Independent review of Aqualinc's Ruataniwha Groundwater model used in support of tranche 2 takes.

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DOCUMENT ACCEPTANCE

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EXECUTIVE SUMMARY

I have been contracted by Aqualinc Research Limited to provide a high-level independent review of their Ruataniwha Basin modelling in support of the proposed Tranches 2 groundwater takes and river augmentation schemes. My review takes into consideration the revised report dated 19-5-2022, the data that has been supplied in response to the first three PDP reviews and considers the points raised in PDP's fourth review.

The model reports stated purpose is to test the hydraulic response of the groundwater and surface water system in the basin from multiple proposed tranche 2 groundwater take applications. Overall, the Aqualinc model seems to conform to the norms of good modelling practice and appears to be fit to assess the direction and magnitude of effects at the groundwater and surface water sites included in calibration. This is in general agreement with the PDP review findings. Further, the model can likely provide a useful indication of the average scale and direction of changes that could occur inside the basin as a result of the proposed takes. However, as noted by previous reviewers, less confidence can be given to prediction sites not included in the calibration. PDP have several reservations about the use of the model, some of which I share. However, in the absence of a viable alternative Aqualinc's model seems to be the most useful tool to assess the proposed takes. Uncertainty analysis included in the final report version has addressed some of the concerns raised that were previously unresolved.

1. INTRODUCTION

My name is Patrick Durney. I am a modelling scientist with Lincoln Agritech Ltd. I have been asked by Aqualinc Research Limited to provide an independent review of their Ruataniwha Basin groundwater model in the context of industry-standard practice and provide commentary on its suitability to assess the magnitude and direction of probable effects of the proposed Tranche 2 takes on the groundwater and surface water resources.

As my area of expertise is hydrogeology and modelling I have limited my review solely to what can be reasonably expected from a numerical groundwater model. As such, I do not provide commentary on areas beyond my specialisation (e.g. possible ecological effects). Nor do I provide commentary on the appropriateness of the technical aspects of previous hearing decisions such as water allocation volumes and reliabilities. My review takes into consideration the latest iteration of the report dated 19-May 2022, data that has been supplied in response to the first three PDP reviews and considers the points raised in their fourth. I have focused my commentary on the performance of the model relative to the surface water resource as this appears to be the most important consideration for the proposed takes.

I have broken my review into the following sections:

1. Model overview and structure appropriateness
2. Calibration
3. Applicability of the model to the task at hand
4. Have the previous reviewers' comments been adequately addressed
5. Limitations
6. Suggestions and recommendations

In terms of my professional background:

I have a Master of Water Resource Management from Canterbury University (2020), and Post Grad Diploma of Engineering Geology University of Canterbury (2007) and a Bachelor of Science in Geology from the University of Canterbury (2005). I am a member of the International Association of Hydrogeologists, a member of the New Zealand Hydrological Society and I am a member of the New Zealand Institute of Management and Leadership.

Before joining Lincoln Agritech in 2019, I have practised as a hydrogeologist in a range of organisations for over 12 years. From 2007 to 2009 I worked as an engineering geologist for Beca Infrastructure Ltd, conducting site investigations and running field monitoring programmes. From 2009 to 2018 I worked for the Environment Canterbury as a groundwater scientist, focusing on surface water and groundwater interaction studies and their numerical modelling, including numerous studies looking at the effects of groundwater abstraction on stream flows. From 2018 to 2019 I worked for the Danish Hydraulic Institute (DHI) as a surface water and groundwater modeller focused on integrated catchment modelling and wetland restoration.

In my role at Lincoln Agritech, I am responsible for modelling both surface water and groundwater resources. My area of focus is on the modelling of surface water and groundwater interaction. I am presently working on two MBIE funded research programmes: Subsurface Processes in Braided Rivers and the Critical Pathways Programme.

My research interests include groundwater recharge, surface water-groundwater interaction, statistical hydrology and managed aquifer recharge for environmental remediation.

2. MODEL OVERVIEW

The stated purpose of the model is to describe and assess the magnitude of the effects the proposed tranche 2 takes on the groundwater and surface water resources of the Ruataniwha Basin. Specifically, the model's scope is to test the hydraulic response of the groundwater and surface water system in the basin from multiple proposed tranche 2 groundwater take applications. To do this, the model needs to adequately capture the main physical characteristics of the study area at an appropriate scale and resolution, both physical and temporal. This means the model needs to be able to assess the impact of groundwater abstraction on both groundwater levels and surface flows including the temporal dynamics of these effects. Further, the model needs to represent surface water in a way that enables augmentation to be explicitly modelled.

2.1 Grid and model domain

Aqualinc's model has been developed using a uniform 200m by 200m grid. Given the area covered by the model (~683 km^2), this seems reasonable. Ten numerical layers have been adopted from the land surface to a maximum of 400 below the surface, the maximum depth was defined by the presence of underlying layers of porous and permeable rock formations. The layers vary from 10 m to 40 m thick and have not been modified from the original model (documented in Weir, 2013). Given the grid resolution and the number of layers seems reasonable (the model has a total of 170,778 active cells) for a regional scale model.

The ability to assess an individual wells stream depletion effects on a specific stream is more limited with a uniform grid of 200m x 200m, than with a simpler analytical equation. This is because the effects modelled are at the resolution of the model, e.g. averaged over each grid cell. In the case of the Aqualinc model, the resolution essentially means that the minimum distance to the river is 200 m (assuming the well is not in the same cell as the river, in which case there is zero distance). Advances in the more recent formulations of MODFLOW allow local refinement around streams of interest and will provide more accurate results than can be achieved with regular grids. Adoption of these more recent formulations is still limited in the industry. The adoption of refinement around the streams would provide additional confidence in the ability to assess localised stream depletion. A finer grid resolution would also provide increased confidence for assessing the direct drawdown effects of individual pumping wells. An alternative pragmatic solution to what's adopted with the present model may have been to reduce the number of computation layers and refine the model grid resolution. However, to describe the combined pumping effects of the proposed takes on the water resource as a whole, the use of the current regular grid is reasonable.

2.2 Rivers

Seventeen rivers are explicitly modelled using the SFR2 package. SFR2 is the most advanced package to explicitly represent surface water in the standard MODFLOW-NWT package and will give the best representation of surface flows without using a dedicated surface water model. The benefits of SFR2 come at the cost of requiring more information than alternative representations of surface flows and increased computational burden. Given the emphasis on assessing the effects of groundwater pumping and augmentation of stream flows the use of SFR2 is justified.

The streams have been modelled using a combination of surveyed cross-sections and estimated cross-sections and follow accepted practice for surface water model representation in groundwater models. Inflows have been specified either using actual observations or estimated using rainfall run-off modelling. Topographic maps suggest a number of additional waterways may be present in the study area. Given that little or no data is available for these and that the majority appear to be intermittently flowing streams it is not unreasonable to not explicitly model them. Without observation data for these streams or inflow data to populate the model with they would likely add little to the model other than further complexity and uncertainty. Aqualinc has used estimated head changes in these areas as a proxy for the scale of effects, however, without explicit representation in the model little can be said of the effects other than that flows are likely to be slightly higher or lower.

2.3 Additional boundary conditions

Aqualinc's Irricalc model was used to estimate values for the land surface recharge boundary. Irricalc is a widely used and documented tool and is appropriate for the model use. The choice of additional boundary conditions (e.g. general head) does not seem to have influenced the mass balances and hence model performance and it is likely they are not needed in the model.

2.4 Simulation period and timesteps

The model is run as a daily timestep transient simulation from 1972 to 2012. The daily timesteps are appropriate for assessing the temporal variations in possible effects of the proposed takes. The simulation period enables a range of climatic conditions to be considered. Ideally, the model would be updated to include the last decades' climate forcing and observation data, however, the justifications provided in the model report and review comment responses appear valid. Overall the simulation period and time stepping seem appropriate for the scenario comparisons the model has been used for.

3. MODEL OPTIMISATION

Model optimisation, often referred to as calibration, generally refers to the process of adjusting model parameters such that model simulated results approximately match field observations. This process may be undertaken manually, using automated approaches or a combination of both. With transient models the usual approach is to attempt history matching of observation time periods, hoping to capture the seasonal effects at both the local and regional scale. Where land-use changes occur during the simulation period these must be included in the simulations. In the New Zealand context, these changes are normally poorly documented making such calibration difficult.

The optimisation approach Aqualinc has taken is somewhat unusual in that they have not attempted continuous history matching across their simulation period. Instead, they have optimised to non-irrigated conditions using winter observation data and also optimised to current full abstraction conditions using the pumping season data. However, as understood from the model report the data around historic irrigation use and areas is unavailable, thus the approach taken is appropriate and preferable to synthesising historic data. While it does not allow full history matching to observation data trends it does provide a reasonable bookend to the range of effects expected from current irrigation practices and provides a reasonable baseline for scenario assessments.

Aqualinc's optimisation used a combination of manual and automated approaches. Hydraulic conductivities and streambed conductance were optimised using PEST, while specific storage has been optimised manually to minimise the computational burden.

3.1 Observation data used in optimisation

The model has used 72 groundwater level observation locations for optimisation. Based on the spatial distribution of these observations, Aqualinc appears to have adopted a reasonable model domain and structure. Optimisation to these sites has been undertaken automatically in steady-state and manually for transient conditions.

Surface water optimisation used five sites including observation data at Tukituki River at Tapairu Road, Waipawa River at RDS/SH2, Mangaonuku River (upstream of the Waipawa confluence) and for the Tukipo River at both SH50 and Ashcott Road. Technically the first two sites are outside the model domain, but given they are located at the terminus of their associated gorges, here limited losses or inputs can be expected, and their use as calibration targets in the model seems reasonable. The periods of optimisation data available are limited and ideally, more continuous data would be available for use in optimisation.

The latter three surface water sites were not used in the original optimisation and were added following review by PDP, with some optimisation subsequently applied. The optimisation to the observation data seems reasonable. Predictions outside optimisation areas are usually less reliable than at sites used in optimisation. Uncertainty analysis has been used to investigate the model's predictive ability in these areas and is discussed later in this document.

3.2 Gaining and losing reaches

PDP's reviews identified that a number of concurrent gaugings have historically been conducted that enable gaining and losing reaches to be identified. PDP suggest that the gaining and losing reaches should be a calibration target. Aqualinc has responded to PDP's suggestions in a memo and also by the inclusion of a new report section comparing the patterns of gains and losses and the approximate gauged loses and gains.

In general, depending on how it is implemented, I agree that gains and losses should be part of the calibration. A pragmatic way to implement this would be to include the gauged flows as part of the calibration objective function. If too little data is available, as may be the case in this instance the approximate gains and losses over a given reach may be included as prior information for PEST regularisation.

3.3 Model parameters

Horizontal and vertical conductivities along with streambed conductance are the main parameters used for automated calibration. Industry-standard pilot point PEST has been used for the steady-state calibration.

Hydraulic conductivities have been constrained in the areas adjacent to aquifer tests and the range of estimated values seems reasonable. Hydraulic conductivities are varied using two groups, one for layer 1, and one for the remaining layers. The second group covers all layers below layer one (2 to 10), the justification for repeating hydraulic conductivities for these layers is the lack of available data. Given the available observation data, this does not appear to have negatively affected the calibration.

Uniform streambed conductivities were assigned for each reach (one unique conductivity for each stream reach) and varied during calibration to fit observation data. The streambed conductance's in each SFR2 boundary cell are calculated from stream width, thickness and wetted perimeter and streambed conductivity. While the streambed conductivities are low, the sensitivity analysis undertaken suggests this to be necessary for the model to fit with observation data.

Specific storage has been calibrated using manually adjusted pilot points.

3.4 Model performance

In terms of fit to observations, as with all catchment-scale models, there are a number of over and under fits to observations and some sites where local scale effects are not predicted exceptionally well. This is not unreasonable for a model of this scale and the model does not appear to be excessively biased (i.e. not always over or under predicting). Local-scale effects of pumping that are evident in some of the HBRC observation records cannot be accurately simulated by the model. This is because abstraction is averaged across the 200m by 200m grid, which has an effect of underestimating local-scale drawdown in the model. The proposed activities would take from deeper groundwater, which will have a muted effect at the surface. It therefore seems a more important modelling objective to simulate broader-scale seasonal fluctuations than individual stream depletion impacts. The model optimisation seems to do this adequately.

Despite the limited surface water flow data available for model optimisation, what data is available seems to have enabled a reasonable fit to mean and low flow statistics. This suggests that the scale and direction of effects of the proposed takes on the calibrated sites can be assessed with confidence. If further work were to be undertaken with the model, it would be good to include some common surface water calibration metrics such as Nash Sutcliff efficiency and or percent bias in the documentation. These metrics would provide additional information on how the calibrated model fits using industry-standard guidance for model performance.

In general, the model performs well compared to the spatial patterns of observed gains and losses, especially given they were not included in calibration. However, there is a bias in the results showing consistent under prediction of both losses and gains this may suggest that river exchanges are not as dynamic in the model as they should be.

3.5 Assessment of uncertainty

As has been noted by the PDP reviews, calibration has not been undertaken for all the modelled streams, this is due to a lack of available data. As PDP notes, this will likely affect the uncertainty in predictions at these sites. To address this Aqualinc have added a new section in the revised report directly addressing uncertainty.

Uncertainty is caused by the inherent limitations in all modelling approaches, such as imperfect knowledge of hydrological conditions and correct model structure. Optimisation performance is defined by a statistical measure called an objective function, that is the summed result of model mismatch to observational targets and there can be many possible combinations of residuals that produce the same objective function value. Observation weighting, used to consider observation importance, can further compound this by scaling the objective function values. In effect, the summed nature of the optimisation statistical measure can lead to many equally plausible hydraulic conductivity fields and parameter sets that result in the same (or similar) objective function value, and which will all lead to slightly different predicted values.

Aqualinc has undertaken linear uncertainty analysis on groundwater levels and mean flows at five stream locations using the steady-state version of their model. Further they have investigated predictive uncertainty on the other modelled streams.

Aqualinc have assumed that parameter standard deviations are 20% for sites with aquifer tests and 50% for those without. As would normally be expected, the outputs, show that the predictive uncertainty of groundwater levels and flows is reduced by the calibration process. In general, the uncertainty analysis provides confidence in the estimated groundwater levels and flows at the observation sites.

Overall, uncertainty in predicted flows is greater than that for groundwater levels. This is partially reflective of the fact that the observed flows include more uncertainty (captured in the objective function weighting) than groundwater levels. Generally, the modelled one standard deviation predictive error in mean flow is less than 2%. Aqualinc have assumed the absolute flow uncertainty (under average conditions) equally applies to the low flow conditions, suggesting that there is 6% to 13% uncertainty in modelled low flow at the five sites.

Not surprisingly, less confidence can be given for streams without observation data. In terms of reduction in uncertainty post-calibration, there is only a slight reduction for the uncalibrated streams. This is perhaps reflective of the choice of standard deviations applied to the simulated parameters. It is possible, that the uncertainties in flow for the uncalibrated streams may be reduced by directly calibrating against gains and losses, but this is still unknown. While the standard deviation in modelled mean flows at the additional sites is low, on the order of several hundred litres per second, it would be good to understand how this relates to the absolute flows predicted. Inclusion of the modelled flows alongside the standard deviations in Table 5 of the report would address this point.

The assessment of the various parameter group contributions to predictive uncertainty has also been provided. On average, streambed conductivity accounts for about 25% (0-77%) of the post-calibration flow predictive uncertainty for the streams, the rest being accounted for by hydraulic conductivity of the aquifer.

The uncertainty assessment has not been extended to the model scenarios. While the linear uncertainty analysis included in Aqualinc's reporting assesses the uncertainty in optimised model performance, assessing the predictive uncertainty between scenarios would require an alternative approach. This could take the form of Monte Carlo simulations, where each scenario is tested against the equally (statistically) well performing model optimisation. However, this comes at considerable time and computational cost.

4. PRACTICAL APPLICATION - ABILITY TO PREDICT THE EFFECTS OF PROPOSED TRANCHE 2 TAKES AND AUGMENTATION

There are always limitations on time and budget that affect what can be expected from model outputs. Given this, the model as built appears to provide a reasonable and pragmatic approach to assessing the impacts of the proposed abstraction and augmentation. Further, the model construction and use appear to be in line with industry-standard approaches.

As stated in the Aqualinc report, the model is unable to precisely give the explicit flows and groundwater levels expected after the proposed abstractions and augmentations. To be useful, the model has been used to look at relative changes between scenarios rather than actual predicted flows. Comparing relative changes removes some of the need to consider model errors (i.e. imperfect head or flow matching). In taking this approach, the simulated changes can be assessed as a departure from a baseline (i.e. the actual observations). The model appears to be fit for achieving this purpose. The use of the model to look at the direction and magnitude of change is reasonable, and is one of the standard approaches used with numerical models to assess the impacts of management scenarios.

Lack of calibration data on the additional streams modelled means there is less ability to address the scale of effects that may be observed on them from the additional abstraction. If the uncertainty analysis for the five surface water calibration sites hold for the remaining streams, this suggests that the expected changes from the proposed takes are likely to be less than the uncertainty in predicted flows. Again, suggesting the model is best used to look at relative change and not the actual predicted flows.

Impacts of the proposed abstraction on streams, and/or possible wetlands, not explicitly modelled are even harder to assess with the existing model. The direction of effects may be ascertained and the scale estimated but exact effects will remain unknown.

4.1 What can the model be used for?

Based on the modelling report and supplementary evidence it appears that the model can provide a reasonable assessment of the scale and direction of changes caused by the additional deep extraction from the proposed Tranche 2 takes. The model also seems to be fit to assess the probable effects of augmentation on streamflow at the main surface water monitoring locations. It seems to be fit to look at the direction of change on the other modelled streams.

The model appears to be fit to assess the approximate magnitude of effects on groundwater head elevation at the resolution of the model. This is to say the model can be used to predict changes in seasonal groundwater levels at 200m by 200m resolution.

5. PREVIOUS REVIEWS AND MODEL LIMITATIONS

As with all studies, there are limitations to what can be gleaned from the model. The PDP and council reviews have highlighted several limitations, many of which are either addressed in the revised report or Aqualinc's prior review responses. Of those remaining that are inside my areas of specialisation, the following are those which seem the principal outstanding limitations at this time:

1. While the model as built appears to provide a reasonable approach to assessing the direction and magnitude of effects, it probably doesn't estimate the maximum possible effects. It is probably best at predicting the average scale of effects on neighbouring bores and streams. If the desire is to investigate the maximum possible well interference or stream depletion, an approach similar to Environment Canterbury's well interference tool may be more appropriate for well interference. While perhaps something analogous to the Hunt analytical solutions (Hunt, 1999) would be suitable for stream depletion. It should be noted that both these alternate approaches likely reflect worst-case scenarios (depending on parameters used) which are less likely to occur in reality. Similar well interference approaches have already been undertaken in Aqualinc's 3'rd review response (Table 1 and Appendix D). These assessments show that using similar parameters, the numerical model generally predicts interference comparable to the equivalent analytical solution, occasionally predicting greater interference.
2. As noted by PDP, there are a number of streams mapped in the catchment that have not been explicitly calibrated against and perhaps several more that are not modelled.
    a. For those that are not calibrated against, there will always be more uncertainty in predicted changes. The linear uncertainty analysis has helped in this regard, but it does not quantify the absolute range of expected changes for each stream. However, this does not preclude the use of results for relative change.
    b. For streams and/or wetlands not included in the model, it is not possible to assess the actual quantum of effects of the proposed changes at these locations. As stated in the report groundwater levels are likely to be lower in these areas, therefore logically if the streams are in connection with the groundwater table, they are likely to be negatively impacted. However, the exact magnitude and extent of change cannot be qualified with the existing model structure. A conservative way to assess the effects of the proposed takes could be to consider all wetlands as depressional springs. Then it could be assumed changes in groundwater levels directly propagate through to changes in water levels in the wetland.
3. As evidenced by the transient model calibration, the model cannot assess the precise effects at all individual monitoring well locations, as a result of the grid resolution. However, an estimate of the relative change is achievable.
4. As PDP notes, the regarding stream flow, the model tends to under predict losses and gains. The inclusion of gauged flows or patterns of gains and losses during calibration could possibly improve these results.
5. PDP's reviews note that streambed conductance values used in the model are low and they suggest a comparison with, or direct calibration to, previously derived estimates, where available. It is important to note that the model streambed conductance values are lumped compensatory values (i.e. they compensate for imperfect knowledge) and are not directly comparable to prior estimates. Therefore, while interesting for comparison, any such prior estimates are unlikely to match those estimated by the optimised model. If it was desirable to include these prior estimates directly in the model optimisation, they should be included as prior preferred values in model regularisation.
6. The model in its present form is unable to investigate predictive uncertainty in the relative change scenarios. In their assessment of effects, Aqualinc compares relative change between scenarios. As already noted, comparing relative changes eliminates simulated to observed mismatch from consideration and permits the simulated changes to be compared to actual observations. However, it does not address predictive uncertainty, where the prediction is the relative change. As indicated in the discussion on uncertainty, to do so requires an alternative and computationally burdensome approach, not generally feasible in commercial projects.

6. RECOMMENDATIONS

If it is intended to continue the development of the model. The following points may benefit from consideration.

6.1 Optimisation

1. Fully automate optimisation to a short time period that covers HBRC gauged flow data and include it explicitly in the calibration metrics.
2. Add the gauged gains and loss patterns as prior knowledge in model regularisation.

6.2 Uncertainty analysis

Perform additional uncertainty analysis on the transient model to provide greater insight into the predictive uncertainty of a model. This would enable the standard deviation in predicted mean annual low flow at key sights to be directly assessed.

7. CONCLUSION

Overall, the Aqualinc model appears to do an acceptable job of representing the catchment water balance, groundwater heads and surface flows at the discharge points. The model structure, inputs and optimisation generally adhere to industry standards. There are a number of limitations regarding the model's ability to predict flows inside the domain, largely due to the lack of available calibration data. These limitations have previously been identified by the PDP reviews. While many limitations have been successfully addressed by Aqualinc's responses some issues remain. Recent uncertainty analysis goes some way to quantifying the effect of these limitations, and clearly shows that model optimisation has reduced the overall uncertainty. Despite the limitations identified in this review, the model can probably be used to successfully investigate the relative changes anticipated from the proposed abstraction and augmentation, especially at the regional scale. The Aqualinc model appears to be useful, and in the absence of a viable and agreed alternative it is probably the best tool for the job.

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