# SHALLOW GROUNDWATER HAZARDS: MONITORING, INTERPRETING, AND USING HIGH RESOLUTION DATA IN AN URBAN SETTING

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## ABSTRACT

Shallow groundwater under coastal cities may pose a hazard in many different ways. For example, groundwater can contribute to surface water flooding, it can undermine the integrity of pavement sub-grade, and it can drive liquefaction susceptibility in liquefiable soils. With sea level rise and changing climate, the hazard from shallow groundwater will change. However, we currently struggle to properly characterise the spatial and temporal variability of shallow groundwater, let alone understand how the hazard will change under changing future conditions.

The hazard is driven by the pervasive nature of groundwater (it is not constrained to flow within obvious channels) combined with the heterogeneity and anisotropy of the sediments within which it flows. Added to this, it is not visible or easily measured: our only opportunity to measure it is through piezometers drilled into the subsurface. These piezometers were typically manually measured on an irregular or regular basis (weekly or monthly), usually by regional and local councils, in order to provide information on the depth to shallow groundwater.

Following the 2010/2011 Canterbury Earthquake Sequence, EQC installed thousands of shallow test piezometers to inform geotechnical engineers about soil conditions. Subsequently, approximately 1,000 were monitored to inform modelling of the water table. This modelling, together with the detailed geotechnical studies, has led to greater understanding of liquefaction vulnerability.

In 2016, the groundwater network was rationalised to approximately 250 sites and instrumented with transducers which logged groundwater levels and temperature every 10 minutes. Whilst the original 1,000 sites provided exceptional spatial coverage, the more limited, high resolution dataset has proved to be a game changer in understanding the temporal dynamics of the shallow groundwater system. The data has provided insights into the short-term groundwater response to rainfall, tidal variations, river flows and evapotranspiration, and has enabled the generation of tens–of-thousands of surfaces to spatially characterize the temporal variability of groundwater levels and flow (for example, the different responses to storm events in different areas).

The data have highlighted the highly dynamic responses of the groundwater table to various drivers. This has huge potential value in understanding the consequential impacts on antecedent conditions contributing to land flooding, changing liquefaction potential, and effects of sea level rise and climate change. However, trying to unravel the drivers and controls of the groundwater level responses has proved challenging.

The monitoring sets a new standard for urban areas overlying shallow groundwater, where hazards such as liquefaction and flooding are contributed to by changes in groundwater levels that can occur over periods of hours or days.

## KEYWORDS

**Shallow groundwater; flood management; high resolution data**

## PRESENTER PROFILE

Dr Helen Rutter is a Senior Hydrogeologist with Aqualinc Research Ltd, having over 25 years' experience working in hydrogeology in the UK, Botswana, and New Zealand. She has in-depth understanding of physical hydrogeology, including resource assessment, recharge processes, groundwater flooding, catchment characterisation, geology and geochemistry. She has carried out extensive research into the hydrogeological impacts of the Canterbury Earthquake Sequence, including a Marsden-funded research project. More recently she has been focusing on the implications of climate change and sea level rise on shallow groundwater in coastal areas, an issue that is facing many councils in New Zealand. She is also involved in developing methods to delineate source protection zones for drinking water supplies.

# 1 INTRODUCTION

New Zealand has many low-lying coastal settlements, for which shallow groundwater is a current or future hazard (usually both). Shallow groundwater levels affect flooding extent, slope stability, liquefaction potential and buoyancy forces. As a result, the groundwater levels at a location, or across wider areas, need to be determined for various purposes.

Until recently, shallow groundwater monitoring has been carried out by collecting groundwater level measurements on a weekly or monthly basis, at best. These data, where available, are used to either assess likely groundwater levels, or carry out analyses, such as interpolating a 'static' water level surface. An interpolation can be based on data points for a set date (usually picking a day within a month), or based on a statistical measure (mean, median, or percentile of the time series of available data).

## 1.1 RISK, HAZARD AND VULNERABILITY

Across New Zealand, the risk that low-lying communities face from existing and future sea level rise (SLR) is of increasing concern. Risk, the probability that adverse effects or harm will occur, is a combination of the hazard (something that causes an adverse effect or harm) multiplied by the vulnerability (the potential for casualty or loss). A hazard has both a magnitude and a frequency. For example, groundwater levels have a measured magnitude, and the frequency is represented by how often that groundwater level is reached (e.g. a median or 85%ile level). However, this provides no information about the actual frequency or duration of inundation events. In reality, inundation that lasts a day and occurs several times a year infers different risks to inundation that occurs for weeks but only once a year. Over the period of record, these may have the same (or similar) frequency, but different implications to hazard risk.

In addition, the probability that any individual rainfall event causes damage depends on antecedent conditions at the time of the event. And this dependence varies spatially.

Understanding the shallow groundwater responses to different drivers is important in many different areas. For example:

- In emergency response and management, real time data can:
    - Be used to contribute to flood forecasting and management where shallow groundwater is contributing to surface flooding; and
    - Focus Civil Defence responses to earthquakes (potential liquefaction occurrence) and flooding.
- With operational issues, real time or historic data can be useful to assess:
    - Sewer infiltration; and
    - Longevity of groundwater flooding.
- Considering infrastructure maintenance, existing data can provide better understanding of the impacts of shallow groundwater on roads and pipe networks.
- During construction (both buildings and infrastructure), depth to shallow groundwater can contribute to better decisions about:

  - Timing of infrastructure works;
  - Dewatering requirements; and
  - Design of basements and buildings.

All of these examples need an understanding of the frequency, magnitude, and duration of groundwater exceedances. A static surface, based on one-off measurements, or statistical measures, cannot take this into account, nor can an assessment of a likely (high or low) groundwater level based on a few measurements.

In the discussion below, focus will be on the use of shallow groundwater level data in addressing city-scale problems. However, much of the findings can also apply to site-specific problems.

## 1.2 LIMITS OF SPATIAL DATA

There are usually limitations and/or bias in the location of monitoring piezometers. This can result in any interpolated surface having areas good confidence, and other areas of low in the resulting water table surface. This was a particular the case in Christchurch because the piezometers e drilled by EQC were largely located in areas where there were ground settlement issues.

## 1.3 LIMITS OF TEMPORAL DATA

Groundwater levels can vary considerably over a range of time scales; from daily responses to rainfall, through to inter-decadal responses to climate cycles. In terms of establishing a groundwater level for a particular site, the method of measurement and analysis can affect how well the assessed level correctly represents actual groundwater conditions. In addition, the way that data are collected may bias the results obtained from manual measurements for various reasons, including inadequate period of measurements, and even the willingness of field workers to venture out on wet days. Added to this is that manual monitoring of a large network takes time: if water levels are measured over a 2 week period, then rainfall events may be captured in some of the collected data and not in others.

There is a common misconception that groundwater levels vary slowly with the seasons and change little from one year to the next. However, this is often not the case. If groundwater level observations are taken sporadically, they may not correctly represent the extreme groundwater levels. For example, if the maximum likely groundwater level is required for a design, and measurements are sampled monthly, they are unlikely to measure peak groundwater levels that may only occur for a (say) matter of hours following a rainfall event in late winter. Ideally, the method used to assess a groundwater level for the basis of designing a structure should account for this variability, and include an assessment of exceedances. This is similar to the way a bridge design needs to account for the likelihood of different flood levels of a river (e.g. 1 chance in 100 of occurring in a particular year, or event return intervals).

In terms of the overall period of measurement, there can be many different temporal and spatial controls on groundwater levels, particularly in an urban setting. These can include stormwater drains, sewers, leaking water mains, and dewatering for construction works. These all contribute to temporal variability in groundwater levels, and are discussed later.

The consequence of unanticipated high groundwater levels can mean post-construction engineering solutions are required to prevent structure damage, limit infiltration, decide on suitable plant species, or to maintain serviceability. Even where higher-than-designed groundwater levels do not have an immediate impact, incorrect assessments of groundwater levels can result in under-designed structures, such that they are less resilient to disasters through:

- Flooding during high groundwater levels;
- Structural failure through increased buoyancy forces during periods of high groundwater levels; or
- Increased liquefaction potential during earthquake events.

# 2 CHRISTCHURCH EXAMPLE

Christchurch is a coastal, low-lying city, and shallow groundwater levels are a problem for many areas. Post-earthquake, issues have worsened in some areas due to land subsidence due to liquefaction. Over time, sea level rise will also impact groundwater levels, further increasing the extent of the areas affected. Added to this, any future seismic events could result in further liquefaction and additional land subsidence.

## 2.1 GEOLOGY

The upper sediments under the city are important as their properties control how groundwater moves through the shallow subsurface. The upper sediments under the city are the Springston and Christchurch Formations. The Springston Formation tends to be coarser grained (gravels, sand and silt) and predominantly occurs to the west of the city, while the finer grained Christchurch Formation (estuarine/marine fine sediments and sands) is exposed in the east of the city. The relationship between the formations is not simple, and complex inter-fingering of both the Christchurch and Springston formations occurs beneath Christchurch City (White, 2007a; White *et al.*, 2007).

Even within the Springston Formation, there is considerable variability. The formation can be divided into river flood channels that contain alluvial gravel as the main component, plus overbank deposits of sand and silt. In some areas (for example, the suburb of Marshland), there are peat deposits. This results in significant variability in the vertical profile across the area. The meandering streambeds of the Heathcote and Avon/Otakaro rivers and their tributaries also incise the surficial sediments, creating local meander loops, channels, and overbank deposits of sand, silt and peat/organics. There are also man-made deposits including landfills (e.g. Bexley Tip), reclaimed tidal areas (e.g. Bromley), and fill on existing land. Thus, although the Springston Formation is generally thought of as an aquifer, it also acts as an aquitard, particularly in the east of the city.

The Christchurch Formation includes beach, estuarine, lagoonal, dune and coastal swamp (inter-dune) deposits (these latter areas are often largely reclaimed with fill). Brown *et al.* (1995) suggest that under Christchurch they are predominantly dune sands with some areas of sand, silt and peat formed from drained lagoons and estuaries.

## 2.2 DRIVERS OF SHALLOW GROUNDWATER RESPONSES

Controls of groundwater depths include:

- Rainfall recharge:
  - Seasonal patterns of recharge; and
  - Climate changes or cycles (including effects of interdecadal oscillations);
- River recharge;
- Tides;
- Evapotranspiration;
- Earthquakes:
  - Subsidence due to ground settlement;
  - Dynamic water table response to earthquakes; and
  - Long term changes in groundwater level.
- Sea level rise.

## 2.3 THE EQC NETWORK

A network of over 1,000 shallow piezometers was installed by EQC in 2011, to provide information about shallow groundwater as inputs into assessments of liquefaction vulnerability. Up to 1,000 holes were monitored manually on a multi-week schedule, but by 2016 the number of sites had reduced (for a variety of reasons) to 786. This dataset enabled very good spatial precision in many areas of

Christchurch, and was considered to provide reasonable temporal coverage. Using the data, GNS (van Ballegooy *et al.*, 2014) developed median and 85%ile groundwater level surfaces for use in liquefaction susceptibility assessments, which in turn fed into land damage assessments and decisions regarding foundation designs.

This work also enabled better understanding of additional factors, such as areas where the sewer system may be above or below groundwater levels; this provides an overview that can be used to focus future repair work (Figure 1).

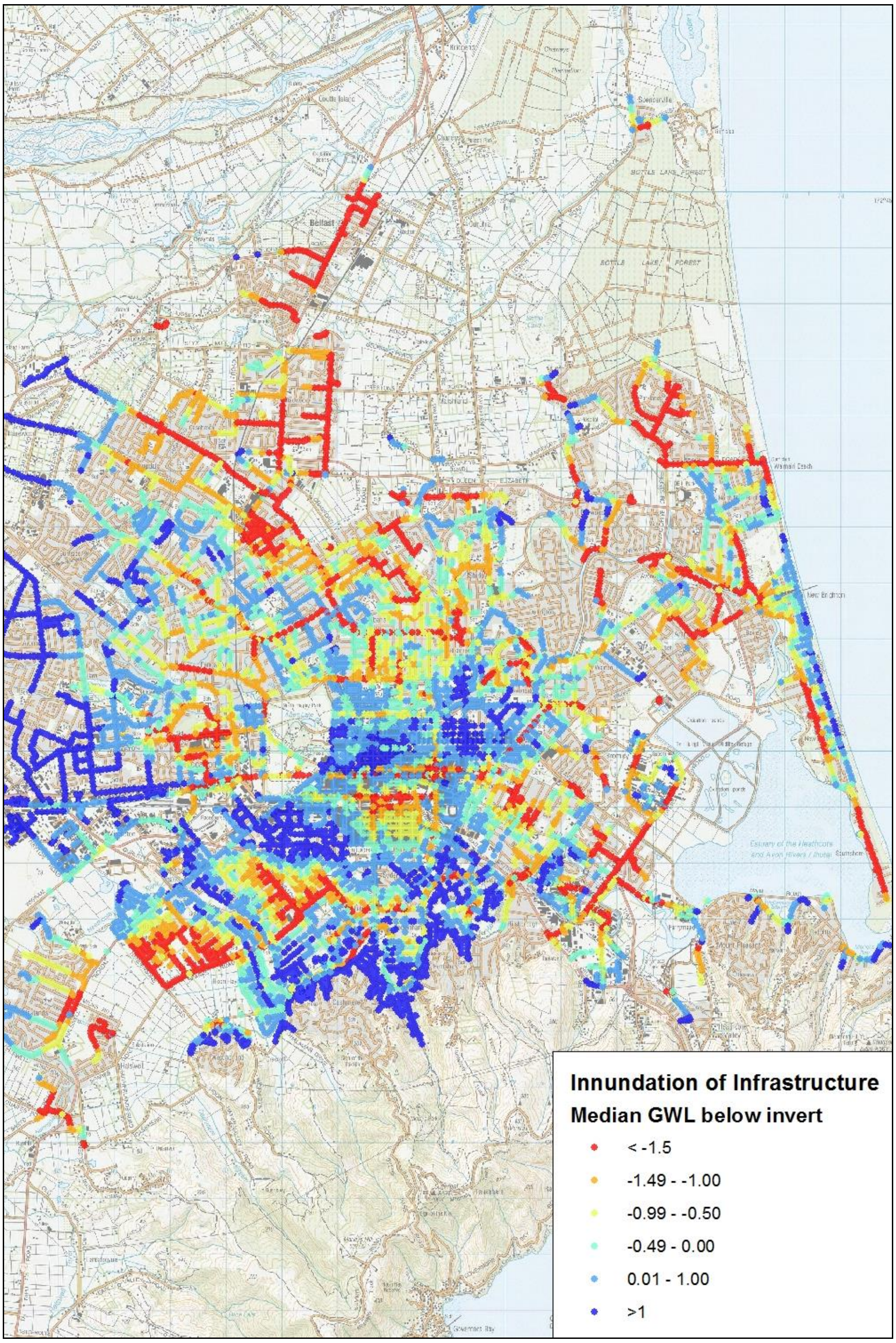

*Figure 1. Areas where sewer network is below groundwater, based on the median groundwater level and sewer invert levels*

## 2.4 APP NETWORK

In 2016, 249 sites were instrumented with groundwater level and temperature sensors, logging every 10 minutes. This automated monitoring of shallow groundwater has allowed measurements of groundwater level variations that were previously not available. This has huge potential value in understanding the variability of groundwater levels, and hence the consequential effects on liquefaction potential, antecedent conditions to flooding, and general issues of groundwater level response to sea level rise and climate change.

he higher-resolution data show a range of groundwater level responses to rainfall and other drivers that are missed with a single weekly or monthly measurement. *Figure 2* illustrates the level of detail that is missed by monthly monitoring, and calls into question the usefulness of periodic measurements.

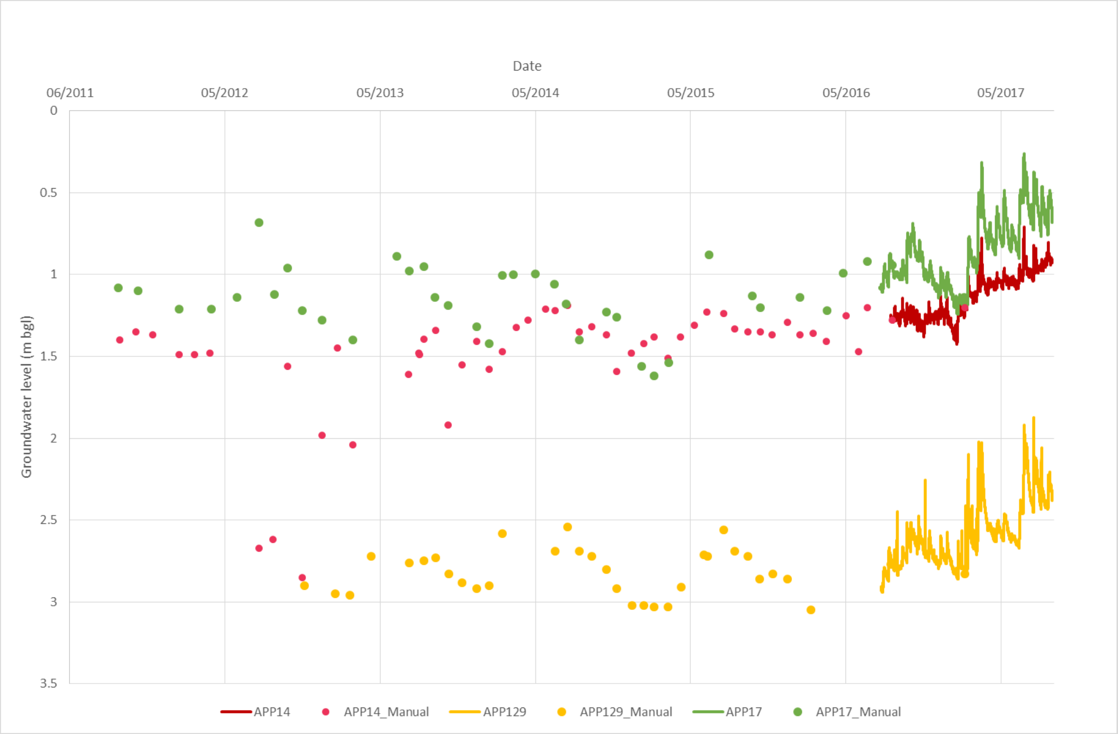

Figure 2. Dipped and high resolution data for three piezometers

Some of the key features of the high-resolution groundwater level data are described below to explain the significance of the data when making any assessment of shallow groundwater in an urban environment.

### 2.4.1 SEASONAL-TYPE GROUNDWATER LEVEL RESPONSES

Many piezometers show a distinct summer recession and winter recovery, as would be expected (see Figure 3). The summer recession is not affected by rainfall events, and groundwater levels remain in recession until the start of winter recharge, as the soil moisture deficit is replenished, and rainfall can become recharge. The recovery can be initiated by specific rainfall events (e.g. the ex-tropical cyclones, Debbie and Cook initiated the recovery in early April 2017 for example). In areas such as this, groundwater flooding is highly unlikely in the summer.  However, in winter, heavy rainfall can drive groundwater levels to the surface for (sometimes) prolonged periods. Infrastructure works in the winter in such areas would require greater dewatering, and there would be little infiltration capacity for further rainfall. However, if dewatering was carried out in the winter, the amount required would vary with time, as groundwater levels recess from short term spikes.

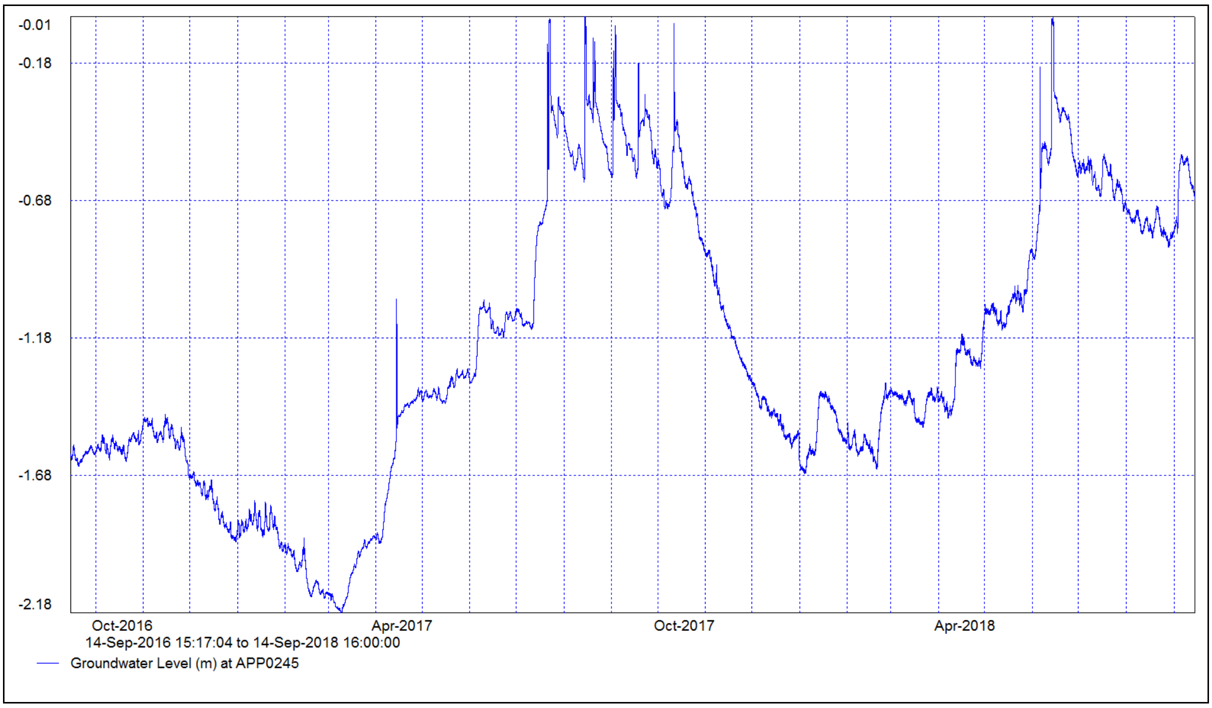

Figure 3: Seasonal-type groundwater level response

### 2.4.2 FLASHY GROUNDWATER LEVEL RESPONSES

In some areas, the hydrographs do not show a distinct seasonal pattern, instead responding to all rainfall events throughout the year (see

Figure 4). In this example, there is a relatively flat 'base level', but the hydrograph resembles more of a streamflow hydrograph, than what would be expected from groundwater. Major rainfall events cause greater peaks in groundwater levels than smaller events, but do not stand out noticeably from the rest of the signal. Periodic groundwater level monitoring is quite likely to miss the peaks, and will be biased towards baseline levels (see

Figure 5). In areas such as this, peaks in groundwater level can occur at any time of year, but are unlikely to be prolonged. As a result, most people are unlikely to realise that groundwater at the surface is actually groundwater, as it would occur simultaneously with rainfall. Infrastructure work could be carried out at any time of year, as the change in the baseline groundwater level is minimal.

An interesting observation was that although many of the flashy-type hydrographs occur in areas that are in close proximity to streams, some are not. APP043 is an example, located in the Burwood subdivision, with no surface water courses in the vicinity (see

Figure 6). In this case, there is a stormwater soakaway close to the piezometer, and it appears that water draining into this causes a temporary spike in groundwater levels that may last from less than an hour to a few hours in duration. This is one example how local infrastructure in the urban environment can affect groundwater level responses.

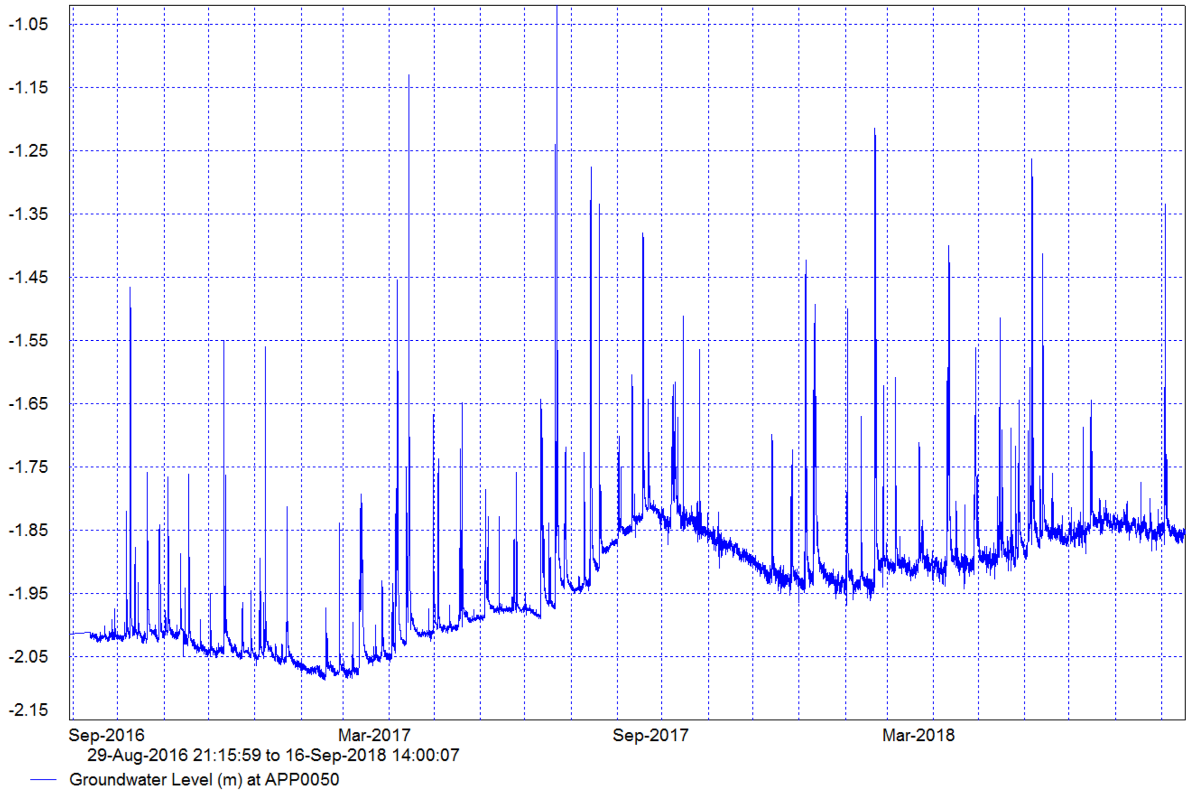

Figure 4. Flashy hydrograph response

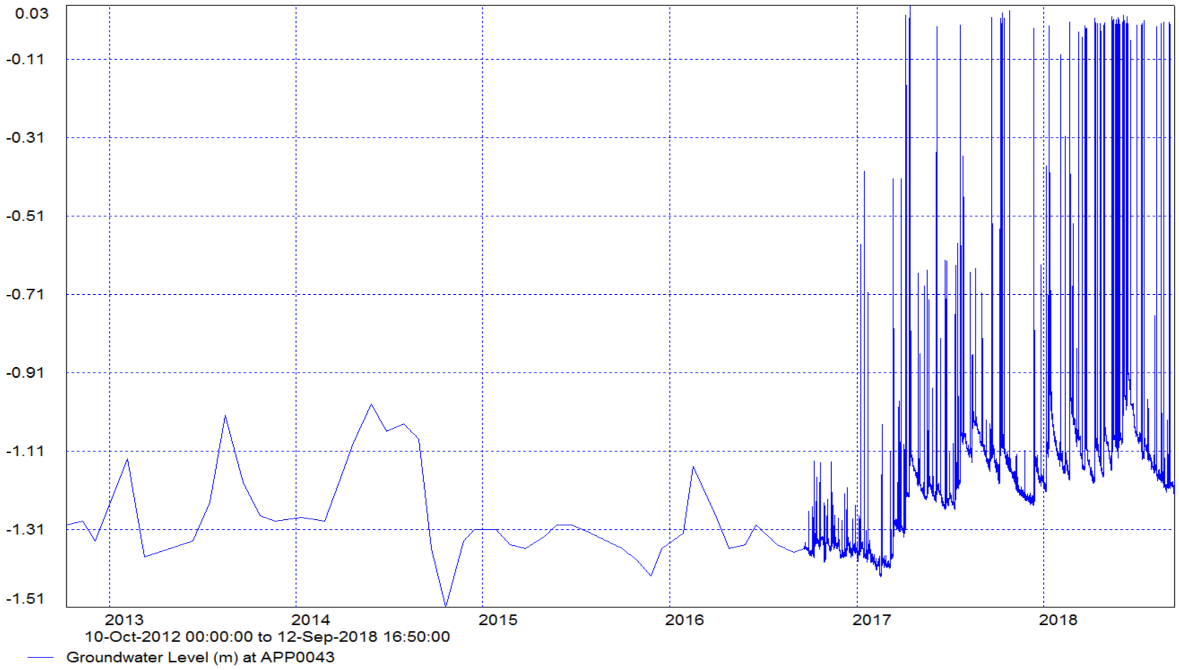

Figure 5. Missing the peaks with manual groundwater level monitoring

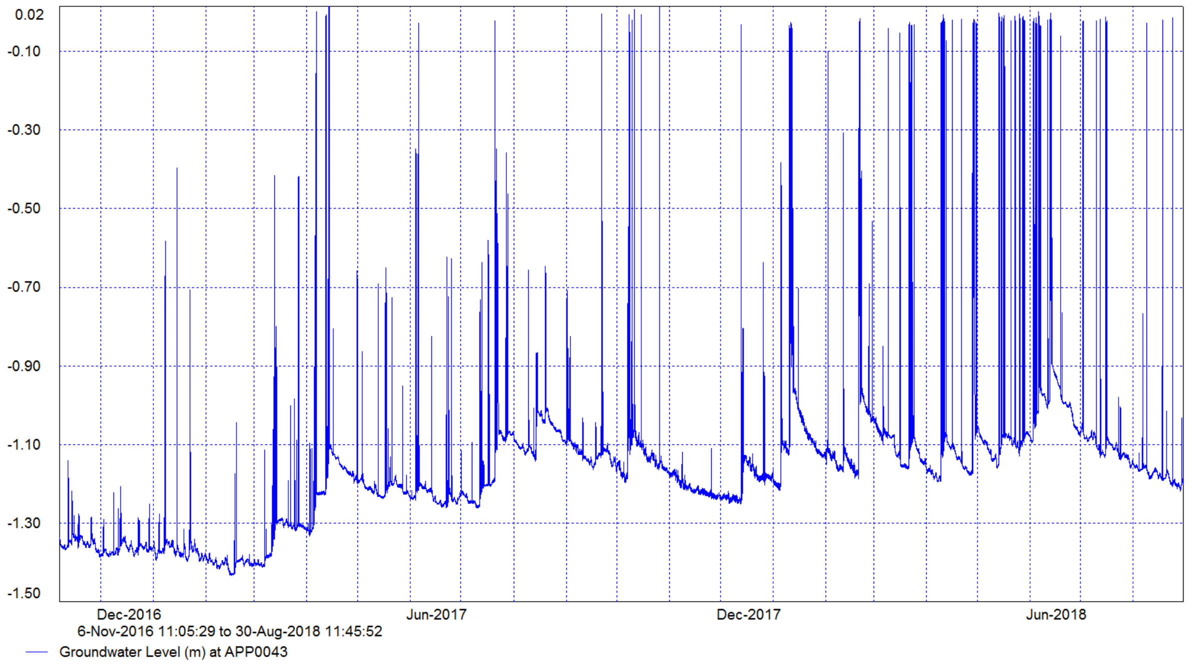

Figure 6. Flashy-type behaviour as a result of stormwater soakaway

### 2.4.3 TIDAL RESPONSES

Tidal signals were observed in numerous piezometers, at distances of up to 500 m from the tidal boundary. The distance to which the tidal response propagated was not consistent across the city. Figure 7 shows the ratio of tidal range in groundwater levels relative to the range of tidal response in the nearby Avon River versus distance from the river. Although there is a logarithmic trend, there is a lot of scatter in the data, most likely reflecting the variability of the sediments in which the piezometers are installed.

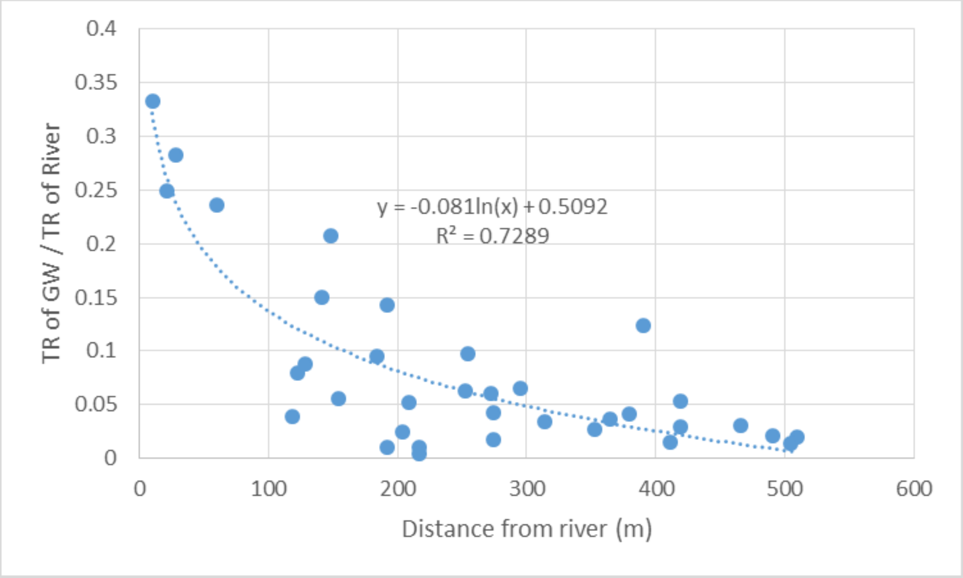

Figure 7. Relationship showing how the influence of the river decays with distance

Even close to the coast or river, the tidal signal is overlain with an additional response to rainfall. In Figure 8, the response of APP165 to rainfall during ex-tropical cyclones in April and July 2017 can be clearly seen in addition to the tidal signal. In particular, the July rainfall resulted in groundwater rising to (or near) the surface twice daily over a number of days. Twice-daily inundation of the road sub-base and infrastructure may have a damaging effect that is worse than constant inundation, particularly if the water is saline.

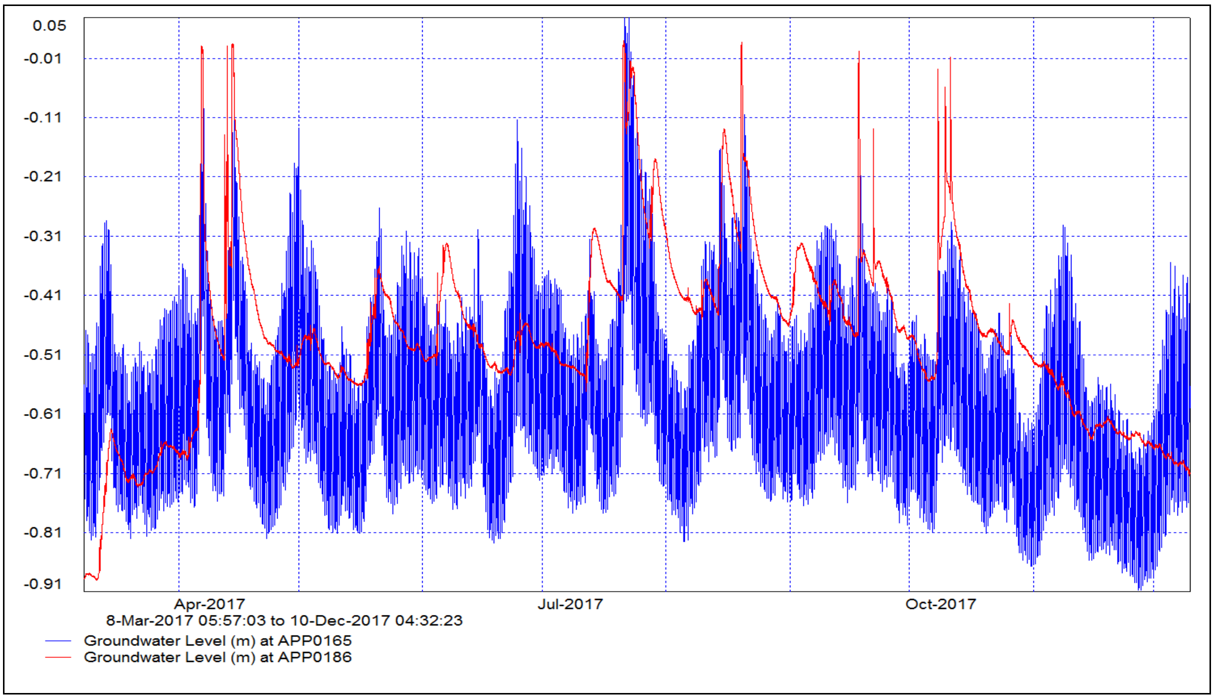

Figure 8. Tidal response in APP165 (80m from coast) vs APP186 (270m from the coast).

### 2.4.4 ANTHROPOGENIC IMPACTS

In addition to the responses to natural drivers, groundwater levels are affected by a number of artificial influences, including dewatering for infrastructure works and sealing sewers that were previously acting as groundwater drains.

Figure 9 illustrates a number of important points. Towards the end of 2016, groundwater levels recovered approximately 1 m, followed by drawdown two weeks later: this was the result of ceasing dewatering over the Christmas break. Furthermore, if considering the data only for the period the September 2016 to March 2017, groundwater depths could have been around 0.8-1m deeper than other times. When put in the context of the longer of data, this shorter time interval can be clearly seen to be anomalous. This hydrograph illustrates many of the issues with temporal data when used to make decisions from groundwater levels:

- The length of record is important, and whether this represents a ‘normal’ or ‘unusual’ period;
- The influence of artificial controls on groundwater levels need to be understood;
- Manual measurements provide a lack of detail and a subsequent inability to incorporate the short term responses to rainfall.

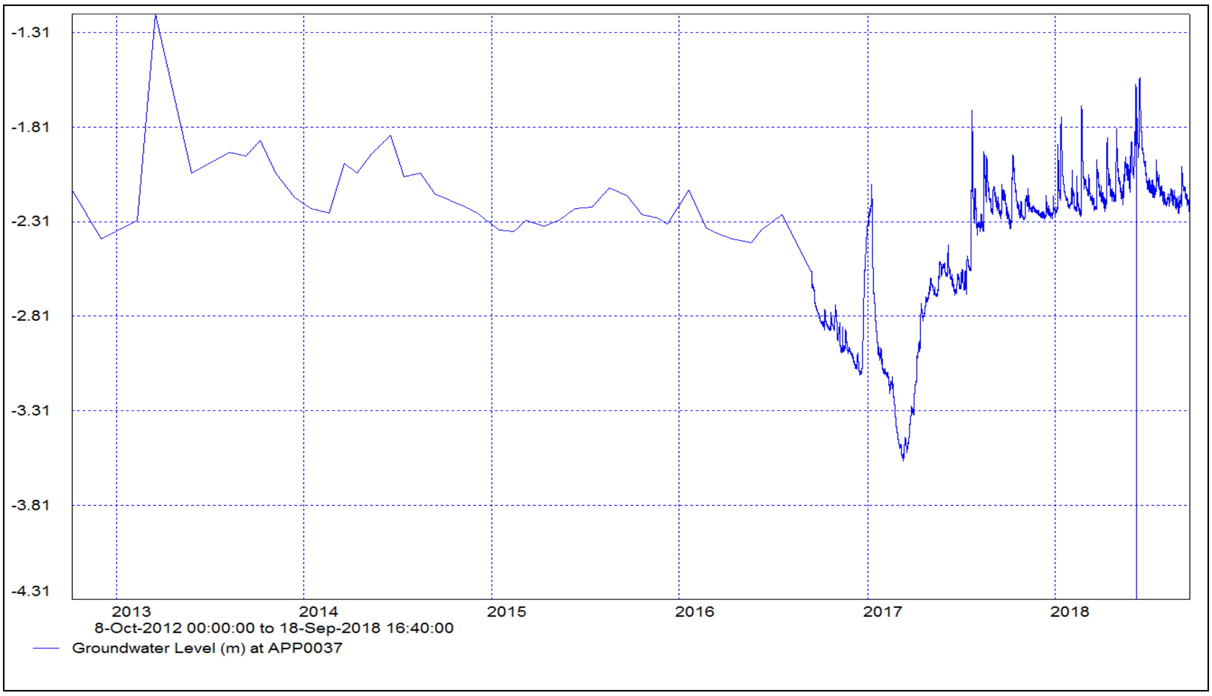

Figure 9. Influence of dewatering on groundwater levels, and representativeness of temporal data

## 2.5 CLASSIFYING GROUNDWATER LEVEL RESPONSES

As is obvious by the range of factors that drive groundwater level responses, attempting to classify the response in different areas is difficult. Simple approaches have been made to classify responses to rainfall (winter and summer), to particular rainfall events (ex-tropical cyclones Debbie and Cook), and to tidal forcing. The success of this has been limited. Figure 10 illustrates the ratio of change in groundwater levels relative to amount of rainfall, based on distinct rainfall events between September 2016 and September 2017. The greater response in winter can be seen, and clearly reflects the fact that some sites show little or no response in the summer due to the soil moisture deficit preventing the rainfall becoming recharge. However, the pattern is ambiguous, and it is not possible to classify areas that respond similarly. More investigation is needed to fully understand and model the complex interaction between groundwater levels and natural and anthropogenic influences.

Until adequate resources are available to investigate the complex problem with regard to risk from shallow groundwater, assessing the number of days above certain thresholds, and the duration of exceedances of the thresholds, may be appropriate. For the purpose of recent work, a threshold of 0.35m below ground level was set, above which groundwater would be considered a hazard. This threshold was decided through extensive consultation with stakeholders, taking into account their concerns. Then, assessing the number of days per year that a 0.35m threshold is exceeded has highlight areas of greatest potential hazard from shallow groundwater (Figure 11).

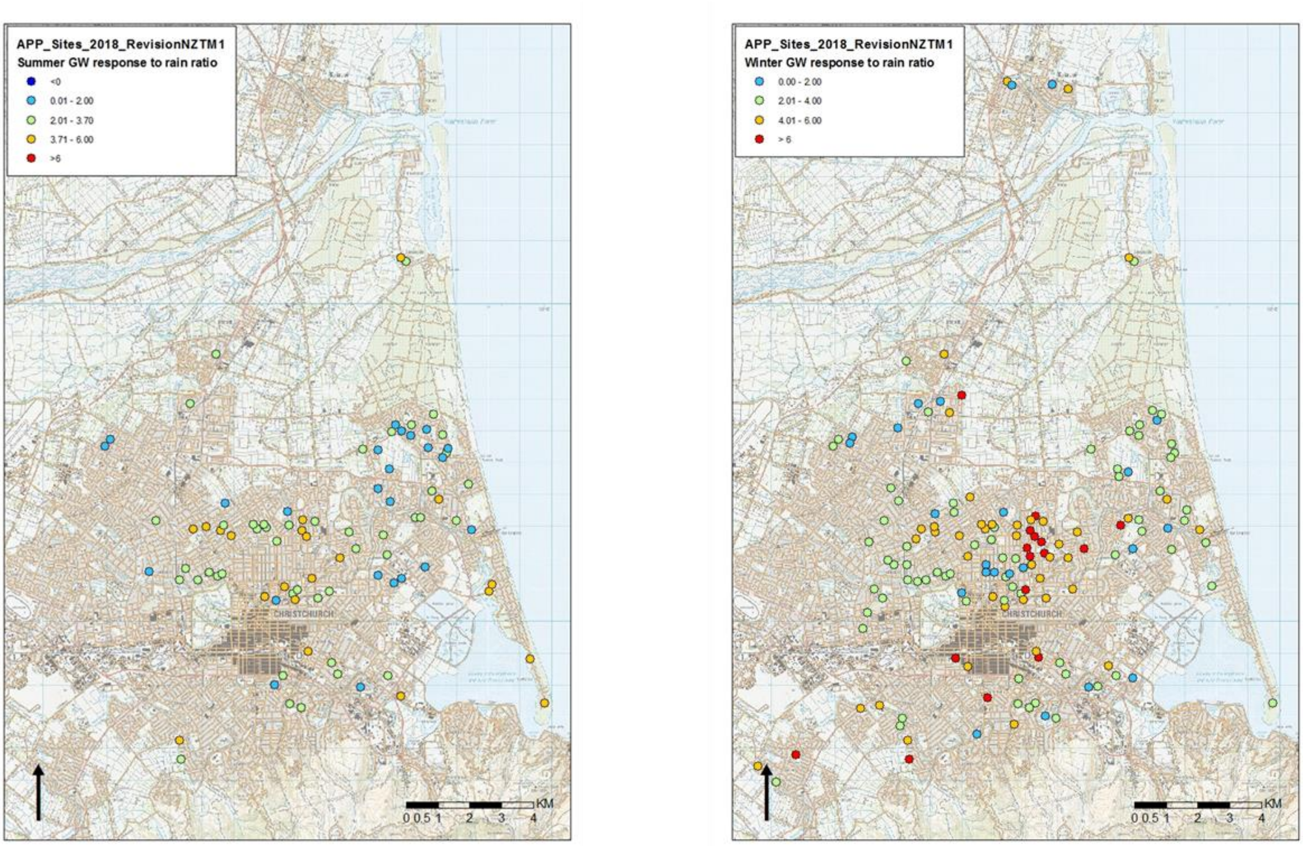

Figure 10. Average groundwater level response to summer rainfall (left) and winter rainfall (right), illustrating the greater response to rainfall in the winter

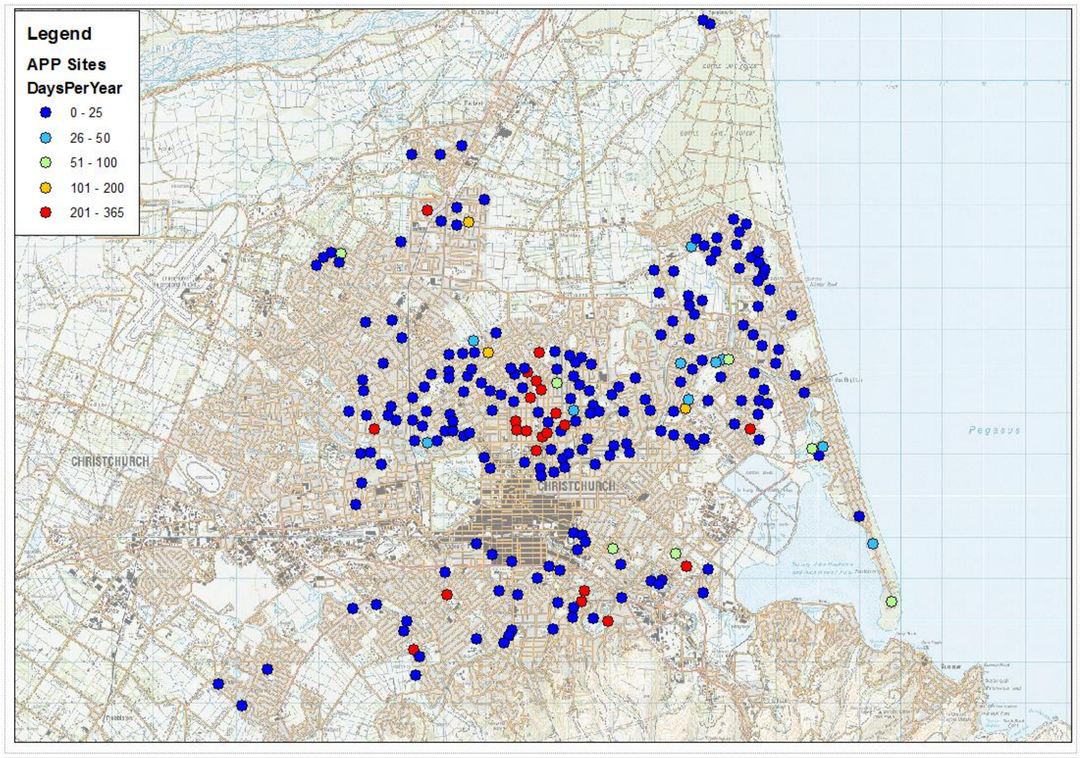

Figure 11. Number of days per year that groundwater levels exceed 0.35 m below ground level

# 3 CONCLUSIONS

Shallow groundwater presents a significant hazard to coastal communities in New Zealand, and one that will only increase with time as sea level rises and extreme events increase. Current monitoring networks may not provide the information that councils will need to assess the hazard correctly. Static surfaces, whilst useful in terms of assessing general areas, are based on data that may not adequately characterise the metric that it is based on, and provide no information about the duration of events. In addition, failure to understand the longer-term groundwater signal may result in biased data being used to make engineering decisions.

We have outlined the history of the current shallow groundwater monitoring network under Christchurch, described how the data can be used to generate static surfaces, and illustrated ways that such surfaces can be used. However, the high resolution data from the smaller network has raised a number of questions about what the periodically-measured data (that we have based these analyses on) is telling us, and how it is used.

The high resolution data can be used to gain much greater understanding of processes of shallow groundwater flow, and the drivers of flow. Initial attempts to define areas that have similar responses have had limited success, which is likely due to the number of natural and artificial controls on groundwater levels, including rainfall, river flow, tides, sewer infiltration, stormwater infiltration, dewatering, etc. This does not stop the data being useful at a local scale, but does not help in predicting effects (for example the risks of groundwater contributing to surface flooding over a wider area). A better understanding of these drivers would result on improved flood prediction and management, understanding of liquefaction susceptibility, and enhanced decisions about road maintenance, infrastructure maintenance, site requirements for dewatering, and planning for new construction.

## REFERENCES

Brown LJ, Weeber JH 1992. *'Geological Map: Geology of the Christchurch Urban Area. Scale 1:25,000.'* Institute of Geological and Nuclear Sciences. Boulanger and Idriss 2014

van Ballegooy, S.; Cox, S.C.; Thurlow, C.; Rutter, H.K.; Reynolds, T.; Harrington, G.; Fraser, J.; Smith, T. 2014. *Median water table elevation in Christchurch and surrounding area after the 4 September 2010 Darfield Earthquake*. Version 2. Lower Hutt, NZ: GNS Science. GNS Science report 2014/18. 79 p. + appendices

White PA, Goodrich K, Cave S, Minni G 2007. 'Waterways, swamps and vegetation of Christchurch in 1856 and baseflow discharge in Christchurch City streams.' GNS Client report 2007/103 to Environment Canterbury. Environment Canterbury report U07/39.