To:	Catherine Moore
From:	Pawel Rakowski
Date:	14/12/2018
Subject:	**Stochastic source protection zone delineation in Heretaunga Aquifer using a numerical groundwater model** **Description of methodology, and results for Hastings District Council municipal bores.**
File Ref:	**5067**
Cc:	Jeff Smith

Contents

HAWKE'S BAY REGIONAL COUNCIL

1 Introduction

This short report provides documentation of stochastic source protection zone (SPZ) delineation in the Heretaunga Aquifer using a numerical groundwater model. Results generated for Hastings District Council municipal drinking water supply bores are reported here as a case study.

The purpose of this work was to provide an alternative to SPZs delineated by Tonkin and Taylor (T+T) for Hastings District Council (HDC). T+T (Reynolds, 2018) used the well head analytic model (WhAEM) developed by the USEPA, which uses a relatively simple, one-layer homogeneous aquifer for representing groundwater flow to each well. While the simple modelling approach allows for relatively rapid model development and calibration, conservatism is required via sensitivity analysis to account for large predictive uncertainty. A consequence of the conservatism due to the modelling method used by T+T is that an unnecessary compliance burden may be placed upon resource use activities that are within conservatively large SPZs.

Moreau *et al*. (2014) reported that numerical modelling is the most accurate delineation method for SPZs, but that it often requires more resources to develop, compared to a simple analytical element model (AEM). Numerical methods are more appropriate for complex aquifer systems such as the Heretaunga Aquifer, as they can provide a better representation of aquifer variation and dynamics than simpler methods such as AEM. Usually numerical methods require significantly greater effort to implement, due to set up and calibration requirements. However, in this case, a calibrated stochastic numerical model suite was available from previous work and only required minimum modifications to be used in capture zone analysis.

The purpose of this document is to provide an alternative modelling approach to protection zone delineation that is more accurate than the WhAEM approach. The methodology is described, along with limitations of the numerical modelling and recommendations for future work. As this science is advancing and improving over time, a flexible approach to mapping of source protection zones is recommended for the TANK plan change.

2 Methodology

2.1 Basic principles of the method

The method is based on use of a numerical model suite:

- Transient MODFLOW model, (Harbaugh et al., 2005),
- Followed by a MODPATH model (Pollock, 2016),
- Runs undertaken using a stochastic model version, developed during model calibration and uncertainty analysis using PEST (Doherty, 2016).

This method is appropriate for complex aquifer systems as described in GNS "Capture zone guidelines for New Zealand" and subsequent technical report (Moreau et al., 2014a, 2014b).

Similar applications of this method for delineation of capture zones were used elsewhere in New Zealand, for example in Greater Wellington Region (Toews et al., 2015). Toews et al. (2015) provides a fully detailed description of the method, which is not repeated here.

2.2 MODFLOW model set up

Simulations are based on a calibrated groundwater model of the Heretaunga Aquifer (version HPM035) (Rakowski and Knowling, 2018) with model scenario HPM_M3 used as a basis for monthly time steps from 1980 to 2015 (Rakowski, 2018).

This model was modified as follows:

- Simulation time was reduced by limiting runs to 10 years (2005-2015) for transient simulations
- Well boundary conditions were modified by reflecting HDC abstraction scenarios (i.e. previous HDC bores were removed and replaced with new scenario rates applied)
- 4 HDC scenarios were applied, consistent with scenarios used by T+T (Reynolds, 2018) as shown in the Table 1(abstraction rates in L/s)

Table 1: Scenarios and associated abstraction rates (L/s) from Hastings bores

Scenario	1	2	3	4
Eastbourne	501	21	211	191
Wilson	0	0	80	0
Frimley	0	480	210	190
Portsmouth	0	0	0	120

- Pumping rates were distributed evenly between bores within a borefield and kept constant during simulation periods
- Each simulation was modified to save model budget and stress period, and to save all budget components, as required by MODPATH

2.3 MODPATH setup

MODPATH 7 was used with the following settings:

- Backward tracking
- Timeseries analysis
- 9 particles were placed on each face of each cell that contained a scenario pumping well (only HDC wells, with a different set up for each scenario). All wells are in layer 2 of the model.
- Particles were released approximately every 30 days in MODPATH simulations. This allows for tracking particles released during different times (and during different hydraulic conditions in the aquifer). Note that in backward tracking, "release" means a final destination for the particle which is a pumping well. This setup provides for changing flow directions and gradients in the aquifer.
- MODPATH reports time from a "reference" time, set at the end of MODFLOW simulation (June 2015) with time tracked backward. Because particles are released every month, the "time from release" instead of the "time from reference time" had to be calculated during post processing. This allows for tracking how far each particle travels in a given time (e.g. 1 year). This post processing was done in R (R Core Team, 2018).
- MODPATH was set up using the python FloPy package (Bakker et al., 2016)

2.4 Stochastic model runs

Uncertainty analysis was undertaken stochastically using 107 model realisations generated during calibration-constrained Monte Carlo analysis (Knowling et al., 2018). Each of the realisations met the calibration criteria, despite having different parameter values. This includes calibration to water age and nitrate concentration, which constrains porosity parameters. Stochastic MODPATH runs were undertaken using PEST software (Doherty, 2016).

The PEST setup was modified (templates, well and river generation scripts, remove observations, etc.) to undertake this analysis with a new model with 10 year duration. Four versions of model were used as per HDC scenarios described in **Section 2.2**.

For each realisation:

- PARREP PEST utility was run to update parameter values (e.g. aquifer conductivity, storage, etc.)
- PEST was run with noptmax = 0 to run the model one time only
- MODPATH files were generated using FloPy for each given scenario (particle locations) and realisation (porosity values)
- Timeseries results and MODPATH listing files were saved for each run
- This process was automated using a python script to automatically generate appropriate files
- Overall the model had to be run 107 x 4 = 428 times. Each run time is about 2 hours.
- Runs were parallelised by running several individual processes concurrently.

3 Results and discussion

3.1 Results processing

MODPATH timeseries files were saved and read into R to allow for processing. Pathline files and MODFLOW output files (hds and cbb) were not saved due to very large file sizes (1.5, 0 .6 and 3.5 GB respectively)

Timeseries files can be plotted directly as points. However, due to the very large number of points (2 million) this is difficult to present for every scenario and realisation. Instead for each realisation and scenario:

- Timeseries files were converted to spatial points data
- This was converted to a raster, using “rasterize” method from R package “Raster” (Hijmans, 2017). This allows conversion of particle locations to a 100x100m raster, with each raster cell representing minimum time from release
- Timeseries data were filtered to only show particles younger than 365 days
- This filtered data set was rasterised, showing “maximum extent of the 1 year travel time” for given realisation and scenario
- An unfiltered data set (10 year travel time) was also rasterised for visualisation of a conservative 10 year travel time.

This “maximum extent of the 1 year travel time” were mapped to raster with value of 1. Then, rasters for each realisation were added together and divided by the number of realisations. This gives the frequency of occurrence in each raster cell, which is interpreted as probability that flow could originate from this cell during the 1-year period. This can be repeated for any travel time, as required for analysis.

3.2 Conservative assumption for pathogen transport

Following initial discussion with a reviewer (Dr Catherine Moore, GNS Science), additional consideration was given to the appropriateness of the MODPATH method for delineation of source protection zones, especially if the purpose of the zone is to protect against pathogen contamination.

To make this model more conservative and appropriate for pathogen risk assessment, 10-year travel time was also analysed. The justification for this is given below.

MODPATH allows for capture zone delineation for a pumping well for a given maximum travel time such as a 1 year travel time. The size of this capture zone depends predominantly on porosity parameters applied in the model. This parameter was constrained during the process of model calibration and uncertainty analysis, using observed mean groundwater age at the observation bores (Knowling et al., 2018).

A limitation of most regional groundwater flow and contaminant transport models, including the Heretaunga Aquifer model, is that they only allow for simulation of "high yield, slow transport" pathways, but not "low yield, fast transport" pathways. This concept is discussed by Hunt (2017) and is summarised here.

The "high yield, slow transport" pathway refers to a dominant source of water, whilst "low yield, fast transport" pathway refers to a non-dominant source of water. Simulating "high yield, slow transport" is appropriate for solute transport (e.g. nitrates), but pathogen transport can occur via a "low yield, fast transport" pathway. In a gravel aquifer, this process may occur through preferential pathways such as open framework gravels. Even though the contribution of "low yield fast transport" pathway to the pumping well pathway may be very small, it may be significant in terms of risk, because even very small concentrations of pathogens such as viruses may pose a serious health risk.

Detailed modelling of "low yield, fast transport" pathways is currently not possible, due to limitations of aquifer composition data and inability to model these small scale structures. However, this aspect potentially could be modelled stochastically (at smaller scales than covered in by this report).

This limitation of the model means that it is likely to underestimate the extent of one-year pathogen travel time. To add a level of conservativism, the model porosity can be reduced by a prescribed factor. This would result in faster travel times, and thus more extensive capture zones.

It was suggested by the reviewer of this report to reduce porosity by a factor of 10. This would bring the porosity to a level similar to porosity used in the T+T assessment (Reynolds, 2018). Unfortunately when this suggestion was made, the model had already been run in a stochastic mode, with a significant run time (over 1000 processing hours), and there was no time available to repeat these runs. Instead, an alternative was proposed using 10 year travel time instead of 1 year travel time. This has a similar effect as porosity change in the capture zone calculation and doesn't require re-running the model because the correction is applied in post-processing of modelling results.

There is a potential issue with this approach, as the transient run time of the model was 10 years. In the original set-up, particles were released every month for 10 years and only one year travel time was analysed. This meant that most of the released particles had a chance to travel for one full year (except for particles released in the last year). For the 10 year travel time, only the first set of particles released in the first month had a chance to travel for 10 years and the rest can only travel for shorter time. For example, particles released in year 5 of the simulation can only travel for 5 years before the simulation terminates. This means that more particles are used to delineate earlier travel times and the number of particles used for zone delineation declines towards the end of a simulation, potentially leading to an underestimated size of the capture zone. However, assessment of this issue indicated that particle trajectory is not greatly affected by transient effects, so this problem is unlikely to have a large effect on the solution (i.e. size of the capture zone), so the setup is considered acceptable.

3.3 Particle traces per realisation

A capture zone can be delineated for each scenario and each realisation. This results in 428 different maps, which is challenging for presentation.

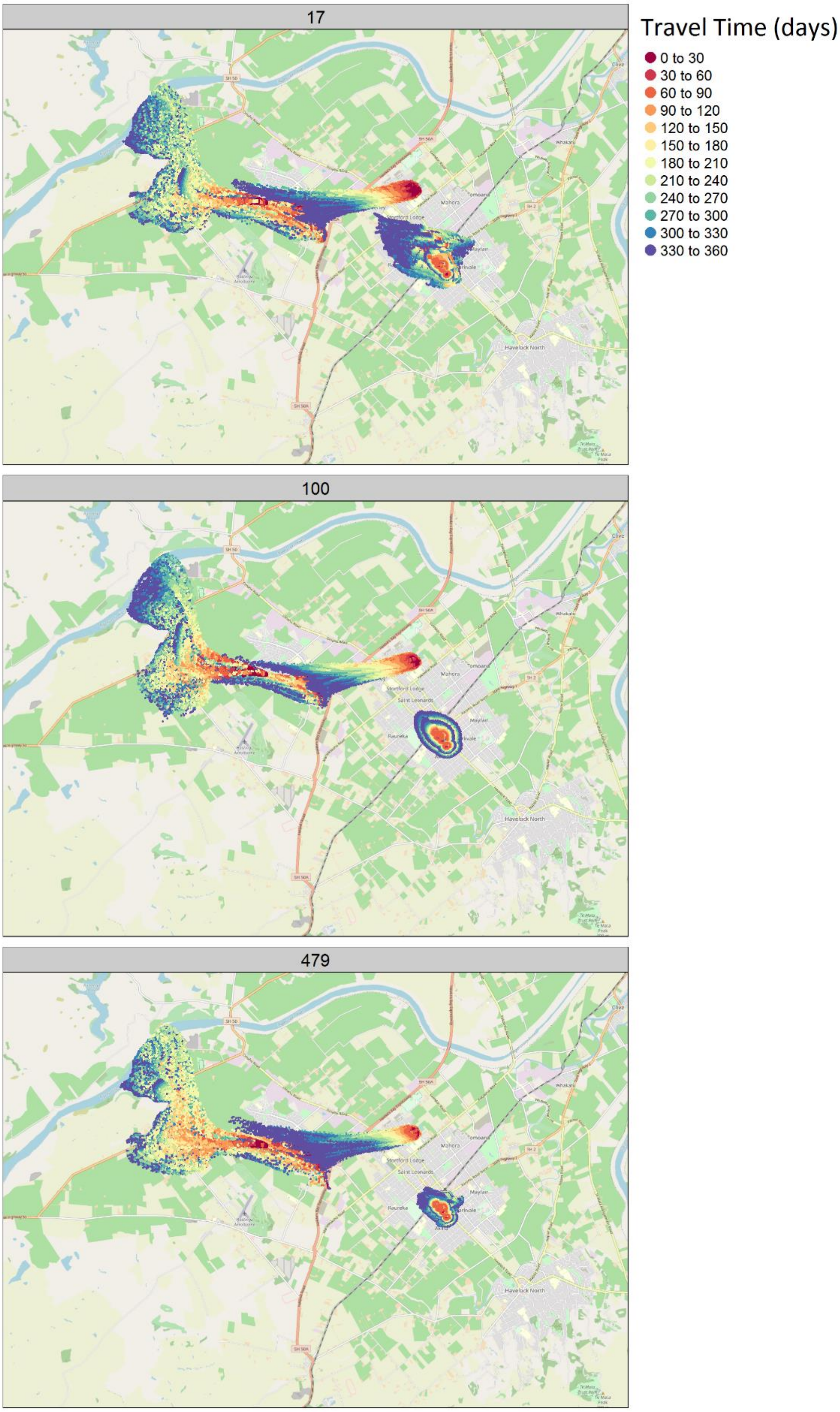

Figure 3-1 presents three selected realisations for all scenarios combined, for one year travel time. Figure 3-1 shows that the extent of one year travel time zone differs significantly between the realisations. Realisation 17 shows that the main cloud of particles is surrounded by a less dense cloud, which extends further. This can be explained by particles originating in layer 2 of the model, which at some point reach layer 1, which in turn causes change in travel velocity.

Additional figures for remaining realisations are presented in an appendix B and C

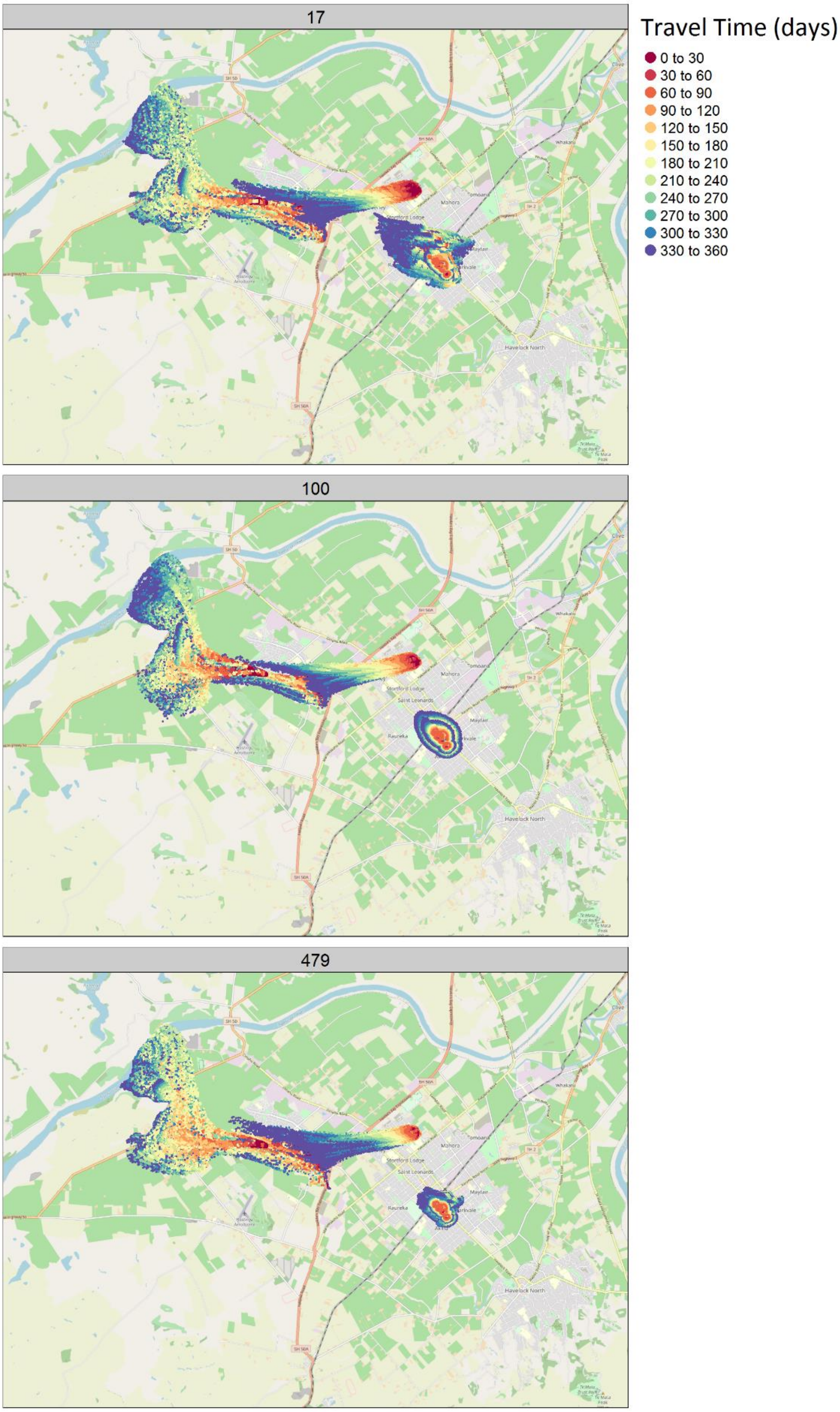

Figure 3-1 One year travel time for selected relations for all scenarios. Colours represent travel time (legend shows the number of days travelled)

3.4 Stochastic results

Probability distribution maps are shown below, for one year and conservative 10 year travel times. Source protection zones developed by T+T are also shown as grey polygons.

Results are presented as probabilities of being in zone 2 (one year travel time) for all model realisations. It is noted from Figure 3-2 that:

- Stochastic zones are wider than zones derived in individual realisations
- When deciding on zones for implementation in planning instruments, decision makers might base this on an agreed statistic, for example 90% probability
- Modelling results indicate that the zone based on one year travel time extends to the losing section of the Ngaruroro River, which has a large upstream catchment and is in connection with the aquifer (the Ngaruroro River loses water to the aquifer). This means that there is potential for any contamination (e.g. animal faeces) in the upper Ngaruroro catchment to be transported with run-off and surface water flow and then enter the aquifer, which can transport it to the drinking water supply within one year. This is especially the case for the Portsmouth and Wilson borefields
- The one year zone also intersects other surface water features, for example Irongate Stream. The Irongate stream normally is spring fed, so water travels from the aquifer to the stream which makes it unlikely to contaminate the aquifer. However, under certain conditions this flow could reverse (e.g. during a flood).
- The 10 year travel time zone is significantly larger than the 1 year zone. The main difference is the extent towards the west. With a 10 year travel time, this zone extends many kilometres west, to the minor losing section of Ngaruroro River. The zone extends beyond the mapped area due to initial set-up of the processing routine, which was focused on the area around Hastings.
- Some of the capture zone falls within the confined and artesian area of the aquifer. Persistent flowing artesian conditions in the aquifer would practically prevent any surface water from entering the aquifer. However, more work is recommended to accurately map the distribution of artesian conditions.

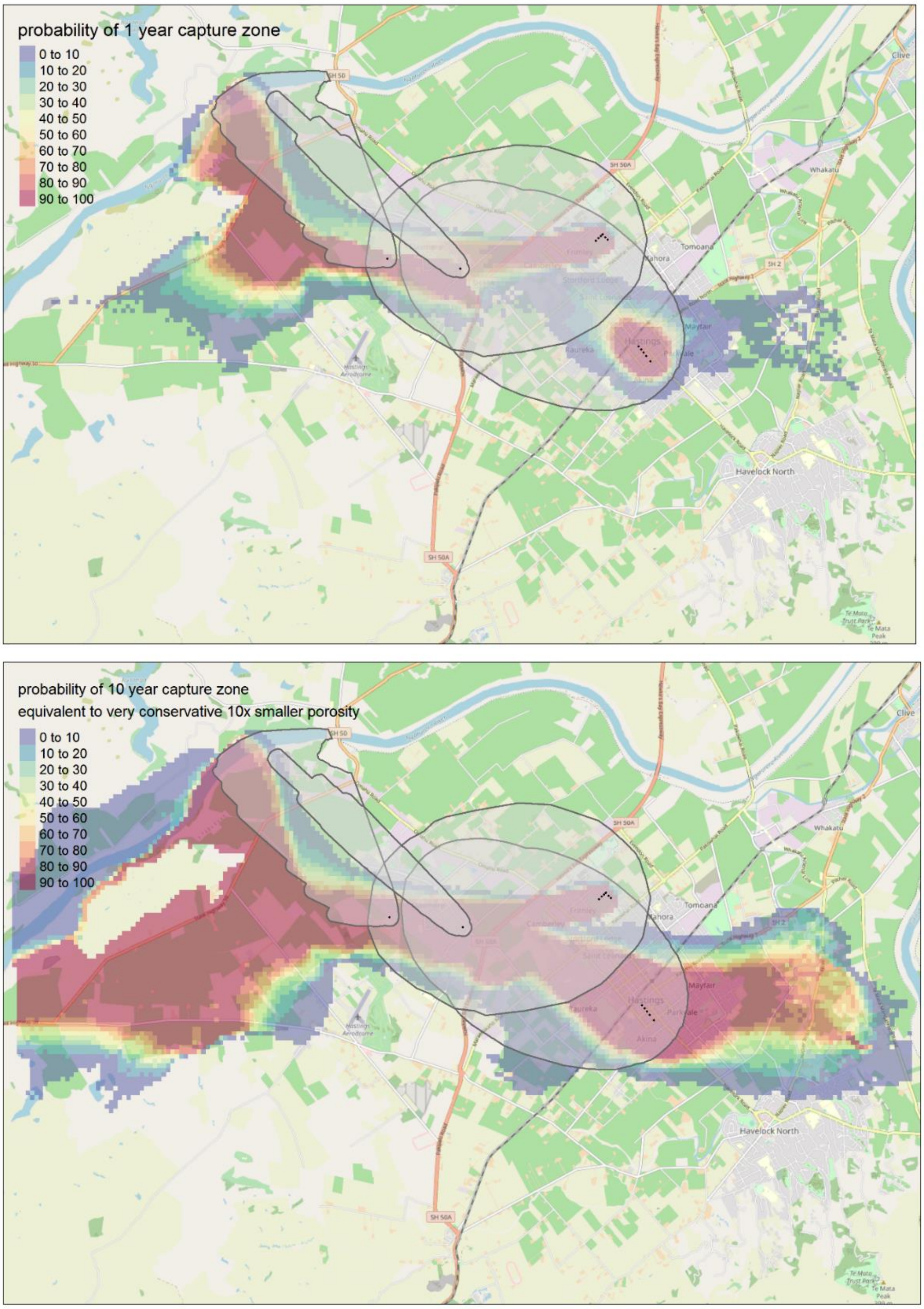

Figure 3-2 Probabilistic capture zones for travel times of one year (top) and 10 years (bottom). Zones with grey shading are those delineated by Reynolds (2018).

3.5 Comparison to Tonkin & Taylor results

These numerical modelling results are different to results reported by Reynolds (2018). This is not unexpected, as the methods used are considerably different. This phenomenon is discussed below.

3.5.1 Flow direction and gradient

The one year travel time zones derived using the numerical model are generally smaller than zones derived by T+T. For example, this is seen between Flaxmere and the Ngaruroro River, where the T+T zone extends in a generally straight line towards the river, whilst the numerically modelled zone initially extends in more westerly direction, and then in more northerly direction, and as a result the numerically modelled zone is located further to the west. There are areas that are covered by the numerically modelled zone, but not by the T+T zone. These areas include land south of Fernhill and west of Flaxmere. Both cases can be explained by the fact that the T+T zone uses only flow direction and gradient in a pumping location, whilst the numerical model uses a complex flow field that is a result of model simulation. Therefore, the numerical model accounts for changes of flow direction and gradient along the particle pathway and the derived zone accounts for this. The numerical model also accounts for impacts of other pumping on groundwater flow such as Napier City Council pumping, which has its own capture zone and impacts the flow field.

3.5.2 Porosity

T+T uses a conservative estimate of porosity of 0.02. Porosity calibrated in a numerical model is highly variable spatially and between realisations. In the area of interest the numerical model mean porosity is 0.1, with quantile range Q10 – Q90 of 0.03 to 0.15, which is higher than assumed by T+T. Higher porosity would result in lower travel velocity and smaller capture zone. The 10 year travel time capture zone is equivalent to using porosity of 0.01, which is even lower than porosity used by T+T and therefore more conservative for delineation of capture zones.

4 Further work

This numerical particle tracking assessment could be further improved by:

- Re-running the assessment with lower porosity instead of longer run time. This would require significant running and re-processing time; or
- Extending the simulation time (e.g. doubling it to 20 years) to allow for release of all particles during the simulation.

In addition, GNS Science is leading a major MBIE funded programme of research (Te Whakaheke o te Wai) to develop methodologies for rapid upscaling and downscaling of groundwater models to incorporate spatial variability of parameters, that both the Heretaunga numerical model and the WhAEM model were unable to fully represent. These methodologies are intended to be deployed throughout New Zealand, but the method development and testing will focus on the Heretaunga Plains.

As noted by the reviewer of this report (Appendix 1), while the numerical modelling presented here may be considered more appropriate than the WhAEM modelling approach, new science in the near future will improve the accuracy and greatly reduce the predictive uncertainty of SPZs developed using the best science that is currently available. Therefore, a flexible approach to SPZ delineation in planning instruments is recommended, so that SPZ maps may be revised without difficulty or delay, as new science is developed.

5 Conclusions

The numerical modelling work undertaken in this assessment provides an alternative to source protection zones delineated by T+T using the WhAEM approach. The extent of zones from each modelling approach is different, due to differences in methodology. It was shown that the numerical method may be more appropriate for a complex system such as the Heretaunga Aquifer System.

The one-year travel time zone indicates that the public water supply bores, especially Portsmouth and Wilson, may be at risk of contamination from a very wide catchment via the Ngaruroro River.

The 10-year travel time zone, designed to conservatively delineate risk of pathogen contamination, is very extensive. The prediction is very conservative, and it may be difficult to improve the certainty of it with available methods. Furthermore, it may be impractical to completely protect such a large area from risk of pathogen contamination. Alternatively, it may be preferred to use the one-year travel time zone to establish source protection zones for non-pathogenic contaminants, and accept the residual risk on microbial contamination which can be managed using the multi-barrier approach to managing risk of contamination (e.g. treatment).

In the confined aquifer, source protection zones may be treated differently due to lower level of risk. However, more work is required to accurately identify all locations with artesian conditions.

While the numerical modelling presented here may be considered more appropriate than the WhAEM modelling approach, new science in the near future will further improve the accuracy and greatly reduce the predictive uncertainty of SPZs developed using the best science that is currently available. Therefore, a flexible approach to SPZ delineation in planning instruments is recommended, so that SPZ maps may be revised without difficulty or delay, as new science is developed.

6 Acknowledgement

Dr Catherine Moore (GNS Science) is sincerely thanked for reviewing a draft of this report. There was little time available for the review and Dr Moore's commitment and carefully considered letter report are greatly appreciated.

7 Further documentation

Plots for all realisations and scenarios are appended to this report (Appendix B and C)

In addition, model files (modflow, modpath, PEST, post processing) are also available for download from gitlab:

https://gitlab.com/crayfisher/modpath_scenarios_heretuanga.git

8 References

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9 Appendix A peer review letter

Note: following the review by GNS, HBRC have undertaken an editorial review of this report.

Letter Report No: CR 2019/08 LR
Project No: 63000199

15 January 2019

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Dear Pawel,

Peer Review: Stochastic Source Protection Delineation in Heretaunga Aquifer Using a Numerical Groundwater Model: Description of Methodology and Results for Hastings District Council Municipal Bores

1.0 BACKGROUND

Hawkes Bay Regional Council have undertaken a stochastic source protection zone (SPZ) delineation analysis for the Hastings District Council municipal water supply wells which are grouped into four bore-fields; Eastbourne Street, Frimley Park, Wilson Road and Portsmouth Road. This work was undertaken to provide an alternative to the source protection zones delineated by Tonkin and Taylor (2018), which adopted the well head analytic model (WhAEM) software from the USEPA, to delineate the SPZ's.

GNS Science (GNS) was commissioned by Hawkes Bay Regional Council (HBRC), to provide a brief review of the methodology adopted for this stochastic source protection groundwater modelling work, and the brief reporting of that work (Rakowski 2018). Note that the author of this review, Catherine Moore, also reviewed the Tonkin and Taylor SPZ delineation report.

This review does not include any examination of the groundwater data in the area nor the numerical model used to undertake the analysis and is restricted to commenting on the adopted methodology. Nor does this review comment on wording or expression in the Rakowski (2018) report.

2.0 MODELLING METHODOLOGY ADOPTED

The stochastic source protection zone delineation methodology as reported, which uses particle tracking with a numerical groundwater model, is considered robust. The workflow detailed in the report, while preliminary, is considered state of the art. Some approximations, and improvements that can be undertaken, are detailed in the report. Two additional issues are discussed below. However, the delineated source protection zones provide an alternative to those delineated by Tonkin and Taylor (2018).

The 10-year travel time work-around used to accommodate the low effective porosities that correspond to the small discrete highly permeable pathways capable of very rapid groundwater transport, is considered acceptable as an interim approach for assessing the source protection zones required for pathogen contamination risk. This 10-year travel time SPZ can be compared with the SPZ2 in the Tonkin and Taylor report (in particular with the version of the zones that allow for the 25-degree variation in groundwater flow direction).

Preliminary work by ESR (Scott and Moore 2019) indicates that there may be significant corruption of the variance and bias terms of travel time probability distributions when upscaling highly heterogeneous alluvial aquifers; this study investigated upscaling errors when moving from a 10cm to a 5m numerical grid. Such corruption, and likely underestimation of the predictive probability distribution is likely with a 100m grid scale used in the Heretaunga Plains numerical model. This issue is the subject of current research (MBIE funded – Te Whakeheke O Te Wai project). It is expected that in future work, local refinements of the Heretaunga Plains model grid in the area around the well fields will allow a more robust assessment of the local travel time risks.

3.0 COMMENT ON COMPARISON WITH TONKIN AND TAYLOR RESULTS

Both the simple WhAEM approach and the more complex numerical method applied by Hawkes Bay Regional Council are fully described in the GNS 2014 Envirolink Report – Capture Zone (Moreau et al. 2014).

Tonkin and Taylor adopted the simple WhAEM modelling approach based on the rationale that this was appropriate given the time-frame available for this study, and when used with appropriate model inputs and assumptions can represent a fit for purpose model for the delineation of SPZ's. The WhAEM software utilises a simple one-layer homogeneous aquifer representation of groundwater flow around and towards each well.

It was noted in the GNS review of the Tonkin and Taylor report:

> *"Simple models can be built and calibrated more quickly than complex models. However, they must be used with caution. Doherty and Moore (2017) discuss how the simpler the model, the more conservative its evaluation of predictive uncertainty needs to be. It also follows that the attractiveness of model complexity lies in the opportunities that it may present for reducing evaluated predictive uncertainty. The Tonkin and Taylor report recommend that future revisions of the SPZ consider the use of an extended model to allow explicit representation of the fast, permeable groundwater pathways, this may allow an opportunity for reducing the predictive uncertainty around the SPZ delineation."*

This work by HBRC has essentially initiated this extended work using the current groundwater model of the Heretaunga Plains.

In general, the Tonkin and Taylor SPZ's are more conservative as they must be, when taking into account the variability of the groundwater flow directions as indicated in the sensitivity analysis plots. Note that these SPZ zones are not the same best estimate SPZ zones superimposed with the HBRC SPZ's in the reviewed document. This conservatism results in greater restrictions to land use than when SPZ's are delineated using a more complex numerical model.

One particular discrepancy between the WhAEM zones and the 10-year SPZ based on the numerical model that warrant attention relates to the groundwater flow direction. The WhAEM capture zones are based on a single groundwater flow direction in the vicinity of the bore field, whereas the numerical model is able to accommodate the changing groundwater flow direction upgradient of the well field. The result of this changing groundwater flow direction is that the numerical model SPZ's extend initially in a westerly direction and then in a more northerly direction. Whereas the Tonkin and Taylor zones extend north-westerly.

This Tonkin and Taylor methodology is also less able to accommodate the flatter piezometric surface in the confined aquifer area, which results in a reduced downgradient capture area than the numerical model approach (e.g. for Eastbourne Street well field).

The consequence of this is that some of the area covered by the HBRC SPZ's are not covered by the Tonkin and Taylor SPZ's, unless the wide range of flow directions explored in the sensitivity analyses of that report are considered.

4.0 CONCLUSIONS AND RECOMMENDATIONS

The modelling approach adopted by HBRC for delineating the SPZ's for the four Hastings bore-fields is considered appropriate and represents an advance on the initial work by Tonkin and Taylor in that it accommodates more of the complexity of groundwater flow system, and in particular the groundwater flow directions and gradients.

It is recommended that future SPZ work in this area consider potential upscaling errors that can occur when upscaling model parameters in highly heterogeneous alluvial aquifers. One way that these errors can be quantified is using paired model analyses (Doherty and Christensen 2011). As noted this issue is the subject of the current collaborative research programme involving both Hawkes Bay Regional Council and GNS Science (MBIE funded – Te Whakeheke O Te Wai project).

Yours sincerely

CMoore

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10 Appendix B Plots of stochastic realisations 1 year

11 Appendix C Plots of stochastic realiations 10 years