UPDATE OF SUBSIDENCE OF WAIRAKEI-TAUHARA GEOTHERMAL SYSTEM

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SUMMARY - The 2001 relevelling of benchmarks across the Wairakei - Tauhara system smoothly extends the subsidence trends established by earlier surveys. In general, subsidence rates since the early 1990s have been steadily decreasing or have been constant. At Wairakei Field, subsidence rates in the main subsidence area are now less than half the maximum rate. In the centre of the area, the subsidence rate is now one quarter the peak rate that occurred during the 1970s. In the Tauhara subsidence area, the trends suggest that maximum subsidence rates may have occurred during the 1990s and rates may now also be starting to decrease. On the western side of the Tauhara subsidence area the subsidence rate has been decreasing since the late 1970s. The only area with a systematic increase in subsidence rates during the 1990s is over the steam zones in the west of Wairakei Field. The maximum increase in subsidence rate here is from about 14 to 27 mm/y.

Over a large part of the Wairakei-Tauhara system, there is a pattern of subsidence that was established between 40 and 50 years ago as a result of production of fluid for the Wairakei power station. There is no evidence that the main subsidence areas at Wairakei and Tauhara Fields have shifted with time. The long subsidence history, together with the relatively small changes in shallow reservoir pressure expected from future production, provide a sound basis for predicting subsidence for the next 25 years. Modelling of future subsidence at both fields suggests that for the next 25 years, subsidence rates will not change greatly from those occurring in the late 1990s. A map of predicted subsidence between 2001 and 2026 has been prepared and is included as part of this paper.

1. INTRODUCTION

Between February and May, 2001, a relevelling survey of the whole of the Wairakei-Tauhara geothermal system was carried out (Currie, 2001). The survey included over 958 survey marks and covered an area of over 85 km^2. The standard error (95% confidence level) for the survey was calculated to be 7 mm, which was as good as, if not better than the uncertainties associated with previous surveys of Wairakei and Tauhara Fields. An analysis of the subsidence trends including the 2001 data has been carried out by Allis and Zhan (2001). This paper presents a summary of the work and its implications for future subsidence at Wairakei and Tauhara fields.

2. RESULTS OF 2001 SURVEY

The subsidence trends that have been apparent since before the early 1970s at both Wairakei and Tauhara Fields are smoothly extended with the addition of the 2001 levelling data. A map of recent subsidence rates using the two most recent field-wide relevelling surveys (1997 and 2001) is presented as Fig. 1. Details of the rates in the vicinities of the Wairakei and Tauhara subsidence areas are shown as Figs. 2 & 3. In general, subsidence rates since the early 1990s have been steadily decreasing or have been constant. In Wairakei Field, subsidence rates in the main subsidence area have been decreasing since the late 1970s and are now less than half the maximum rate. At P128 (near the centre of Wairakei subsidence) an "instantaneous" subsidence rate based on a 2000 level and the 2001 field-wide leveling indicates that the rate is now close to 100 mm/y, less than a quarter the peak rate. The average rate for the period 1997 to 2001 at P128 is 143 mm/y (Fig. 2). In the subsidence area of Tauhara field, the trends suggest that maximum subsidence rates may have occurred during the 1990s and rates may now also be starting to decrease. On the western side of the Tauhara subsidence area, the subsidence rate has been decreasing since the late 1970s. An analysis of historic subsidence rates around Tauhara field confirms that the subsidence pattern here has been present since at least the 1970s, with no evidence of a significant change in the edges of the subsidence area since that time (Allis and Zhan, 2001).

To highlight the areas of recently changing subsidence rates, a map has been prepared by subtracting the 1991-1997 subsidence rates from the 1997-2001 subsidence rates. Some of the benchmarks in the Wairakei-Tauhara system were not levelled in 1991, so some 1991 levels were linearly interpolated from the 1986 and 1994 surveys. For less than 5% of the data, there were no levels in 1991 or 1994, so the subsidence rates for 1991-1997 are assumed to be the same as the 1986-1997 levels. The resulting map, which depicts changes in subsidence rates

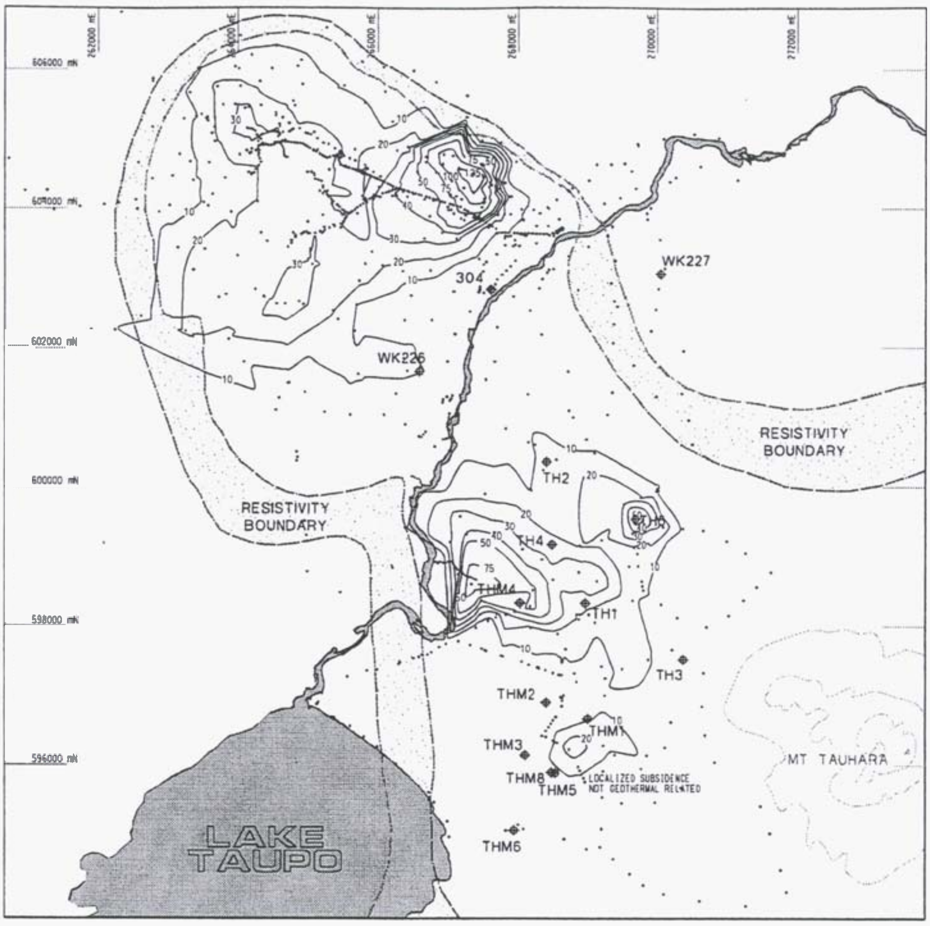

Figure 1. Subsidence (mm/yr) map for the Wairakei-Tauhara system for the period 1997-2001.

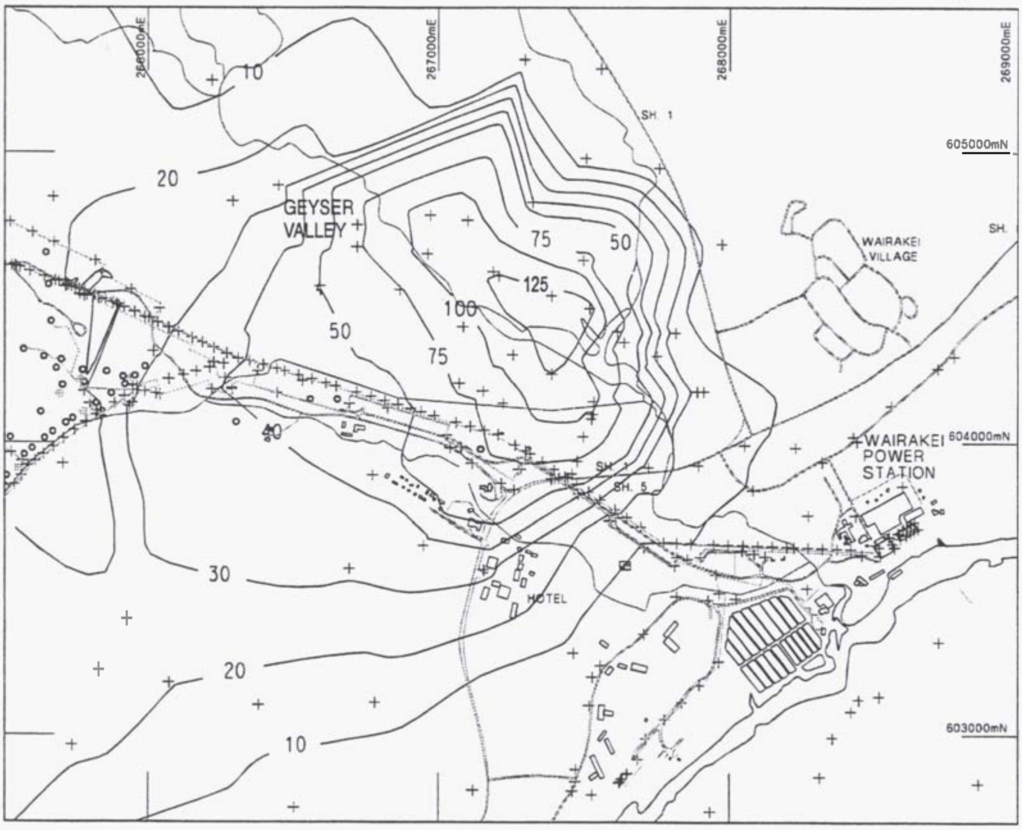

Figure 2. Subsidence (mm/yr) in the Wairakei area (1997-2001).

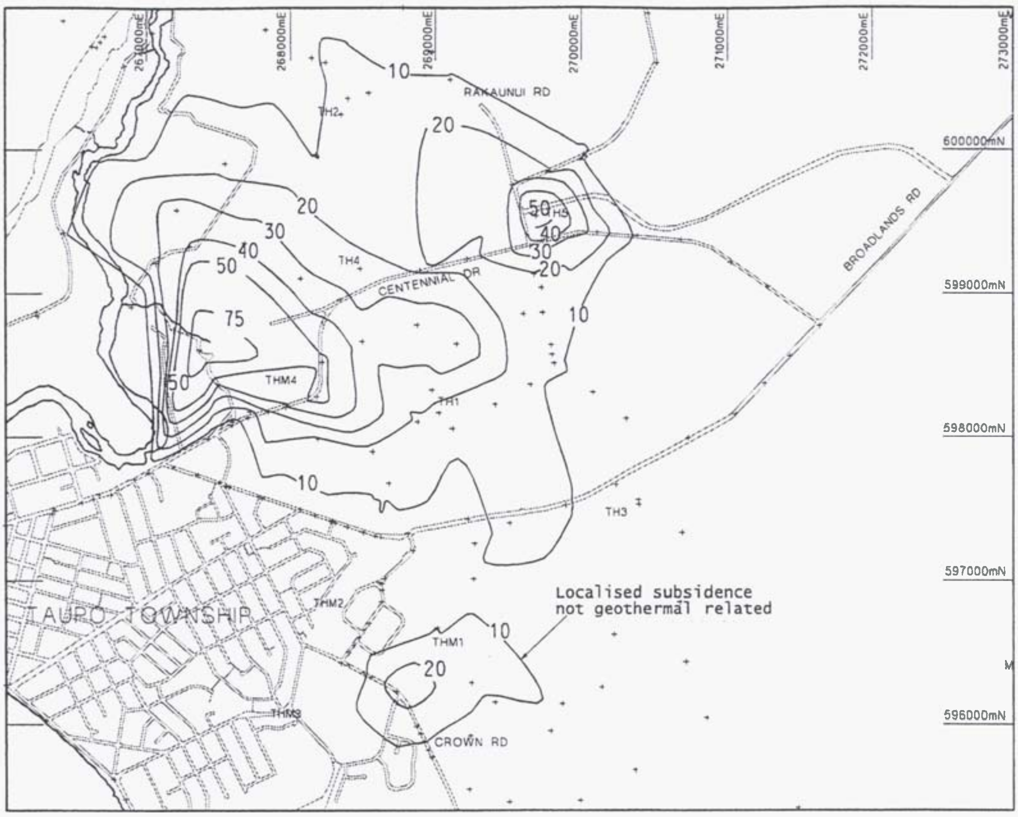

Figure 3. Subsidence (mm/yr) in the Tauhara area (1997-2001).

during the 1990s, is shown as Fig. 4. Negative numbers on the contours imply the subsidence rate is decreasing with time. The only area of the Wairakei-Tauhara system where subsidence rates have increased during the last 10 years is over the steam zones in the west of Wairakei field. The greatest increase occurs in the Te Mihi steamfield, where some benchmarks show increased subsidence rates from about 14 to about 27 mm/y. The greatest decrease in subsidence has occurred near the centre of the Wairakei subsidence area. Here the decrease in rate during the decade exceeds 100 mm/y (from 240 to less than 140 mm/y).

3. PREDICTING FUTURE SUBSIDENCE

Over a large part of the Wairakei-Tauhara system, there is a pattern of subsidence that was established between 40 and 50 years ago as a result of production of fluid for the Wairakei power station. This pattern has been documented in the literature since the 1970s (e.g. Hatton 1970, Stillwell 1975, Allis and Barker 1982; DSIR 1988; Allis 1990, Allis 2000b and Allis and Zhan, 2000). Technical reports forming part of consent applications in connection with Wairakei and Tauhara field developments prepared by ECNZ and Contact Energy in 1990, 1992, 1996 and 2001 contained detail on subsidence and related matters.

Historic subsidence rates initially increased with time as the effects of the deep pressure decline extended upwards into rocks with lower permeability and higher compressibility. Since the late 1970s over most of Wairakei Field, and probably since the 1990s at Tauhara Field, subsidence rates have stabilized and begun to decrease. The 40 – 50 year subsidence history, together with the relatively small changes in reservoir pressure expected from future production (see below), provide a sound basis for predicting subsidence for the next 25 years.

3.1 Modelling Future Subsidence

Models suitable for forward prediction of geothermal subsidence at Wairakei have been developed since 1997. Allis (1999, 2000a), and Allis and Zhan (2000) discuss in detail the origin of the subsidence and the modelling method used to calculate future predictions at Wairakei and Tauhara Fields. The modelling uses a finite element package coupling compaction and fluid flow. Because the subsidence is occurring at relatively shallow depth in compressible, low permeability units, the drainage process is predominantly vertical. The one-dimensional analysis assumed in this modelling is locally valid but caution is needed when applying it near areas of suspected lateral flow in high permeability layers (Allis, 2000a). The model also does not simulate the formation of steam zones. If the pressure variations in the subsidence model are close to known pressure variations above and below the compacting units, there is confidence that the one-dimension fluid flow assumption is valid.

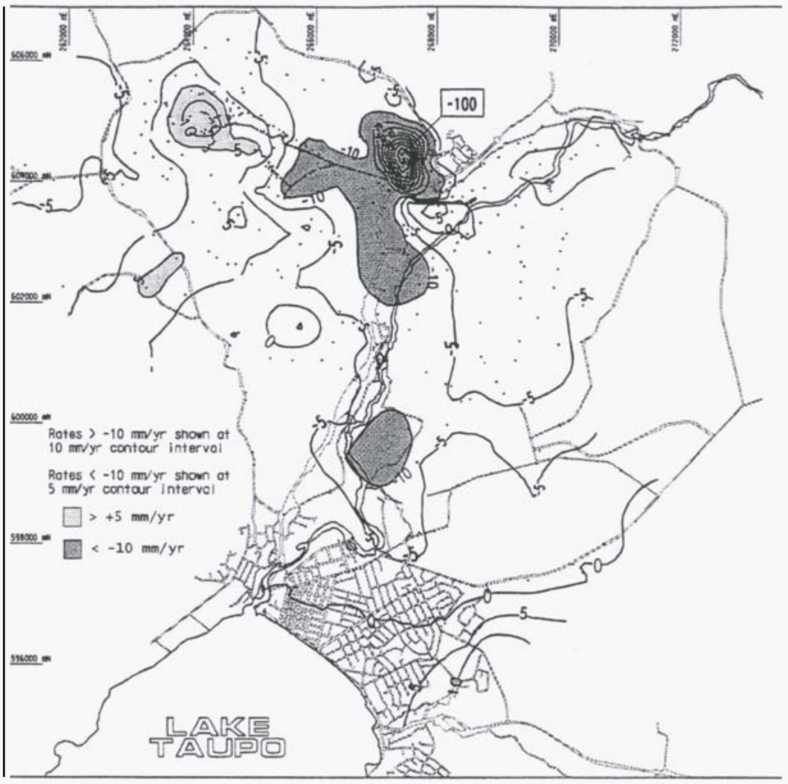

Figure 4. Change in subsidence rate between the early 1990s and the late 1990s. (negative numbers imply decrease in subsidence rates)

A linear stress-strain relationship (i.e. constant compressibility) is also reasonable for the compacting sediments because they are at maximum load (i.e. have a virgin compressibility because they are at their maximum burial depth). There is no evidence that the sediments have been previously unloaded or strengthened, for example through erosion or cementation, prior to development of the field. The base of the compaction models have an assumed pressure trend with time that is based on a combination of known pressure data and the trends predicted by the 3-dimensional simulator of Mannington et al., (2001). The simulation predictions estimate the likely pressure variations in the vicinity of the compacting sediments as a result of future production and reinjection in the Wairakei-Tauhara system between 2001 and 2026.

At Wairakei Field, evidence from the curvature of the subsiding ground surface, the rates of horizontal and vertical ground movement, and deformation in well casings, all indicate that the compaction is occurring at between 100 and 300 m depth, probably within the upper Huka Falls Formation (HFF) mudstone unit. Previous modelling of the drainage of this unit and its consequent compaction, using the observed pressure trend immediately beneath this unit (i.e. in the pumice breccia unit near the middle of the HFF) was able to replicate the observed groundwater level changes in the eastern borefield through the 1970s and 1980s (Allis, 2000a). During the 1990s, groundwater levels receded to the level of the adjacent Wairakei stream, and the water levels no longer reflected pressure within the mudstone unit.

When the 2001 levels for benchmarks A97 (near Wairakei Information Centre) and P128 (near centre of subsidence) are plotted onto the previous model predictions for these marks (Allis, 2000a), the new levels lie on top of the best-fit predictions (Figs. 5 & 6). Near the centre of the Wairakei subsidence area the subsidence rate is decreasing more rapidly than the model predicts. The actual subsidence rate between 1997 and 2001 was 140 mm/y compared to the previously modelled rates of 180–220 mm/y. The two best-fit models of Allis (2000a) predicted an additional 2 – 4 m of subsidence at P128 by 2026, with the total maximum subsidence then being between 17 and 20 m. Alternatively, if it is assumed that the future subsidence rate at P128 no longer diminishes but remains constant for the next 25 years at its 2000-2001 value of 100 mm/y, this would add 2.5 m of subsidence to this benchmark. This is similar in magnitude to that predicted by the models.

The modelling results presented in Allis (2000a) for the Wairakei subsidence area assumed that pressure in the HFF pumice breccia layer remains constant for at least the next 30 years. The numerical simulation modelling of Mannington et al. (2001) suggests that shallow pressure beneath the eastern borefield has decreased by about 2 bars

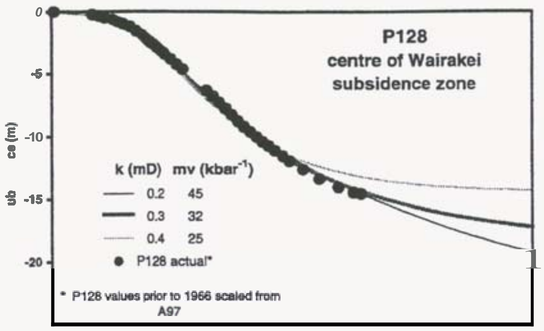

Figure 5: Update of subsidence trend at **P128** near the center of the Wairakei subsidence area (modified from Allis, 2000a). Three compaction models are shown. **k** is the permeability of the upper Huka Falls Formation, and **mv** is its compressibility.

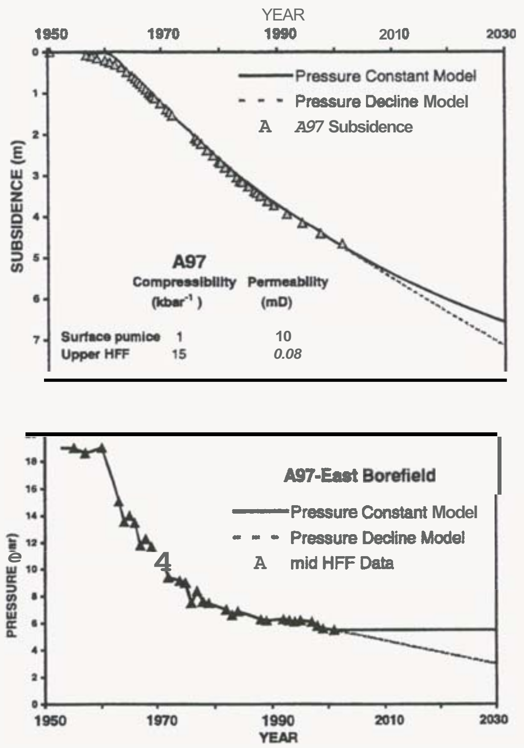

Figure 6: Compaction model for **A97,** with two input pressure trends assumed at the base of the upper HFF mudstone.

between **1980** and **2001,** and it will continue to decrease by an additional **2.5** bars between **2001** and **2026.** The response of the subsidence models to a varying input pressure trend is shown in Fig. 6 where the subsidence prediction for **A97** for two input pressure trends beneath the main compacting unit in the HFF are plotted. One model assumes almost constant pressure beneath the upper HFF mudstone since the mid **1980s** (i.e. similar to the modelling in Allis, 2000a), and the second model assumes a slowly declining pressure trend similar to that predicted by the numerical simulation of Mannington et al. **(2001).**

Model results for **A97** show that the total subsidence between **2001** and **2026** could vary by about 0.5 m depending on whether the mid HFF pressure remains constant or decreases by **2.5** bar. This uncertainty is reasonable, given the total pressure decline in the HFF breccia due to development of about **15 bar,** and the cumulative subsidence of **7** ± **1** m by **2026.** The future subsidence (between **2001** and **2026)** at **A97 is 2.5** ± **1** m, the uncertainty being in the range **25 –** 50%. A similar uncertainty applies to the total subsidence around the whole of the Wairakei subsidence area by **2026,** including that at **P128.** This is believed to be a reasonable representation of the uncertainties due **to** the combined effects **of** future production, reinjection and possible field inflows that may not be so well represented in the **3-D** simulator, as well **as** uncertainties due to the compaction modelling process.

Allowing for the possibility that pressure beneath the Wairakei subsidence area could decrease by **2 – 3** bars between **2001** and **2026,** the total maximum subsidence since development in the **1950's** would be **19** ± **2** m. The additional maximum subsidence at Wairakei from **2001** to **2026** is expected to be in the range **4** ± **2** m.

Similar modelling **has** also been carried out for the Tauhara subsidence area (Allis and **Zhan, 2001).** The **2001** leveling data closely matches the previous modelling presented by Allis, **(1999).** Subsidence modelling undertaken in **2001** incorporates future pressure trends predicted at the base of the HFF by Mannington et al., **(2001).** The results show that subsidence rates in the late **1990s** are likely to stay at about their present rates for the next **25** years. The reason for the relatively constant subsidence rates is the slow decline in reservoir pressure at greater depth due to the combined effects of production and injection at Wairakei and Tauhara Fields (approximately 5 bar decline beneath this part of Tauhara field over **25** years). **An** additional **1.5** m of subsidence is predicted along Centennial Drive between **2001** and **2026** where it traverses the area of maximum subsidence.

3.2 Subsidence between 2001 and 2026

Future subsidence across the Wairakei-Tauhara system has been predicted based on the compaction models located in the areas of highest subsidence rate. At both the Wairakei and Tauhara subsidence areas, the modelling suggests that subsidence rates are not going to change significantly from their present values and it is reasonable to linearly extrapolate subsidence from **2001** out to **2026** by assuming that the **1997-2001** rates remain unchanged. Inspection of the modelled trends, the degree of fit to the observed subsidence trends, and consideration of the various factors potentially influencing future subsidence rates, suggests an uncertainty of about ± 50% in these predictions. The predicted future subsidence considering future production **and**

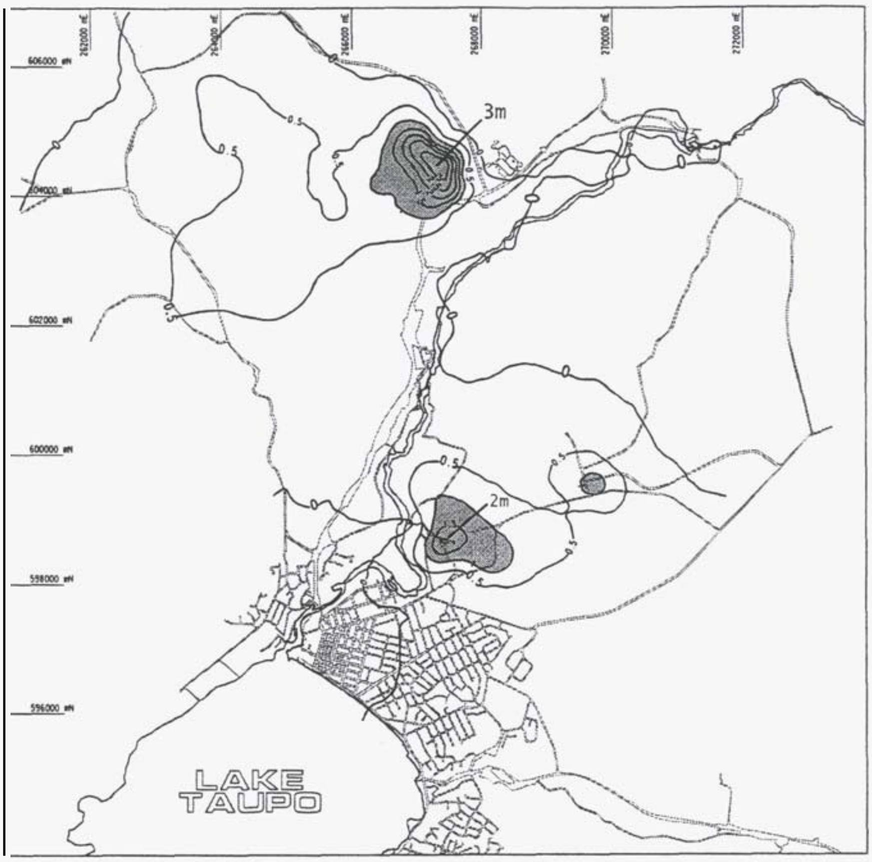

Figure 7. Prediction of subsidence (metre) at the Wairakei-Tauhara system during the period 2001-2026. Areas with more than 1 m of subsidence between 2001 and 2026 are shaded.

injection from the Wairakei – Tauhara geothermal system from 2001 to 2026 is mapped in Figure 7.

The future subsidence across the Wairakei-Tauhara system is expected to be similar in character to the subsidence pattern established over the last 40 years. However, the rates of subsidence that were greater than 100 mm/y, (resulting in 5 – 15 m of subsidence), that were present over a 1 km^2 area in the vicinity of the Wairakei Eastern borefield during the 1970s and 1980s have largely dissipated. The area with subsidence rates of more than 100 mm/y between 2001 and 2026 is expected to be less than 0.2 km^2, and the additional subsidence in this restricted area will range between 2.5 and 4 m. This is an elongated (~ 1 km x 0.2 km) area trending northwest and approximately coinciding with the Wairakei Stream and parallel to the nearby resistivity boundary. The area where at least 1 m of subsidence is expected to occur is approximately circular, about 3 km^2 in area, and largely coinciding with the Eastern Borefield and the northeast comer of Wairakei Field (i.e. inside 40 mm/y contour on Fig. 2).

In Tauhara Field, the subsidence rates are expected to be less than 100 mm/y everywhere. The area expected to experience more than 1 m of subsidence covers about 0.5 km^2, is triangular in shape, and is centred in the vicinity of the north end of Spa Hotel Road (i.e. inside the 40 mm/y contour on Fig. 3). The maximum subsidence in the centre of this area is expected to be 2.4 m ± 1.2 m. An area of less than 0.05 km^2 centred on TH5 near Rakaunui Road will also experience about 1 m of subsidence.

4. POTENTIAL IMPACTS OF THE SUBSIDENCE

In the Wairakei subsidence area, the future subsidence between 2001 and 2026 will be about one quarter the total subsidence that occurred between the 1960s and 2001. Peak rates are similarly diminished, so many of the effects noticed during the 1970s and 1980s will not be repeated and most deformation is likely to be restricted to the farmland and forests to the west of the SH 1 / SH 5 Wairakei intersection. Ponding of the Wairakei Stream in the centre of the subsidence area will continue, but at a significantly lower rate than has occurred previously.

In the Tauhara subsidence area, the expected subsidence between 2001 and 2026 is similar in magnitude to the total subsidence that has occurred since the 1960s. Except for the minor Centennial Drive impacts of some loss of camber and drainage problems at Centennial Drive (Recorded in J Minchington's 1999 Environment

Court Evidence), no other issues have been reported to Contact Energy from the subsidence that has been ongoing since the **1960's**. In view of the open ground and the lack of large engineering structures inside this area, future impacts are also likely to be minimal.

The ground strain (differential ground movement) that accompanies subsidence will be accumulating, and will be directed towards the centre of subsidence. The highest rates of ground strain occur where the subsidence gradient is highest. The most vulnerable area is along the Spa Hotel Road which runs at right angles to the subsidence contours (i.e. parallel to direction of differential ground movement). Here, rigid structures such as curbing and underground pipelines adjacent to the road will be under tension for the first 500 m from the Spa Road intersection. The rate of extension is likely to be about half the differential settlement rate, or 30 - 70 mm/y over a distance of 500 m (i.e. strain rate of about 10^{-4} y^{-1}).

Vertical settlement or tilting of the ground surface is not likely to cause any problems, The area has steep relief (> 50 m), and the maximum amount of tilt between **2001** and **2026** is less than 0.5 degrees (this occurs part way along Spa Hotel Road). The uncertainty in these estimates is similar to that estimated for the subsidence amounts, ± 50%.

5. CONCLUSIONS

Over most of the Wairakei-Tauhara system subsidence rates during the **1990s** have been diminishing or remain about constant. Maximum rates in the centre of the Wairakei subsidence area are now one quarter of the maximum rates during the late 1970s. Modelling **of future** subsidence using predicted reservoir pressure trends indicates that the present day rates will not change significantly for the next **25** years.

Subsidence modelling, as well as other related information such as casing deformation, suggests that HFF sediments between about **100** and 300 m depth are the most vulnerable to compaction as a result of pressure drawdown. The compressibility of these sediments in the Tauhara subsidence area is about one tenth that in HFF mudstone beneath the centre of the Wairakei subsidence area, and about a third that of the HFF mudstone beneath the Wairakei Information Centre (A97). The original recommendations of **DSIR** to the Waikato Valley **Authority** in **1988** (DSIR, 1988) concerning subsidence potential at Tauhara Field remain valid. Geothermal development strategies should minimize pressure drawdown in the HFF, particularly in the mid HFF pumice "aquifer" unit.

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