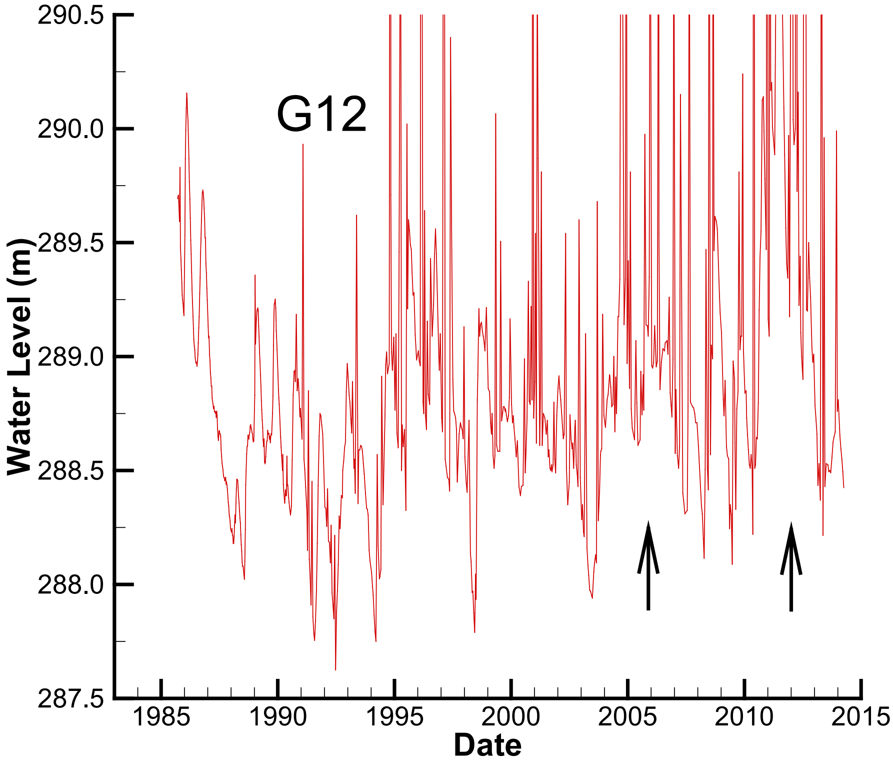

Figure 4.3 Water level in G12, on the same vertical scale as the other G-well plots. The data for G12 contains numerous spikes to above 290.5 m but in this figure has been clipped at to maintain the same vertical scale for all the G-wells plots. The arrows indicate two broad peaks which also occur in G11 and G13.

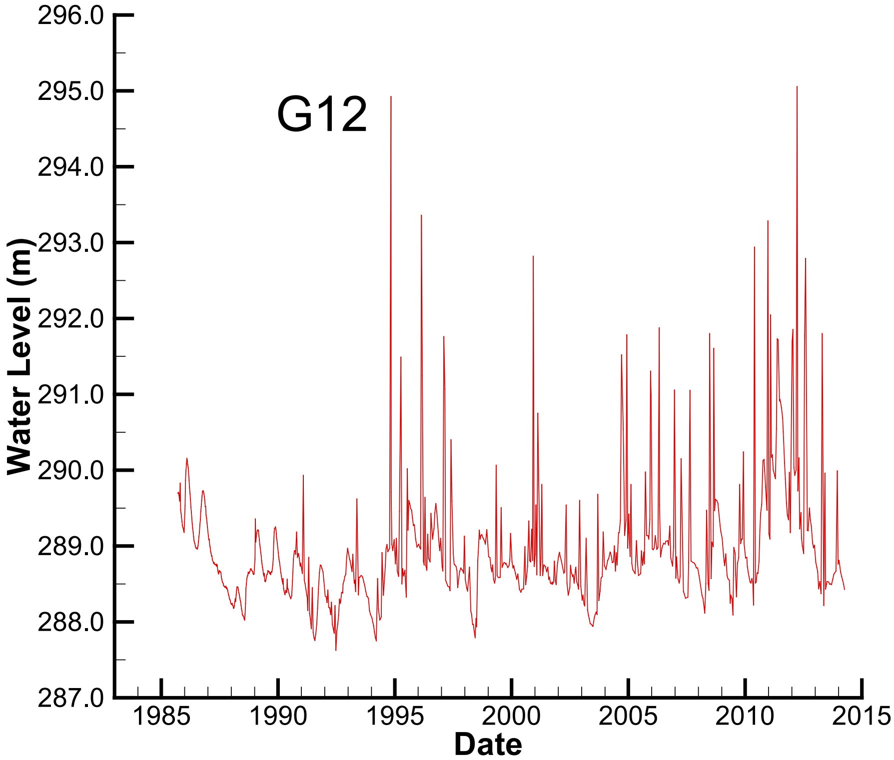

Figure 4.4 Water level in G12. The plot shows the data unclipped, so that the spikes in water level are fully visible.

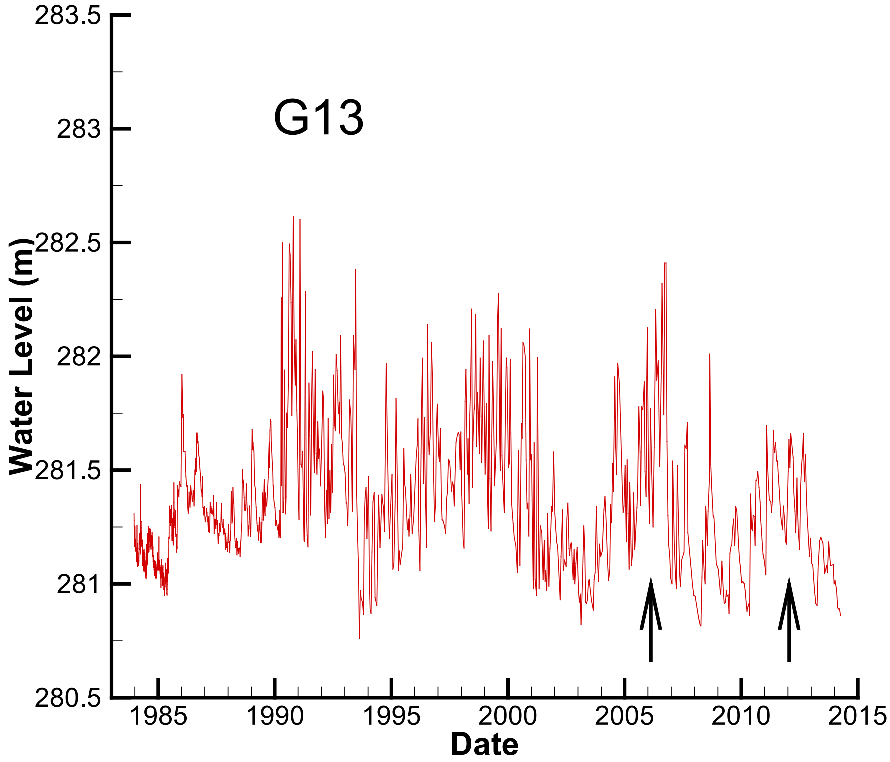

Figure 4.5 Water level in G13. The arrows indicate two broad peaks which also occur in G11 and G12.

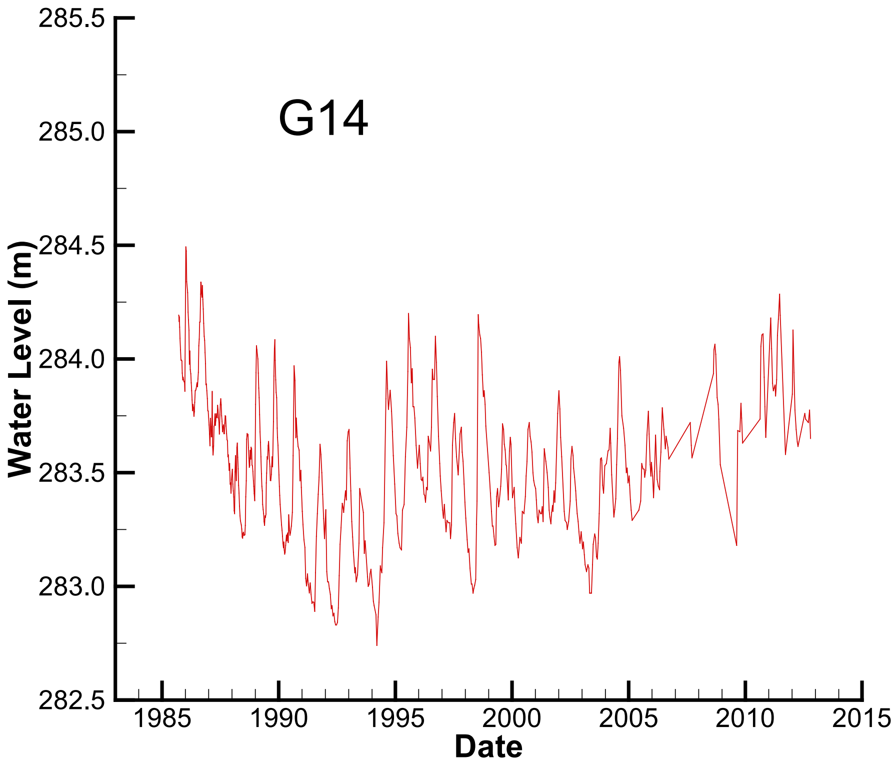

Figure 4.6 Water level in G14.

5.0 ACKNOWLEDGEMENTS

I wish to acknowledge the help I have received from Graham Timpany and others at NIWA Rotorua, and thank Graham in particular for answering numerous questions concerning these data. I also thank internal reviewers at GNS Science for many helpful suggestions and David Harte for his assistance with the statistical/data analysis package R.

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