Groundwater Response to the Dewatering of a Volcanic Vent

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ABSTRACT: Three Kings Quarry is located within one of a number of volcanic vents which lie within the Auckland Volcanic Field. These vents have punched through the regionally extensive and thick Waitemata Group. At Three Kings, scoria and basic intrusives form the vent material. Low permeability tuff, representing pulverized country rock blown out during initial explosive phases, forms a raised ring around the vent. Basaltic lava has ponded within the vent and overspilled a low point in the tuff ring to the north-west. Recent Tauranga Group sediments have been deposited on the Waitemata surface, underlying, intercalated with, and overlying the volcanics.

Groundwater levels in the vent and surrounding area have been monitored since December 1993.Dewatering of the vent to allow quarrying below the water table commenced in March 1999. Since the onset of dewatering, groundwater levels in the vent have been drawn down by approximately 23 m. Associated lowering of water levels in the Waitemata Group has led to the under-drainage of overlying compressible sediments of the Tauranga Group resulting in potential for pockets of increased land settlement, although long-term settlement monitoring shows that this has not occurred.

Geological and hydrogeological data, long-term groundwater monitoring data, and development of conceptual and numerical models has allowed a better understanding of the groundwater response to dewatering and the extent of dewatering-related drawdown. It also has shown the presence of a high permeability zone within the Waitemata Group associated with vent formation.

This paper discusses the diverse facets of groundwater behaviour that have been observed during the period of dewatering and provides some recommendations for managing and monitoring groundwater effects in this kind of hydrogeological setting.

1 INTRODUCTION

Winstone Aggregates operates the Three Kings Quarry located on the Auckland isthmus within the Auckland City metropolitan area (Fig. 1). The quarry extracts basalt and scoria from one of the many volcanic vents that occur within the Auckland Volcanic Field – a Quaternary-aged eruption centre which is still active (the most recent eruption occurring about 600 years ago, forming the island of Rangitoto).

The base of the quarry has been excavated below the pre-pumping water table since dewatering was commenced in March 1999. Groundwater levels have been drawn down approximately

23m since dewatering was commenced with the base of the quarry currently at approximately 34m RL at its deepest.

The effect of dewatering on groundwater levels has been monitored in a number of piezometers within various strata both inside and outside the Three Kings volcanic vent. These groundwater monitoring data have been used in subsequent studies to refine the hydrogeological model of the system and its response to dewatering. The groundwater monitoring has been undertaken in association with surface settlement monitoring due to the potential for dewatering-induced settlement around the volcanic vent. The potential significance of settlement effects is reasonably high as Three Kings Quarry is located in an established suburban area within Auckland City with approximately 6000 residential dwellings within the predicted potential zone of groundwater drawdown.

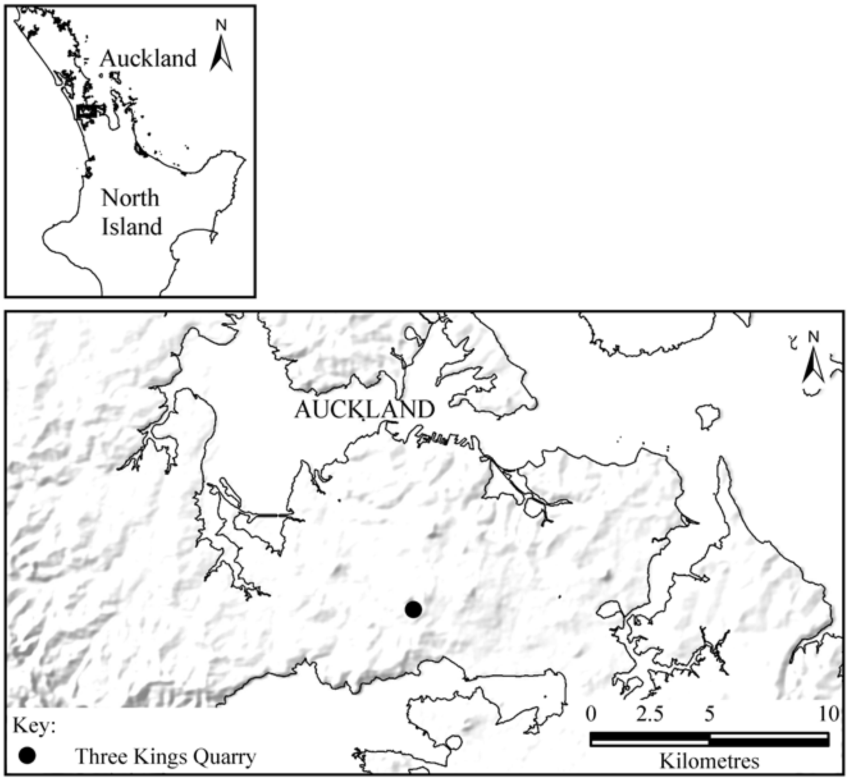

Figure 1. Three Kings Quarry location

2 GEOLOGY

The geology in and around the Three Kings Quarry is described in a number of publications (e.g. Kermode 1992; Searle 1988) and can be divided broadly into four main groups: basalt/dolerite, scoria, tuff, and non-extrusive sediments (Fig. 2). Basalt/dolerite and scoria dominate the quarry area and form a roughly circular outcrop defined by the surface expression of the Three Kings volcanic vent. The basalt/dolerite is intercalated with or intruded into the scoria and forms a high elevation lava moat around the periphery of the vent. Tuff and non-extrusive sediments (principally Waitemata Group and younger Tauranga Group) occur outside this area.

The oldest rocks outcropping in the area are those of the early Miocene Waitemata Group. This group is inferred to be between 1000 and 2000m thick and is ubiquitous in the area, forming what can be considered the basement. The group consists mainly of flysch (alternating mudstone and lithic sandstone) with subordinate breccia and conglomerate, and rare limestone and quartzoze sandstone. Waitemata Group sediments in the vicinity of the Three Kings vent appear to be sub-horizontally bedded, with some steeper dipping zones present locally. At the Waitemata Group palaeosurface is a zone of weathered rock which has been found at the site to vary in thickness between approximately 4m and 10m, with thickness generally increasing with increased distance from the vent (PDP 2003a).

The Tauranga Group was deposited unconformably on the Waitemata Group palaeosurface, and is often found within the palaeovalleys and low-lying areas. Deposition of the Tauranga Group sediments occurred during the late Pliocene to late Pleistocene, overlapping with the period of volcanism associated with the Auckland Volcanic Field. As a result, this group can be found both beneath and above lava flows from nearby volcanic centres, notably One Tree Hill flows in the south-east, Mt Roskill flows in the south-west, and the Three Kings flow to the north. It is often found filling the palaeo-depressions formed where these lava flows butt up against the Waitemata Group. This group comprises airborne and waterborne pumiceous deposits, stream and coastal alluvium including carbonaceous units (peat and lignite), hillslope and coastal alluvium, and intertidal and beach ridge littoral deposits. Tauranga Group sediments can be obscured/buried by more recent volcanic deposits.

Eruption of the Three Kings volcano took place approximately 20,000 to 25,000 years ago. The volcano punched through the Waitemata Group sediments, in the form of an inverted cone, which was then filled with volcanic deposits (Fig. 3). The implications of the Three Kings eruptive cone emplacement on the hydrogeological properties of the surrounding rocks are discussed later in this paper.

Previous work (Kermode 1992) has identified the presence of four scoria cones within the Three Kings volcanic complex – Big King, East King, Highest King, and Central Cone. The volcanic deposits comprise large quantities of scoria as well as basalt in the form of dykes and feeder pipes. The scoria is often loose although areas of altered or welded scoria have been noted around the former locations of the Highest King and Central Cone (Fisher 2002).

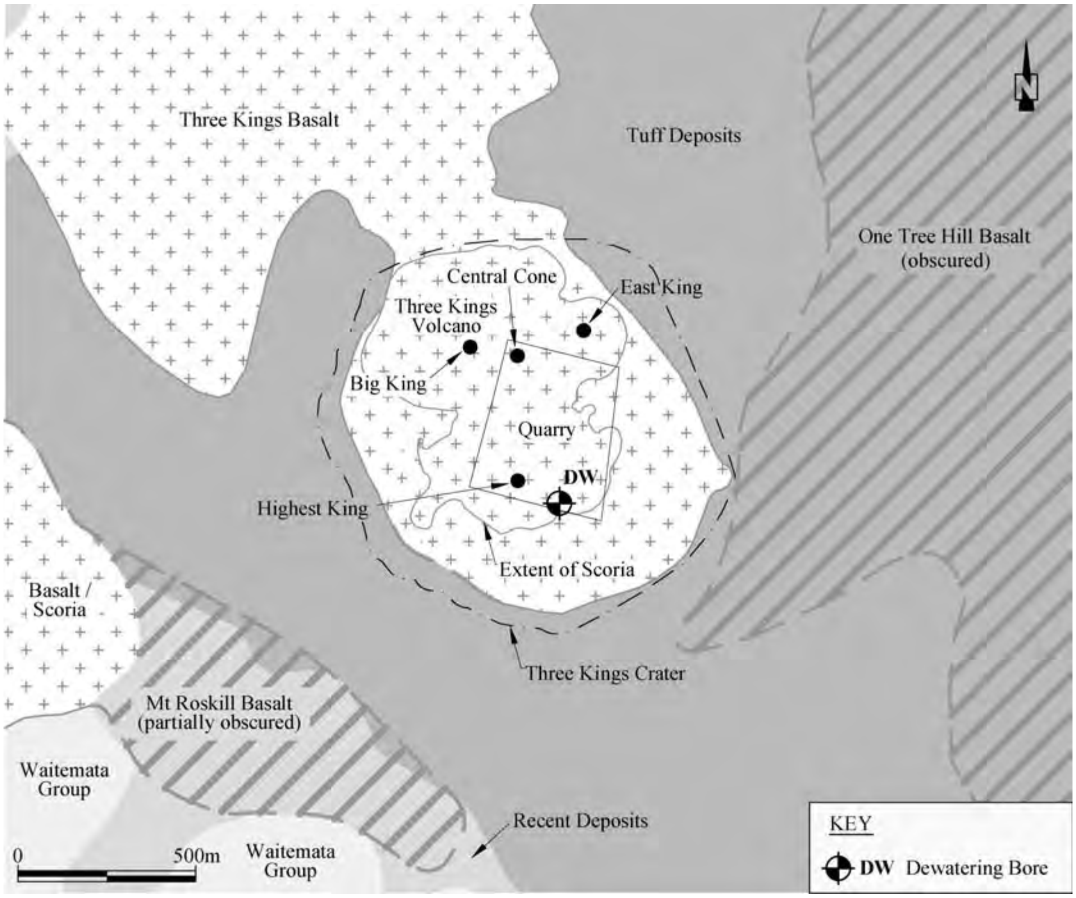

Figure 2. Three Kings geology

Estimates of the full depth to the base of the inverted cone have been made based on the angle of repose of the granular sediments forming the vent walls. The slope on the cone was suggested to be 37 degrees (Fisher, 2002) which would place the vertex of the inverted cone-shaped vent at somewhere between -160 and -170m RL (up to 194m below the current base of the quarry).

Tuff blown out during the initial explosive stages of eruption sits on top of Waitemata and Tauranga Group deposits and forms a bund-like feature, referred to as a tuff ring, around the vent. Investigations have found the tuff deposits to vary between approximately 4m and 18m in thickness (PDP, 2003a), generally with fewer tuff deposits present south-west and west of the vent. Basalt lava filled a moat between the scoria cones and the tuff ring.

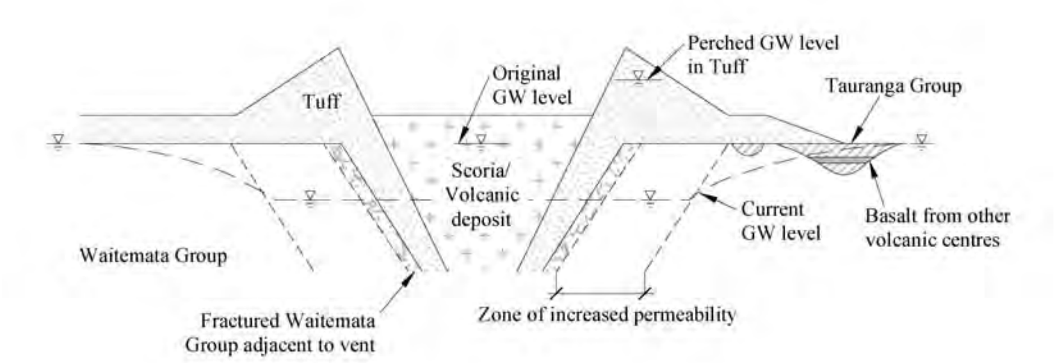

Figure 3. Simplified geological cross-section (north-south)

Breaching or overtopping of the tuff ring by lava has occurred to the north-west of the vent to form the Three Kings lava flow which extends over 10km down into the present Waitemata Harbour.

Previous work (Fisher, 2002) has noted the presence of cavities in the form of vertical pipes within the scoria and lava caves within the basalt flows. These have been observed to be several metres across. Whilst two caves have been uncovered within the vent itself (PDP, 2008), in general caves are not thought to occur to any significant extent in this area due to the ponded nature of the flows, but instead largely occur in the flows outside the vent.

3 HYDROGEOLOGY

3.1 *Pre-dewatering Groundwater Levels and Flow*

The available data show that pre-pumping water levels within the Three Kings volcanic vent were around 57m RL and were similar across the vent. The data also suggest that groundwater levels within the Waitemata Group close to the vent were generally at the same level as groundwater levels within the volcanic vent prior to the onset of dewatering. However, no information is available prior to dewatering in the Waitemata Group at greater distance from the vent.

A high permeability contrast exists between the basalt and the surrounding sediments and, as a consequence, groundwater flow is concentrated within the high permeability volcanics and is controlled by the geometry of the surrounding lower permeability sediments. Higher rates of recharge also occur in the vent volcanics. For water levels to have been maintained around the 57m RL level in the vent the recharge to the vent would need to have been balanced by outflow. This outflow is thought to have occurred through an area where the basalt has breached the tuff ring to the north, and then travelled down through the lava flow northward to discharge into the Waitemata Harbour.

Groundwater flow within the basalt is dominated by secondary porosity in the form of fractures and larger structures such as lava caves. Within the scoria, groundwater flow is closer in nature to the intergranular flow which occurs in sediments, although pipes and cavities are known to occur and may influence groundwater flow locally.

The low permeability of the tuff means that groundwater flow within this unit is generally only minor and occurs within perched and water table groundwater systems (Fig 3). There are two general trends in the tuff that lead to a general increase in saturated thickness with distance from the vent rim. Outside the rim the base of the tuff falls in elevation due to the Three Kings volcano's position on a ridge in the Waitemata Group. In addition, there is a general increasing degree of textural fineness of the tuff material away from the vent. As the tuff becomes finer, the permeability reduces and the drainage reduces resulting in the observed increased saturation.

The Waitemata Group can be considered a multi-layered aquifer with the mudstone/siltstone layers acting as aquitards and preferential flow occurring within the sandstone units. However, fracturing occurs to varying degree within this unit and can significantly enhance permeability and flow.

Regional groundwater flow within the Waitemata Group can be considered to be all but static compared with that within the vent volcanics.

The Tauranga Group sediments are not laterally extensive and so are not particularly significant with respect to regional groundwater flow. However, with respect to the effects of dewatering they are the most significant of the geological units as they are particularly prone to settlement when dewatered. Lithology within this unit can vary laterally and horizontally and influence groundwater flow directions and the occurrence of local perching.

3.2 *Hydrogeological properties*

3.2.1 *Permeability*

The volcanics in the Auckland isthmus are generally of very high permeability. The interconnecting lava flows and vents which fill in the old Waitemata Group landform are a major aquifer in the area and are used both for groundwater abstraction and for disposal of stormwater. Work carried out for the studies of Mt. Wellington (PDP, 1990) suggest that permeability in the vent volcanics in this setting is in the range 3×10^{-6} to 1×10^{-3}m/s. Whilst the vent contains basalt/dolerite, a large proportion of the central area of the vent contains scoria. This can be considered analogous to a coarse gravel in terms of permeability which would suggest a range of 10^{-4} to 10^{-2}m/s (Domenico & Schwartz, 1990). Significant horizontal/vertical anisotropy is generally not observed within the basalt/dolerite and scoria.

The Waitemata Group is also utilised for groundwater abstraction, although it is significantly lower yielding than the isthmus volcanics (up to around 400m^3/d compared with several thousand m^3/d). Typical permeability values for this unit are in the 10^{-8} to 10^{-6}m/s range. Slug testing of piezometers installed in the Waitemata Group around the site (PDP, 2003) suggested two distinct permeability zones (Fig. 4): Group A wells located close to the vent displayed permeability in the range 8×10^{-5} to 7×10^{-9}m/s with a geometric mean of 6.59×10^{-7}m/s. Group B wells located further from the vent displayed a range of 4×10^{-10} to 3×10^{-8}m/s with a geometric mean of 7.70×10^{-9}m/s. The nature of the lithologies in this group (alternating sandstones and mudstones) means that vertical permeabilities are generally lower than horizontal. No site-specific information is available regarding vertical hydraulic conductivity values within the Waitemata Group surrounding the quarry. Groundwater modelling of the Waitemata Group at other sites suggests vertical permeability may be approximately one order of magnitude less than the horizontal conductivities (PDP, 2000).

3.2.2 *Storativity*

Storativity (or specific yield) values for unconfined aquifers typically range from 0.01 to 0.30, while storativity values for confined aquifers range between 0.005 and 0.00005 (Freeze & Cherry, 1979). The storativity of a partially confined aquifer usually falls between the lower range for an unconfined aquifer and the upper range for a confined aquifer.

The vent volcanics aquifer is an unconfined system and therefore the storage coefficient would be expected to fall into the range 0.01 to 0.30.

The Waitemata Group in and around the quarry is considered as partially confined due to the discontinuous presence of overlying basalt, tuff, and/or unconsolidated materials and its multi-layered aquifer nature within the surrounding area.

Storativity values obtained from pumping tests at the Britomart site (PDP, 2000) generally ranged from 1×10^{-4} to 1×10^{-3}. Taking a typical value of 3×10^{-4} and an effective aquifer thickness for the tests of 30m produces a specific storage of 1×10^{-5}/m. This value has been used for the modelling analysis at Three Kings.

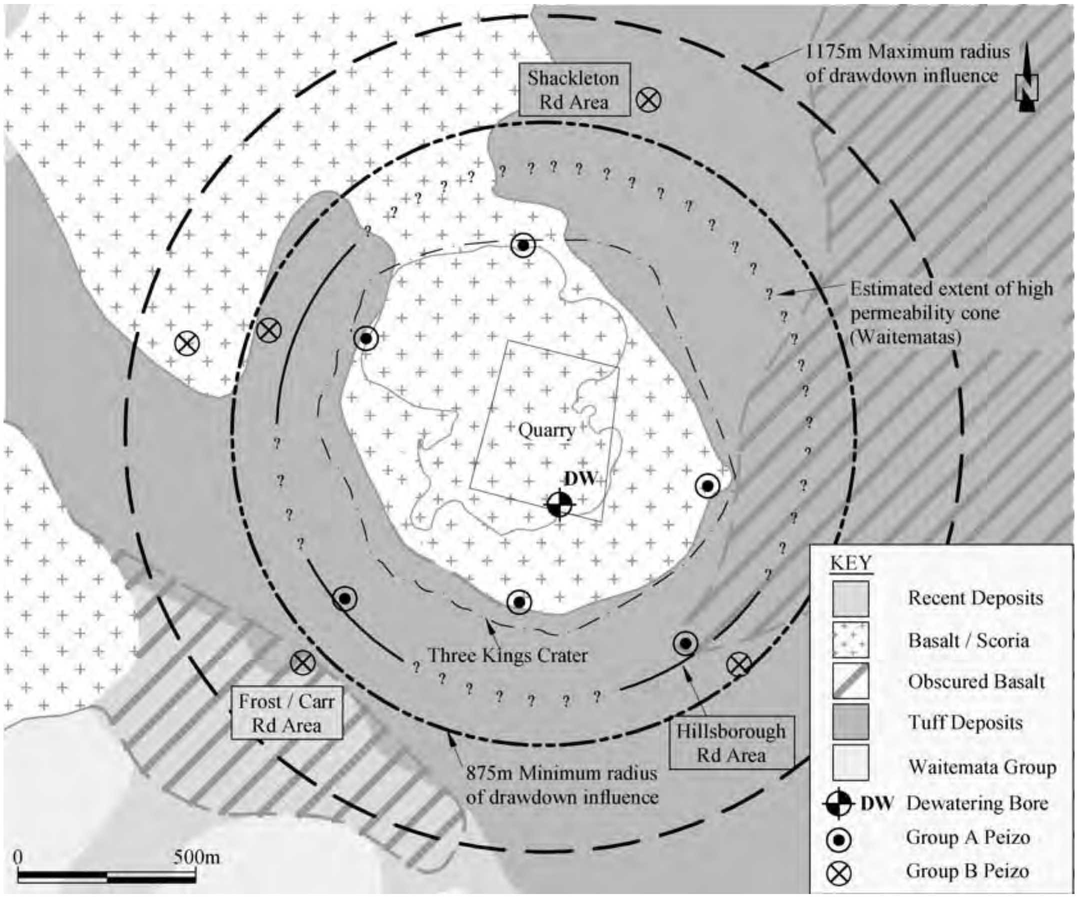

Figure 4. Key features in relation to dewatering

3.3 *Recharge*

Recharge to the Auckland isthmus volcanics is generally high due to their high permeability and fracture-based permeability which reduces field capacity and capillary action. Recharge rates vary hugely depending on the type of land cover and the presence or absence of reticulated stormwater disposal. Recharge rates over the isthmus volcanics have been determined to be between 4 and 94% (PDP, 2005a). Within the vent at Three Kings the cover is predominantly residential and commercial and stormwater is disposed of to ground. Recharge rates are consequently high and modelling of the vent indicates that as much as 88% of rainfall becomes recharge in this area (PDP, 2005b; PDP, 2008).

Lower permeability means that recharge through the Waitemata Group is much lower than through the vent volcanics. Typically recharge rates through this material are taken to be somewhere between 1 and 8% of annual rainfall. There is little to no site-specific information available regarding recharge to the Waitemata Group. Detailed groundwater modelling for the Britomart transport centre suggests a recharge rate of 1% (PDP, 2000) through Tauranga Group materials and volcanic cover sediments. Recharge through exposed Waitemata Group sediments is expected to be similar, although higher rates are expected in the higher permeability zone adjacent to the Three Kings vent.

4 QUARRY DEVELOPMENT AND DEWATERING

Quarrying at Three Kings began over 80 years ago. Over this period all but one of the original volcanic cones, Big King, were progressively removed. Prior to the 1960s, quarrying occurred above the level of land surrounding the vent. However, since then the quarry has been excavated below this level. In March 1999, dewatering operations were commenced in preparation for excavation of the quarry below the water table.

Dewatering of the quarry takes place from a bore located at the southern boundary of the quarry site (Fig. 2). Over the period of dewatering, two main stages of pumping have occurred – an initial, higher rate of approximately 4250m^3/d (average), and a subsequent lower rate of approximately 2400m^3/d (average). Reduction in pumping to maintain a groundwater level of 34mRL took place in October 2002. This is illustrated on Figure 5.

The current quarry extends over an area of approximately 15ha and down to a minimum elevation of 34m RL in the south-east quadrant of the quarry. Dewatering maintains the groundwater level below the quarry at an elevation of approximately 34m RL.

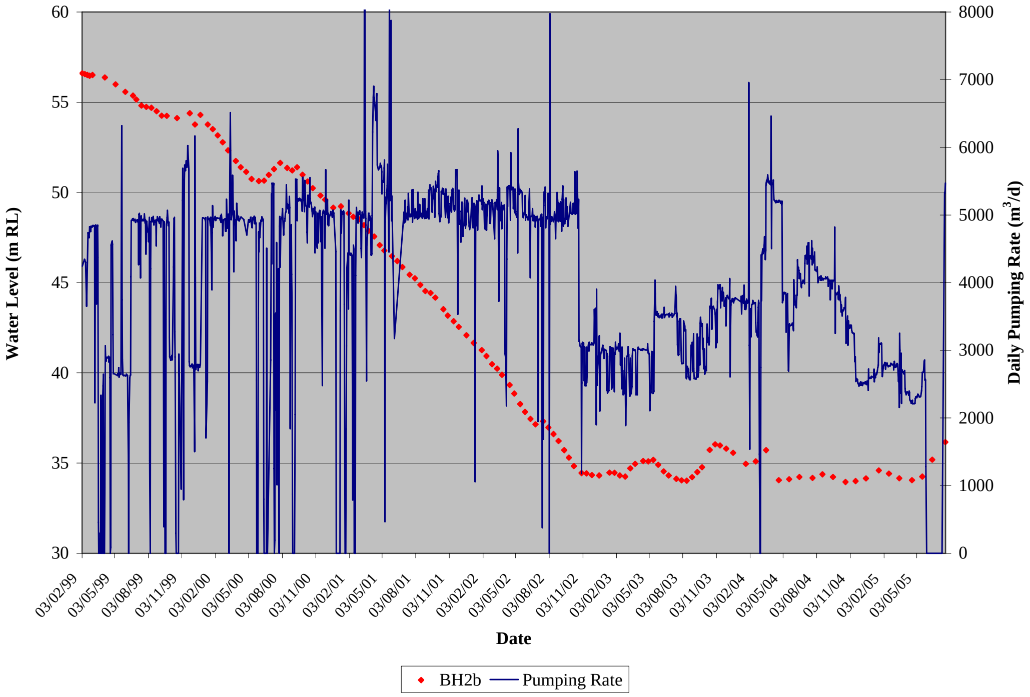

Figure 5. Three Kings Quarry pumping rate

5 GROUNDWATER RESPONSE TO DEWATERING

5.1 *Groundwater Monitoring Network*

Groundwater levels have been monitored in a number of piezometers around the quarry. A total of 66 piezometers (including 7 pneumatic piezometers) at 34 monitoring locations have been put in place which include piezometers within the quarry itself and piezometers extending out as far as 1200m from the quarry centre.

The earliest groundwater monitoring data start in December 1993 with 6 piezometers. Since that time the size of the network has increased in a number of steps until February 2005 when the most recent additions to the network were made.

5.2 *Response in the vent volcanics*

The response of the vent volcanics to dewatering is shown in Figure 6. The figure shows declining water levels in all of the piezometers during the first, high abstraction rate phase of dewatering. Reduction of the abstraction rate in October 2002 to the maintenance pumping abstraction rate produced a rapid response, with groundwater levels in the vent levelling off and remaining level. The holding of steady groundwater levels indicates that at this stage inflows to the vent – recharge and inflow from the units surrounding the volcanics – are in balance and thereby allows quantification of these inflows.

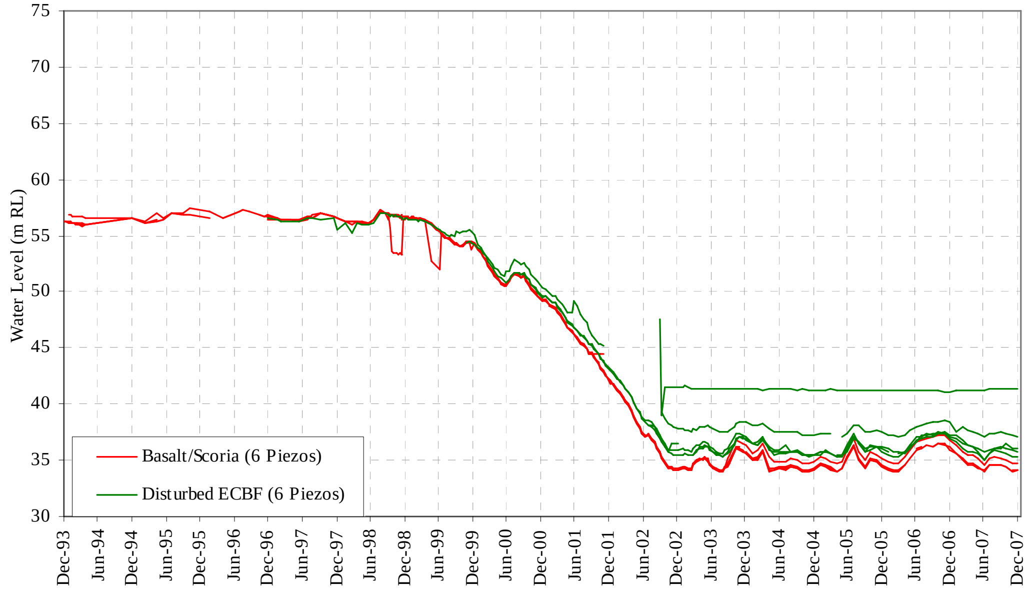

Figure 6. Groundwater response to dewatering in the vent volcanics and surrounding disturbed Waitemata Group

One of the most notable features illustrated on Figure 6 is the uniformity of response within the volcanics. All piezometers throughout the vent appear to act as one. This confirms the very high permeability of the volcanics and also indicates that variation in lithology (e.g. scoria and basalt/dolerite) and the presence of cavities and structures such as dykes do not lead to significant heterogeneity within the volcanics with respect to groundwater flow and response to dewatering.

5.3 *Response in the Waitemata Group*

Examination of groundwater levels for wells screened within the Waitemata Group has been carried out based on groundwater levels for those wells screened at 0m RL only (PDP, 2003). This mostly neutralises the effects of vertical gradients apparent within the Waitemata Group, and allows for a meaningful comparison of the data collected radially outward from the vent centre.

From these data it appears that there is a definite zone within the Waitemata Group where groundwater drawdown levels reflect those seen within the volcanic vent wells (Fig. 6). This zone appears to extend roughly 700m radially outward from the centre of the volcanic vent (Fig. 4) and is roughly circular in nature. It also correlates with the distribution of higher permeability seen in the Group A wells. The behaviour of the Waitemata Group in this 200m thick band reflects that of the vent rather than that of the surrounding lower permeability Waitemata Group shown in Figure 7.

The zone of higher permeability Waitemata Group is likely a result of the disturbance to the surrounding rocks caused by the volcanic explosion (Fisher 2003) and as such is expected to follow the contour of the volcanic vent (i.e., broader at ground surface and tapering inward at depth, similar to a cone).

Since the pumping hold point in the quarry was established at about 34m RL in October 2002, several bores have shown an associated response to the changed pumping regime. These are all bores within the high permeability zone around the vent that was identified in PDP, 2003a. The time to first response to changes in the maintenance pumping regime takes approximately 5 months for boreholes at the outer edge of the high permeability zone.

Some piezometers at a distance of approximately 1000m from the centre of the vent have shown a delayed recovery response to the change in pumping regime in October 2002. Recovery of water levels since active dewatering ceased has taken between 2 and 6 years to occur with the water level in one bore still showing signs of recovery. Water levels in these bores have increased between 0.5 to 6.0m since October 2002.

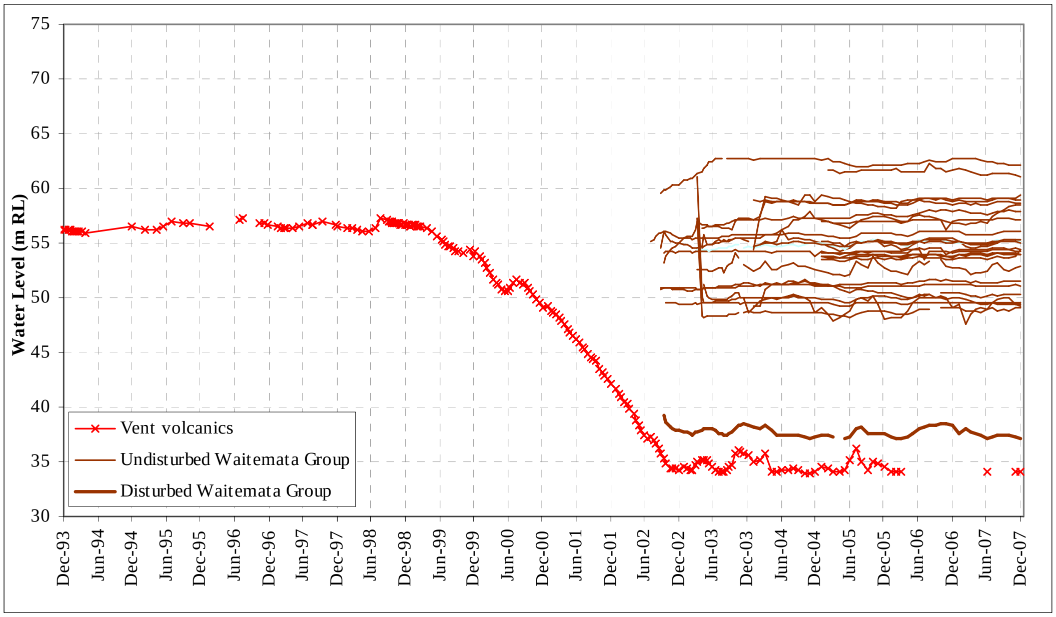

Figure 7. Groundwater response to dewatering in the undisturbed Waitemata Group

Monitoring data also show that response propagation in the normal Waitemata Group outside the high permeability zone is very slow. Significant responses due to the start of pumping in 1999, only travelled 100 – 300m into the normal Waitemata Group beyond the high permeability zone during the first 3 ½ years (PDP, 2003b). Modelling suggests the maximum extent of this drawdown-affected zone to be somewhere between 875m and 1175m (Fig. 4).

It is also apparent that there is a definite downward gradient within the Waitemata formation (PDP, 2003b). The magnitude of the downward gradient (based on differences between the water levels) decreases with increased distance from the vent centre. Within the high permeability zone head differences of 3m to 10m occur between shallow and deep piezometers at the same location with associated vertical gradients of between 0.004 and 0.32. Outside this zone, head differences are in the range of 1m to 3m, equivalent to gradients of 0.03 to 0.14. The gradients generally appear to decrease with depth.

The presence of vertical gradients may reflect several characteristics of the system, including the layered strata of the Waitemata Group creating a fragmented drainage effect within the upper sections of the formation and/or vertical variability in either the vent materials or the Waitemata Group itself.

5.4 *Response in the Deposits overlying the Vent Volcanics and Waitemata Group (Tuff and Tauranga Group)*

Groundwater within the tuff occurs mostly within perched systems and is mostly unaffected by direct drainage resulting from dewatering in the vent, and from underdrainage, which could be brought about by reductions in pressure in the underlying Waitemata Group. This is demonstrated by the few and very small responses observed in monitoring wells. Only one borehole, located close to the inner edge of the tuff ring in the north-west, showed any significant response since the start of pumping, showing a fall in water level of approximately 1.2m.

It is thought that the presence of low permeability weathered Waitemata materials and/or Tauranga Group sediments beneath the tuff inhibits underdrainage effects in the tuff. This is supported by the fact that no such material was encountered at the base of the tuff in the one bore showing a response.

A number of areas within the zone of dewatering were initially identified as having the potential for settlement as a result of underdrainage of compressible Tauranga Group sediments due to dewatering of the underlying Waitemata Group. These include areas to the south/south-east of the vent (around Hillsborough Road/Mt Albert Road), and to the south/southwest of the vent (Frost Road and Carr Road) and an area to the north of the vent (Shackleton Road). These areas are shown on Figure 4.

The regional surface geology is overlaid by the settlement contours on Figure 9. Inspection of this figure shows that there is a very weak, if any correlation between settlement magnitude and the areas of known or expected compressible deposits.

To the north, the Shackleton Road area occurs over a palaeovalley within the Waitemata Group sediments. A thin lens of Tauranga Group occupies the base of the valley, but is separated from the edge of the main Three Kings basalt lava flow in the vicinity by over 10m thickness of tuff materials. The area is approximately 1 km from the centre of the quarry, well outside the projected high permeability zone within the Waitemata Group. As a result, groundwater conditions in this area in both the volcanic and Waitemata Group materials do not appear to have been significantly influenced by the Three Kings dewatering and consequently it appears that dewatering of the Tauranga Group has not occurred.

To the south-east, the One Tree Hill Basalt (Fig. 2) has been observed to control water levels in nearby tuff ring areas (PDP, 2003b). In this area groundwater levels deep in the Waitemata Group suggest a response to pumping (being around 37m RL), but those in the overlying basalt and shallower sediments are significantly higher than this (just under 50m RL). Despite effects being seen in the sediments underlying the basalt at this location, the maintenance of a high vertical head gradient between the basalt and the underlying sediments would suggest low vertical connectivity or a high permeability contrast.

Tauranga Group sediments have also been intersected In the Frost Road/Carr Road area to the south-west, mostly above (but also below) a basalt flow from Mt Roskill - a similar situation to that encountered to the south-east. Drawdowns in the Waitemata Group here will diminish upwards through the Tauranga Group to zero at the base of the basalt.

These observations indicate that, due to their high permeability, basalt flows tend to exert a controlling or buffering influence on the piezometry in those sediments immediately underlying or overlying the flow. This is illustrated in Figure 8 which shows the lack of effect in tuff overlying basalt and the similarity in response between Tauranga Group and basalt in the area of the One Tree Hill flow. Piezometry in these flows is related to recharge directly to them and abstraction directly from them. Those flows close to the vent but unconnected and derived from external volcanic centres do not show a response to pumping in the Three Kings vent.

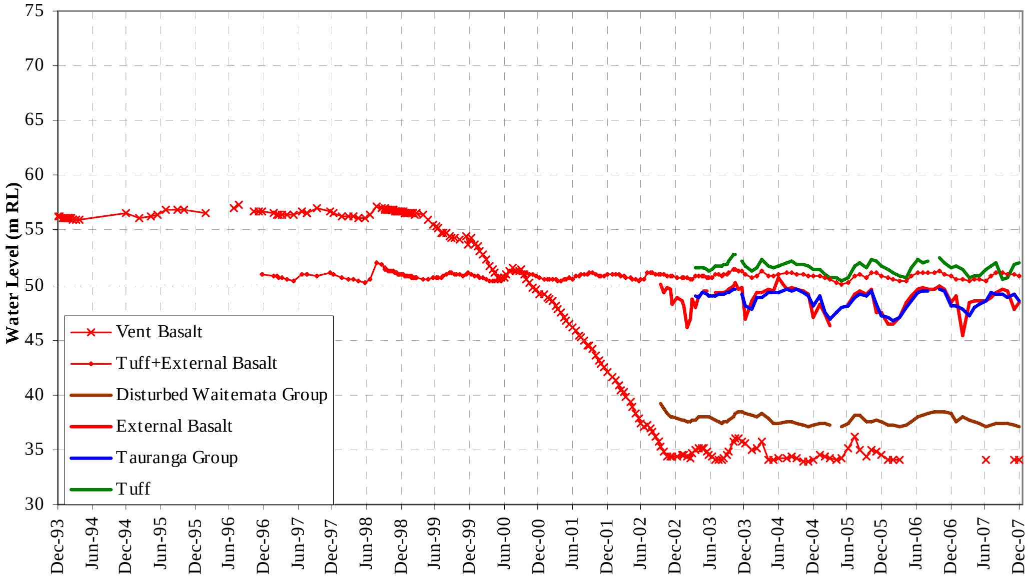

Figure 8. Groundwater response to dewatering at selected locations

Where Tauranga Group sediments are in direct contact with the Waitemata Group the upwards transmission of drawdown effects into these materials will depend on the permeability contrast between the Waitemata and Tauranga Groups. The stiffer more clayey portions of the Tauranga Group are known from studies at the Britomart site to have a similar permeability to the weathered Waitemata Group and could therefore be susceptible to drawdowns in the Waitemata Group (PDP, 2000). The softer more organic portions of the Tauranga Group tend to exhibit a higher permeability and have a lower susceptibility to Waitemata Group drawdowns. Even where susceptible to drawdown the small but significant permeability contrast between the two groups means that a residual saturation of about 3m is expected in the tuff and Tauranga Group. This has been observed in some areas.

The potential difference in response between compressible sediments overlying basalt and those directly overlying the Waitemata Group would suggest that around the margins of basalt flows there is the potential for differential settlement. However, the most recent settlement data show that there is very little correlation between the presence or absence of tuff and Tauranga Group sediments and the pattern of settlement (which is shown on Figure 9). These data indicate that the primary factor determining the degree of settlement is the drawdown within the Waitemata Group sediments (measured in piezometers close to 0m RL).

Figure 9 shows the distribution of surface settlement about the quarry since dewatering commenced. For the maximum measured drawdown of 23m, the maximum settlement response measured is 28mm, with settlements typically in the order of 5-15mm. Relatively low settlement in the vent despite high drawdown is due to the presence of low compressibility basalt and scoria, with relatively higher settlement in the area of disturbed Waitemata Group outside the vent where drawdowns are also high. Settlement then decreases at further distance from the vent. Where the piezometers and survey mark location provide a direct correlation between measured drawdown and surface settlement a very rough rule of thumb of approximately 1 mm of surface settlement for every 1 m of drawdown is apparent, irrespective of surface geology.

The lack of correlation between the distribution of higher settlements and the presence or absence of tuff or Tauranga Group sediments may be due to a combination of lack of drawdown within these sediments and a lower than expected difference in settlement response between these sediments and the Waitemata Group. Unfortunately, the lack of pre-dewatering data in some of these sediments, particularly the Tauranga Group deposits (which makes total drawdown difficult to determine) makes it difficult to estimate which of the two factors is the more important.

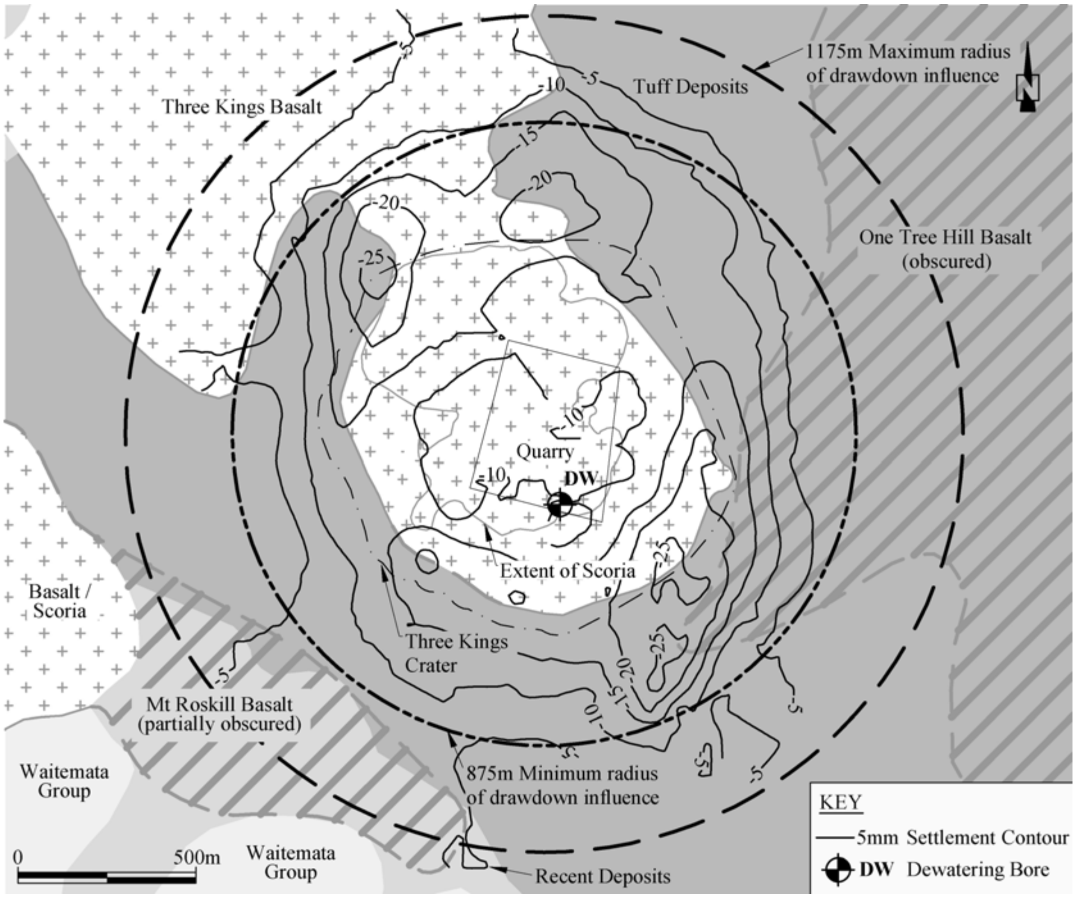

Figure 9: Settlement around Three Kings Quarry

6 FINDINGS FROM GROUNDWATER MODELLING

It is beyond the scope of this paper to discuss groundwater modelling in detail; however, extensive groundwater modelling of the vent dewatering has been carried out to provide predictions of drawdown to assist in management of the site and for prediction of settlement (Subsurface Imaging, 2002; PDP, 2003a; PDP, 2005b; PDP, 2005c). Modelling has been focused on the key components of the hydrogeological system, the vent volcanics and the Waitemata Group. Determining drawdown in these units allows prediction of the degree of underdrainage of overlying sediments.

Calibration of the model against ongoing groundwater level monitoring data has allowed refinement of the water balance inputs and the hydrogeological parameters. The key findings to come out the modelling are:

- Recharge rates are very high in the vent materials at 88% of annual rainfall.
- Recharge rates in the Waitemata Group are higher over the area of disturbed Waitemata Group (10%) compared with undisturbed Waitemata Group (1%).
- Hydrogeological parameters are estimated to be as per Table 1 below.
- Extent of effects of dewatering to the current level is likely to be limited to a radius of between 875 and 1175 m from the centre of the vent.

Table 1. Summary of calibrated hydrogeological properties

Lithological Unit	K_H (m/s)	K_V/K_H (m/s)	Storage Coefficient*
Vent volcanics	2.0×10^{-4}	1	0.1
Disturbed Waitemata Group	9.4×10^{-7}	1	$0.1(S_y)/1\times10^{-5}(S_s)$
Undisturbed Waitemata Group	1.5×10^{-8}	0.1	$0.1(S_y)/1\times10^{-5}(S_s)$

*S_y = unconfined storage, S_s = confined storage.

7 GROUNDWATER LEVEL MONITORING AND THE SETTING OF GROUNDWATER TRIGGER LEVELS FOR SETTLEMENT

Due to the potential for ground settlement, groundwater levels are being monitored at the site to pick up any declining trends groundwater levels in areas considered especially susceptible to settlement. A methodology was developed for the setting of trigger levels to provide an alert for groundwater decline in these sensitive areas. This methodology needed to take into account natural variation in groundwater levels that was not attributable to any dewatering activity. These variations differ from one borehole to another which meant that the natural groundwater level range should be individually identified for each borehole.

It was considered that restriction to the range of the measured values as an indication of the natural range would be misleading, particularly for the boreholes with little data. For this reason, a statistical analysis of the measured values was employed to determine a lower “limit of probability” below which it is statistically unlikely that any measured value could be “normal”.

When considering the normal distribution of values within a group of data, certain coefficients (known as *z values*) are derived to describe how many standard deviations (SD) either side of the mean relate to a certain probability that all the values within the population fall within that range. This is illustrated in Figure 10.

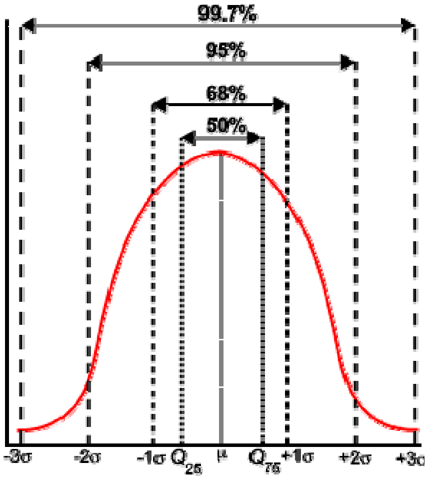

Figure 10. Z-values for a normal distribution

A 99% probability of a value being ‘normal’ relates to a z value of 2.58. In the case of Three Kings the minimum baseline level for any one borehole was defined by the lower 99% limit of probability. The probability limit is determined by subtracting (2.58 x the SD of the measured values) from the calculated mean of the measured values.

Trigger levels were set at 99% of the annual seasonal fluctuation below the mean of the measured values.

Re-evaluation of the minimum baseline level was carried out periodically as new monitoring data were collected. To do this, confidence limits were used to confirm that the new datasets were not statistically significantly different from the historic datasets.

A confidence limit is used to relate the mean of a sample to the mean of a population. Using 95% confidence limits, for example, means that you can be 95% certain the mean of a population will fall within the limits prescribed. Confidence limits use the same z values as the probability limits defined in the previous section, but are related to the standard error of the mean (SEM) of the sample rather than the SD. The SEM is calculated by dividing the SD by the square root of the number of values (N) in the sample.

$$SEM = \frac{SD}{\sqrt{N}}$$

One sample is considered, statistically speaking, significantly different from another if their 95% confidence intervals do not overlap. For Three Kings it was determined that if the upper 95% confidence limit of the mean in any one 12 month monitoring period was higher than the lower 95% confidence limit of the mean from the previous 12 month monitoring period, or if the lower limit from one period is lower than the upper limit of the previous period (i.e. the two intervals overlap), then the data from the two periods were not significantly different. In this case the minimum baseline level can be safely re-evaluated using data from both periods.

8 CONCLUSIONS

The dewatering of the Three Kings vent and the subsequent investigation, monitoring, and modelling work has provided useful information on the hydrogeology of vents and surrounding rocks in the Auckland Isthmus area.

One of the key findings is that emplacement of the vent has caused locally-enhanced permeability in the surrounding rocks. This is relevant to dewatering operations as large dewatering-induced drawdown can spread rapidly into this zone of enhanced permeability. When modelling or predicting drawdown (and settlement predictions) in similar situations account needs to be made for this enhanced permeability zone. An understanding of the geometry of this zone is also required when locating monitoring points (both groundwater piezometers and surface level survey marks) and designing monitoring plans.

The modelling work that has been carried out for the Three Kings Quarry has allowed the refinement of permeability and recharge figures for the volcanics and Waitemata Group. It has allowed a quantification of the degree of permeability enhancement in the disturbed Waitemata Group, showing it to be approximately midway between volcanics and undisturbed Waitemata Group.

Drawdown in sediments overlying the Waitemata Group is generally minor in tuff deposits, where the presence of low permeability layers results in the perching of groundwater levels and inhibits the effect of underdrainage.

In the compressible sediments of the Tauranga Group the effect of underdrainage in the Waitemata Group can be strongly influenced by the nature of the contact between the Tauranga Group and the nature of any intervening sediments. Where basalt flows from centres that are not being dewatered are present these tend to be unaffected by drawdown and can control the water levels in surrounding sediments. Where weathered Waitemata Group is present this can reduce the propagation of drawdown into the overlying Tauranga Group sediments.

In the setting of trigger levels for determining the presence of groundwater drawdown the natural variation in groundwater levels needs to be taken into account. This can be achieved by defining an appropriate limit of probability. In the case of the Three Kings, groundwater trigger levels were selected as 99% of seasonal variation.

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