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Computer Modelling Retrospective on Wairakei and Ohaaki

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ABSTRACT

Our modelling studies of the Wairakei and Ohaaki geothermal fields have been ongoing for more than 30 years and it is now possible to check back on the predictions made from early studies carried out in the 1990s and early 2000s and determine how well the predictions made by those models compare with reality.

There are several problems with a retrospective assessment of the 1990s and early 2000s models. The most significant is that the future scenarios considered then are different from the actual production and injection strategies followed. We overcame this difficulty by using the actual production /injection history with the old models. In general the models perform quite well in matching the production history but in both cases they are too conservative and the actual performance of Wairakei and Ohaaki has been better than that predicted by models from the late 1990s or early 2000s. In both cases the number of make-up wells used in the original future scenarios turned out to be more than have actually been required

The main discrepancies arise because of the development of new and/or deeper production zones, not included in the old models. In some cases, e.g. the shallow steam zone at Te Mihi (Wairakei), the permeability has turned out to be even higher than the high value used in the old model and production has continued past the point when the old model predicts failure should occur due to a large pressure decline.

1. INTRODUCTION

The Geothermal Modelling Group at the University of Auckland has been carrying out modelling studies of Wairakei-Tauhara and Ohaaki on behalf on Contact Energy Limited (and its predecessors) for ~ 30 years. The early models were very simple (Blakeley and O'Sullivan, 1981; Blakeley *et al*., 1983) but by the late 1990s and early 2000s quite large 3D models were being used. This current study gives a retrospective assessment of two of those models: one for Wairakei-Tauhara and one for Ohaaki. The model of Wairakei-Tauhara considered here (called here WK1998) was developed in 1998 and contains 1515 blocks (O'Sullivan *et al*., 1998). It is a relatively early 3D model in a sequence of models (discussed by O'Sullivan, 2009) leading up to the current model (called here WK2013) which contains 41,458 blocks. The model of Ohaaki (called here OH2004) is more recent, dating from 2004, and contains 6588 blocks (Zarrouk *et al*., 2004; Zarrouk and O'Sullivan, 2006).

Both models are run on the AUTOUGH2 simulator (Yeh *et al*., 2011, 2012), the University of Auckland's version of TOUGH2 (Pruess *et al*., 1999).

In each case the retrospective assessment is carried out in four stages:

(i) Results for a future scenario from the original modelling study were simulated up to 2012.

(ii) The schedules of new wells added after the date of the original modelling study are compared with the schedule of make-up wells used in the future scenario simulations.

(iii) The old models are run from the date of the original modelling study up to 2012 using the actual production and injection schedules.

(iv) The old models are run from the date of the original modelling study up to 2012 using the actual production and injection wells, but allowing some wells to operate on deliverability so that their performance declines as the reservoir pressure drops but they do not fail completely.

2. WAIRAKEI MODEL

The model WK1998 (1515 blocks) of Wairakei –Tauhara is almost the same as the 1509 block model (O'Sullivan *et al*., 1998) which was the first model of Wairakei to include the shallow unsaturated zone and to use an air/water equation of state (EOS4 in TOUGH2). The extra 6 blocks came from a small adjustment of the top few layers in the model to better match the topography. The model grid is shown in Figure 1. For comparison the grid for model WK2013 (41,458 blocks) is shown in Figure 2. Obviously the WK1998 model is relatively coarse, particularly in the area outside the resistivity boundary.

In order to transfer the recent production and injection history from the WK2013 model to the WK1998 model the feed-zone blocks in WK1998 had to be identified and the corresponding entry in the GENER section of the TOUGH2 data file had to be rewritten. This process was automated using PyTOUGH scripts (Croucher, 2011, 2013; Wellmann *et al*., 2012, 2013).

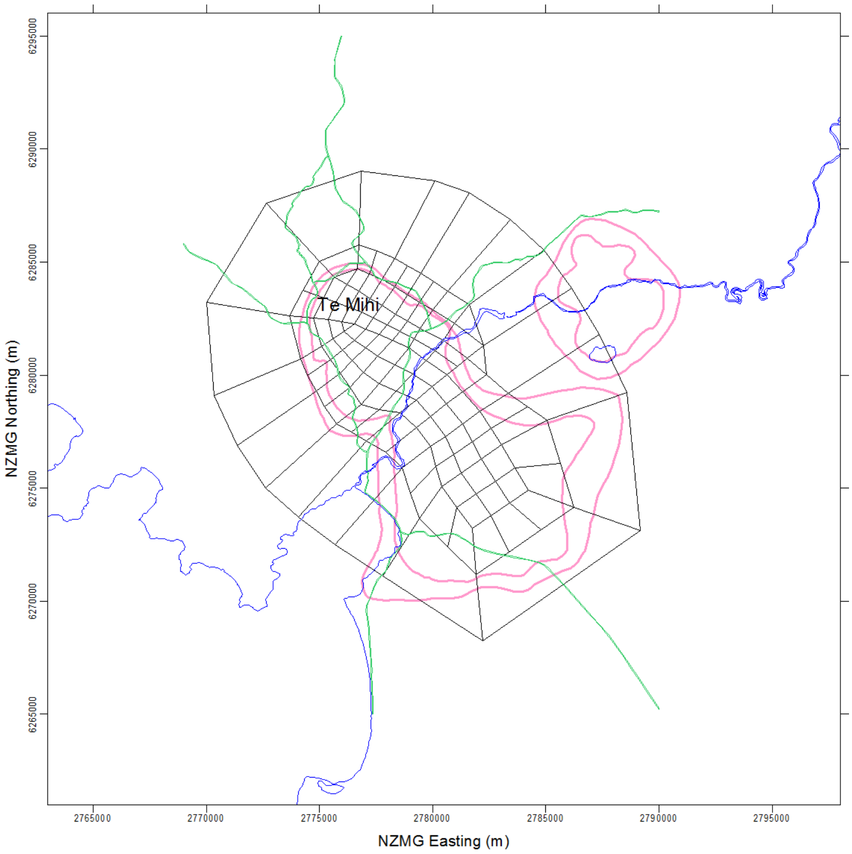

Figure 1: The WK1998 model grid. The blue line represents Lake Taupo and the Waikato River. The pink line is the resistivity boundary of the Wairake-Tauhara and Rotokawa fields. Coordinates are New Zealand Map Grid (NZMG).

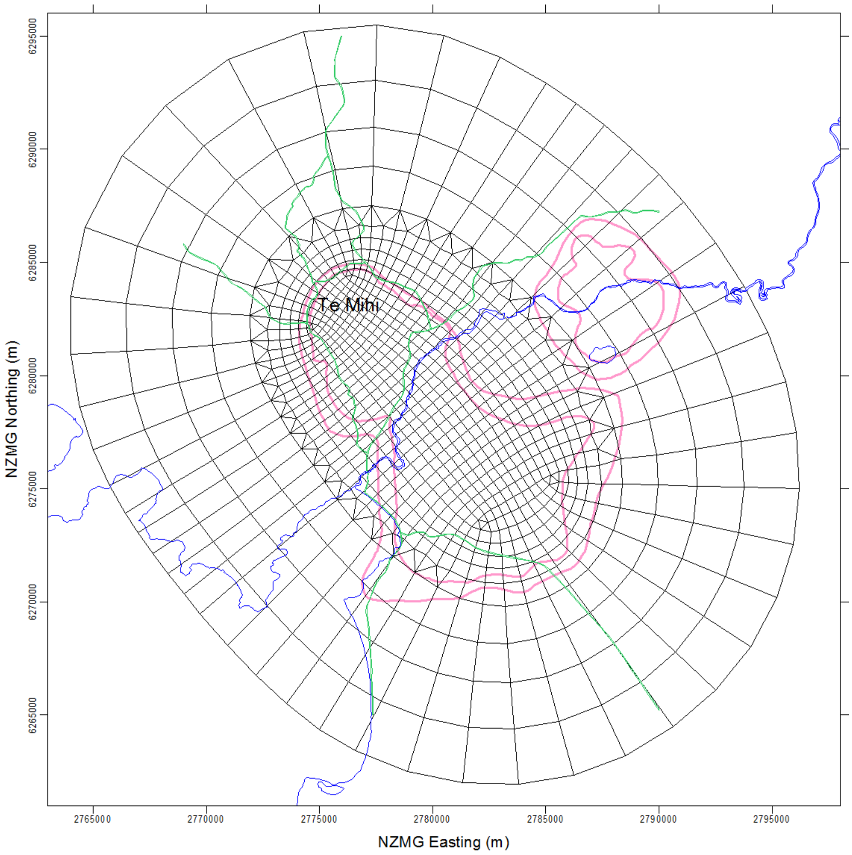

Figure 2: The WK2013 model grid.

3. OHAAKI MODEL

The grid for the OH2004 model (6588 blocks) of Ohaaki is shown in Figure 3. For comparison the grid for the current model (the OH2013 model with 45,250 blocks is shown in Figure 4. OH2004 was the first model of Ohaaki based on a regular rectangular block structure. The earlier, coarser, models had an irregular structure and fewer blocks (Zarrouk *et al*., 2004).

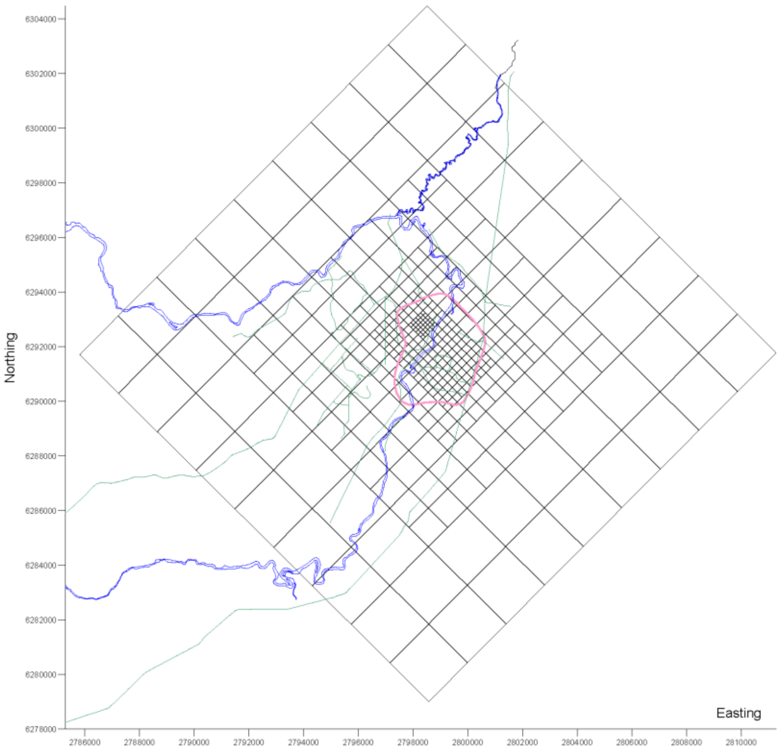

Figure 3: The OH2004 model grid. The blue line represents the Waikato River, the green lines major roads and the pink line the resistivity boundary of the Ohaaki field. Coordinates are NZMG.

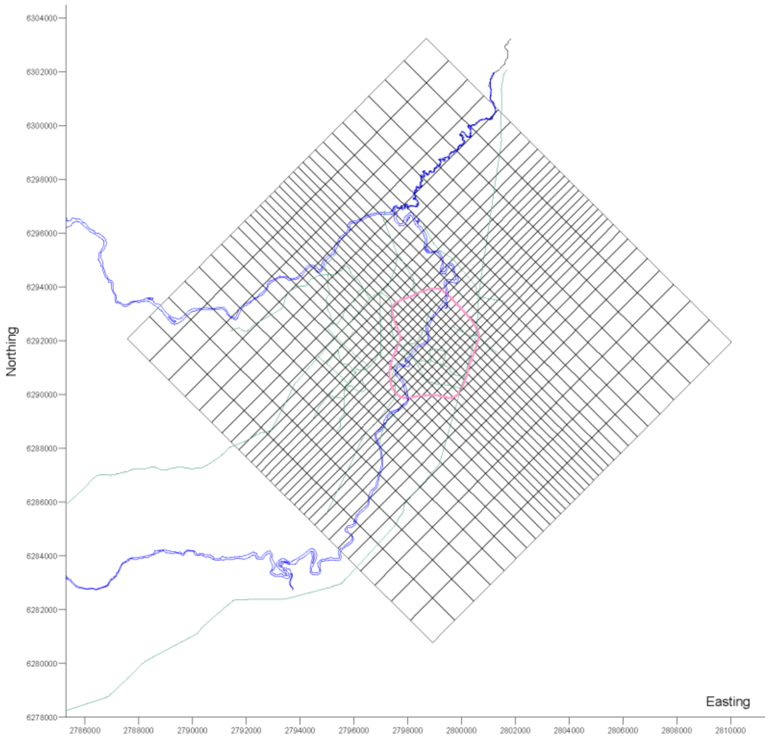

Figure 4: The OH2013 model grid.

4. WAIRAKEI RESULTS

4.1 Future Scenario from the Original 1998 Modelling Study

The natural state and production history results were available from the 1998/1999 modelling study. The final results at the end of 1995 were used as the initial state for "future scenario" simulations considered in the present study. In the first simulation Model WK1998 was used to re-run one of the scenarios originally considered back in 1999. A start date of 1 Jan 1996 was used for the simulation in order to include some of the past history match in the simulation. The results for the total mass flow are shown in Figure 4 and for the mass flow from the Te Mihi steam zone in Figure 5. The projected total mass flow is higher than the actual historical values, but the projected mass flow from the Te Mihi area is considerably lower. This because the old scenario includes several deep liquid make-up wells that ended up not being required because the shallow steam zone at Te Mihi turned out to be more productive than expected.

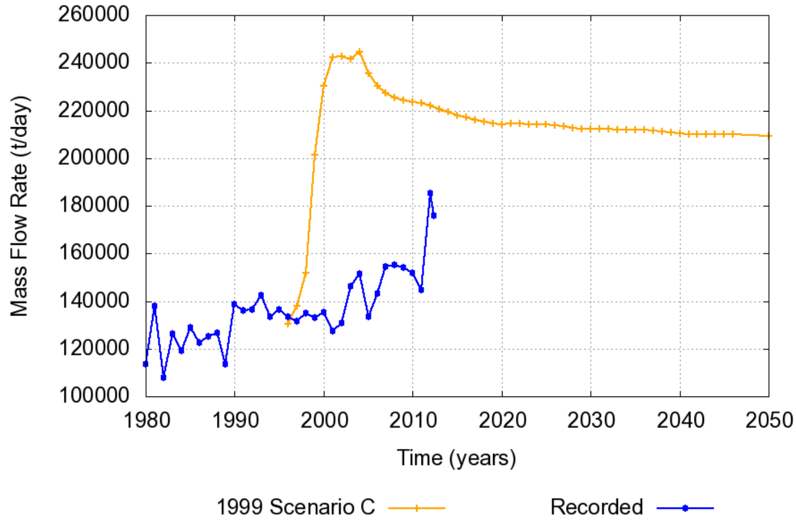

Figure 4. Total mass production for Wairakei - model WK1998 and actual production

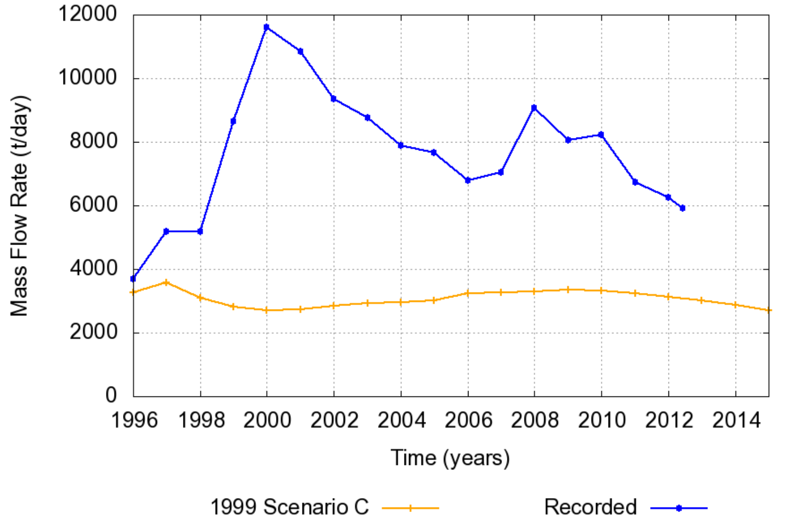

Figure 5: Mass production from the Te mihi steam zone - model WK1998 and actual production

Table 1 shows the schedule of new wells assumed for the future scenario and the schedule of actual new well drilled at Wairakei between 1997 and 2012. The locations of the two sets of make-up wells are shown in Figure 6. Table 1 shows that almost twice the number of make-up wells was used in the model scenarios as turned out to be necessary and Figure 6 shows that the southern part of Te Mihi was targeted more than the northern zone, whereas both were used for make-up wells in the original future scenarios. More productive wells were found at Te Mihi (e.g. WK242-245) than were envisaged by the productivity indices used for make-up wells in the model. Some of the wells produced from the shallow steam zone with a correspondingly high enthalpy of ~2800kJ/kg and at moderate flow rates (e.g. WK238, 240, 241, 252). Whereas all of the make-up wells in the model produced from the deep liquid zone.

Well name	Actual date drilled	Average flow over first few years of production kg/s	Make-up wells in original scenario	Date drilled in scenario	Average flow over first few years of production kg/s
WK237	16/04/1997	5.3	MK1, MK2	1/01/1997	7.0, 20.0
WK238	30/06/1998	33.2	MK3, MK4,	1/01/1998	51.3, 51.3
WK239	30/07/1998	45.3	MK5	1/01/1998	50.8
WK240	30/06/1999	22.5	MK6	1/01/1999	43.5
WK241	30/07/1999	21.4	MK7, MK8	1/01/1999	41.8, 42.3
WK242	10/01/2002	135.6	MK9, MK10	1/01/1999	51.2, 48.6,
WK243	18/05/2005	128.0	MK11, MK12	1/01/1999	54.0, 55.4
WK244	3/07/2005	150.2	MK13, MK14	1/01/1999	55.1, 54.6
WK245	10/08/2005	120.6	MK15, MK16	1/01/1999	79.4, 78.7
WK248	1/03/2006	N/A	MK17, MK18	1/01/2000	69.5, 71.8
WK247	3/08/2006	71.4	MK19, MK20	1/01/2000	72.3, 71.1
WK249	23/06/2007	7.9	MK21, MK22	1/01/2000	39.6, 34.4
WK250	11/07/2007	6.7	MK23, MK24	1/01/2000	38.0, 43.1
WK251	24/07/2007	9.9	MK25, MK26	1/01/2000	44.2, 43.5
WK607	25/08/2007	2.0	MK27, MK28	1/01/2001	58.5, 53.7
WK253	20/10/2007	91.7	MK29, MK30	1/01/2001	58.1, 65.4
WK254A	28/11/2007	60.2	MK31, MK32	1/01/2001	65.4, 63.6
WK252	24/07/2008	17.3	MK33, MK34	1/01/2001	28.6, 23.4
WK255	30/08/2008	122.0	MK35, MK36	1/01/2002	16.9, 23.4
WK256	26/09/2008	116.7	MK37, MK38	1/01/2002	35.1, 33.8
WK257A	8/11/2008	N/A	MK39, MK40	1/01/2002	51.7, 46.7
WK258	30/04/2009	56.9	MK41	1/01/2002	50.4
WK259	6/06/2009	63.3	MK42, MK43	1/01/2003	48.2, 52.3
WK260	1/07/2009	107.8	MK44, MK45	1/01/2003	50.7, 19.1
WK246A	2/08/2009	N/A	MK46, MK47	1/01/2003	16.9, 13.7
WK263	4/08/2010	51.1	MK48	1/01/2003	15.9
WK264	23/09/2010	52.7	MK49, MK50	1/01/2004	27.1, 24.4
WK265	29/10/2010	N/A	MK51, MK52	1/01/2004	42.8, 38.6
WK261	21/02/2011	53.6	MK53, MK54	1/01/2004	40.8, 43.3
WK262	15/03/2011	68.7	MK55, MK56	1/01/2004	48.3, 46.8
WK266	6/04/2011	N/A			
WK122	25/10/2011	N/A			
WK123A	10/05/2012	N/A			
WK267A	23/07/2012	N/A			
WK268	24/07/2012	N/A			
WK269	18/08/2012	N/A			
WK124A	23/08/2012	N/A			

Table 1: Schedule of actual wells drilled and new wells assumed for the future scenario

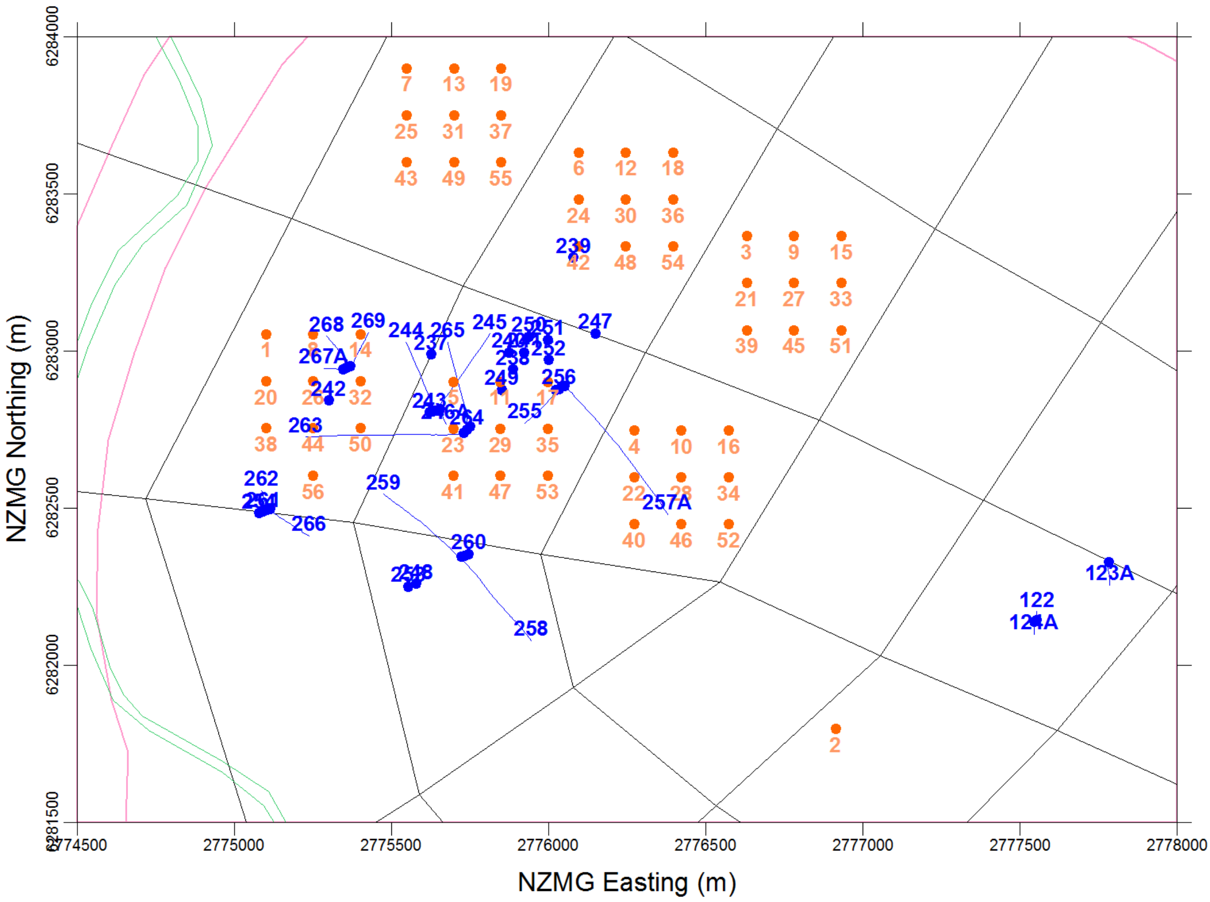

Figure 6: Location of make-up wells – actual wells are in blue, model make-up wells in orange.

4.2 Simulation Using the Actual Production and Injection Schedules

In the next simulation (Scenario WK_S1) the actual production and injection history for 1996 to 2012 was used as input for model WK1998. However this simulation failed to finish as the pressure at certain blocks dropped too low (see Figure 7). The main problem area was the shallow steam zone at Te Mihi. In retrospect this result could have been anticipated as the horizontal permeability in this region in WK1998 is 400 mD whereas in WK2013 a value of 2000 mD is used, based on calibration of the model with pressure decline data measured after 1999.

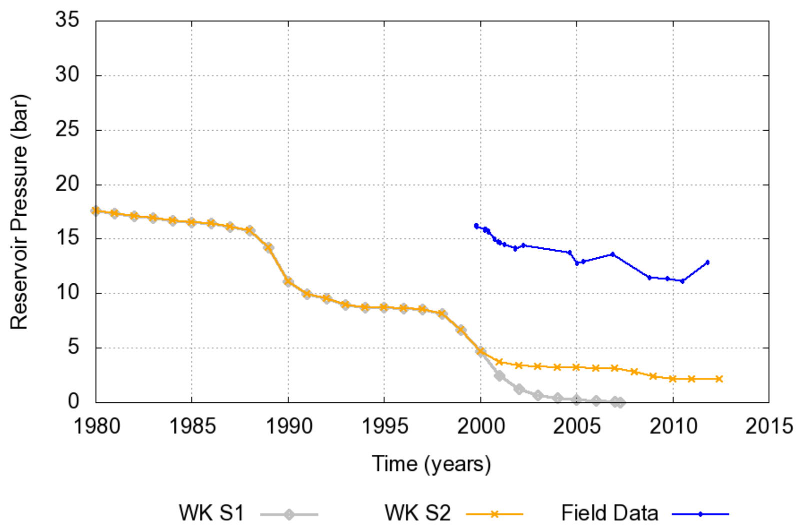

Figure 7: Pressure at the Te Mihi steam zone

4.3 Wells on Deliverability

In the final simulation (Scenario WK_S2) some of the production wells in the shallow steam zone were put on deliverability and thus their flow rate was allowed to decline as reservoir pressures dropped. The following wells were operated in this mode: WK241, WK238, WK240, WK234, and WK237. As shown in Figure 8, the simulation now ran to the target completion date of 2012. The plots of total mass flow and average flowing enthalpy for all the Te Mihi wells (Figure 9 and Figure 10) show that model WK1998 produced almost the same amount of mass as the actual value recorded since 1996 but with a slightly reduced average enthalpy. The model matches the history for the enthalpy of the Te Mihi wells up to 1997 very well. For the "future" scenario beyond 1997 Scenario S1 matches the enthalpy well but fails to complete whereas Scenario S2 somewhat underestimates the enthalpy.

As shown in Figure 12 the model enthalpy for the Western Borefield wells is too high both for history matching and for the future scenario simulations.

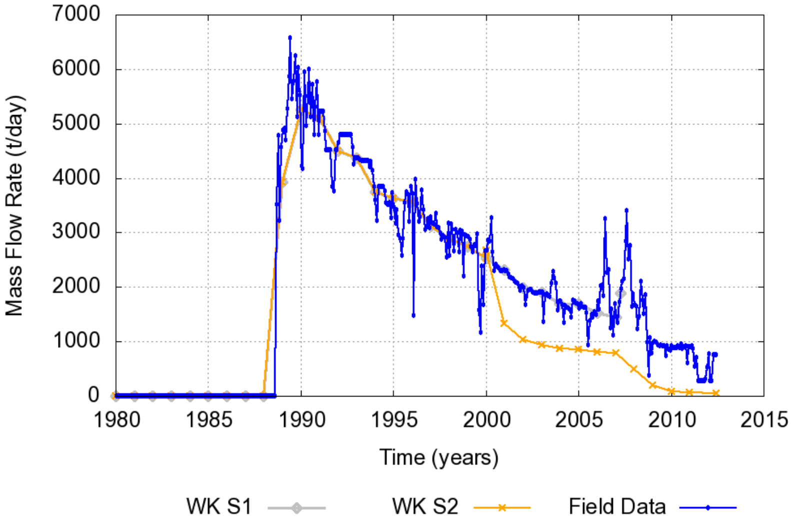

Figure 8: Mass flow from Te Mihi steam wells: WK241, WK238, WK240, WK234, and WK237.

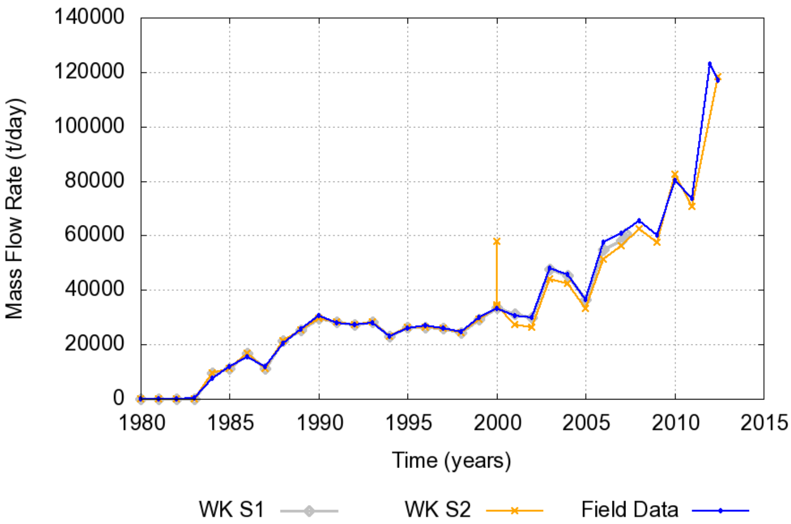

Figure 9: Total mass flow from all Te Mihi wells

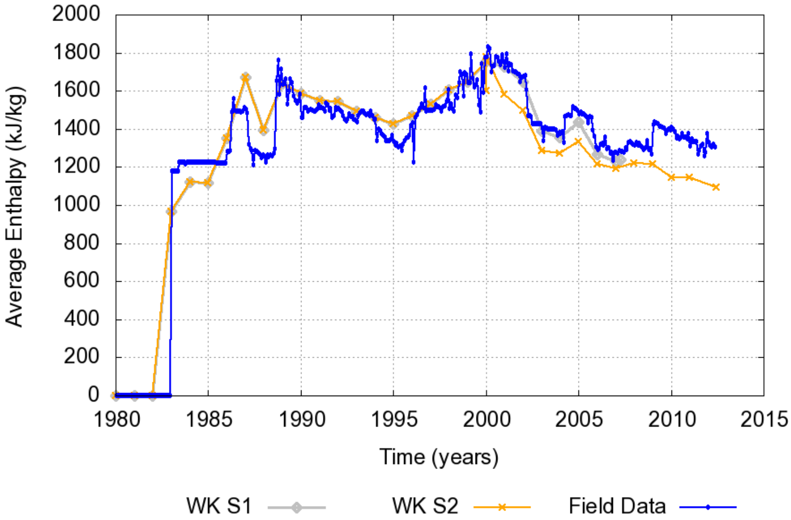

Figure 10: Average flowing enthalpy from all Te Mihi wells

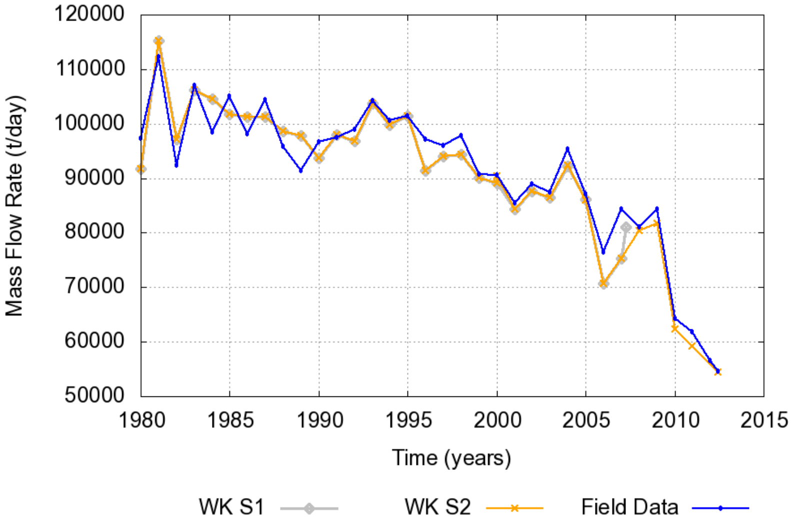

Figure 11: Total mass flow from all Western Borefield wells

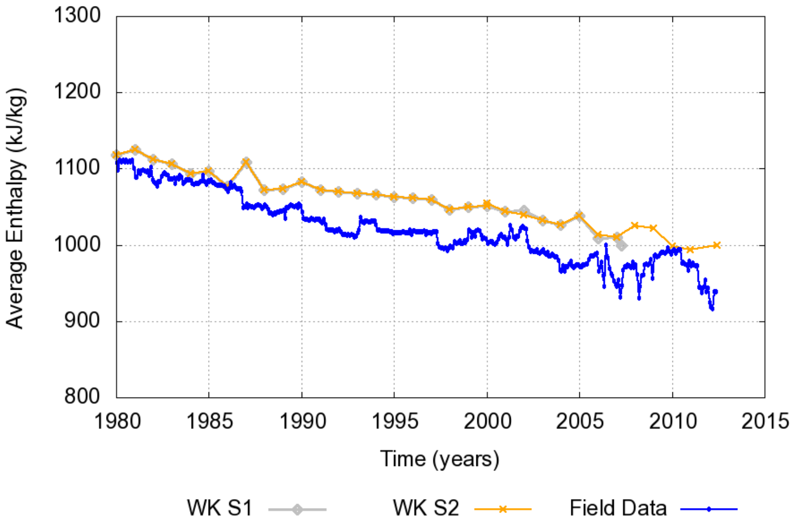

Figure 12: Average flowing enthalpy from all Western Borefield wells

5. OHAAKI RESULTS

5.1 Future Scenario from the Original 2004 Modeling Study

The results for total mass flow, for a future scenario simulation using model OH2004, with a start date of 2004, are shown in Figure 13. The actual production history is also shown. This scenario had a target take of 40,000t/day, using 5 make-up wells at the start of the scenario and then 10 more wells were introduced as necessary to make up the target total mass flow. From Figure 13 it can be seen that initially turning on 5 make up wells, in order to make up 40,000t/day, was unnecessary, as the mass flow increased up to a peak of 55,000t/day. The OH2004 model can easily cope with a take of 40,000t/day, using the prescribed productivity indices of make-up wells, but the actual production from 2004 – 2012 is closer to 35,000t/day -30,000t/day.

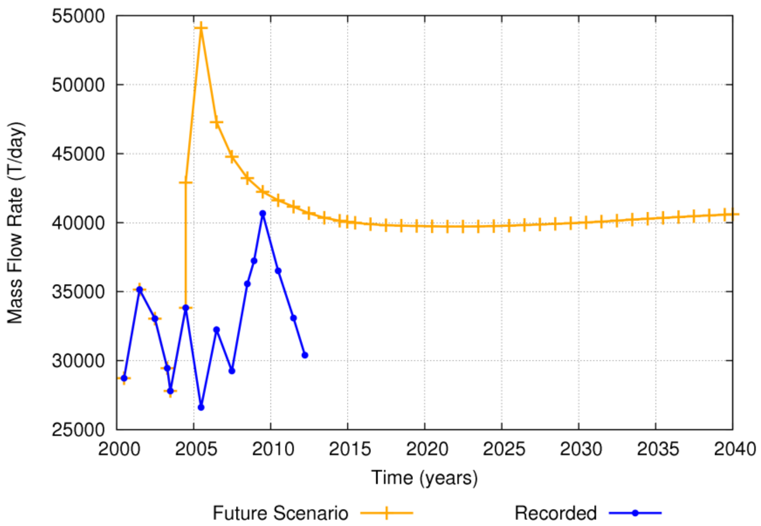

Figure 13: Future scenario result for total mass flow from model OH2004 and actual production since 2000

Because the actual mass flow rates were unknown for the future scenario, make-up wells drilled in the scenario were allocated productivity indices (PI's) based on average flow rates of current large producing wells (in 2004). The PI's allocated were 0.70E-12 for all make up wells except well 8 and well 13 which were allocated a PI of 0.90E-12. As shown in Figure 13, the mass flow target in the scenario was easily reached using make-up wells with the prescribed productivity indices. In retrospect, the PI's allocated were too optimistic as the recorded mass flow averages nearly 10,000t/day less than the scenario prediction.

Table 2 shows the schedule of new wells assumed for the future scenario and the schedule of actual new wells drilled at Ohaaki between 2004 and 2012. The locations of the two sets of make-up wells are shown in Figure 14. As shown in Figure 14 the locations for the actual wells drilled are in the general west bank area envisaged as the site for make-up wells back in 2004 but they are somewhat more spread out and further west than in the 2004 plan.

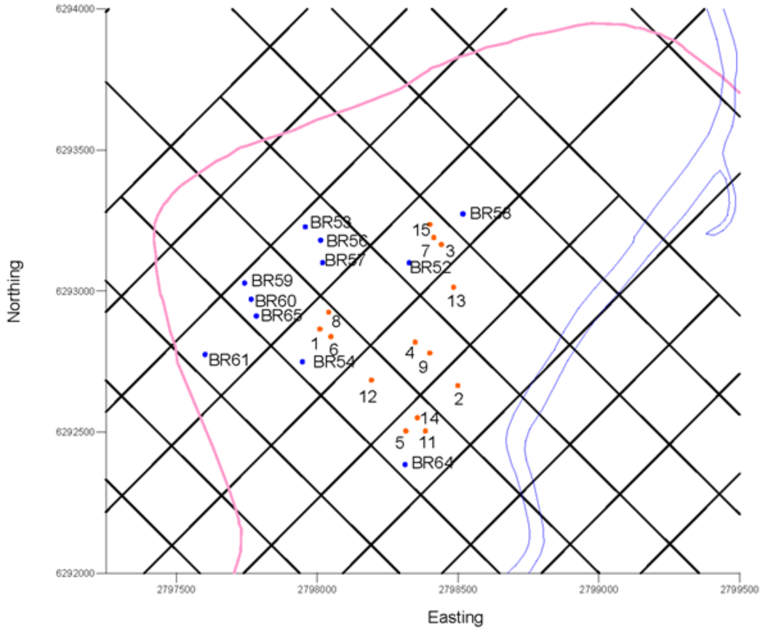

Figure 14: Location of make-up wells – actual wells are in blue, model make-up wells in orange.

Well name	Actual date drilled	Average flow over first few years of production kg/s	Corresponding make-up well in original scenario	Date drilled in scenario	Average flow over first few years of production (in future scenario) kg/s
BR51	18/11/2005	34.3	1	1/1/2004	53.5
BR52	18/01/2006	14.3	2	1/1/2004	13.4
BR53	16/02/2006	44.5	3	1/1/2004	27.4
BR54	3/10/2006	26.8	4	1/1/2004	33.7
BR55	1/05/2007	N/A (reinjection)	5	1/1/2004	22.2
BR56	19/01/2007	51.5	6	1/1/2004	28.1
BR57	1/03/2007	28.9	7	1/1/2004	35.0
BR58	10/04/2007	18.1	8	1/1/2004	30.6
BR59	21/05/2007	9.8	9	1/1/2004	28.2
BR60	21/06/2007	66.8	10	27/6/2005	32.9
BR61	21/06/2007	56.3	11	27/6/2005	23.7
BR62	21/07/2007	N/A (reinjection)	12	27/6/2005	30.4
BR64	12/08/2009	?? (comes online later in 2012)	13	27/6/2005	38.7
BR65	26/10/2009	27.9	14	27/6/2005	23.7
???	???	??	15	27/6/2005	28.2

Table 2: Schedule of actual wells drilled and make-up wells used in the model for the future scenario

5.2 Simulation Using the Actual Production and Injection Schedules

In this simulation (Scenario OH_S1) the actual production and injection history from 2004 to 2012 was used as input for model OH2004. However the simulation failed to finish as the pressure at certain blocks dropped too low (see Figure 13). The problem area was on the East Bank at -350mRL – which was surprising as it was expected that increased production due to a deep drilling program undertaken over 2005- 2007 (Rae *et al*., 2007) on the West Bank, in parts of the model not previously calibrated, may have resulted in an incorrect pressure drawdown.

The low pressure zone causing the simulation to fail is near the feed-zone for well BR51 on the East Bank. BR51 is a multi-feed well with feed-zones at elevations of -350mRL and -550mRL. BR51 comes online for production in 2006 and has a high mass flow rate. The permeability in the vicinity of the feed-zones for BR51 in the 2004 model is too low to support the required mass extraction, thus causing the pressure to drop rapidly. A plot of pressure versus time is shown for the BR51 feed-zones for simulation OH_S1 is shown in Figure 15. BR51 feeds from the contacts between the Broadlands Dacite lava dome, the Rangitaiki Ignimbrite and the Rautawiri Breccia. Permeability in this zone was set in the OH2004 model at 1mD ($1x10^{-15}$ m^2), which is much smaller than the value of 50mD used in the OH2013 model on the basis of calibration against post-2006 data.

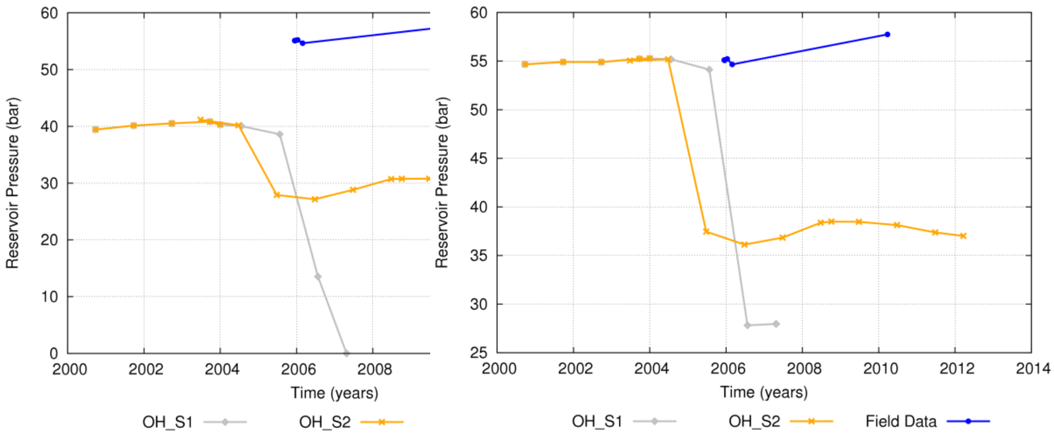

Figure 15: Pressure vs Time for BR51 upper (left) and lower (right) feed-zones

5.3 Wells on Deliverability

In the final simulation (Scenario OH_S2) well BR51 was put on deliverability at its start-up time and thus the production rate was allowed to decline as reservoir pressures dropped. The desired initial production rate (known from the production history) was used to calculate the appropriate PI for BR51.

In this case the simulation ran from the start date of 2004 until the target completion date of 2012. Results are shown with a small amount of production history included (2000 – 2004) to show the transition from history matching into the future scenario simulation. The plots of total mass flow and average enthalpy (Figure 14 and Figure 15) show that model OH2004 is able to produce almost the same amount of fluid, of a similar quality, for both scenarios.

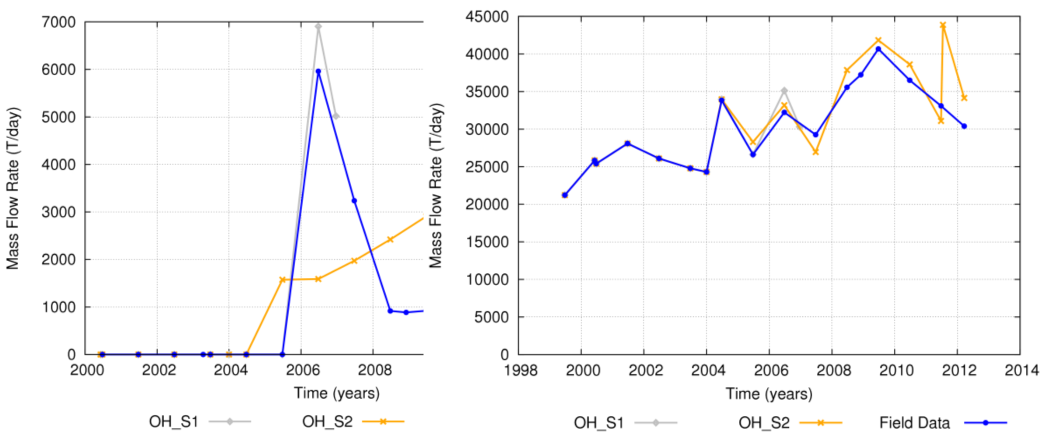

Figure 14: Mass flow from well BR51 (left) and total mass flow from all Ohaaki wells (right).

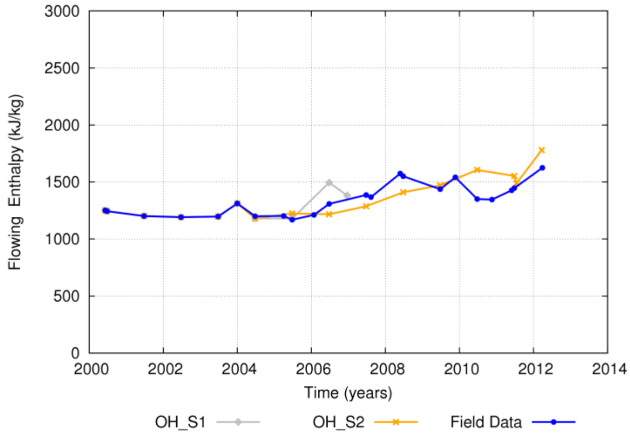

Figure 15: Average flowing enthalpy from all Ohaaki wells.

6. SUMMARY AND CONCLUSIONS

This study shows that the future scenarios ran in 1998 for Wairakei and in 2004 for Ohaaki have turned out not to be correct. In both cases the simulation results show a much larger total mass take than turned out to be actually used.

In the case of Wairakei some of the wells drilled turned out to be better producers than the make-up wells in the model and the Te Mihi shallow steam zone turned out to be more permeable and more productive than in the model. When the actual production/injection history for 1996-2012 was used in the model it failed to complete the simulation because some pressures dropped too low. This problem was fixed by allowing a few wells to operate on deliverability so that their feed-zone pressures did not drop too much, but their production rate declined below the measured values. In this final simulation Model WK1998 performed well, matching most of the measured data from 1997 to 2012.

For Ohaaki the 2004 future scenario simulations assumed more make-up wells would come into operation quickly than turned out to be the case. In the model there were 15 new make-up wells in operation by mid-2005 whereas there were actually only four new wells drilled by the end of 2006. Thus the prediction of total mass take from the model was too optimistic. When the actual production/injection history for 2004-2012 was used it failed to complete the simulation because the pressure in one of the feed-zones for BR51 dropped too low. When this well was placed on deliverability the final simulation with Model OH2004 performed well, matching most of the measured data.

So both models had some small zones which were not sufficiently permeable but the main problem for both models was in specifying the performance of future make-up wells or in specifying the drilling program. Back in 1998 for Wairakei we underestimated how well some of the future wells would perform and in 2004 for Ohaaki we assumed an unrealistic drilling program.

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