Peer review of saline intrusion model and risk assessment for the exploration phase of the Wellington Harbour Exploration Bores Project

Prepared for Wellington Water Limited

By Dr Leanne Morgan

June 2018

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1. Introduction

This report presents a peer review of groundwater modelling work carried out by Earth in Mind as part of the exploration phase Wellington Harbour Exploration Bores project (termed SP1a). The SP1a project has the objective of determining whether the Waiwhetu aquifer below Wellington harbour can provide an alternative resilient drinking water supply for central Wellington in the event of a civil defence emergency. To determine this, the SP1a project addressed significant information gaps regarding the geological and hydrogeological properties of the offshore extension of the Waiwheto and underlying Moera aquifers. This was achieved through geophysical exploration, geological analysis, exploration drilling and testing of two bores in Wellington Harbour. The new information was used to refine an existing conceptual model of groundwater flow beneath Wellington Harbour. This conceptual model was subsequently used during the refinement of an existing groundwater flow model. The refined groundwater flow model was then used as the basis for the development of a variable density flow and transport (i.e., SEAWAT) model. The groundwater models were used to assess risk of seawater intrusion associated with offshore extraction from the Waiwhetu aquifer in Wellington Harbour, in the event of a civil defence emergency.

This peer review is based on work documented in the report:

Gyopari M, Grant K, Begg J, Nodder S, Knowling M, van der Raaij R, Wellington Harbour Exploration Bores Project: Hydrogeological Analysis of SP1a Exploration Phase: Abstraction Feasibility Assessment and Recommendations, Draft for review 16/3/2018.

The purpose of the report is clearly stated as 'presenting the hydrogeological analysis following the completion of the SP1a project phase in the context of assessing the feasibility of offshore groundwater abstraction'. The report is well structured and well written, with good quality figures.

It has been requested by Wellington Water Limited that this peer review address the following:

1. the general set up and re-calibration of the MODFLOW model following revision of the offshore geology;

2. the adequacy and veracity of saline intrusion risk assessment approaches using MODFLOW and variable density SEAWAT models;
3. the set-up and employment of the SEAWAT (or other) models;
4. the approach taken to assessing aquifer risks (principally saline intrusion) of offshore abstraction;
5. the appropriateness of model assumptions and sensitivity/uncertainty analyses;
6. whether an adequate or appropriate degree of conservatism has been applied in the context of uncertainties and risk;
7. that the conclusions and recommendations are reasonable.

Each of these points are addressed below.

2. Review comments

2.1 The general set up and re-calibration of the MODFLOW model following revision of the offshore geology

The report describes the development of the HAM4 (Hutt Aquifer Model), which is a refinement of the HAM3 groundwater model. The HAM3 model is presently used for management of the onshore Waiwhetu aquifer by Wellington Water Limited and the Greater Wellington Regional Council. The Lower Hutt aquifers currently deliver around 40% of the water supply to Wellington Metropolitan region (EIM, 2014).

Through the SP1a project, existing and new offshore seismic data has been supplemented by hydrostratigraphic information provided by the drilling of two offshore wells in Wellington Harbour. This has resulted in an improvement in understanding of the offshore hydrogeology of Wellington Harbour and the development of an updated conceptual model for these aquifers.

The HAM3 model geology is based on a 3D geological model developed in 2010, and includes the offshore aquifers under Wellington Harbour. The conceptual model for HAM3 assumes that the Waiwhetu aquifer extends under the entire harbour and through the harbour entrance area, and that this aquifer is confined by fine grained sediments. Discharge occurs through the confining layer and through discrete springs in the sea floor. The location of most of the leakage out of the offshore aquifer was assumed to be through diffuse leakage through the overlying aquitard and through sea-floor spring vents. Some connectivity at the harbour entrance was also assumed. This conceptual model conforms to generalised representations of offshore fresh groundwater discharge mechanisms, where the fresh groundwater is connected to modern day terrestrial recharge, e.g., Kooi and Groen, 2001; Bakker, 2006; Post et al., 2013.

As detailed in the report, the new geological model developed as part of the SP1a project does not substantially alter the general HAM3 offshore conceptualisation but, rather, provides a refinement of the offshore morphology of, and relationships between, the main hydrostratigraphic units. The main hydrostratigraphic units are the Petone marine silt aquitard (Q1), Upper Waiwhetu gravel Aquifer (UWA) the Q3 aquitard and the Lower Waiwhetu gravel Aquifer (LWA). Importantly, the Q3 aquitard has been included in the HAM4 model, and was not present in the HAM3 model. The extent of the UWA is more limited in the HAM4 model compared to the HAM3 model. Also, in the harbour heads there is a general merging of units into a heterogeneous, course grained and heterogeneous area where vertical leakage may be enhanced. Also, the extension of the aquifers in the Cook Strait is recognised as being possible, although likely restricted by a bar of low permeability material beneath the harbour heads. The conceptual model used for the HAM4 model, shown in Figure 7.2, adequately reflects this refined geological conceptualisation.

The boundary conditions in the offshore component of the HAM4 model are suitable. The use of a constant head boundary condition that uses the upper quartile value of the tidal range is good and follows a conservative approach to assessing risk of seawater intrusion. The equivalent freshwater head calculations described on p. 59-60 are correct but, as pointed out, SEAWAT automatically calculates the equivalent freshwater head from the assigned head data and concentration data. The approach taken to ensure that SEAWAT calculates the equivalent freshwater head at the seafloor is good.

The use of a general head boundary at the southern harbour entrance boundary appears suitable. The sensitivity analysis indicates that flow into the harbour from the Cook Strait can be simulated using the general head boundary. The conductance is quite large and suggests that this boundary condition is perhaps acting as a constant head. Sensitivity analysis of the conductance was not carried out. The report indicates that, ‘the GHB boundary does not appear to play an important part in terms of evaluating the saline intrusion risk in the main part of the harbour'.

Hydraulic properties in the onshore portion of HAM4 are unchanged from the HAM3 model. The hydraulic parameters and zonation used in the offshore component of the HAM4 model are described as retaining some of the parameter values for the onshore component of the model or having been adjusted to reflect the offshore conceptual geological model. Parameter values assigned to different layers are adequately described at pp. 61-66 and in Table 7.2.

It is worth bearing in mind that the selection of parameters for the HAM4 flow model will influence the offshore extent of fresh groundwater simulated in the SEAWAT model. A number of analytic solutions exist for the extent of offshore fresh groundwater in subsea aquifers (e.g., Kooi and Groen, 2001; Bakker, 2006; Bakker et al., 2017), where it is assumed that the offshore groundwater derives from terrestrial recharge (as is thought to be the case for the Wellington Harbour aquifers). These analytic solutions show that offshore fresh groundwater extends further offshore when the overlying aquitard has a lower hydraulic conductivity and/or larger thickness, the underlying confined (or semi-confined) aquifer has a higher hydraulic conductivity, and/or the groundwater head gradient driving freshwater offshore is steeper. In addition to these factors, Michael et al. (2016) have shown that well-connected heterogeneities in the subsea geology may lead to offshore fresh groundwater extending further distances offshore than would be expected in homogeneous aquifers.

The modelled thickness of the Q1 aquitard is variable over the offshore area, generally thickening in the offshore direction, with a thickness of around 20 m in the vicinity of the E8 exploration well. From Figure 7.11 and 7.12, the K_h value assigned to this layer in the majority of the harbour area and in the vicinity of the wells is 5 E-4 m/d, which is very low. I note that the EIM (2014) report indicates that the HAM3 model has a K_h of 0.63 m/d and a K_v of 5E-4 m/d for this layer. Also, during calibration of HAM3 it was found model results were relatively insensitive to K_h but very sensitive to K_v. The value of K_v for this layer in HAM4 is given as 1E-5 in Table 7.2 and on p. 50 it states that a low value of K_v for this layer will be employed to force connectivity in the harbour entrance area. There is a risk here that by using a very low vertical hydraulic conductivity value for the Q1 the offshore extent of fresh groundwater in the

UWA may be overestimated and the drawdown in the UWA, as a result of pumping, may also be underestimated.

The modelled thickness of the UWA is shown in Figure 7.7. It thins in the offshore direction and is around 10 m thick in the vicinity of the E8 well. Figure 7.13 shows that the K_h values in the UWA are zoned to reduce in the offshore direction. A K_h at the lower end of the range is used for the offshore UWA to induce larger drawdowns under extraction. It is worth noting that this approach will also alter offshore flow and reduce the offshore extent of fresh groundwater in the aquifer, as detailed above. Note that the caption in Figure 7.13 refers to zone 2 and this should probably be zone 3.

The modelled thickness of the Q3 aquitard is shown in Figure 7.8. This aquitard thickness is highly variable in the offshore portion and relatively thin nearby to well, E8 i.e., in the range of 0 to 10 m. Figure 7.14 and Table 7.2 indicate that a K_h value of 1 m/d and K_v value of 1E-3 m/d has been employed for the Q3 aquitard. This K_v value was assigned based on lithological descriptions. As per the comments regarding the Q1 aquitard, the K_v value used in this aquitard is going to be important in determining the offshore extent of fresh groundwater and the risk of seawater intrusion via drawdown from the E8 well.

Storage and porosity values applied in HAM4 follow those used in HAM3, except that a low porosity value was applied in the offshore layers to maximise advective dispersion within the solute transport model. It should be noted that this will alter the velocity values offshore i.e., increase them. It will also reduce the solute mass within the SEAWAT model. It would perhaps have been better to carry out a sensitivity analysis with varying dispersivity values, as part of the SEAWAT modelling.

The HAM4 model is characterised in the report as an 'aquifer simulator' of high complexity which is required to have a Class 3 confidence level (Barnett et al. 2012) to meet its prediction-focused purpose. While the onshore portion of HAM4 (which is essentially the same as HAM3) may fall within this category of confidence, it would be better to characterise the offshore portion of HAM4 as having a Class 1 to Class 2 confidence level given the few existing wells from which to obtain reliable groundwater and geological information, as well as the limited observations and measurements in the offshore domain. While it may not be common practice to designate portions of models as having different confidence level classes, there is a need here to explicitly acknowledge that the offshore portion of HAM4 has a different level of confidence to that of the onshore portion.

The calibration used a transient flow model that runs for 5 years from 2007 to 2012. This is described as a period with a wide range of climatic conditions. Calibration targets were the same as those used for the HAM3 model. This includes offshore spring discharge of 1-2,000 m^3/day and one offshore observation bore at Somes Island, with some additional measurements available from exploration bores E3a and E8. It is noted that the model is very stable and only takes 20 minutes to run, which is good.

As stated in the report, a limited manual recalibration has been carried out through the adjustment of K values in the offshore portion of the aquifer domain – principally K_v in the harbour entrance area since these control the pressurisation of the sub-harbour Waiwheto aquifers. As such, the calibration process is relatively simple.

The measured versus modelled hydraulic heads shown in Figure 7.22 illustrate a good match. The report would benefit from a brief description of how, if at all, these plots differ for the HAM4 model compared to the HAM3 model, especially for the Somes Island monitoring well. Please add units to the axis labelling of Figure 7.22.

2.2 The adequacy and veracity of saline intrusion risk assessment approaches using MODFLOW and variable density SEAWAT models

The potential sources of saltwater intrusion in Wellington Harbour are described in the report at p. 44 as being via:

- Lateral encroachment of a saline interface in the southern part of the harbour;
- Vertical leakage through the harbour floor due to thin or absent aquitard;
- Backflow of seawater through submarine sea floor spring vents in the Petone marine silt aquitard and along the bedrock-aquitard contact where decoupling (through seismic activity for example) could result in pathways for flow to the underlying Waiwhetu gravels;
- Seepage down the outside of the bore casing;

- Lateral migration from formations that contain connate saltwater;
- Vertical migration from a saline formation below the Waiwhetu aquifer (i.e., the LWA) and through pumping induced upconing.

These sources of saltwater intrusion are clearly illustrated in Figure 6.1 and fit with the conceptual model of the offshore section of Wellington Harbour described in Chapter 5.

Figure 6.2 indicates that the majority of the areas where saltwater intrusion might occur is along the Eastbourne coast and Falcon Shoals (via leakage through the harbour floor), also nearby to the E8 exploration well (via up-coning and flow from the LWA); at the harbour entrance (through lateral encroachment), and at sea floor spring vents (through backflow if the hydraulic gradient is reversed).

The description of the Ghyben Herzberg theory in section 6.2 is correct and its use as a high-level criterion to assess the risk of lateral seawater intrusion at critical points seems reasonable. However, as pointed out within the report, the SEAWAT model provides insights into interface location and movement. Why not use the SEAWAT model alone to assess this risk factor?

A buffer of approximately 1 km between any bore and bedrock contact or spring vent is recommended and this seems reasonable. It is worth noting that the veracity of this approach could be explored further using the SEAWAT model.

An approach is given for calculating the critical artesian pressures required at spring vents to ensure that backflow from the ocean via the spring vent (and into the UWA) does not occur. It is proposed that a critical condition at the spring site exists when the ocean pressure at the sea floor, accounting for density effects, is equal to the freshwater pressure in the underlying aquifer. This approach seems reasonable. In general it is logical that the head in the underlying aquifer needs to be larger than the density corrected head in the overlying seawater column for backflow not to occur.

To assist with the clarity of the mathematical derivation in this section please number the equations and refer to the equation numbers during the derivation, and define dimensions or units of all parameters when they are first referred to. Please clarify what is meant by $\rho_f g$ is reduced to 1. This step in the mathematical derivation is unclear.

The risk of saltwater ingress along bore casings was determined to be low as long as there is a guaranteed and tested annulus seal. This is reasonable.

As detailed in the report at section 6.5, water quality sampling from all aquifers intercepted by the E3a and E8 exploratory bores show a small percentage (2 – 4%) of seawater mixing. Some areas, such as at the E8 bore site (LWA) exhibit considerably higher salinity concentrations suggesting that salinity may be localised and variable throughout the offshore aquifers. The report suggests that the saline water encountered during drilling may be connate i.e., water held in the pores of the rocks when the aquifers were formed. It is also possible, however, that this salinity pattern is reflective of the diffuse interface between fresh groundwater and seawater in the subsea aquifers. Further modelling using the SEAWAT may provide insight into this question, but is likely beyond the scope of the current project. The report suggests that seawater intrusion via contamination from connate saltwater is perhaps the most probable, and this seems reasonable given the proximity of the higher salinity groundwater to the E8 well, where extraction is proposed.

2.3 The set-up and employment of the SEAWAT model

Saltwater intrusion problems involve both solute transport and variable density flow. Modelling variable-density groundwater flow can be challenging because the groundwater flow equation and the advective dispersion equation are coupled through the groundwater density, and have to be solved within the same simulation. This poses additional challenges to the modelling process, in particular a potentially large increase in computational burden, which may impose restrictions on model calibration and sensitivity analyses. This is, presumably, the reason for not using the SEAWAT model during the calibration phase of this project. However, as noted above, the calibration was a reasonably simple manual calibration involving the varying of K_v. It would be good to provide a brief justification for why the flow model and not the SEAWAT model was used for the calibration process. It is worth noting that there may have been benefits from using the SEAWAT model during calibration in terms of gaining insights into the emplacement and extent of observed groundwater salinity concentrations in the UWA and LWA.

As detailed in Section 7.10 of the report, the calibrated HAM4 MODFLOW model was converted into a SEAWAT model to carry out scenario modelling. On p. 80 it is stated that the objectives of the SEAWAT model are to discern regional scale patterns and trends in salinity due to abstraction.

The SEAWAT settings are described in section 7.10.3. The uncoupled flow and transport mode was selected. This means that the flow field is affected only by the user specified density array and not the solute concentrations calculated by the model (Langevin, 2003). This is in contrast to the coupled flow and transport mode, where the flow field is affected by the fluid density array that results from the modelled solute concentrations. The latter can involve longer run times but is the more accurate of the two approaches. What was the reason for selecting the uncoupled flow and transport mode?

Please provide additional details in relation to the parameters used for dispersivity (longitudinal, horizontal and transverse). From this, the Peclet number (i.e., the ratio of the cell size to the dispersivity) can be calculated. A value less than 4 is recommended to reduce numerical instabilities, although values as large as 10 have been shown to work by some authors (Barnett et al., 2012). Also, what Courant number was used? The Courant number is the ratio of the product of the advective flow velocity and the time step, divided by the grid cell size. The Courant number needs to be less than or equal to unity, which basically states that during a given time step, a solute particle can traverse not more than a single model cell (Barnett et al., 2012).

Why is diffusion not considered to be important within the system? Diffusion can be an important mechanism in aquitards, especially over longer time periods and hence may be important within the baseline equilibrium simulation.

Please comment on whether the grid size is expected to have a significant impact on the movement of solute in the simulations.

The concentration boundaries are set as constant, whereby the concentration of the boundary cells representing the contact with the ocean are fixed. An alternative (and more accurate) approach is to set the concentration boundaries up such that seawater flows into the model at the boundary and groundwater of the ambient concentration flows out at the boundary. Using this approach, seawater inflow to the aquifer causes the coastal boundary cells to approach seawater concentration, whereas groundwater discharge generally causes boundary salinities to fall. However, given that the uncoupled flow and transport mode was selected, it is likely that the choice of concentration boundaries will not have a significant impact on the model results because the flow field is not affected by solute concentrations calculated within the model.

The refining of layers for some of the modelling scenarios is confusing and if there was little difference in the results it seems strange that the results for the refined model were presented.

As detailed in section 7.10.4, a baseline equilibrium simulation was run using constant stresses and average recharge conditions for a period of 5000 years to obtain a steady state head and concentration distribution. It would be good to briefly detail how average recharge conditions were determined. How long did it take to reach a steady state head and concentration distribution within this model? A plot showing the change in heads and concentration during this simulation period at selected sites would be interesting. It is worth noting that the system will have undergone changes in sea levels associated with glacial periods (sea levels were 120 m lower than today around 19,000 years ago, for example) and this is likely to have a significant influence on the position of the freshwater saltwater interface. It might also have a bearing on the emplacement of the higher salinity groundwater in the LWA.

As detailed in section 7.10.5 of the report, a stabilised extraction effects simulation was carried out whereby the model was run from the end of the 5,000 year baseline equilibrium simulation for an additional 50 years with abstraction turned on at Waterloo. This is designed to broadly simulate the abstraction history from the terrestrial UWA and provides stable (using summer stress conditions, which represent low recharge) starting heads and concentration for subsequent abstraction scenario testing. The 50 years of onshore extraction resulted in simulated seawater intrusion at the harbour heads and toward the centre of the harbour and eastern margins in the LWA and the Moera Gravels.

The salinity levels observed in the E8 exploration bore have not been matched, particularly in the LWA. This is not particularly surprising given the simple calibration carried out using the flow model for the offshore portion of the model.

2.4 The approach taken to assessing aquifer risks (principally saline intrusion) of offshore abstraction

The SEAWAT model was used to run a series of abstraction and sensitivity scenarios to assess the feasibility of abstraction from the UWA at the E8 site. The E8 site does not provide the opportunity to abstract from the LWA because it contains brackish water at this location. The main threat to the feasibility of abstracting water at the E8 site is up-coning of higher salinity water from the LWA into the UWA Aquifer at and in the vicinity of the E8 site.

Each of the abstraction scenarios were run for 1 year using constant aquifer stresses. Low summer recharge was assumed. The starting point for the simulations was the end of the 50 year stabilised extraction effects simulation. In most of the simulations a constant salinity concentration of 2 kg/m^3 was imposed on the LWA in an attempt to match observed salinity observations. It undoubtedly would have been better to have a base model that had salinity concentrations that better matched those observed in the exploration wells. Had the SEAWAT model been used during calibration, instead of the flow model, it might be possible to say more about why this was not achieved. Nevertheless, this approach of 'forcing' the salinity concentration in the LWA seems reasonable and is better than using the salinity concentrations present at the end of the 50 year stabilised extraction effects simulation, which are too low.

The report correctly points out that the SEAWAT model has important limitations in terms of not being able to accurately simulating salinity concentrations due to uncertainties and assumptions inherent in the model. Rather, the model is useful for developing intuition about saline intrusion pathways and trends which could contribute to the risk of saline intrusion. It is good that this limitation is identified and it should be made clear throughout the document. In this regard, the model is not suitable for determining a sustainable yield from the UWA at E8, as proposed within section 7.12.3. This should be recognised and the wording modified to reflect the confidence level class (1 or 2) in the offshore section of the HAM4 model and SEAWAT model.

The risk of saline intrusion via spring backflow has been assessed by comparing heads taken from the model and comparing those to the critical heads calculated using the approach outlined in Section 6, which also account for the highest tidal level. This seems a reasonable and conservative approach.

In addition, modelled heads have been compared to minimum levels determined using Ghyben-Herzberg to identify areas where low pressures might induce seawater intrusion. This approach seems somewhat unnecessary as the SEAWAT model should, if set up correctly, show areas where seawater intrusion is occurring. Nevertheless, this approach is generally considered reasonable.

Table 7.4 presents the model scenarios and an assessment of the outputs. This matrix is good and presents a clear summary. From these results and Table 7.5 the model appears to be responding to abstraction pressures in a manner that makes sense conceptually. The results indicate that there is evidence for using a model with increased layer refinement and exploring the impact of increased heterogeneity in the aquitards.

In Figures 7.47, 7.49 and 7.53 there is a band of lower salinity groundwater in between high salinity water in the harbour mouth. Any idea what is causing this?

There are a couple of textual issues that would assist with this clarifying this section:
In Table 7.4 the scenario naming conventions are not consistent from Scenario 4 onwards. Also, what is the pumping rate of E8 for Scenario B3a – it is missing. Please add the results from Scenario B7 to table 7.5. In Figure 7.43 is the pink or blue area assigned the constant salinity concentration of 2 ppt? Please ensure figures showing concentration versus time have a unit on the time axis.

2.5 The appropriateness of model assumptions and sensitivity/uncertainty analyses

Given the limited data available for the offshore component of the aquifers there has been a need to make a large number of assumptions in relation to aquifer geology, aquifer hydraulic properties and salinities. These assumptions have, in general, been well documented and justified with reference to the hydrogeological conceptual model of the system. As detailed in the report at section 7.3, the modelling approach has been undertaken within a context of uncertainty and with a view to conservative assessment of the seawater intrusion risk. This is appropriate given the purpose of the modelling activity i.e. to assess risk of seawater intrusion associated with offshore extraction. The points listed in section 7.3 are reasonable but please note my comments elsewhere in relation to the use of a low K_v value for the Q1 aquitard, use of a low K value for the UWA and the use of a low effective porosity.

As discussed above, one of the most important assumptions with regard to seawater intrusion risk is likely to be related to the heterogeneity of the offshore aquifer materials, especially the aquitards overlying and below the Upper Waiwhetu aquifer. Presently, the model reflects an assumption of limited heterogeneity in the offshore aquifer hydraulic parameters. A more detailed sensitivity and uncertainty analysis is needed to better understand the potential risk of saline intrusion into the UPA in the vicinity of the E8 bore under increased heterogeneity. In general, limited sensitivity and uncertainty analysis has been carried out. This need has been is recognised within the report and I understand that a formal uncertainty analysis has started. This has the potential to improve the understanding of the range of uncertainty inherent in the model predictions. Will this uncertainty analysis use the flow model or the SEAWAT model?

Scenarios are reasonable with regards to pumping rates from E8 and Waterloo. It would be interesting to run additional simulations that assess what happens when pumping from E8 ceases and pumping from Waterloo recommences at a representative rate. Does the seawater intrusion at the harbour heads and elsewhere continue or dissipate and how quickly does this occur?

2.6 Whether an adequate or appropriate degree of conservatism has been applied in the context of uncertainties and risk

This point has been addressed in the above section.

2.7 That the conclusions and recommendations are reasonable

The report concludes that there is a risk of seawater intrusion at the harbour heads, at the eastern side of the harbour and through spring backflow, but that these risks can be managed through controlling extraction rates. A pumping rate is proposed (10 ML/d) that is thought likely to lessen the risk of seawater intrusion via these mechanisms. While the scenario modelling does show that this volume of extraction does not induce simulated drawdowns such that seawater intrusion occurs via springs and in the eastern part of the harbour, the confidence classification of the model in the offshore portion of the aquifer is not high enough to warrant any conclusions regarding potentially safe extraction volumes.

The most critical seawater intrusion risk and potentially ‘fatal flaw’ is identified as being via extraction induced flow from the more saline LWA into the UWA. The high level of risk associated with this seawater intrusion mechanism is reasonable considering the conceptual model and simulation results. The Q3 aquitard is thin (around 4 m) in the region where offshore extraction is proposed. Even at relatively low pumping (i.e., 10 ML/d) this risk remained evident from the model simulations.

It is recommended in the report that due to the high level of uncertainties and assumptions inherent in the model it is necessary to physically pump test a production bore at full capacity for as long as it would be used in an emergency and monitoring the aquifer closely for salinization. This is a conservative and good recommendation. It is worth noting that the HAM4 SEAWAT model (and any uncertainty modelling) will be extremely useful for guiding the selection of monitoring sites for this test.

The report recommends that prior to any further exploration activities occur, a formal parameter and predictive uncertainty analysis should be carried out along with a risk-based hypothesis testing analysis. This extra modelling activity will certainly help to improve the decision making potential of the HAM4 SEAWAT model.

There is also merit in exploring the use of alternative abstraction methods to reduce the aquifer drawdown. Some intuition about the feasibility of these approaches could be gained using the HAM4 SEAWAT model.

The recommendations provided in section 8.2.3 consist primarily of additional field tests and monitoring, as well as modelling using new information obtained from the SP2 field activities. These recommendations are reasonable.

3. Response to review comments

In response to the review presented in section 2 above, Dr Mark Gyopari carried out additional modelling and made changes to the report. The latest version of the report has had some minor rewording and corrections in chapters 1 – 6, significant changes in Chapter 7 (Numerical modelling) and a new Chapter 8 has been added, which presents an alternative calibration, a new Chapter 9 has been added which details calibration/uncertainty analysis carried out by Matt Knowling. Chapter 10 is now the discussion, limitations and recommendations.

The final version of the report is:
Gyopari M, Grant K, Begg J, Nodder S, Knowling M, van der Raaij R, Wellington Harbour Exploration Bores Project: Hydrogeological Analysis of SP1a Exploration Phase: Abstraction Feasibility Assessment and Recommendations, Final report 30/5/2018.

The additional work carried out by Dr Mark Gyopari has responded well to the comments made within section 2 of this report. Specific details of the changes made in response to the review are detailed below in section 3.1. The additional modelling and preliminary calibration using SEAWAT have offered additional insights into dispersive processes in the offshore aquifers. In response to comments around the use of a low aquitard K_v, an alternative calibration was carried out that used a higher aquitard K_v value and (necessarily) a higher spring discharge – with both values being within the plausible range. The results from scenario modelling using the main model and the alternative calibration model indicate that there is a potentially fatal flaw associated with the cross contamination of more saline water moving from the Lower Waiwhetu aquifer into the Upper Waiwhetu aquifer. This is in line with the conclusions presented in the previous version of the report.

Chapter 9 was authored by Matt Knowling of GNS Science and details further modelling carried out to explore in more detail the identified salinization risk from the lower Waiwhetu Aquifer. The work comprised an analysis of uncertainty associated with model outputs. Unfortunately, stochastic calibration attempts using the HAM4 model encountered numerical instability and large model run times, which meant the model could not be used to quantify uncertainty and risk. Also, it was shown that the observed brackish water in the Lower Waiwhetu aquifer and fresher water in the Upper Waiwhetu aquifer could not be reproduced in the HAM4 model, which meant that the model could not be used to quantify risk of salinization (from the Lower Waiwhetu via pumping in the Upper Waiwhetu). It is recommended that a smaller-scale process driven model that can include heterogeneity be developed and used to exploration of the risk associated with abstraction from E8.

The current version of the report has similar conclusions and recommendations as those presented in the previous version and these are considered to be reasonable and in line with the results obtained from the modelling. The report recognises that there is insufficient physical information to confidently assess the risk associated with the identified potential fatal flaw (cross-aquifer contamination). A number of staged recommendations are made for a second SP2 exploration phase. This staged approach is good and, when coupled with numerical modelling, will assist to increase the information available for making decisions around aquifer cross contamination potential. The initial stage involves exploration drilling targeting the E8 area and the proposal to design exploration bores in such a way that they can be turned into monitoring bores is excellent. Pump testing and water quality testing during the exploration drilling activities will improve the conceptual and numerical model and assist with decision making with regard to whether a full-scale production test bore should be constructed and then used for an initial pump test and then a long term pump test. The recommendation around groundwater monitoring are excellent. The recommendation to continue to carry out numerical modelling as the project progresses and to use numerical modelling to assist with the placement of monitoring wells via a 'data worth' analysis is also good.

3.1 Response notes

Reponses notes to Dr Leanne Morgan's Draft Peer Review of: Saline intrusion model and risk assessment for the exploration phase of the Wellington Harbour Exploration Bores Project (April 2018).
Mark Gyopari 25/4/18

I have addressed most of your principal comments Leanne – I've copied the sections of your review that I have responded to (in italics) and then made comment.

The modelled thickness of the Q1 aquitard is variable over the offshore area, generally thickening in the offshore direction, with a thickness of around 20 m in the vicinity of the E8 *exploration well. From Figure 7.11 and 7.12, the Kh value assigned to this layer in the majority of the harbour area and in the vicinity of the wells is 5 E-4 m/d, which is very low. I note that the EIM (2014) report indicates that the HAM3 model has a Kh of 0.63 m/d and a Kv of 5E-4 m/d for this layer. Also, during calibration of HAM3 it was found model results were relatively insensitive to Kh but very sensitive to Kv. The value of Kv for this layer in HAM4 is given as 1E-5 in Table 7.2 and on p. 50 it states that a low value of Kv for this layer will be employed to force connectivity in the harbour entrance area. There is a risk here that by using a very low vertical hydraulic conductivity value for the Q1 the offshore extent of fresh groundwater in the UWA may be overestimated and the drawdown in the UWA, as a result of pumping, may also be underestimated.*

I generally think that, following observation of the drilling cores - which shows the aquitard to be a very plastic clayey silt - that a kv value range of 1e-4 to 1e-5 is reasonable. However, I take your point around the non-conservatism of assigning a low-end value. I wanted to force greater connectivity at the ocean in the southern part of the model to allow seawater to enter – if I allow more leakage in the main aquitard area, I need to compensate by reducing the kvs in the harbour entrance area so that the observed aquifer pressures are maintained. There is also a release of water through the submarine springs which will reduce some of the throughflow and counter this? But, thinking about this quite a bit (!) I have presented an alternative calibration version – the new Chapter 8 – in which I have increased the aquitard kv to 1 e-4 and also significantly increased the spring discharge (by a factor of 4 – we don't have a good handle on the actual discharge but it could conceivably be around 10MLD ish). Under these conditions, the gradient further to the south becomes considerably flatter (I get a better fit at E3) – but the heads in the harbour entrance area need to be higher to maintain the calibration…so the flow field is essentially flattened out.

The alternative calibration has proved a bit of a headache in that Seawat became very unstable and I needed to reduce the MT3D time stepping quite a bit… The outcome may be a better calibrated model, but the scenario modelling indicates the same order of magnitude cross aquifer contamination. Perhaps it has been a worthwhile exercise?

I realise the issue of parameter non uniqueness and uncertainty – GNS will be attempting to address this and also attempting to calibrate the lower Waiwhetu aquifer concentrations…Matt is working out the methodology as the Seawat approach using the regional model is looking to be untenable due to run times.

The modelled thickness of the UWA is shown in Figure 7.7. It thins in the offshore direction and is around 10 m thick in the vicinity of the E8 well. Figure 7.13 shows that the Kh values in the UWA are zoned to reduce in the offshore direction. A Kh at the lower end of the range is used for the offshore UWA to induce larger drawdowns under extraction. It is worth noting that this approach will also alter offshore flow and reduce the offshore extent of fresh groundwater in the aquifer, as detailed above. Note that the caption in Figure 7.13 refers to zone 2 and this should probably be zone 3.

Agree with you here also. GNS will be doing work around the sensitivity of the model predictions to the aquitard parameters.

Storage and porosity values applied in HAM4 follow those used in HAM3, except that a low porosity value was applied in the offshore layers to maximise advective dispersion within the solute transport model. It should be noted that this will alter the velocity values offshore i.e., increase them. It will also reduce the solute mass within the SEAWAT model. It would perhaps have been better to carry out a sensitivity analysis with varying dispersivity values, as part of the SEAWAT modelling.

I have now used a porosity of 0.2 for all my model runs… again I defer to Matt around sensitivity of porosity and dispersivity – but I have dome some manipulation of dispersivity during the calibration and some sensitivity testing during one of the scenarios (3).

The HAM4 model is characterised in the report as an 'aquifer simulator' of high complexity which is required to have a Class 3 confidence level (Barnett et al. 2012) to meet its prediction-focused purpose. While the onshore portion of HAM4 (which is essentially the same as HAM3) may fall within this category of confidence, it would be better to characterise the offshore portion of HAM4 as having a Class 1 to Class 2 confidence level given the few existing wells from which to obtain reliable groundwater and geological information, as well as the limited observations and measurements in the offshore domain. While it may not be common practice to designate portions of models as having different confidence level classes, there is a need here to explicitly acknowledge that the offshore portion of HAM4 has a different level of confidence to that of the onshore portion.

I entirely agree with you here and have modified my text to reflect this (7.7.1)

Saltwater intrusion problems involve both solute transport and variable density flow. Modelling variable-density groundwater flow can be challenging because the groundwater flow equation and the advective dispersion equation are coupled through the groundwater density, and have to be solved within the same simulation. This poses additional challenges to the modelling process, in particular a potentially large increase in computational burden, which may impose restrictions on model calibration and sensitivity analyses. This is, presumably, the reason for not using the SEAWAT model during the calibration phase of this project. However, as noted above, the calibration was a reasonably simple manual calibration involving the varying of Kv. It would be good to provide a brief justification for why the flow model and not the SEAWAT model was used for the calibration process. It is worth noting that there may have been benefits from using the SEAWAT model during calibration in terms of gaining insights into the emplacement and extent of observed groundwater salinity concentrations in the UWA and LWA.

My original modelling presented in the draft report did not attempt to calibrate the seawat model to observed concentrations, principally then because of difficulties experienced in obtaining reasonably run times during the equilibrium run. However, I have manged to get a more stable version running and calibration at least to the upper Waiwhetu Aquifer has been achieved. This is now documented in the report. However, I have had no success in simultaneously calibrated to the brackish water in the lower Waiwhetu Aquifer at E8. My feeling through working with the model is that the high salinity is probably due to dispersion/diffusion in a very heterogeneous system – the very flat hydraulic gradients possible mean that the system is very sensitive to small changes in these parameters. The closeness of the two aquifers (LWA and UWA) means that the two qualities may co-exist in a state of quite fragile equilibrium?? My concern is that by pumping the upper, this equilibrium is upset … I guess my scenarios are indicating this risk. I have tried to bring this point out in the report.

The SEAWAT settings are described in section 7.10.3. The uncoupled flow and transport mode was selected. This means that the flow field is affected only by the user specified density *array and not the solute concentrations calculated by the model (Langevin, 2003). This is in contrast to the coupled flow and transport mode, where the flow field is affected by the fluid density array that results from the modelled solute concentrations. The latter can involve longer run times but is the more accurate of the two approaches. What was the reason for selecting the uncoupled flow and transport mode?*

The early model runs were proving difficult and the coupling was turned off. It is now back on and all simulations presented use an implicitly coupled mode in Seawat.

Please provide additional details in relation to the parameters used for dispersivity (longitudinal, horizontal and transverse). From this, the Peclet number (i.e., the ratio of the cell size to the dispersivity) can be calculated. A value less than 4 is recommended to reduce numerical instabilities, although values as large as 10 have been shown to work by some authors (Barnett et al., 2012). Also, what Courant number was used? The Courant number is the ratio of the product of the advective flow velocity and the time step, divided by the grid cell size. The Courant number needs to be less than or equal to unity, which basically states that during a given time step, a solute particle can traverse not more than a single model cell (Barnett et al., 2012).

Dispersivity parameters are now documented (7.8.3). Peclet no was initially is 5 for the main model calibration, then increased to 10 (model cell size being 100m / long. Disp = 20 then 10m for calibration).

Why is diffusion not considered to be important within the system? Diffusion can be an important mechanism in aquitards, especially over longer time periods and hence may be important within the baseline equilibrium simulation.

Diffusion has been added and initially set at 1e-4 and later decreased to 1 e-5. It doesn't seem to make a significant different to the modelled concentrations….dispersivity really dominating.

Please comment on whether the grid size is expected to have a significant impact on the movement of solute in the simulations.

I have not done any sensitivity testing on the grid cell size – the 100m spacing I would imagine is very fine for a regional scale model?

The concentration boundaries are set as constant, whereby the concentration of the boundary cells representing the contact with the ocean are fixed. An alternative (and more accurate) approach is to set the concentration boundaries up such that seawater flows into the model at the boundary and groundwater of the ambient concentration flows out at the boundary. Using this approach, seawater inflow to the aquifer causes the coastal boundary cells to approach seawater concentration, whereas groundwater discharge generally causes boundary salinities to fall. However, given that the uncoupled flow and transport mode was selected, it is likely that the choice of concentration boundaries will not have a significant impact on the model results because the flow field is not affected by solute concentrations calculated within the model

I agree with you here, at this stage this may be a refinement that could be considered in future.

The refining of layers for some of the modelling scenarios is confusing and if there was little difference in the results it seems strange that the results for the refined model were presented.

Sorry about this, the modelling was an evolutionary process. The version used now is the 14 layer one for all simulations.

As detailed in section 7.10.4, a baseline equilibrium simulation was run using constant stresses and average recharge conditions for a period of 5000 years to obtain a steady state head and concentration distribution. It would be good to briefly detail how average recharge conditions were determined. How long did it take to reach a steady state head and concentration distribution within this model? A plot showing the change in heads and concentration during this simulation period at selected sites would be interesting. It is worth noting that the system will have undergone changes in sea levels associated with glacial periods (sea levels were 120 m lower than today around 19,000 years ago, for example) and this is likely to have a significant influence on the position of the freshwater saltwater *interface. It might also have a bearing on the emplacement of the higher salinity groundwater in the LWA.*

Average recharge conditions were simply derived from the long term hydrographs to represent a mean condition in the system. The time that it took to reach steady state conditions is now documented in the report (figs 7.31/32). As it seems to take a relatively short period of time to equilibrate (400 yrs or so) long term sea level changes are possibly not an issue. The sea has only been in the harbour about 10,000 yrs (since the end of the last glaciation – Waiwhetu gravels are terrestrial).

The report correctly points out that the SEAWAT model has important limitations in terms of not being able to accurately simulating salinity concentrations due to uncertainties and assumptions inherent in the model. Rather, the model is useful for developing intuition about saline intrusion pathways and trends which could contribute to the risk of saline intrusion. It is good that this limitation is identified and it should be made clear throughout the document. In this regard, ***the model is not suitable for determining a sustainable yield from the UWA at E8, as proposed within section 7.12.3. This should be recognised and the wording modified to reflect the confidence level class (1 or 2) in the offshore section of the HAM4 model and SEAWAT model.***

I entirely agree with this comment – I have tried to reflect the uncertainty and limitations of the modelling more clearly throughout.

As discussed above, one of the most important assumptions with regard to seawater intrusion risk is likely to be related to the heterogeneity of the offshore aquifer materials, especially the aquitards overlying and below the Upper Waiwhetu aquifer. Presently, the model reflects an assumption of limited heterogeneity in the offshore aquifer hydraulic parameters. A more detailed sensitivity and uncertainty analysis is needed to better understand the potential risk of saline intrusion into the UPA in the vicinity of the E8 bore under increased heterogeneity. In general, limited sensitivity and uncertainty analysis has been carried out. This need has been is recognised within the report and I understand that a formal uncertainty analysis has started. This has the potential to improve the understanding of the range of uncertainty *inherent in the model predictions. Will this uncertainty analysis use the flow model or the SEAWAT model?*

Matt at GNS has begun work on the uncertainty analysis but I believe is working out an appropriate methodology using a more localised model – he originally intended to use the regional seawat model but is needing to re-think due to the long run times and fragile stability.

The report concludes that there is a risk of seawater intrusion at the harbour heads, at the eastern side of the harbour and through spring backflow, but that these risks can be managed through controlling extraction rates. A pumping rate is proposed (10 ML/d) that is thought likely to lessen the risk of seawater intrusion via these mechanisms. While the scenario modelling does show that this volume of extraction does not induce simulated drawdowns such that seawater intrusion occurs via springs and in the eastern part of the harbour, the confidence classification of the model in the offshore portion of the aquifer is not high enough to warrant any conclusions regarding potentially safe extraction volumes.

Agree with this – I have tried to frame the modelling insights around provision yield estimates with provisos that they may go up or down depending upon further analysis and field testing (if these happen).

4. References

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