Review (1968-2016) of Subsidence at Ohaaki geothermal field, New Zealand

Abdul Nishar [1], Chris Bromley[2], Fabian Sepulveda[1], Sang Goo Lee[1]

[1] Contact Energy Ltd, Taupo, New Zealand, [2] GNS Science, Taupo, New Zealand

abdul.nishar@conactenergy.co.nz, c.bromley@gns.cri.nz

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ABSTRACT

Parts of the Ohaaki geothermal field have been adversely affected by subsidence resulting from 30 years of geothermal fluid extraction. At the centre of the area of largest subsidence, the total has reached 6.7 ± 0.1 m, with maximum subsidence rates decreasing from over 510 mm/year during the 1993-1996 period to 150 ± 10 mm/year during 2012-2016. The general location of the subsidence anomaly has not changed significantly, although the location of the area of maximum subsidence rate has shifted over time. Following a review of the spatial and temporal variation of subsidence rates, along with supporting evidence such as reservoir pressure, subsurface geology, and material compressibility, we postulate an explanation for the changes. To appropriately manage infrastructure and environmental effects, reliable forecasts of subsidence are important. Consequently, we also test previous predictive models of ground deformation against actual levelling data to assess predictive uncertainty.

1. INTRODUCTION

A spatial and temporal relationship between subsidence and fluid extraction has been observed in several New Zealand geothermal fields, including Wairakei and Ohaaki (Bromley et al, 2015). Pressure drawdown in the shallow formations (typically < 400 m depth), combined with the presence of compressible materials (hydrothermal clays or mudstones with plastic yielding properties), is thought to be the principal causative mechanism of subsidence in these fields (Allis and Zhan, 2000; Bromley, 2006; Allis et al., 2009, Bromley et al, 2015).

At Ohaaki, located in the Broadlands area of central North Island, New Zealand. an extensive array of levelling benchmarks has allowed subsidence areas to be closely monitored. The magnitude of level changes, as well as spatial and temporal patterns, are further investigated for this study. To this end, maps of subsidence rates for selected survey periods, and plots of selected benchmark levels with time for the period 1968-2016 are presented and discussed.

Several adverse effects can be associated with land subsidence, including damage to surface infrastructure and buildings (Bloomer and Currie, 2001), increased risk of flooding and inundation, and subsurface deformation of well casings (Allis et al, 2009). Because of this, and because of the relationship of subsidence with reservoir development, efforts have been made by previous researchers to forecast subsidence. In this paper we also discuss the predictive uncertainty of such historical forecasts.

1.1 Ohaaki Reservoir Changes

The Ohaaki Field is a high-temperature, liquid-dominated geothermal system located in the Taupo Volcanic Zone (**Figure 1**). The bore-field is separated geographically into West Bank (north-west of Waikato River) and East Bank (south-east of Waikato River; **Figure 1**). A conceptual model of the geothermal system is illustrated by way of a hydro-geological cross-section in **Figure 2**.

Investigations into the potential of the Ohaaki Geothermal Field (formerly known as 'Broadlands') for power production started in the mid 1960's, with field-wide production testing during the period 1968-1974 (Allis et al., 1997a). Ohaaki power station (104 MWe of conventional steam turbines) was commissioned in 1988. The 1988-2016 production history of the Ohaaki geothermal field is graphically summarised in **Figure 3**. During the initial phase of power production (1988-1995), fluid mass extraction from the West Bank was greater than that of the East Bank, and most fluid take was sourced from the intermediate depth reservoir (400-1000 m). During the following period (1995-2006), mass take from East and West Bank intermediate reservoirs was similar, but subject to a steady decline, with the West Bank showing a slightly faster decline rate. From 2007, mass take increased again in the West Bank because of drilling into a deeper reservoir (> 1000 m; Brockbank and Bixley, 2011). A peak in the West Bank deep reservoir mass take was reached around 2008-2010, after which mass take was sustained at about 20,000 t/day. For most of the recent period (2010-2016), mass take has continued to decline (to about 5,000 t/day) in the East Bank sector.

Since 1988, most of the separated brine and surplus steam condensate from the cooling tower has been reinjected. A small proportion of the brine is injected beneath Ohaaki Pool as a mitigation measure to sustain ~9 l/s discharge from this natural feature into the Waikato River (Hunt and Bromley, 2000). For the first few years, brine was reinjected into deep peripheral wells, but rapid fluid returns from injection to production wells forced a switch to shallow (~300m-800m deep) edge-field injection sites (Clotworthy et al., 1995). The surplus cold condensate is injected into edge-field boreholes near the power station (**Figure 1**). Approximately 30% of the mass produced is lost to the atmosphere as vapour through a natural draught cooling tower. The resulting net mass loss has contributed to an overall decline in reservoir pressure, and initially (1988-1995) the expanding 2-phase zone caused a measurable decrease in gravity due to density change. Positive gravity changes from 1995 onwards, however, have indicated that some mass recharge has been occurring. This is inferred to be within the intermediate depth aquifer.
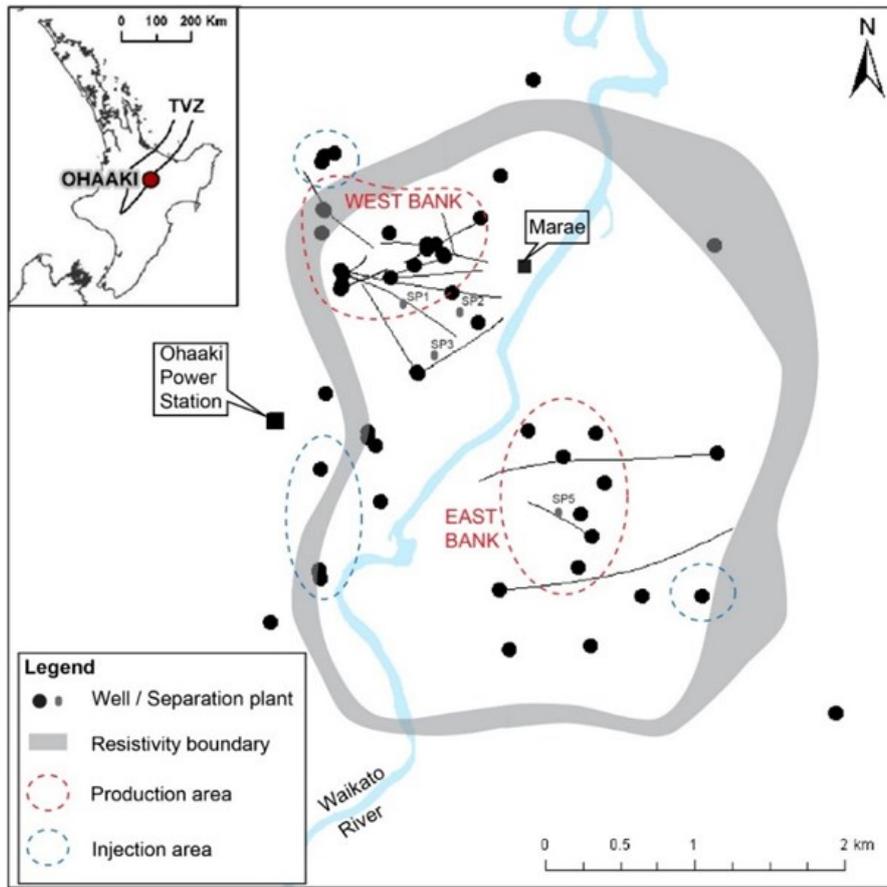
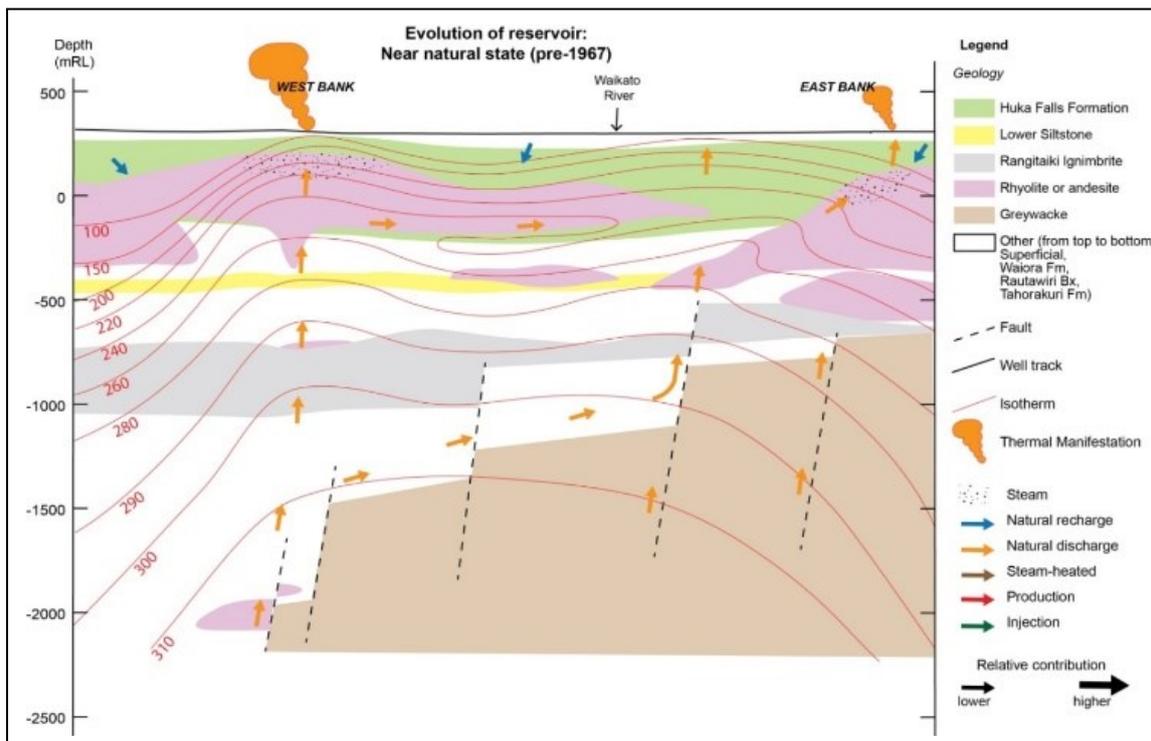**Figure 1. Ohaaki Geothermal field**

Figure 2. Conceptual model of Ohaaki, with NW-SE hydro-geological section showing faulted basement surface, overlying formations (e.g. "Inner Ohaaki Rhyolite" doming beneath west bank) and primary fluid flow directions through aquifers separated by aquitards.
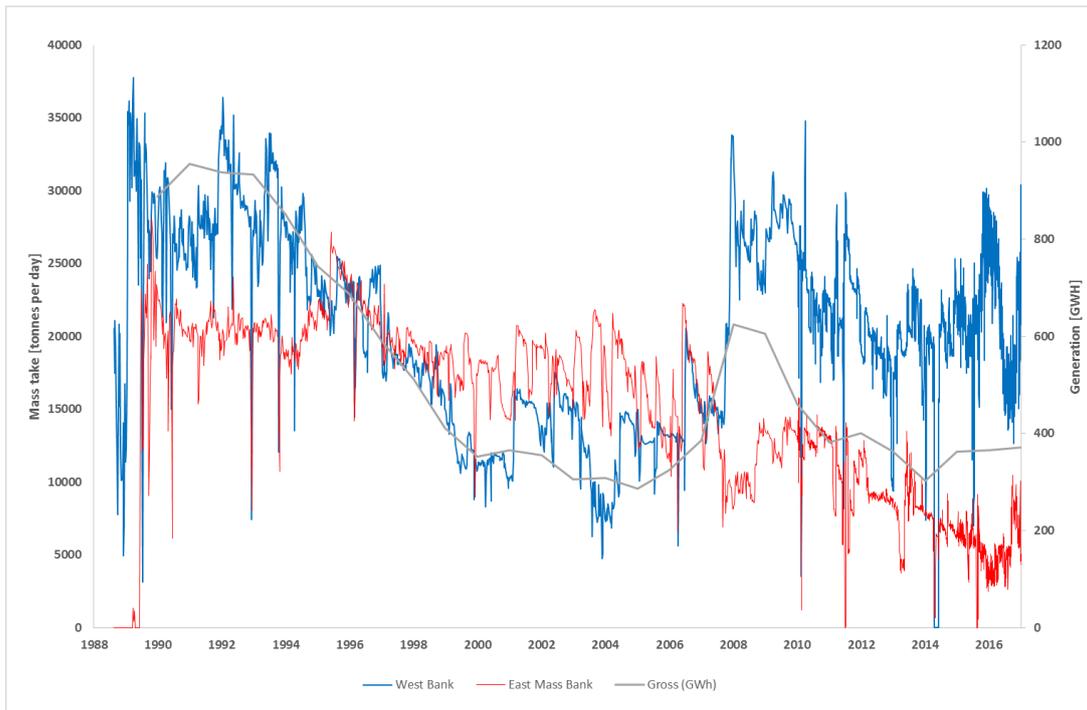
Figure 3. Ohaaki geothermal field production history (1988-2017).

During the period 1988-1995, pressure drawdown due to net fluid extraction was observed across the entire Ohaaki geothermal field (e.g. Brockbank and Bixley, 2011; Clearwater et al., 2011), affecting the intermediate reservoir (400-1000 m depth interval) and shallow aquifers (100-400 m depth interval). Groundwater level changes were observed locally only in the West Bank sector (Hunt and Bromley, 2000). Intermediate reservoir pressures started recovering around 1995 and shallow (Inner Rhyolite) aquifer pressures similarly started recovering around 2004. Overall, the period since 2008 has been characterised by relatively stable pressures in the shallow aquifers (**Figure 4**). [BR4 pressure declined by 1.4 bars in 2013-2016 but recovered 1.4 bars in 2016-2019.]
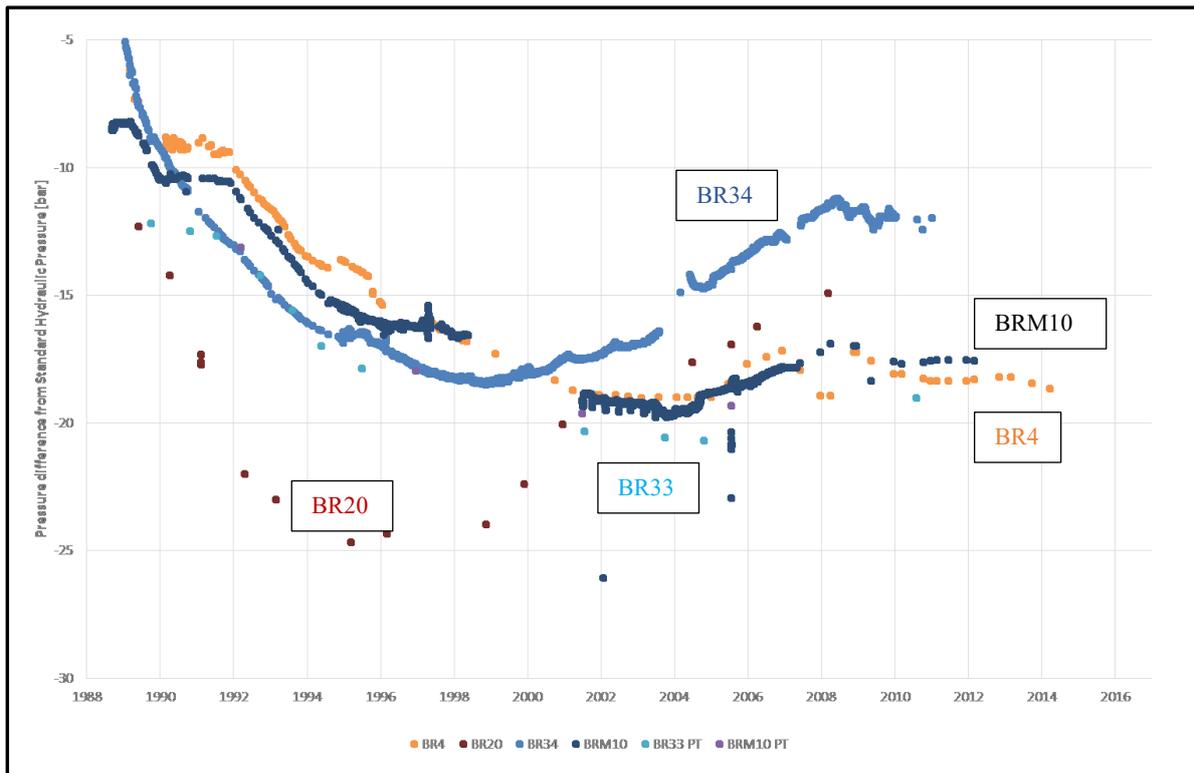

Figure 4. Trends over time in pressure (relative to pre-development standard hydraulic pressure) for different aquifers: intermediate production (BR20), edge-field production (BR34), middle of inner Ohaaki Rhyolite (BR33) and top of Rhyolite (BRM10/BR4). These show progressive time-lag and attenuation, from intermediate to shallower depths.

2. RESULTS OF ANALYSIS OF OBSERVED SUBSIDENCE

2.1 Method

An extensive network of benchmarks (**Figure 5**) is used at Ohaaki to monitor deformation, with the first set of benchmarks installed prior to the testing phase (1968). The benchmarks are levelled using precise digital levelling techniques with invar bar-coded staves. Details are given in Currie and Bloomer (2001). The average subsidence rates (mm/yr) were derived from these level data and contoured (**Figures 6 and 7**) for the periods: 1968-1988 (Testing); 1988-1995 (Early Production), 1995-2006 (Production II), 2006-2012 (Production III) and 2012-2016 (Production IV). The software package used for interpolation is ArcGIS (10.3) and the geostatistical and spatial interpolation technique uses Kriging. The measured level changes over time are fitted with continuous functions using the methodology of Sepulveda et al. (2017), which is based on the original concept of sigmoidal curve fitting of Bromley et al. (2006).

Deformation is recorded relative to a reference site located about 4 km east of Broadlands Road on the Kaingaroa Plateau (**Figure 5**). It therefore includes some regional component of tectonic deformation associated with the Reporoa Basin and the edge of the Taupo Volcanic Zone. This background tectonic subsidence has historically been about 3 to 5 mm/yr and contributes to an assessed uncertainty of +/- 5 mm/yr in geothermal subsidence.
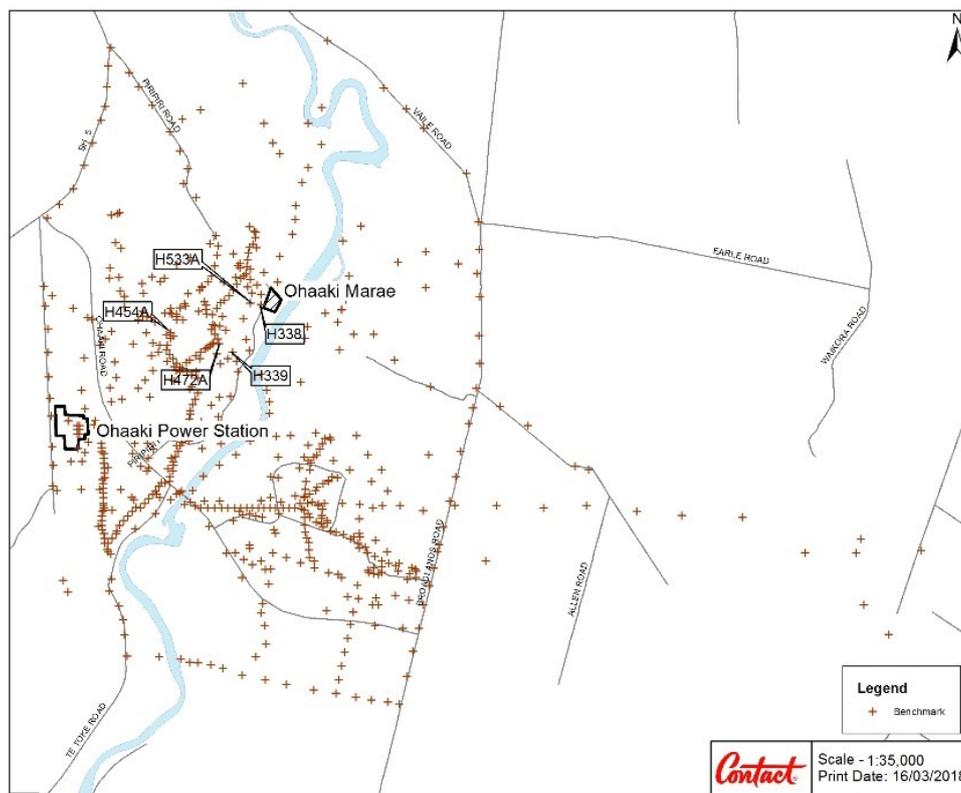

Figure 5. Benchmark network at Ohaaki geothermal field

2.2 Subsidence History

Subsidence at a maximum rate of 52 mm/yr was first observed within the West Bank production sector of Ohaaki during the testing phase (1968-1974; **Figure 6**). The cumulative subsidence during this test discharge period (extraction without reinjection) reached a maximum of 0.25 m. After a pause of 14 years (the recovery period of 1974-1988), during which levels stabilized but did not rebound, renewed subsidence was again noted in association with full-scale production from 1988 (**Figure 7**). Because subsidence had been detected during the period of discharge testing, it was also anticipated from 1988.

Subsidence associated with the production phase developed over a broader area compared to that of the testing phase (**Figure 7**), although the area of highest subsidence rate remained on the West Bank. The shape of the anomaly broadly resembles that of a ring or a moat. This is consistent with the occurrence of Huka Falls Formation lake-deposited mudstones, which are draped around a former island (a buried rhyolite dome, named "Inner Ohaaki Rhyolite", **Figure 2**) within the ancient Huka Lake. Maximum subsidence rates within this subsidence 'ring' have shifted over time from a site 250 m north of SP1/H454A (1968-76, **Figure 6**) to a site 250m west of Ohaaki Marae (1988-1995, **Figure 7A**), then to a site near SP1 (>1995, **Figure 7B to 7D**).

Subsidence rates peaked at about 1995 for most sites on the eastern and southern sides of the ring-shaped anomaly but were delayed to about the year 2000 for the anomaly centred near SP1. Furthermore, while the eastern and southern parts of the anomaly have declined in subsidence rates by an average of 80% since their 1993-1995 maximum of up to ~540 mm/yr, the SP1 area has only declined by an average of 60% since a 1998-2002 maximum of up to ~420 mm/yr. Consequently, the SP1 area is now the location of maximum rate (~170 mm/yr) and of maximum accumulated subsidence (6.7 m), whereas rates near the Waikato River and Ohaaki Marae, where flood inundation is the most serious of potential consequences, have dropped to less than 45 mm/yr. Attempting to understand the mechanism behind these observations is an important objective of this study.
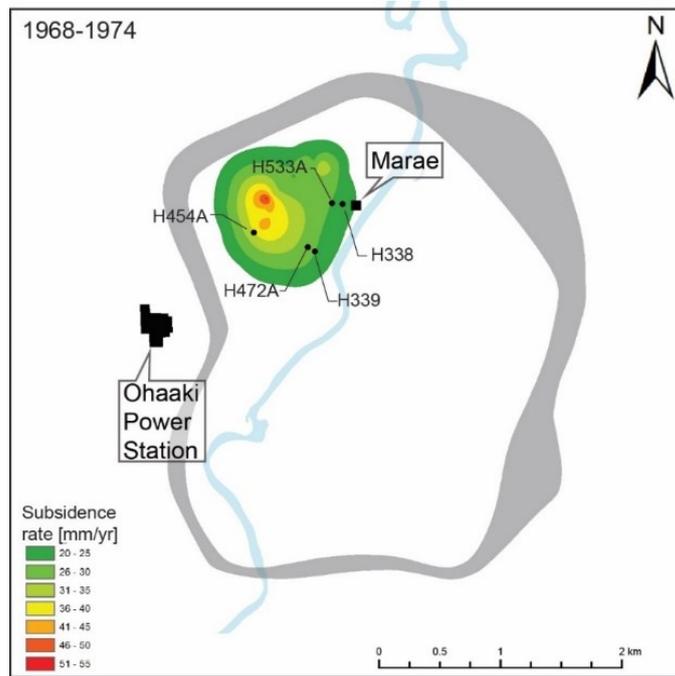
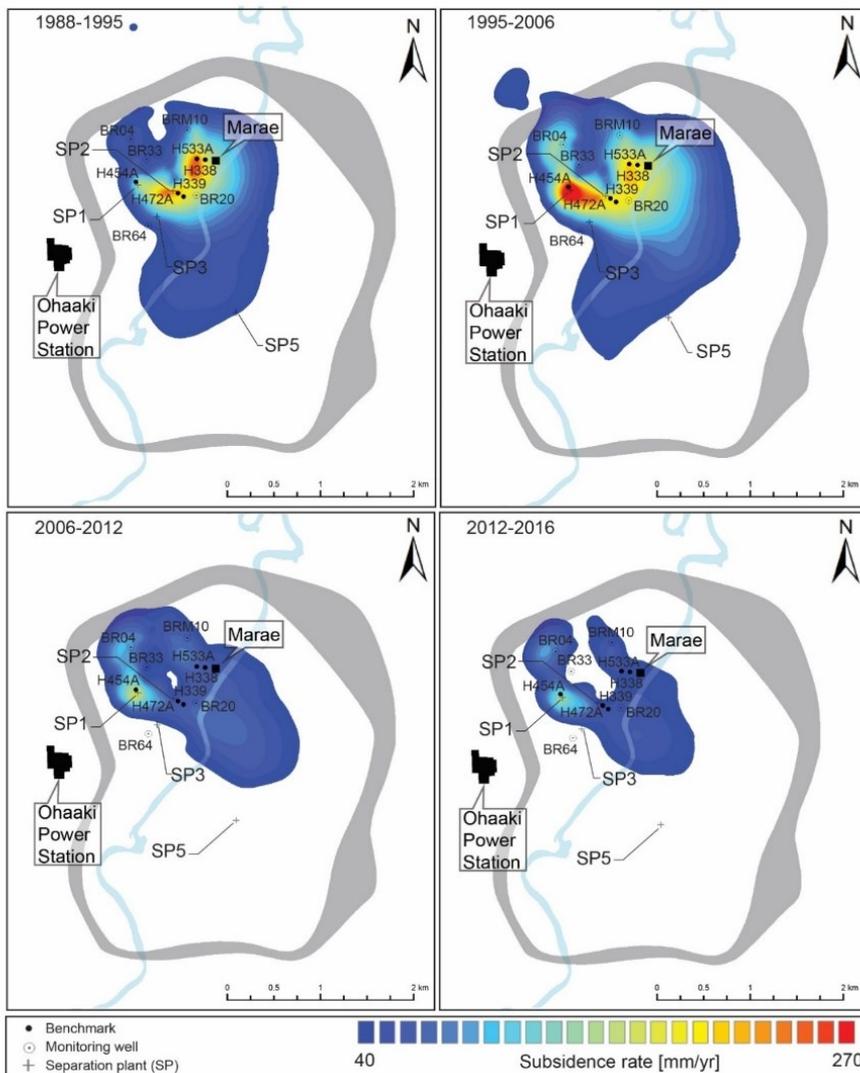**Figure 6. Subsidence rates (mm/year) for testing phase (1968-1974) at the Ohaaki Geothermal Field.**

Figure 7. Subsidence rates in Ohaaki Field (mm/year; 1988 - 2016)

The subsidence has impacted steam-field pipelines, wells and facilities on the West Bank, and has also resulted in a local deepening and widening of a section of the Waikato River. This has impacted the Ohaaki Marae and associated Maori cultural sites, and wetland areas. Subsidence rates near the Marae peaked in 1994 at ~330 mm/yr but have since reduced to less than 45 mm/yr. (Rate history is taken from a nearby benchmark, NWA5). Between 1968 and 2016, accumulated subsidence here reached about 3.5 m.

Rates of subsidence over time have generally increased then decreased, but with different trends on different sides of the anomaly as noted above (**Figure 7**). These differences in subsidence timing and amplitude from different local areas are interpreted to be caused by lateral variations in properties of the compacting formations, in conjunction with a gradual migration of reservoir pressure decline upwards through overlying aquifers. Local variations in compressibility and thickness affect the subsidence amplitude, while permeability and thickness variations affect the rate of pressure diffusion through the compacting formations.

3. PAST PREDICTIONS AND UNCERTAINTIES

In 1977, a report by the Ministry of Works and Development (MWD, 1977) predicted that Te Ohaaki Marae site, on the banks of the Waikato River, would eventually (after some 40 years) become untenable due to subsidence-induced, increased flood risk. This assessment of the vulnerability of the Ohaaki Marae to flooding, although based solely on subsidence rates observed during early 1960's and 1970's test discharges, has proven to be reasonably accurate.

In 1995, a worst-case subsidence prediction was made based on linear projection of the high subsidence rates observed after the first 7 years of full-scale production. Up to 7m subsidence was anticipated near wells BR21-22 (adjacent to the Waikato River) and up to 3.5m near SP1. However, the actual subsidence rates declined after 1995 in the BR21-22 area, so total subsidence reached just 4.2m by 2006, whereas the rates at SP1 peaked in 2000, and subsidence reached 5m by 2006. These differences illustrate the uncertainties that arise from applying a linear projection to short-term subsidence rates. This was also recognised at the time and, in 1998, Allis showed that the uncertainties in linearly projected total subsidence by 2005 were at least +/- 3 m. Allis also noted the implications of a reduction in subsidence rates for the Ohaaki Marae. He expressed the view that his previous (1995) predictions were too pessimistic, and that flooding of the Marae, which he had predicted (in 1995) would occur in 2005, would take much longer (until 2015). He also surmised that subsequent events might demonstrate that prediction to be unduly pessimistic also. This has indeed proven to be the case.

Subsequent models developed by Allis and Zhan (2000), Bromley (2006) and Bromley and Reeves (2013) have also been used to provide predictions. Simple subsidence predictions make use of the fact that accumulated subsidence can be calculated from the product of formation thickness (m), compressibility (MPa^{-1}) and effective stress change or pressure decline (MPa). However, the low permeability of the compacting formation has an important delaying effect through slow diffusion of pressure change from adjacent aquifers. Also, clay yielding, which is a non-linear, load-dependant process, has a delaying effect on observed subsidence.

In 1998-2000, one-dimensional modelling of the subsidence rate changes at Ohaaki was undertaken by Allis and Zhan (2000). This work was supported by compressibility measurements from cores of Huka Falls Formation (HFF) sediments, collected from borehole BRM12, within the main subsidence anomaly (Read et al, 2003), and pressure measurements from the inner Ohaaki Rhyolite aquifer nearby (at BRM10, **Figure 4**). The finite-element model, which coupled compaction, fluid flow and liquid pressure diffusion processes, achieved an optimized fit (**Figure 8**) to the history of subsidence (up to 1998) for benchmark (H472A, **Figure 6**).
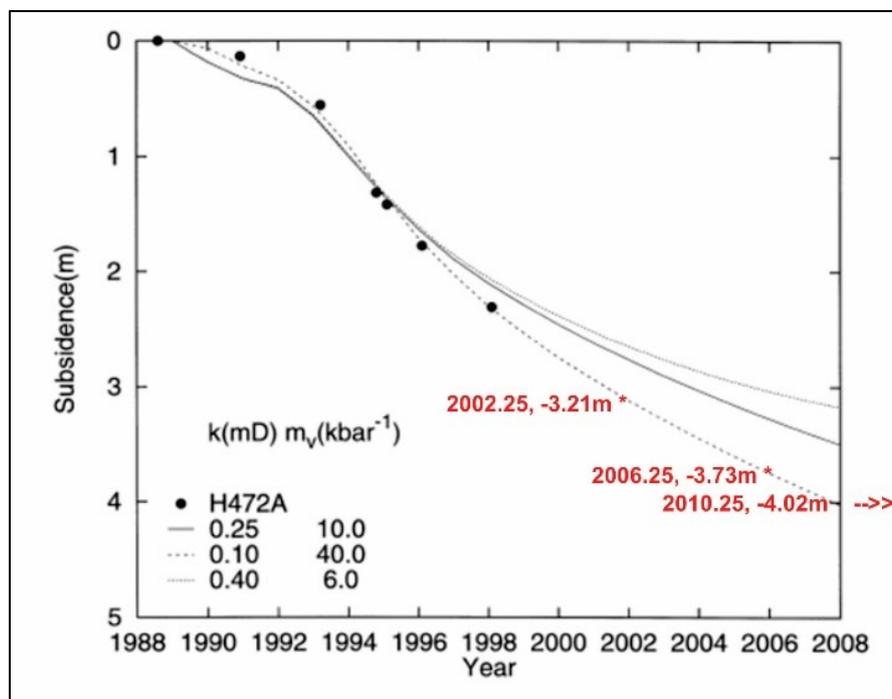

Figure 8. Model prediction (from Allis and Zhan, 2000) of subsidence at benchmark H472A (Fig.6), (observed = black dots) and comparison with subsequent level data (red stars) at this site in 2002, 2006 and 2010.

This simple 2-layer, 2-parameter, best-fit model consisted of a mudstone layer, 150 m thick, of permeability 0.1 mD, and compressibility 0.4 MPa^{-1}, overlying an aquifer (150 m thick) of Ohaaki Rhyolite (100 mD, 0.001 MPa^{-1}). Ten-year predictions to 2008, based on this model, and assuming no further decline in Ohaaki Rhyolite pressure, have proven to be reasonably accurate when compared with actual data in 2002 and 2006. Although in this case the model appears quite successful in predicting future subsidence, significant uncertainties remain because of a range of complexities. These include the assumption of negligible effects from pressure change in the Ohaaki Rhyolite aquifer, horizontal fluid flows (2D effects), transients due to yielding behaviour, and two-phase fluid effects.

In 2012-2013, a fitted analytical function (sigmoidal or Boltzmann type) was used to represent the effect of slow pressure diffusion processes on subsidence rates (Bromley, 2013). This achieved good fits to the smooth non-linear historical subsidence data. But again, there were uncertainties attached to future subsidence projections based on these models because of unknown changes that might occur to the controlling parameters (e.g. pressure and yielding). Accordingly, when the uncertainty in future projections of subsidence was assessed, it was not calculated based on the closeness of the fit to historical data, but it was instead assessed by accounting for the possible sources and likelihood of change to the underlying factors that affect future subsidence rates. From 2013 onwards, the assessed uncertainty was +/-33% on projected subsidence rates. This is a reduction on the 1997 assessed uncertainty for accumulated subsidence at the centre of the anomaly of +/- 3m (or +/- 42%), but is still significant.

These uncertainties have implications in terms of predicted effects. The observed effects to date include those resulting from vertical settlement, uniform tilt, differential tilt and horizontal strain. In the past, these have affected Te Ohaaki Marae and adjacent grounds, wetlands along the banks of the Waikato River, and other structures within the Ohaaki borefield, such as well-pads, pipelines, roads, separator stations and waste-water ponds. Even though subsidence rates have generally been declining since 2000, uncertainty in the future rate of subsidence is still a source of uncertainty in the severity of projected and cumulative effects.

4. SUBSIDENCE MECHANISMS

The principal subsidence mechanism at Ohaaki is 'aquitard drainage'. This consists of non-recoverable compaction of slowly-draining and anomalously-compressible clay layers, consisting of hydrothermally-altered lake-sediments. Such layers are located adjacent to partly-confined aquifers which are undergoing pressure decline in response to fluid withdrawal. Pressure decline causes increasing effective vertical stress by reducing pore pressure support within the rock matrix. For 'yielding' clay-rich deposits, this process is largely inelastic and irreversible. The cross-section in **Figure 2** shows the location, depth and thickness of the inner rhyolite aquifer where pressure decline has occurred, and the overlying aquitard of Huka Falls Formation (HFF) mudstone which is slowly draining into it.

Other elastic (that is, reversible) deformation mechanisms are also possible contributors to the subsidence. These include: rock contraction due to cooling; volumetric contraction due to deep reservoir pressure decline; and ground inflation (swelling) due to reinjection pressure. However, modelling shows that these mechanisms produce surface effects that are at least an order of magnitude smaller in amplitude and rate than the principal inelastic mechanism.

Yielding is a non-linear process of consolidation of the clay-rich deposits. Under increasing vertical stress (or load) the clays and porous sandy sediments initially deform elastically, then, once a certain yield stress is passed, they deform in-elastically (that is, permanently) and at much higher rates (i.e., at a higher effective compressibility). Observations at Ohaaki support this mechanism as having played a part in the pattern of subsidence over time. The observations include:

(a)   a delay of several years between the onset of reservoir pressure decline and the acceleration of subsidence;

(b)   the lack of rebound of levels during the period of pressure recovery after 1972; and

(c)   the observed correlation (after a delay) between subsidence rates and initial pressure decline within the relatively-shallow inner Ohaaki Rhyolite aquifer (which underlies the HFF) but no measurable response to the subsequent pressure increase.

Another factor in the pattern of subsidence is the proximity of the subsidence anomaly to an area of significant geothermal fluid surface discharge, including steaming ground areas across the top of the buried Ohaaki Rhyolite dome, and a liquid discharge from the nearby Ohaaki Pool (Ngawha). The subsurface passage of boiling fluids and steam has, over time, hydrothermally altered the in-situ formations, thereby locally affected their properties. The result is material weakening, that is, an increase in the average rock compressibility at effective stresses above the yield-point.

As **Figure 9** illustrates, the subsidence rates slowed down across the main anomaly after 2000 (on the western side) and after 1995 (on the eastern side). The inferred explanation for the slow-down is that shallow pressures in the adjacent inner Ohaaki Rhyolite aquifer (as illustrated in **Figure 4**) levelled off from 1995 and then began to rise again from 2004 in response to liquid recharge (edge-field reinjection combined with groundwater recharge). An increase in micro-gravity values after 1995, provides supporting evidence of this process of shallow liquid recharge, resulting in mass and density increases.

Very low vertical permeability throughout the bulk of the HFF, which separates the inner Ohaaki Rhyolite aquifer from the overlying groundwater aquifer, is evident from the minor effect, with a few isolated exceptions (Bromley et al, 1993) of reservoir pressure decline on shallow ground water levels. The consequence of this low HFF vertical permeability is that pressure diffusion through the HFF is very slow. Hence the subsidence was observed to continue for some years, albeit at a reducing rate, even when the pressures in the underlying aquifer were rising. Furthermore, the rising pressure had a negligible direct effect in terms of countering subsidence with uplift, because of the permanent and irreversible nature of the yielding.
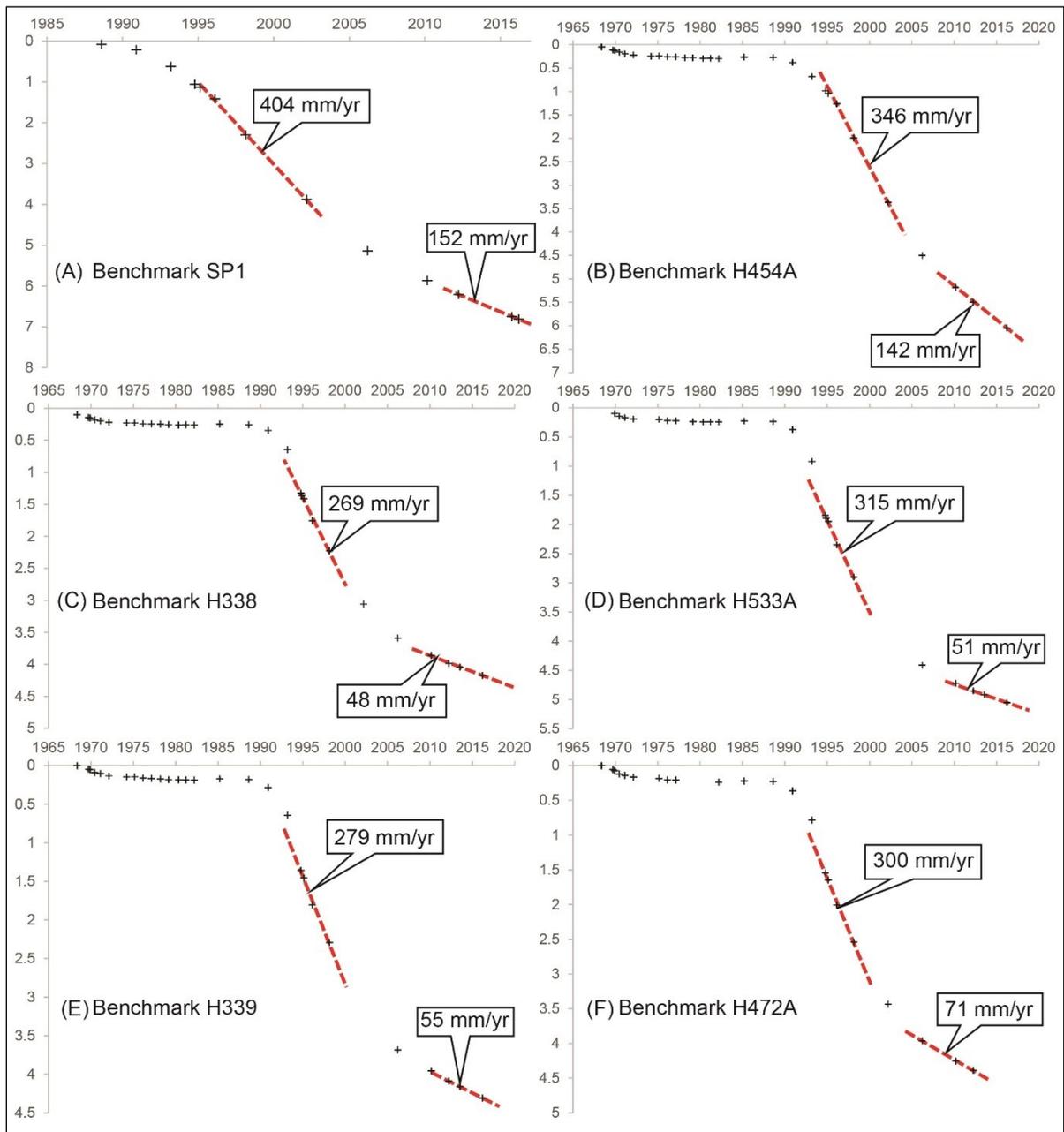
Figure 9. Plot of cumulative subsidence in meters (Y axis) with time in years (X axis) for selected benchmarks as shown in Figure 7. Average subsidence rates for mid-term and most-recent periods are approximated by linear trends.

Subtle differences in the timing of pressure changes (that is, levelling off, then increasing in pressure), is observed for different monitor boreholes in **Figure 4**. This provides a plausible explanation for the observed geographic difference in subsidence rate history between the central, western and eastern flanks of the buried Ohaaki rhyolite dome (**Figure 7**).

5. PREDICTED RATES OF SUBSIDENCE IN 2013

In 2013, subsidence rates were again projected into the future, this time for the purposes of assessing potential effects of the planned continuation of fluid extraction at Ohaaki for another 35 years, at 40 kt/day, and assuming a continued net mass loss (after reinjection) of about 30% (Bromley et al, 2013). [Note that actual fluid extraction since 2013 has averaged 26 kt/day and 52% has been reinjected.] Historical subsidence trends were matched using available aquifer pressure, compressibility and thickness information. A sigmoidal function (Boltzmann type) was used to account for slow pressure diffusion into low permeability, compressible layers. Subsidence rates beyond the 2012 survey were then predicted using shallow pressure changes simulated using the 2013 version of the TOUGH2 reservoir model, together with the same diffusion and compressibility-thickness parameters that achieved the best subsidence history match. Future pressure trends were based on TOUGH2 predictions from the optimum reservoir operation scenario.

Table 1 shows accumulated subsidence (1988 to 2016, in metres) for three representative locations at H476A near well BRM10 (**Figure 7**), at SP1 (**Figure 7**), and at NWA5 near Ohaaki Marae, close to H338 (**Figure 6**). Also listed is projected subsidence between 2012 and 2060 and the difference between the actual bench mark level from the 2016 survey and the projected level. The modelling process of matching and projecting is illustrated in **Figure 10** for the three representative locations.

Table 1. Summary of subsidence projections (accumulated total since 1988 in metres)

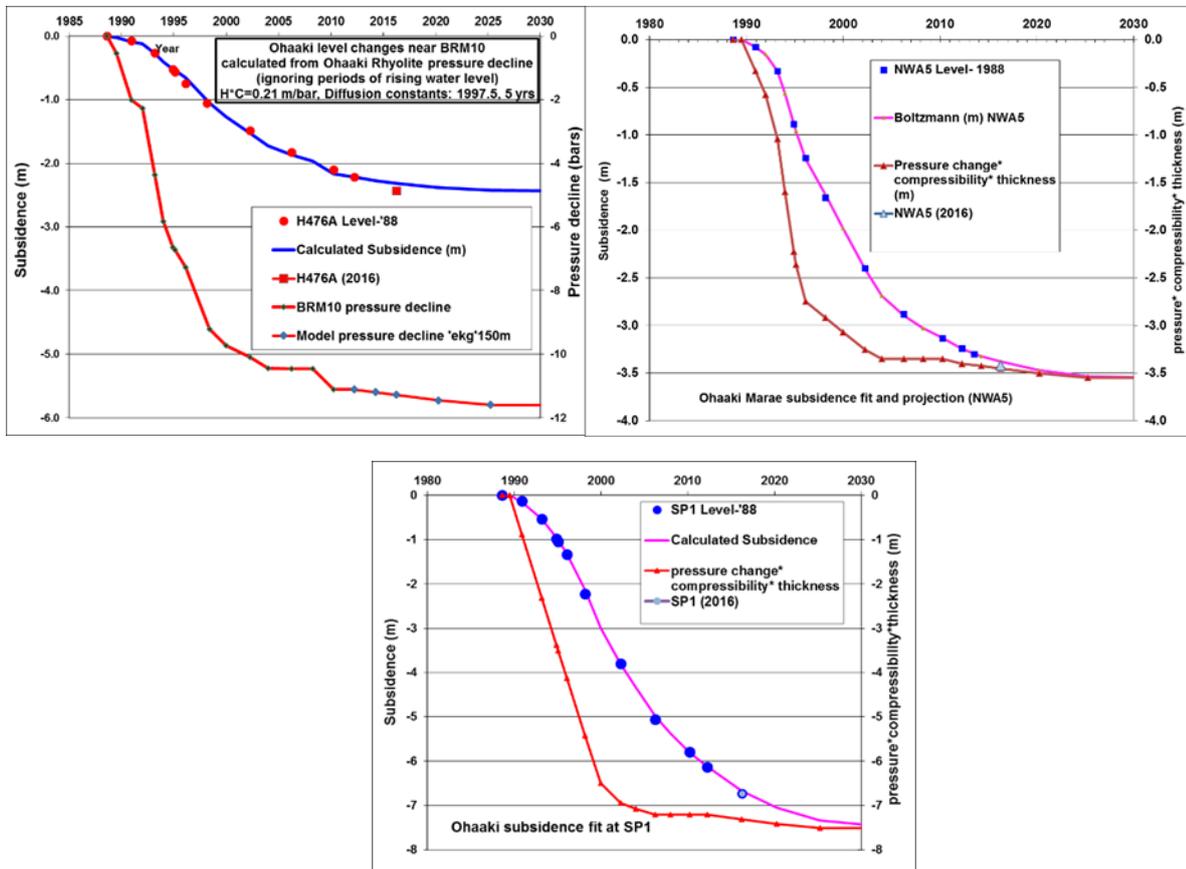| Scenario model (40kT/yr)	24/3/2012 Actual	24/3/2016 Projected	24/3/2016 Actual	2030 Projected	2060 Projected	Projected difference 2012-2060	Difference 2016 actual-projected
H476A	2.2	2.31	2.43	2.43	2.43	0.23	0.12
SP1	6.13	6.67	6.73	7.43	7.51	1.38	0.06
Marae NWA5	3.24	3.38	3.41	3.54	3.55	0.31	0.03

Figure 10. Historical (from 1988), predicted (from 2012) and actual (2016) cumulative subsidence at three locations (BRM10-H476A, Ohaaki Marae-NWA5, & SP1).

The subsidence driving function (red) is a product of pressure decline, compressibility and thickness. Pressure rises are ignored; they have negligible effect because the yielding process is considered irreversible. Predicted pressure decline (>2012) is from the reservoir model at 150 m depth in a central block. A fitted sigmoidal (Boltzmann) function simulates diffusion of aquifer pressure changes through aquitards. The details are provided below:

$S(T)= S1(1-1/(1+\exp((T-T1)/T2)))$; where S = subsidence in meters; T = time in years; T1 and T2 are time constants for the pressure diffusion process; and S1(T) is the driving function derived from the product of measured pressure change P(T), compressibility C, and compacting layer thickness H. For the three examples in **Figure 10**, the relevant constants are given in Table 2.

Table 2. Sigmoidal (Boltzmann) fitted function parameters

	T_1 (mid-year)	T_2 (years)	C*H (m/bar)
H476A	1997.5	5	0.21
SP1	2001	6.5	0.27
Marae NWA5	1997	5	0.13

In the first case, at benchmark H467A, the observed pressure drop in nearby monitor borehole BRM10 (**Figure 4**) is used to calculate the driving function. The model uses a fitted sigmoidal pressure diffusion function and compressibility-thickness product (0.21 m/bar at H467A) to achieve the best match. After 2012 the same parameters are used but with aquifer pressure changes predicted from the reservoir model at 150m depth near the centre of the subsidence anomaly. Beyond 2025, the reservoir model predicted rising or stabilizing pressures throughout the shallow aquifers that affect the compacting formations, so this eventually leads to near-zero projected subsidence rates.

5.1 Subsidence Uncertainty Discussion

The assessed uncertainty on future subsidence rates in 2013 was +/- 33%, based on observations, judgement and experience. One of the main sources of uncertainty, and one reason for the assessed error in projected subsidence rate, is the difficulty in predicting aquifer pressure within the inner Ohaaki Rhyolite formation. The reservoir model was optimally designed to simulate deeper production-reinjection effects but was not well-suited to accurately simulate or predict pressure and temperature changes in aquifers within the top few hundred meters, which is where the subsidence originates from. Currently, there are practical modelling limitations causing this. However, these uncertainties will gradually diminish as model upgrades overcome such limitations.

Another source of uncertainty is the degree and timing of yielding. Compressibility tests on cores from well BRM12 suggest that the effective vertical stress at which yielding commences is variable. Hence the timing of a transition to high compressibility yielding can vary with depth and location, depending on heterogeneity within the formation, the lithologic load, the change in liquid pressure and the yield transition stress.

The variability in properties due to heterogeneity has the effect of smoothing out the timing of the effects in terms of surface subsidence. Hence, although there is a possibility of a transition to significantly higher rates in the future, due to increased yielding, this is assessed to be of reduced likelihood due to the overall averaging effect of the variation in yielding properties.

6.0 IMPLICATIONS OF PREDICTED SUBSIDENCE: RIVER-BANK FLOODING

In order to undertake a prediction of the extent and severity of a major flood-event, the predicted subsidence and hydrological information on river flows were combined. The purpose was to show the extent of temporary inundation that could occur during a 1:100-year flood event, by applying the worst-case level changes (by 2028) assuming the operational scenario of 40,000 t/day fluid extraction. Predicted ground level changes between 2013 and 2028 are presented as a contour map in **Figure 11**.
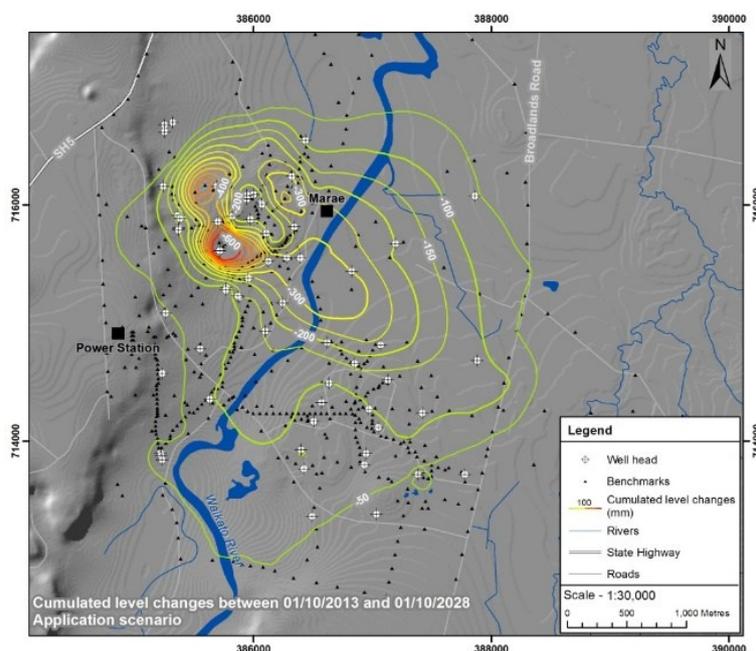

Figure 11. Contour map of predicted subsidence (in mm over 15 years), accumulated between 2013 and 2028, assuming the optimum operational scenario (40,000 t/day extraction).

This provides a means for assessing the future inundation risk along the banks of the Waikato River for different flood levels. Maximum water levels reached during future floods are simulated using a terrain model, which deforms over time using the predicted ground level changes. The water levels for the respective flood conditions are effectively fixed at the southern and northern ends of the anomalous subsidence area, where subsidence rates are close to zero (<10 mm/yr). During periods of high flow-rate, the water level between these two locations (4.2 km apart), is assumed to follow a linear gradient of 0.1 m/km. This is based on hydrological modelling of water levels during a large flood event (328 m³/s in July 1998) and supported by surveyed water levels along the river bank during a period of moderate flow-rate (207 m³/s in October 2007).

The water levels at the Ohaaki bridge flowrate gauging site (located ~1km SE of the Ohaaki Power Station in **Figure 11**) were re-calculated in terms of reduced level, mRL, by correcting measured stage heights for subsidence using the history of levels at a nearby benchmark. Using this method, the level reached by the top flood event between 1998 and 2011 was found to be 290.2 mRL and that of a 1:100-year flood event was calculated to be 290.4 mRL based on flood frequency modelling. The river level

difference between the bridge and the Marae during a flood event is about 0.2m, so the crucial water level to consider for a 1:100-year flood is 290.2m at the Marae.

The accumulated change in level (1967-2012) at Ohaaki Marae has been about 3.4 m (**Figure 12**). The subsidence was projected to increase by an additional 0.3 m over the period 2012-2030 (Table 1). In 2013 the lowest building floor level at the Marae was at 291.3 m so by 2030 it was projected to have subsided to 291.0 m, 0.8 m above the predicted 1:100-year flood level discussed above.

6.1 Inundation Uncertainty Discussion

One source of uncertainty in the calculated, subsidence-induced, inundation predictions originates from the 1:100-year flood level predictions. These use a flood probability distribution, called a 'Generalised Extreme Value' (GEV), which accounts for the fact that extreme events are moderated by the flood control measures using Lake Taupo control gates, the Tongariro flow diversion scheme and the Waikato hydro-dams. The control gates are managed in such a way that the level of Lake Taupo does not exceed 357.25m during normal hydro-dam operations and will not exceed a maximum of 357.5m more often than once in a hundred years. Therefore, the probability that a rainfall event causing a 1:100-year Waikato River flood coinciding with a period of absolute maximum Lake Taupo level, is considered extremely remote. Except for 'force majeure' events such as volcanic eruptions, it is reasonable to assume, therefore, that the peak magnitude of large floods passing through the Waikato River at Ohaaki will continue to be moderated by temporarily holding back the discharge from Lake Taupo.

The uncertainty originating from the GEV flood probability distribution applied to the Ohaaki Bridge data is +/- 0.16m in water level for the 1:100-year flood prediction. A further uncertainty in water-level of +/- 0.1m originates from the downstream Lake Ohakuri backwater effect, because it is not possible to predict in advance what the controlled level of this lake will be during a peak flood event. The total uncertainty is therefore +/- 0.26m. Allowing for this uncertainty gives a maximum 1: 100-year flood level of 290.46 mRL at Ohaaki Marae.

As described in section 5.1, another source of uncertainty is the subsidence prediction. By 2030, the additional subsidence at Te Ohaaki Marae is expected to amount to about 0.3 m. Considering the assessed uncertainty of +/- 33% or +/- 0.1 m, the subsidence could be as much as 0.4 m (Table 1). Combining the three sources of uncertainty into a worst-case total of + 0.36 m, the water level by 2030 during a 1:100-year flood could rise to be within 0.44 m of the lowest building floor level at the Marae.

In summary, if, in future, a flood event occurs of magnitude equal to a 1:100-year return period, then the Marae buildings are likely to be surrounded by water during the peak period of the event. By 2030, with an additional subsidence of up to 0.4m, the water surface during such an event is likely to be close to ground level beneath the buildings. Consequently, and after assessing the uncertainties in these projections (discussed above), the decision was made jointly by Contact Energy and the Marae owners, to build a flood protection bund around these buildings.

Figure 12. Photographs taken in 1978 (left) and 2017 (right) illustrate long term changes in average river level.

7. CONCLUSIONS

The shape of the subsidence anomaly at Ohaaki resembles that of a ring or a moat, consistent with the occurrence of Huka Falls Formation lake-deposited mudstones surrounding a buried rhyolite dome. Over time, the location of the anomaly has not changed significantly, although the centre of maximum subsidence rate (up to 0.5m/yr) has shifted. A probable explanation of this comes from a review of the spatial and temporal variation of subsidence rates, along with reservoir pressure trends, subsurface geology, and material compressibility. The differences are interpreted to be caused by heterogeneity in properties of the yielding formations, in conjunction with a gradual migration of reservoir pressure decline through overlying aquifers. Local variations in compressibility and thickness affect the subsidence amplitude. Permeability and thickness variations affect the rate of pressure diffusion through the compacting formations and yielding stress affects timing. The reliability of past forecasts of subsidence have been tested against actual levelling data, showing that they fit within the assessed uncertainty. The subsidence predictions were useful, along with flood level predictions, to inform the design of remedial infrastructure improvements (flood bund) to protect existing buildings.

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