Greater Wellington
Te Pane Matua Taiao

COVER NOTE

Greater Wellington has undertaken this work as part of information gathering leading up to the Whaitua Kāpiti process. This is only part of the information base that the Whaitua Kāpiti Committee may draw from and is not considered to be definitive.

REPORT

Tonkin+Taylor

Kāpiti Whaitua

Hydrogeological Modelling Inputs

Prepared for
Greater Wellington Regional Council

Prepared by
Tonkin & Taylor Ltd

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Exceptional thinking together

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1 Introduction

Tonkin & Taylor Ltd (T+T) has been engaged by the Greater Wellington Regional Council (GWRC) to undertake hydrogeological scenario modelling as part of the Kāpiti Whaitua process, including conversion of an existing numerical groundwater flow model[1] owned by GWRC. The purpose of this work is to assist the Kāpiti Whaitua Committee with the development of water quantity objectives and abstraction limits within the Kāpiti region. This technical report details the work completed and has been undertaken in accordance with our signed agreement dated 6/8 July 2021.

1.1 Project background

GWRC has developed a Whaitua process for setting water quality and quantity objectives and limits in collaboration with the community as required by the National Policy Statement for Freshwater Management (NP-SFM)[2]. To better inform the Kāpiti Whaitua process, GWRC have undertaken a programme of collating scientific information to help determine best management regimes and test abstraction limits and minimum flows for the Waikanae and Ōtaki rivers.

As part of the Whaitua process, a hydrogeology stocktake was undertaken to determine what existing knowledge and models could be used to assist setting water quantity objectives and abstraction limits. The outcomes of the stocktake were reported in the draft discussion document included in Appendix A of this report.

The draft discussion document indicated that the existing GWRC numerical groundwater model[1] could be appropriate for use as part of the Whaitua process due to the incorporation of model components that mimic groundwater-surface water interactions and spatial variability across the Kāpiti region. However, this GWRC model required conversion into a more interoperable format for further analysis. GWRC and other stakeholders agreed to this recommendation.

In addition to the model conversion, it was necessary to understand potential effects of climate change and water demand to the hydrology of the Kāpiti Coast Whaitua. Model scenarios that incorporated climate and water demand change projections were required to assist the GWRC Whaitua science team as well as the Whaitua committee with decision-making. The development and execution of these model scenarios was therefore a primary objective of the work described in this report.

1.2 Scope of work

In order to meet the project objectives, we have undertaken the following scope of work:

- Conversion of the existing Visual MODFLOW and associated model files into format suitable for use with the FloPy python package for MODFLOW[3] modelling.
- Development of model scenarios in conjunction with the GWRC Whaitua science team. These model scenarios comprise the adaptation of the existing GWRC model input files to represent each model scenario.
- Execution, post-processing and visualisation of the scenario models.

The work undertaken as part of this project is described in this technical report. In addition, selected post-processed model outputs and visualisations have been transmitted with this report.

[1] Gyopari, M.C., Mzila, D., Hughes, B.N., 2014. *Kapiti Coast groundwater resource investigation: catchment hydrogeology and modelling report*. Greater Wellington Regional Council
[2] www.mfe.govt.nz/fresh-water/freshwater-acts-and-regulations/national-policy-statement-freshwater-management.
[3] Harbaugh, A.W., 2005, *MODFLOW-2005, the U.S. Geological Survey modular ground-water model -- the Ground-Water Flow Process*: U.S. Geological Survey Techniques and Methods 6-A16. https://doi.org/10.3133/tm6A16

The scope of work is subject to the following limitations and assumptions:

- No recalibration of the model or amendment of model hydraulic parameters was undertaken.
- No amendment of the model domain or grid was undertaken.
- Model scenarios were run for the existing GWRC model period (19 years from July 1992 – 2011). We have not allowed for extension of the modelling period as part of this work.
- No comparison of the GWRC Kāpiti model with other numerical flow models was undertaken.

Further information about the additional scenario modelling approach is contained in the draft discussion document included in Appendix A.

2 Model conversion

The existing numerical groundwater flow model was developed using Visual MODFLOW software. This comprises a graphical user interface that assists with the numerical modelling process, as well as proprietary numerical solvers for the solution of groundwater flow. The version of Visual MODFLOW used for initial model development is no longer supported by the current publishers of the software. Because of this, and to facilitate the use of the numerical model for scenario analysis and resource evaluation, the model was converted into native MODFLOW format.

2.1 Model source files

The model source files were provided to T+T using the Microsoft Teams platform. Three versions of the model were reviewed as part of this analysis; these are summarised in Table 2.2 below.

Table 2.1: MODFLOW File sources

Model name	Directory name	Uploaded by	Model date[a]
FINALKAPITIMODEL	Kapiti_ModelDougMz	Rebecca Morris, GWRC	1/10/2013
KAPITI	Kapiti_original_2014-04-15	Mike Taves, GNS	15/4/2014
FINALVALIDATION	Kapiti_FINALVALIDATION	Rebecca Morris, GWRC	26/9/2012

[a]According to *DIS* package comments

The *KAPITI* version of the model was selected for conversion as it had the most recent model date. Differences and similarities between the MODFLOW packages for each model provided have been included in Appendix B, B1.

2.1.1 Abstraction rates

The abstraction rates in the provided *KAPITI* files were not consistent with the simulated abstraction rates outlined in Figure 68 of Gyopari, et al.[1] (Figure 2.1 left, below). This is because the *KAPITI* well package was modified to assess groundwater abstraction in the Waikanae region for a shortened period. It was therefore necessary to adopt a more appropriate abstraction regime for this analysis.

GWRC provided a number of additional well package files and the file that best matched the original simulated values (entitled *NEWFINALALLOCAT.wel*) is shown below (Figure 2.1, right). This well package file was adopted for the base scenario model. We note that the modelled abstraction rates are not an exact match of the original simulated values, with the base abstraction rates in *NEWFINALALLOCAT.wel* approximately 4,000-5,000 m^3/day higher than the simulated values in the report. Also, the *NEWFINALALLOCAT.wel* regime moves stepwise, as opposed to the simulated abstraction in the original model report[1].

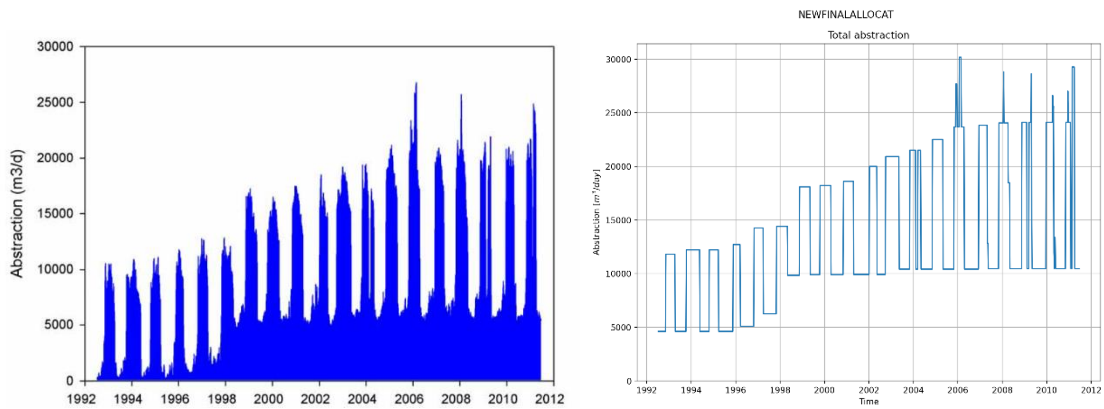

Figure 2.1: (left) - GWRC model simulated abstraction (Fig.68[1]) and (right) - total abstraction in converted base model.

2.1.2 Numerical solvers

Visual MODFLOW uses its own proprietary numerical solvers ('engines') for modelling. The MODFLOW preconditioned conjugate-gradient solver was used for numerical solution of the model. It was necessary to change the following solver parameters to achieve model convergence with the converted models:

- Head change criterion (*HCLOSE*) – changed from 0.00002 m to 0.01 m
- Relaxation parameter (*RELAX*) – changed from 1.0 to 0.99

2.1.3 Final source files used

Table 2.2: MODFLOW File sources

MODFLOW package	File source
Discretisation (DIS), Basic (BAS), Drain (DRN), Evapotranspiration (EVT), Block-centred flow (BCF6), Recharge (RCH), Stream (STR)	*Kapiti_original_2014-04-15/KAPITI*
Wells (WEL)	*NEWFINALALLOCAT.WEL*
Output control (OC), Preconditioned Conjugate-Gradient solver (PCG)	User-defined

Model conversion to native MODFLOW files was undertaken using the [*FloPy*] python package. Two converted models were created:

- *kapitibase* – this is the base model that will be used for scenario testing.
- *kapitival* – this is the validation model used to compare the provided model outputs with the converted model.

2.2 Model validation

2.2.1 *kapitival* validation

To ensure that the conversion had been successful, model output files from the original *KAPITI* Visual MODFLOW model and the converted *kapitival* model were compared.

2.2.1.1 Hydraulic head and drawdown

Hydraulic head model outputs from the *KAPITI* and *kapitival* models were compared by calculating cell-by-cell differences for all stress periods.

Relative percentages of absolute hydraulic head and drawdown model output differences greater than specified levels are summarised in Table 2.3. These were calculated by dividing the number of exceedance observations by the total number of observations for all cells and all stress periods. The proportion of differences exceeding 1 cm is 0.23%, indicating that the converted *kapitival* model can reproduce the existing hydraulic heads at all time steps and model grid cells.

Table 2.3: Summary of hydraulic head differences

Absolute difference greater than	Proportion of differences in all grid cells and time steps
0.01 m	0.23%
0.1 m	0.00000339%

2.2.1.2 Total budgets

The cell-by-cell budget file provided in the files could not be read using *FloPy* due to differences in source code compilation. However, a comparison of incremental water budget components at the end of each model period could be made using model listing output files provided. This provides an indication of temporal differences between the original and converted model files only – spatial differences between the models are unable to be resolved with these outputs.

Selected water budget output time-series are shown in Figure 2.2, with the converted *kapitival* model budget outputs plotted as orange dots over the original *KAPITI* model time-series. The time-series indicates that there is good agreement between the two model outputs. In addition, differences between the two outputs are plotted in light red in Figure 2.2 on the right-hand y-axis. All water budget model output time-series comparisons have been included in Appendix B, B2.1.

Differences at each time step are generally at least three orders of magnitude lower than the budget volume. Spikes in the budget difference values may be associated with sudden changes in boundary conditions, such as rainfall or flood events.

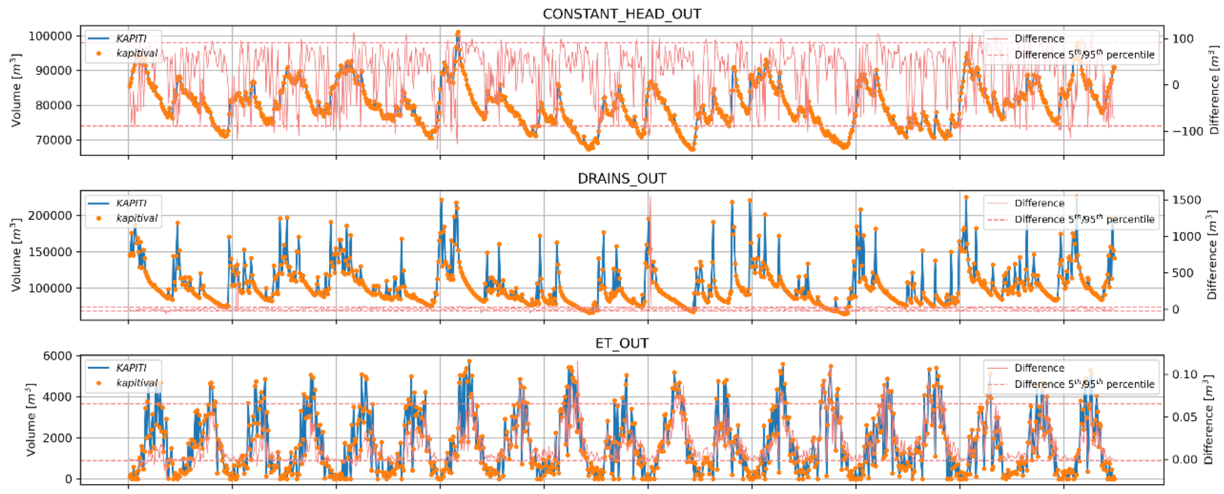

Figure 2.2: Comparison of selected water balance model outputs. All water budget mode output time-series are included in Appendix B, B2.1.

2.2.2 *kapitibase* validation

In order to validate the converted *kapitibase* model, the outputs of that model were compared with water balance figure in the original model report[1]. Simulated catchment water balances depicted in Appendix B, B2.2, show that, although the temporal development of the water balance is similar, there are some differences between the model used in the original model report and the *kapitibase* model:

- Discharges (losses) to constant head boundary conditions (i.e., the sea) are smaller in *kapitibase* than in the original model.
- Discharges to drains appear to be generally similar between the two models.
- Cumulative changes in aquifer storage have a similar temporal progression, but the changes in *kapitibase* appear dampened (i.e., peaks and troughs are smaller) in contrast to Figure 78 of the 2014 model report[1]. It is difficult to resolve the reasons for differences in catchment water balances between the original model report and the *kapitibase* model, particularly as we cannot be sure that the model files used to create the respective models were identical. This validation comparison does demonstrate that the temporal behaviour of different water balance components between the different models is similar, and that the components are within the same order of magnitude.

2.3 Discussion

Outputs from the converted validation model showed good agreement with time-series of water balances of the source model, suggesting that the conversion process does not have a significant impact on the model outputs.

However, comparisons of the *kapitibase* model with figures from the original model report indicate that there are some differences in water balance components. This may be due to differences in model input package file versions used, or in how the components were summarised/plotted. Despite these differences, the temporal behaviour is generally captured and within the same order of magnitude. We therefore consider the *kapitibase* model to be appropriate for scenario analysis, where relative differences between scenarios with the same base model are to be considered.

Further model validation may be required should GWRC wish to use the converted model for resource evaluation. This may include additional validation of the existing model parameters using additional boundary conditions (e.g., river inputs, groundwater abstraction) and observations (i.e., groundwater levels) from 2011 to present, and/or recalibration of the model parameters to that additional data.

2.4 Jupyter notebook

A jupyter notebook has been developed to facilitate the use of the converted GWRC groundwater model by others. This notebook and associated documentation will be transmitted with this report.

3 Model scenarios

Models can assist with decision making by providing a framework for understanding how hydrological changes in a catchment influence hydrological behaviour in the catchment. A numerical model can be separated along these lines into boundary conditions and model outputs. Model boundary conditions (‘forcings’ or ‘changes’) are generally derived from observed phenomena and can then be extrapolated based on projections of future phenomena. Model boundary conditions that are directly relevant to the Whaitua process include:

- River flows
- Rainfall recharge
- Groundwater abstraction
- Sea levels

Model outputs (‘state variables’) provide a quantitative understanding of hydrological behaviour in a modelled area of interest. As noted above, the sustainable management of water in the Kāpiti region is a key focus of the Whaitua process. The following model outputs are therefore relevant as part of scenario modelling:

- Fluxes between surface water and the groundwater domain.
- Fluxes from spring-fed streams and at groundwater-dependent ecosystems (i.e., wetlands).
- Groundwater levels across the catchment.

The objective of hydrogeological model scenarios described in this report is to provide information for the Kāpiti Whaitua process that may help to determine best management regimes with respect to groundwater abstraction limits and minimum stream flows. Issues likely to be of particular interest to the Whaitua science panel and committee include impacts on groundwater-dependent ecosystems, spring-fed streams and wetlands.

In this section, we describe how the existing GWRC groundwater model boundary conditions were amended to create an ensemble of model scenarios.

3.1 Scenario modelling approach

The GWRC Whaitua science team indicated that the scenarios should encompass:

- Three time horizons: 2040, 2080 and 2120.
- Three Representative Concentration Pathways (RCPs): 2.6, 4.5 and 8.5.
- Multiple water demand conditions, including no abstraction (‘naturalised’), current abstraction and maximum abstraction.

For the Kāpiti Whaitua scenarios, we have categorised model boundary conditions as being driven by changes in:

- Climate:
  - Sea levels
  - River flows
  - Rainfall recharge, or
- Water demand:
  - Groundwater abstraction
  - Diffuse abstraction.

The adaptation of the model boundary conditions listed above is described in the remainder of this section.

As noted in Section and described in Section 2, the existing GWRC model was converted into native MODFLOW file format to facilitate scenario modelling. Each model scenario comprised the existing calibrated model parameters (i.e., aquifer and land surface recharge parameters), and the amended model scenario parameters/boundary conditions. The transient model was run for the 19-year GWRC model period with weekly stress periods. The ensemble of Whaitua model scenarios consisted of the combination of each time horizon, RCP and water demand profile, comprising a total of 40 model runs. The Whaitua model scenarios are summarised in Table 3.1.

Table 3.1: Hydrogeological model scenarios summary

	Change	**Time horizons**									
	Time horizon	**1992-2011**	**2040**			**2080**			**2120**		
	RCP	-	**2.6**	**4.5**	**8.5**	**2.6**	**4.5**	**8.5**	**2.6**	**4.5**	**8.5**
Climate change	**Sea level change**	-	Adjust coastal constant head boundary by relative sea level rise values, based on estimated values in Bell et al. (2017)[4]								
	River flows	-	Apply seasonal multiplier to STR stream routing package based on estimated values for the Manawatu in Collins et al. (2018)[5]								
	Rainfall recharge	-	Estimated from Pearce et al. (2017)[6]								
Water demand	**Well abstraction**	Increased abstraction from wells and diffuse sources for the following water demand profiles: 1 No abstraction (Naturalised) 2 Modelled abstraction 3 Current actual abstraction 4 Maximum allocation									

This scenario modelling approach outlined in this section contains a number of limitations that may affect both modelling results and the interpretation of those results. These limitations include:

- No relationship or feedback mechanism between climate change and water demand has been included. In reality, it should be expected that water demand may change due to changes in climate, such as longer irrigation periods during times of drought.
- No additional model calibration has been performed using observations made since 2011.
- No amendment of the existing GWRC model has been undertaken to account for changes in the hydrological regime, e.g., Waikanae River Recharge with Groundwater project (RRwGW), large infrastructure projects (e.g., Mackays to Peka Peka Expressway) or urban development.

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[4] Bell, R.G., Lawrence, J.H., Allan, S., Blackett, P., Stephens, S., New Zealand, Ministry for the Environment, 2017. *Coastal hazards and climate change: guidance for local government.*

[5] Collins, D., Montgomery, K., Zammit, C., 2018. *Hydrological projections for New Zealand rivers under climate change* (No. 2018193CH). NIWA

[6] Pearce, P., Fedaeff, N., Mullan, B., Sood, A., Bell, R., Tait, A., Collins, D., Zammit, C., 2017. *Climate change and variability - Wellington Region* (No. 2017066AK). NIWA

3.2 Climate change boundary conditions

As noted above and summarised in Table 3.1, we consider the following model boundary conditions to be significantly affected by climate change:

- Sea levels
- River flows
- Rainfall recharge.

In this section, we describe how we have amended the model boundary conditions to represent hydrological changes in the catchment across multiple time horizons and RCP scenarios.

3.2.1 Sea level rise

Sea levels are expected to rise globally due to the effects of climate change. The Ministry for the Environment has published guidance for local government regarding coastal hazards and climate change (Bell et al., 2017[4]). This includes New Zealand-wide regional sea-level rise predictions that are "derived from the median projections of global sea level rise for the RCPs presented by the IPCC in its Fifth Assessment report" (p104[4]). These predictions are shown in Figure 3.1 below (Fig.27, p.105[4]).

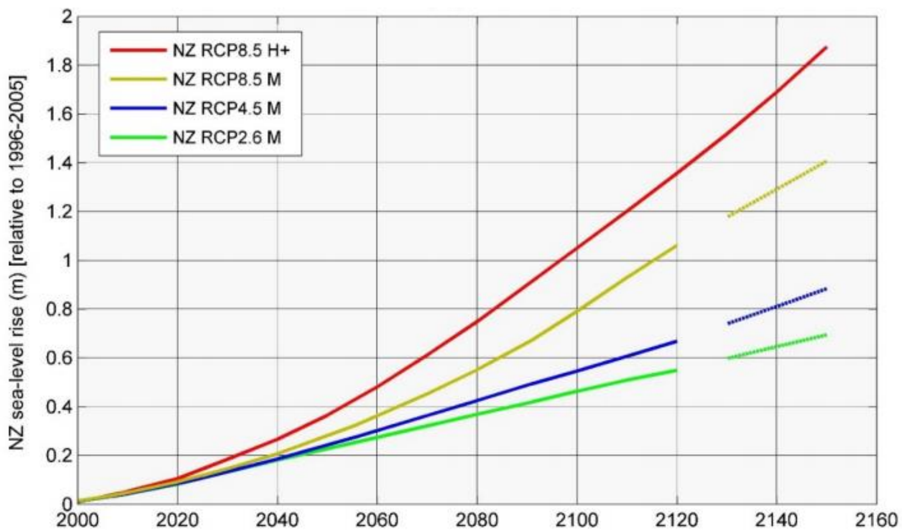

Figure 3.1: New Zealand-wide regional sea-level rise projections to 2150 (Bell et al, 2017[4], Fig.27, p.105).

Sea level is a controlling boundary condition in the existing GWRC groundwater model, with model grid cells in the marine portion of the model domain set to a constant head value of 0 metres above sea level. Sea level changes have been represented by adjusting this constant head boundary condition based on the projected relative rise.

The sea level adjustments for each time horizon and RCP have been derived visually from Figure 3.1 and are summarised in Table 3.2. Note that these sea level rise adjustments do not incorporate the effects of local vertical land movement, which is expected to also influence relative sea level changes in the future. In addition, the adjusted sea level is constant for the duration of each model scenario.

Table 3.2: Sea level rise adjustment summary.

Time horizon	1992-2011	2040			2080			2120		
RCP	-	**2.6**	**4.5**	**8.5**	**2.6**	**4.5**	**8.5**	**2.6**	**4.5**	**8.5**
Sea level rise adjustment [m]	-	0.2	0.2	0.2	0.35	0.45	0.55	0.55	0.65	1.05

3.2.2 River flows

As part of disruption to regional water cycles, climate change is expected to have an impact on river flows. River flows represent important input boundary conditions to the existing GWRC model, with stream flow boundary conditions for *STR* package surface water features shown on Figure 3.2.

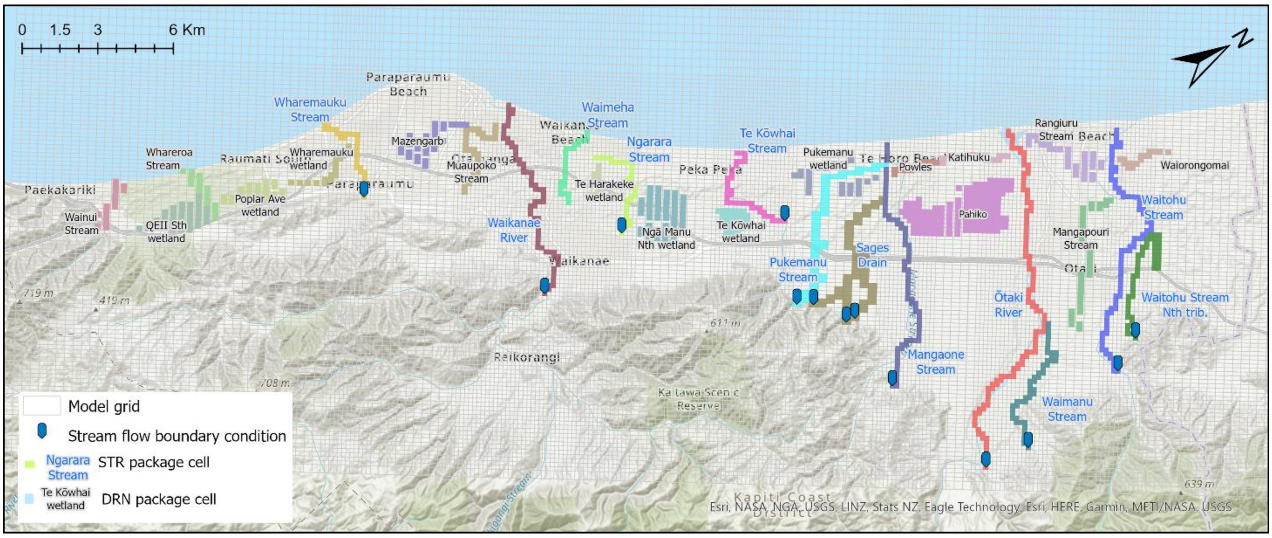

Figure 3.2: STR and DRN package cell locations.

Relative changes in seasonal mean discharges due to climate change have been predicted for New Zealand rivers in a previous study (Collins et al., 2018[5]). Hydrological modelling was conducted for each river included in that study using TopNet[7] and incorporating down-scaled climate projections and catchment-specific variables, such as land use and rainfall records.

The closest river modelled in the Collins et al. (2018[5]) study was the Manawatū River. In the absence of other predictions of relative changes in seasonal mean discharge for streams and rivers in the Kāpiti Whaitua, we have adopted the Manawatū River predictions. The Collins et al. (2018[5]) study did not include a 2120 time horizon, therefore we have manually extrapolated relative changes for this time horizon based on the 2040 and 2080 projected values.

The projected relative changes in seasonal mean discharge have been applied to the scenarios by applying seasonal multipliers to the existing GWRC model river inflow boundary time-series. The seasonal multipliers have been interpolated using a sinusoidal function so that the scenario time-series varies smoothly. The multipliers used for seasonal mean discharge used are tabulated in Table 3.3.

[7] Clark, M.P.; Woods, R.A.; Zheng, X.; Ibbitt, R.P.; Slater, A.G.; Rupp, D.E.; Schmidt, J.; Uddstrom, M.J. 2008:. Hydrological data assimilation with the Ensemble Kalman Filter: use of streamflow observations to update states in a distributed hydrological model. *Advances in Water Resources*: 31, 1309-1324.

Table 3.3: Projected relative changes in seasonal mean discharge [%]

RCP	2040 [a]				2080 [b]				2120 [c]			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
2.6	-1	-1	3	1	-6	0	3	3	-10	-2	3	5
4.5	-9	1	1	3	3	-8	-2	-6	-13	-8	-4	-8
8.5	-1	4	0	-2	-16	-9	5	-9	-20	-11	7	-13

[a] Values adopted for the Manawatu River from Collins et al. (2018, Table 3-1 p.22).
[b] Values adopted for the Manawatu River from Collins et al. (2018, Table 3-2 p.25).
[c] Manually extrapolated from 2040 and 2080 projected changes.

3.2.3 Rainfall recharge

Climate change is likely to precipitate a change in global rainfall patterns. This would likely alter patterns of rainfall (or land surface) recharge of groundwater resources. Climate indicators for the Kāpiti Coast reported in Pearce et al. (2017[6]) that are relevant to rainfall recharge include:

- Total rainfall – more rainfall means more water available for groundwater recharge.
- Wet days over 25 mm per day – proxy for rainfall intensity. Higher rainfall intensity will lead to more runoff and reduced groundwater recharge.
- Potential evapotranspiration deficit – more evapotranspiration leads to less water available for groundwater recharge.

Using GWRC's Climate Change Mapping tool[8], we have undertaken a visual review of how the climate indicators above are predicted to change in the future. This visual inspection indicated that total rainfall and potential evapotranspiration deficits were likely to vary across time horizons and RCPs and we therefore included these indicators in our climate change scenarios. The mapping tool indicated that wet days with over 25 mm of rainfall per day would not vary between ±5 days a year across time horizons, RCP or seasons. Therefore, this climate indicator was not included in the development of rainfall recharge boundary condition amendments.

Changes in total rainfall have been adopted from climate change projects prepared for the Ministry for the Environment[9] (MfE). These include down-scaled projected changes in seasonal precipitation for the Wellington Region at Paraparaumu. Seasonal changes have been applied to the existing GWRC model recharge boundary conditions by multiplying them by the appropriate predicted relative change in rainfall.

Potential evapotranspiration deficits have been estimated based on a visual review of that climate indicator in the GWRC Climate Change Mapping tool[8]. The lower bound of the predicted potential evapotranspiration deficit for each time horizon and RCP has been adopted for scenario modelling. The existing GWRC model recharge boundary conditions have been adapted to account for this by subtracting the deficit value from the existing boundary condition.

The predicted effects on rainfall recharge and model boundary condition amendments have been summarised in Table 3.4.

[8] https://mapping1.gw.govt.nz/gw/ClimateChange/
[9] Ministry for the Environment 2018. *Climate Change Projections for New Zealand: Atmosphere Projections Based on Simulations from the IPCC Fifth Assessment, 2nd Edition*. Wellington: Ministry for the Environment. https://environment.govt.nz/assets/Publications/Files/Climate-change-projections-2nd-edition-final.pdf

Table 3.4: Predicted effects on rainfall recharge

Time horizon		2040[a]			2080[b]			2120[c]			Model boundary condition amendment
RCP		2.6	4.5	8.5	2.6	4.5	8.5	2.6	4.5	8.5	
Predicted relative changes in total rainfall [%]	Autumn	2	1	1	3	2	1	-1	0	-2	Apply multiplier to rainfall-recharge time-series
	Winter	4	6	6	5	8	13	5	9	11	
	Spring	1	1	1	3	2	1	2	2	2	
	Summer	0	0	0	2	2	1	2	1	-1	
Potential evapotranspiration deficit [d] [mm/year]		NC	60-80	60-80	NC	60-80	80-100	NC	60-80	140-170	Subtract value from rainfall recharge time-series

[a] Projected changes between 1986-2005 and 2031-50 for Wellington/Paraparaumu region (MfE, 2018[9], Table 10, p78).
[b] Projected changes between 1986-2005 and 2081-2100 for Wellington/Paraparaumu region (MfE, 2018[9], Table 11, p80).
[c] Projected changes between 1986-2005 and 2101-2110 for Wellington/Paraparaumu region (MfE, 2018[9], Table 12, p83).
[d] Estimated based on visual review of GWRC Climate Change Mapping tool[8] (derived from Pearce et al., 2017[6])

3.3 Water demand boundary conditions

Water demand is expected to change in the future driven in part by changing land use in the Kāpiti region, including increasing residential land use and associated decrease in agricultural land use. This will likely play a significant role in how water resources are managed and likely affect the hydrological regime of the Kāpiti Coast Whaitua.

3.3.1 GWRC water allocation

GWRC has developed a proposed Natural Resources Plan (PNRP) for the management of the coast, soil, and discharges to land, freshwater and air. Chapter 10[10] of that document includes allocation amounts for surface and shallow groundwater ('Category A') and deeper groundwater ('Category B') in the Kāpiti Coast Whaitua. We understand that these allocation amounts have been informed in part by previous scenario modelling undertaken by GWRC using the existing numerical model.

GWRC has also provided information regarding active groundwater and surface water takes in the Kāpiti Coast Whaitua[11]. Allocation amounts and currently active groundwater takes have been summarised for each catchment management unit in Table 3.5.

3.3.2 Existing GWRC groundwater model

The existing GWRC groundwater model[1] includes two types of groundwater abstraction:

- **Abstraction wells** modelled using the *WEL* MODFLOW package (see Figure 3.3):

  These represent consented groundwater takes between 1992-2011. These vary temporally, as depicted in Figure 3.4.

- **Diffuse groundwater abstraction** modelled using the *EVT* MODFLOW package:

  These represent small permitted-activity groundwater takes and have been estimated based on the population density in the period between 1992-2011.

[10] GWRC, 2019. *Proposed Natural Resources Plan, Appeals version 2019.* *https://pnrp.gw.govt.nz/assets/Uploads/Chapter-10-Kapiti-Coast-Whaitua-Appeal-version-2-2019.pdf*
[11] *Active_Groundwater_and_Surface_Water_Take_Environmental_Parameters.xlsx*, received via email on 20 October 2021 from Rebecca Morris, Senior Groundwater Scientist, GWRC.

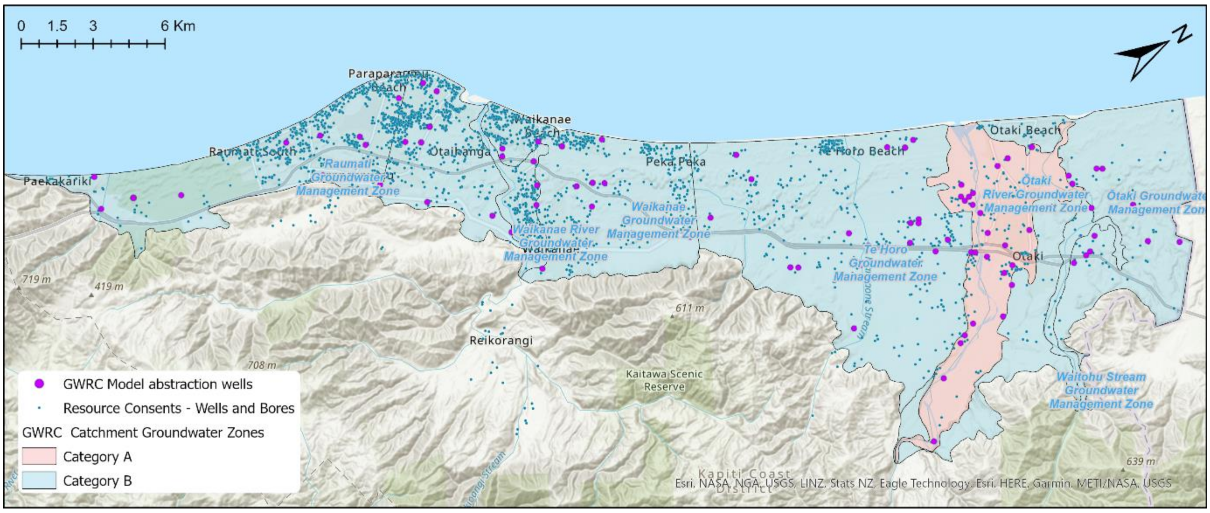

Figure 3.3: Modelled abstraction wells and existing well and bore consents in the Kāpiti Coast Whaitua.

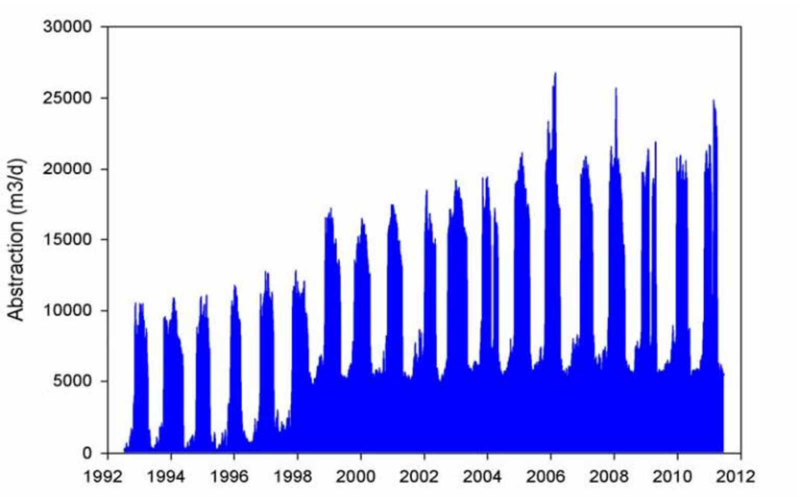

Figure 3.4: Simulated daily groundwater abstraction on the Kapiti coast between 1992 and 2011 (Fig.68, Gyopari et al., 2014[1]).

3.3.3 Whaitua model scenarios

The following water demand profiles have been developed for the Whaitua scenario analysis in conjunction with the GWRC Whaitua science panel:

- **No abstraction** – no point and diffuse abstraction.
  This water demand profile is considered to represent 'naturalised' flows in the model domain.
- **Modelled abstraction** – the abstraction rates and diffuse abstraction from the existing GWRC model (see Figure 3.4).
- **Actual abstraction** – based on available information from GWRC, KCDC and others.
- **Maximum allocation** – based on annual allocation volume in the Kāpiti groundwater management area.

To model actual abstraction and maximum allocation water demand profiles, it was necessary to assign appropriate boundary conditions. Scenario abstraction multipliers were derived for each catchment management unit in the Kāpiti Coast Whaitua using the following:

- **Actual abstraction** – divide the currently consented abstraction by the median modelled abstraction.
- **Maximum allocation** – divide the annual allocation amount by the median modelled abstraction.

Model boundary conditions for each water demand profile were calculated by applying the relevant abstraction multiplier to the *WEL* and *EVT* abstraction packages for that scenario. Allocation and multipliers for all water demand profiles have been summarised in Table 3.5. An example of how the water demand boundary conditions were amended is depicted in the time-series in Figure 3.5.

Table 3.5: Catchment management and water demand profile allocation summary

Catchment management unit	Allocation amount [million m³/year]	Currently consented[c] [million m³/year]	Modelled (median) [million m³/year]	'Maximum allocation' scenario		'Actual allocation' scenario[d]	
				Multiplier	Modelled abstraction [million m³/year]	Multiplier	Modelled abstraction [million m³/year]
Waitohu	1.08[a]	0.11	0.23	4.7	1.08	0.48	0.11
Te Horo	1.62[a]	0.83	0.62	2.61	1.62	1.34	0.83
Waikanae	2.7[a]	2.4	0.36	7.5	2.7	6.67	2.4
Raumati	1.23[a]	0.41	1.9	0.65	1.23	0.22	0.41
Ōtaki River	18.6[b]	3.3	2.7	6.89	18.6	1.22	3.3

[a] Category B groundwater takes, GWRC Proposed Natural Resources Plan, Chapter 10[10] Table 10.3

[b] Category A and B groundwater takes, GWRC Proposed Natural Resources Plan, Chapter 10[10] Table 10.2

[c] All groundwater takes

[d] Based on active water consent records from GWRC[11].

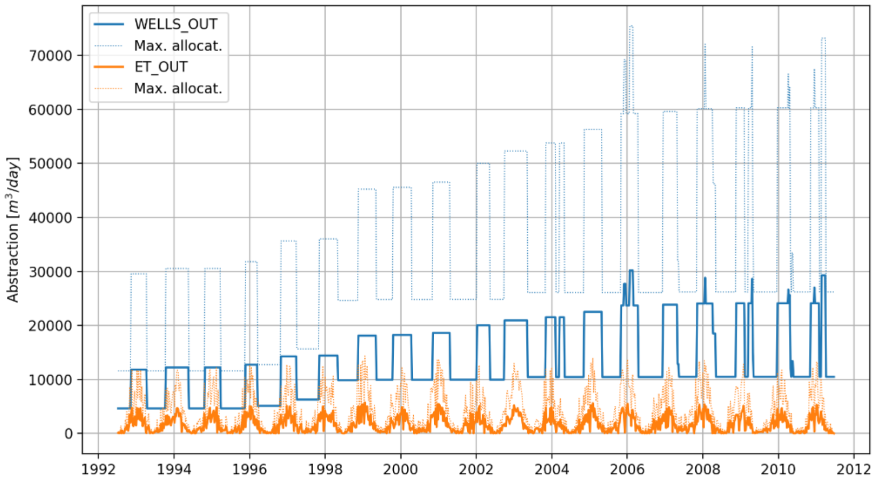

Figure 3.5: Modelled abstraction 1992-2011 and example 'maximum allocation' abstraction rates.

4 Model outputs

The model outputs from the scenario ensemble that we consider most relevant to the Kāpiti Coast Whaitua process include:

- Stream/river outflows
- Stream-aquifer exchanges
- Drain (wetland) discharges
- Groundwater levels (hydraulic heads).

In this section we discuss the scenario model outputs, including a brief description of how various model components are formulated and post-processed. We note the following:

- The 2040 4.5 RCP *actual abstraction* and 2040 2.6 *actual abstraction* scenarios were not completed due to model non-convergence.
- Hydraulic head time-series have been post-processed into median and 95th percentile values for each model layer and each scenario. These files have not been transmitted with this report due to the size of the data set, but the files can be made available on request.

4.1 *STR* package

The MODFLOW STR package[12] was used in the existing GWRC groundwater model to simulate the exchange of water between a stream and aquifer for the twelve streams and rivers shown in Figure 4.1.

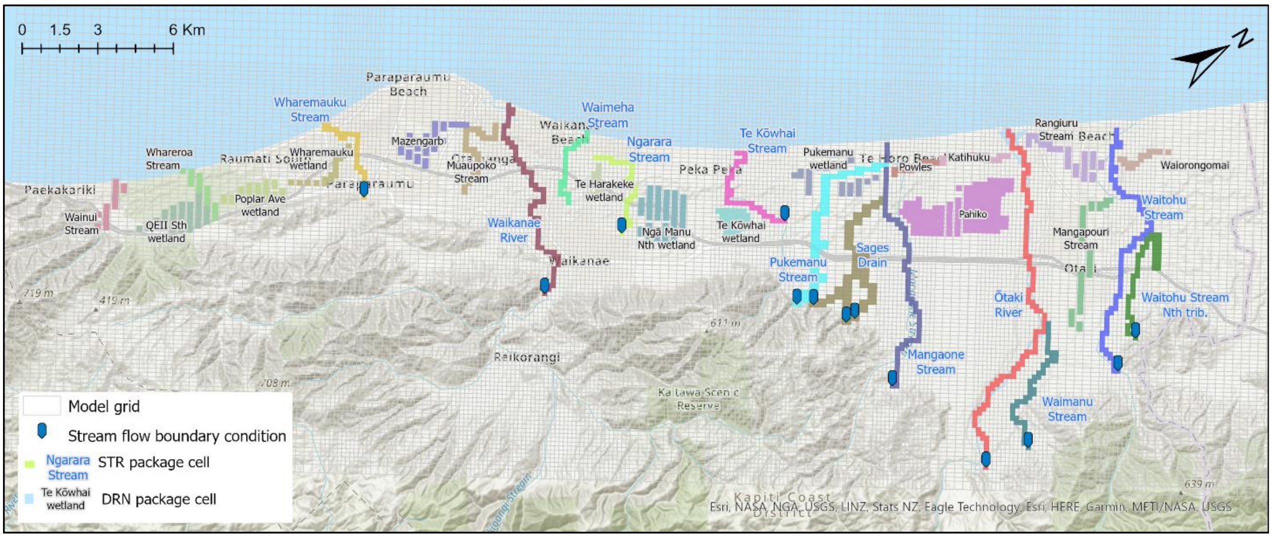

Figure 4.1: STR and DRN package cell locations.

This package models the discharge of water from the groundwater domain to the surface based on the difference between the hydraulic head in a model cell and the base elevation of a given stream feature[12] (Figure 4.2B). The exchange of water is moderated by the conductance of the stream feature, which can be conceptualised as low-conductivity sediments at the stream-bed. River levels are calculated based on the geometry of the channel and the discharge in the river segment. Surface water flow is routed instantaneously downstream in the *STR* package.

[12] Prudic, D.E., 1989. *Documentation of a computer program to simulate stream-aquifer relations using a modular, finite-difference, ground-water flow model* (USGS NS No. 88–729). U.S. Geological Survey,. https://doi.org/10.3133/ofr88729

For the existing GWRC model, bed conductance was "calculated using the length of the river in each river cell (*L*), the width of the river in the cell (*W*), the thickness of the river bed (*M*), and the hydraulic conductivity of the river bed material (*K*)" (p90[1], refer Figure 4.2A below). Estimated parameters and the "resultant calculated conductance values produced plausible estimates of streamflow gains and losses during model calibrations" (p90[1]).

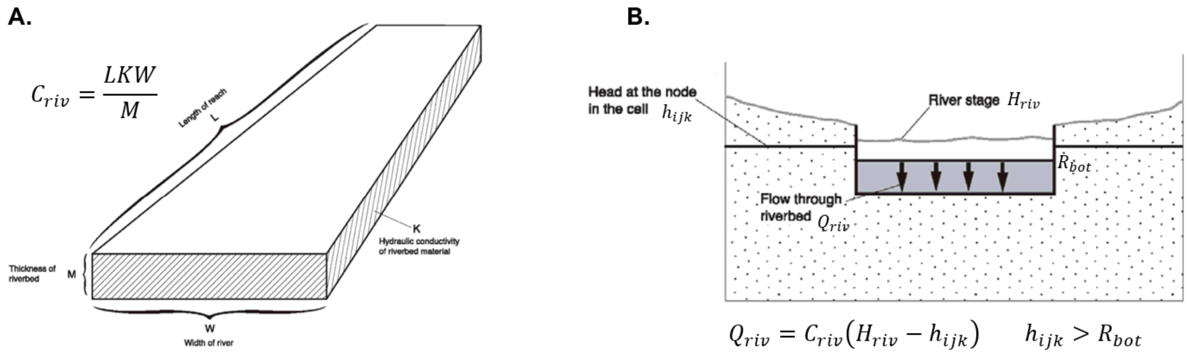

Figure 4.2: A. Conceptualisation of riverbed conductance in an individual cell (Harbaugh, 2005[3], Fig.6-6). B. Cross-section showing how stream-aquifer fluxes relate to groundwater and river levels (Harbaugh, 2005[3], Fig.6-7A.).

Outputs from the MODFLOW STR package outputs include both surface water flows and stream-aquifer exchanges. These are calculated along segments, which are groups of model grid cells that are assigned to the same stream reach. Each of the streams and rivers modelled in the existing GWRC model comprise multiple segments.

4.1.1 Surface water flows

STR package surface water flows are outputted as a time-series per stream segment. The surface water flows time-series outputs for each scenario have been extracted for each of the twelve surface water features labelled on Figure 4.1. Time-series for all *STR* segments have been saved into CSV[13] format and transmitted with this report.

STR package surface water flow outputs have been plotted for each of the twelve surface water features, an example of which is depicted in Figure 4.3. These plots include all scenarios and have been arranged according to RCP and time horizon. The time-series depicted in Figure 4.3 have been further aggregated by grouping the outputs into week number and taking the mean output value for each week number. This produces a time-series across a single year.

[13] Comma-separated values with naming convention *{time horizon}_{RCP}_{water demand profile} stream flow out.csv*

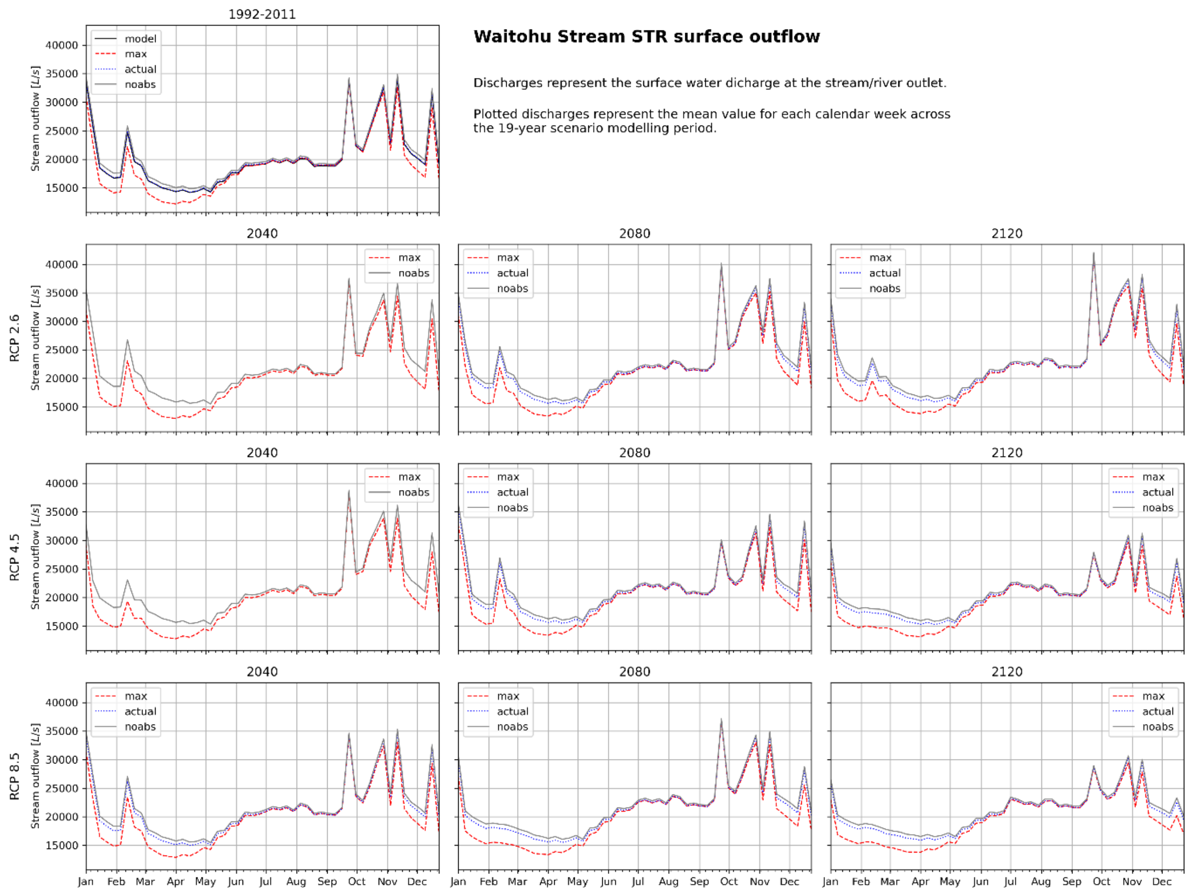

Figure 4.3: Example plot of STR package surface water flow outputs.

4.1.2 Stream-aquifer exchanges

STR package stream-aquifer exchanges are outputted as a time-series per stream segment. The stream-aquifer exchange time-series outputs for each scenario have been extracted for each of the twelve surface water features labelled on Figure 4.1. Time-series for all *STR* segments have been saved into CSV[14] format and transmitted with this report.

STR package stream-aquifer exchange outputs have been plotted for each of the twelve surface water features, an example of which is depicted in Figure 4.4. These plots include all scenarios and have been arranged according to RCP and time horizon. The time-series depicted in Figure 4.4 have been further aggregated by grouping the outputs into week number and taking the mean output value for each week number. This produces a time-series across a single year.

[14] Comma-separated values with naming convention *{time horizon}_{RCP}_{water demand profile} stream Leakage.csv*

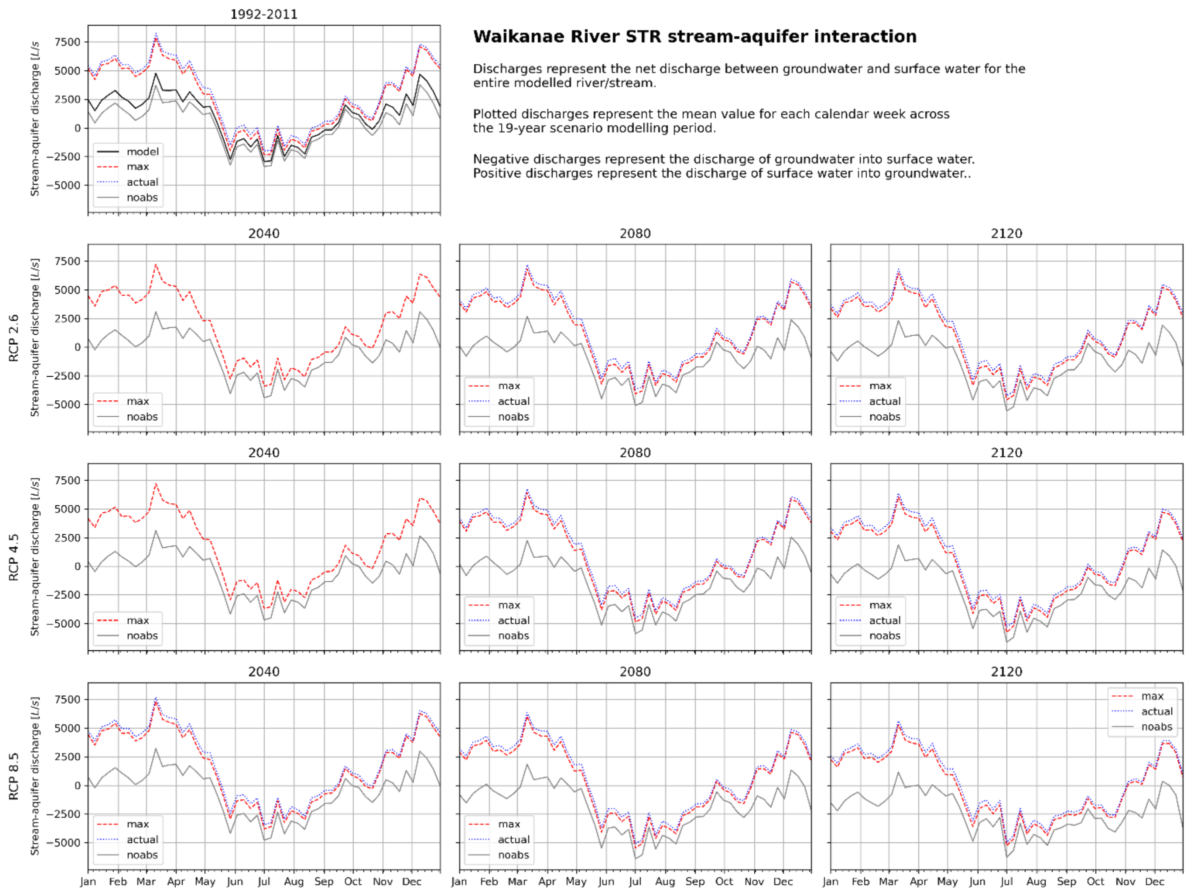

Figure 4.4: Example of a STR package stream-aquifer exchange plot.

4.2 *DRN* package

The MODFLOW DRN package was used in the existing GWRC groundwater model to simulate groundwater discharges in seventeen wetland features at the locations shown in Figure 4.1.

This package models the discharge of water from the groundwater domain to the surface based on the difference between the hydraulic head in a model cell and the base elevation of a given drain feature[3]. The drain discharge is moderated by the conductance of the drain feature, which can be conceptualised as low-conductivity sediments at the drain-bottom. For the existing GWRC model, “conductance values for the drain beds were derived from the model calibration” (p90[1]).

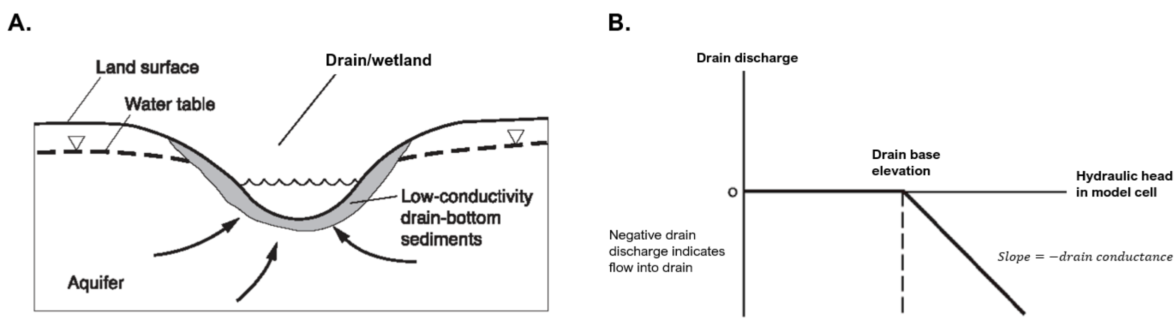

Figure 4.5: A. DRN *package conceptualisation (Harbaugh, 2005[3], Fig. 6-12) B. Plot of drain discharge as a function of hydraulic head (Harbaugh, 2005[3], Fig. 6-10).*

The *DRN* package, as implemented in the existing GWRC model, only allows for the discharge of groundwater to the surface (i.e., no recharge of groundwater within wetlands). In addition, any water discharged from a drain/wetland feature is removed from the modelled system.

4.2.1 Model outputs

DRN package discharges are outputted as a time-series per model cell. The discharge time-series outputs for each scenario have been aggregated into seventeen wetland features shown on Figure 4.1 by adding the time-series for all cells in the feature together to create a single time-series for that feature. Time-series for all seventeen modelled wetland features have been saved into CSV[15] format and transmitted with this report.

DRN package outputs have been plotted for each of the seventeen wetland features, an example of which is depicted in Figure 4.6. These plots include all scenarios and have been arranged according to RCP and time horizon. The time-series depicted in Figure 4.6 have been further aggregated by grouping the outputs into week number and taking the mean output value for each week number. This produces a time-series across a single year.

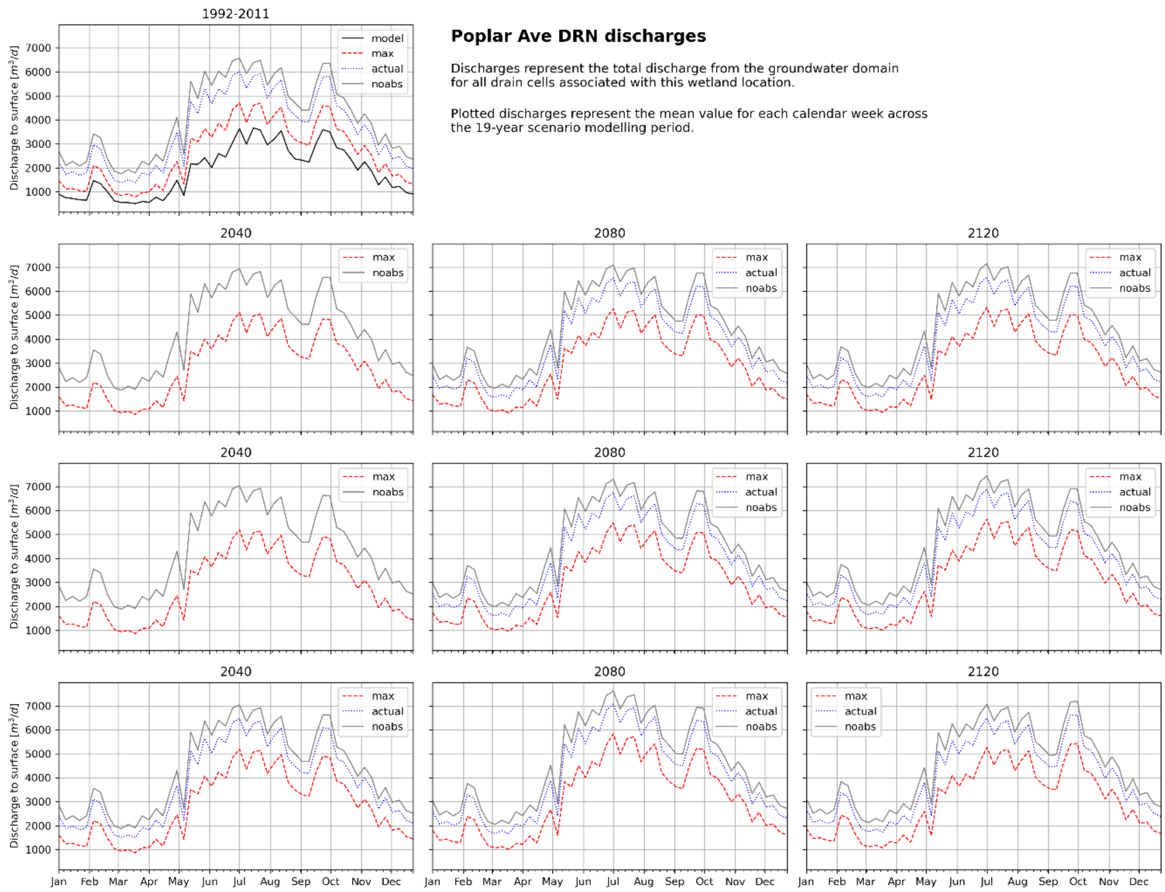

Figure 4.6: Example plot of DRN package outputs.

[15] Comma-separated values with naming convention *{time horizon}_{RCP}_{water demand profile} wetlands discharge.csv*

4.3 Discussion

Interpretation of the scenario model outputs will be undertaken by the GWRC Whaitua science team but we offer the following general comments regarding the scenario model outputs:

- Groundwater levels, and associated discharges to wetlands and streams, are influenced by a combination of all the boundary condition changes. Groundwater levels in the proximity of the coast are likely to rise as sea level rises. Local sea level rise may also impact saline intrusion risks; however, these risks have not been considered in this report.
- For all RCPs and time horizons, the groundwater discharging to streams and wetlands is higher in the *no-abstraction* water demand scenarios. Groundwater discharging to streams and wetlands is generally lowest during the summer period when groundwater levels are lowest.
- Surface water outflows generally showed little difference between water demand profiles, suggesting that these variables are primarily influenced by boundary conditions (i.e., upstream discharges, climate variables). For larger rivers (i.e., Waikanae, Ōtaki) there is no discernible difference between the water demand scenarios. In many of the surface water features, differences between the water demand profiles were more pronounced in the summer period (December-May).
- Some surface water features showed a slight decline in outflows with increasing time horizons and RCPs.
- Many stream-aquifer interaction model outputs show little difference between water demand scenarios, particularly *actual allocation* and *maximum allocation* scenarios. This may indicate that the locations may not be strongly influenced by groundwater abstraction, but more influenced by boundary conditions.
- Some stream-aquifer interaction model output differences between the water demand profiles were more pronounced in the summer period (similar to that observed for surface water outflows).
- In general, wetland discharges were lowest during summer periods. *Maximum abstraction* water demand scenarios generally had the lowest average discharges.
- Many wetland discharge model outputs show little difference between water demand scenarios, particularly *actual allocation* and *maximum allocation* scenarios, similar to some stream-aquifer interactions.

5 Conclusions

T+T has completed hydrogeological modelling tasks to support GWRC's Whaitua planning process for the development of water quantity and quality objectives in the Kāpiti Coast region. These tasks included:

- The conversion of an existing GWRC model to openly available formats.
- Development of model scenarios to represent potential changes in the hydrology of the Kāpiti Coast region.
- Execution, post-processing and visualisation of the model scenarios.

The existing GWRC groundwater flow model has been converted into native MODFLOW format using *FloPy* tools. Multiple versions (and associated model files) of the existing model were made available, but the version with the latest time step was assumed to be the most current version of the model. Two converted models were created to: (i) validate the converted model with the source model output files (*kapitival*); and (ii) generate a base model that can be used for future scenario analysis (*kapitibase*). The validation model showed good agreement with previously published model results and the base model could be used for subsequent scenario modelling.

Model scenarios were developed in consultation with the GWRC Whaitua science as well as Kāpiti Coast District Council and their representatives. The scenarios comprised three time horizons (2040, 2080, 2120), three Representative Concentration Pathways (2.6, 4.5, 8.5) and three water demand profiles (no abstraction, actual allocation and maximum allocation). The original model boundary conditions for the scenarios were amended using multipliers based on previous national and local studies of climate change. A model ensemble comprising 40 scenarios was executed as part of this study.

Scenario model outputs of interest for the Whaitua science team include surface water flows, stream-aquifer exchanges and drain (wetland) discharges. Model outputs for each feature of interest were aggregated and means time-series for each scenario were plotted. Examples of these plots have been provided in the body of this report, with plots for all outputs and locations of interest transmitted with this report. Median and 95th percentile groundwater surfaces are also available on request.

The ensemble of scenario model outputs provides a quantitative overview of how climate change and water demand may affect the hydrology of the Kāpiti Coast Whaitua. Due to the assumptions made in the scenario development and in the existing GWRC model, it is most appropriate to interpret the relative differences between the member scenarios of the ensemble, as opposed to the absolute discharges of the model outputs. We have developed a workflow that would support further scenario development and analysis based on the direction of the Whaitua committee's interest and inquiry.

6 Applicability

This report has been prepared for the exclusive use of our client Greater Wellington Regional Council, with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose, or by any person other than our client, without our prior written agreement.

Tonkin & Taylor Ltd

Report prepared by:	Authorised for Tonkin & Taylor Ltd by:
....	....
Jeremy Bennett	Sarah Schiess
Senior Groundwater Scientist	Project Director

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Appendix A: Kāpiti hydrogeological stocktake memo

Kāpiti hydrogeology stocktake – Purpose and Scope of work

Draft for discussion, 1 April 2021

1 Purpose

The Whaitua process is GWRC's method for setting water quality and quantity objectives and limits in collaboration with the community as required by the National Policy Statement for Freshwater Management (NP-SFM)[1]. The Kāpiti Whaitua process is due to start in mid-2021, and the necessary information to inform the Whaitua needs to be prepared by the end of 2021 – this includes any **hydrological/modelling work to determine best management regimes and test abstraction limits and minimum flows for the Waikanae and Ōtaki rivers** (as the major suppliers of public water supply for the Kāpiti area).

2 Scope of work

In order to determine what work might be needed, a "stocktake" is first required to look at existing knowledge and models and how they could be refined (for example, updating with latest regional climate change projections[2]). This includes looking at the existing knowledge base and any current models (and their outputs), unpacking what they do and don't do and recommending opportunities for improvement or refinement that would assist the Whaitua with setting water quantity objectives and abstraction limits, and that could be completed within the timeframe noted above.

This stocktake was limited to what GWRC and Kāpiti Coast District Council (KCDC) have in-house, although it could include other relevant models that are easily discoverable and potentially accessible. Further, the scope would need to cover both groundwater and surface water hydrology. It is anticipated that the outcome would be recommended options as to what further work/model refinements should be done to assist with the Whaitua decision-making process, including likely scope, timeframe and costs of any such recommended work.

To meet the objectives of the stocktake, the following scope of work was undertaken:

- A project kick-off meeting with relevant stakeholders (GWRC/KCDC).
- Review of available existing models and resources, including:
    - Assessment of model suitability for Whaitua assessment objectives.
- Production of this brief technical memo outlining the models/resources reviewed, and recommendations for further assessment to support the Whaitua process. This technical memo will form part of any final reporting for additional modelling work undertaken.
- A technical workshop to present the findings of the stocktake and discuss recommendations and scope for the next stage of work.This may be defered until further model evaluation has been completed.

3 Model assessment objectives

The overall objective is to determine best management regimes and test abstraction limits and minimum flows for the Waikanae and Ōtaki rivers. Issues of particular interest include groundwater-dependent ecosystems, spring-fed streams and wetlands, as well as groundwater flooding. The assessment methods should provide information the hydrological and hydrogeological behaviour within the Kāpiti region, including:

- Groundwater levels
- Surface water flows
- Groundwater-surface water fluxes.

[1] www.mfe.govt.nz/fresh-water/freshwater-acts-and-regulations/national-policy-statement-freshwater-management.

[2] www.gw.govt.nz/assets/Climate-change/Climate-Change-and-Variability-report-Wlgtn-Regn-High-Res-with-Appendix.pdf

Any numerical models used during the assessment should have the ability to provide outputs of the data listed above ('state variables').

For the purposes of the Whaitua process, the modelling will focus on generational (i.e., to 2050) and long-term (i.e., to 2100) changes to the following:

- Groundwater abstraction / water demand
- Surface water hydrology (i.e., flood frequency)
- Groundwater/aquifer recharge (including land use change, climate change)
- Climate change effects (i.e., sea level rise, saline intrusion)
- Changes in stormwater management (i.e., rainwater tanks, soakage disposal)
- Water quality (saline intrusion).

Factors that are relevant to changing hydrological regimes but that will not be included in this study include: Surface water flow effects (including river flooding, backwater effects), and groundwater and surface water quality (including solute transport, algal blooms).

The suitability of models for use as part of the Whaitua process will be informed by the ability of the model to make state variable predictions at points of interest based on scenarios (and associated parameters) described in the following section. The modelling is intended to support high-level Whaitua decision-making. As such, model operability and spatial coverage may be prioritised over model precision, particularly when making relative comparisons of scenario model outputs.

Points of interest

Where possible, relative differences in Indicators of Hydrological Alteration (or similar flow statistics) used in Keenan (2020[3]), should be assessed at the following points of interest:

- Groundwater-dependent ecosystems and wetlands. These have been mapped previously in the Whaitua area by Boffa Miskell (refer Figure 1). The modelling will focus on conditions in the wetlands considered 'Likely Nationally or Regionally Significant' in that figure. Changes to these features will be quantified based on hydraulic head and groundwater-surface water fluxes (where modelled).
- Groundwater observation points (i.e., hydraulic head).
- River and stream reaches – fluxes between groundwater and surface water will be quantified for individual stream segments.

Therefore, the models used in the assessment should have the ability to provide model outputs at these locations.

[3] Keenan L 2020. *Hydrological impacts of water allocation in major rivers of Whaitua Te Whanganui-a-Tara.* Prepared for Greater Wellington Regional Council by Awanui Science.

Likely Nationally or Regionally Significant	Significant at District Level / May Be Regional Significant w/ Additional Investigation	Limited Value / May Be Significant at District Level	May Not Be Significant or Insufficient Information
Muaupoko Swamp Forest	El Rancho Wetlands	Andrews Pond	Crown Hill Manuka Bush
Nga Manu Wetland	Osbournes Swamp	Kaitawa Reserve Swamp Forest	Kāpiti Airfield Raupo Swamp
Raumati South Peatlands B	Pekapeka Road Swamp	Kāpiti Airfield Wetland A	Kāpiti Airfield Wetland B
Te Hapua Swamp Complex A	Ratanui Swamp	Kowhai Stream Mouth (Hadfields)	Kāpiti Road Wetland A
Te Hapua Swamp Complex D	Raumati South Peatlands A	Ngarara Bush	Lions Down Bush
Te Hapua Wetland Complex D	Te Hapua Wetland Complex B	Ngarara Road Wetland D	Ngarara Lake
Te Harakeke Wetland	Te Hapua Wetland Complex C	Otaihanga Landfill South	Ngarara Road Wetland A
Waikanae Saltmarsh	Tini Bush	Poplar Ave Wetland	Ngarara Road Wetland B
	Waimeha Lagoon – Victor Weggery Reserve	Te Hapua Swamp Complex E	Ngarara Road Wetland C
		Te Hapua Swamp Complex F	Otaihanga Landfill Central
		Turf Farm Dune Forest	Otaihanga Landfill North
		Unsurveyed site 5	Reikorangi Road Bush D
		Waimanu Lagoons	Unsurveyed Site 11
		Waimeha Stream Mouth	Unsurveyed site 12
		Wharemauku Stream Mouth	Waikanae River Oxbow

Figure 1: Ranking of Kāpiti Coast Wetlands by Boffa Miskell. (Source: Beca, 2017).

4 Previous modelling investigations

Numerous hydrological/hydrogeological investigations have been undertaken in the Kāpiti region for a range of applications, including water supply, transport infrastructure and flood hazard planning. The most recent (and potentially relevant) hydrogeological studies include:

- **'GWRC Model':** Gyopari M, Mzila D and Hughes B. 2014*. Kāpiti Coast groundwater resource investigation: Catchment hydrogeology and modelling report*. Greater Wellington Regional Council, Publication No. GW/ESCI-T-14/92, Wellington.
- **'RRwGW Model':** CH2M Beca Ltd. 11 August 2017. *River Recharge with Ground Water – Updated Groundwater Modelling 2017.* Prepared for Kāpiti Coast District Council. Ref: NZ1-14340712-50 0.50. The numerical groundwater model is described in Appendix B of this report.

Both models are three-dimensional, transient, numerical groundwater flow models built using the finite-difference model code MODFLOW. They incorporate geological information from boreholes and conceptual geology as separate hydrogeological zones, with the parameters of these zones calibrated using the PEST parameter estimation software to get a 'best fit' to groundwater level observations across the model domain.

A summary of differences the two models is provided in the following table:

Item	GWRC Model	RRwGW Model
Model domain	This model covers the entire Kāpiti Whaitua region	This model extends from Raumati South to just north of Peka Peka Road (Raumati and Waikanae groundwater zones)
Time discretisation	19 years (July 1992 to 2011), weekly stress periods	36 years, weekly stress periods

Item	GWRC Model	RRwGW Model
Land surface recharge	Calculated using the Rushton method[4], incorporating gridded climate data (rainfall and potential evapotranspiration) and assumed soil and runoff properties	Calculated based on observed rainfall at a single location and assumed soil and land use recharge factors
Streams/Rivers	Uses the *Streamflow routing 1 (STR)* model package[5], that allows water to be exchanged between the stream and groundwater system, and the transfer of surface water to downstream nodes, where it can re-enter the groundwater system.	Uses the *River (Riv)* model package, that allows water to be exchanged between the stream and groundwater system. However groundwater exfiltrated into the river nodes is removed from the system[5].
Wetlands	Selected wetlands are modelled using the *Drain (DRN)* model package, where groundwater may be discharged from the system, dependent on groundwater head. These fluxes can quantified as model outputs.	Groundwater conditions at wetlands have been considered based on hydraulic head outputs at these locations only.
Calibration	Transient calibration to four years of groundwater level records, then verification to 19 years of groundwater level records	Transient calibration to eight years of transient groundwater level records
Model availability	GWRC and GNS have provided original Visual MODFLOW files to be used in the modelling process	Beca have offered to provide selected model inputs and outputs to assist with the modelling efforts

5 Model assessment options

To achieve the Whaitua modelling objectives, we propose the following options:

1 Further analysis of existing model inputs and outputs.

2 Additional scenario modelling using existing GWRC model – abstraction only.

3 Additional scenario modelling using converted GWRC model.

These options are described in the following sections, and have been summarised in the table below:

Option (Indicative cost, timeframe)	Pros	Cons
1. Further analysis of existing model inputs and outputs	• No additional model runs required. • The RRwGW model already considers multiple groundwater abstraction scenarios.	• Limited to existing model inputs and outputs (i.e., no consideration of the hydrological changes listed in Section 3).

[4] Rushton, K.R., Eilers, V.H.M. and Carter, R.C., 2006. Improved soil moisture balance methodology for recharge estimation. Journal of Hydrology, 318(1-4), pp.379-399.

[5] USGS, 2018. Head-Dependent Flux Boundary Packages, in Online Guide to MODFLOW.

Option (Indicative cost, timeframe)	Pros	Cons
($7,000 - 10,000, 1 month)		• Only one scenario output for the GWRC model. • Parameterisation of recharge and shallow groundwater features in the RRwGW model may not be as robust as in the GWRC model • RRwGW abstraction scenarios are only limited to the Raumati and Waikanae groundwater zones
2. Additional scenario modelling using existing GWRC model – abstraction changes only ($15,000 - 20,000, 2 months)	• The GWRC model's parameterisation of surface features and recharge may be considered more realistic; therefore, the scenario model outputs may be a better representation of future hydrological conditions. • Use of similar abstraction rates in both the GWRC and RRwGW models will allow for multi-model comparisons, and give an indication of predictive uncertainty. • 'Naturalised' flows can be modelled by removing abstraction in additional model scenarios. • Limited additional modelling and scenario development will be required.	• Scenario modelling limited to just changes in abstraction. •
3. Additional scenario modelling using converted GWRC model ($30,000 - 40,000, 3-4 months)	• Scenarios can be developed to specifically address potential hydrological changes in the catchment, as agreed with the Whaitua technical leads. • The GWRC model's parameterisation of surface features and recharge may be considered more realistic (refer above). • The existing GWRC model would be converted into a more inter-operable format, allowing it to be used for other applications (e.g., ecological assessments). • 'Naturalised' flows can be modelled by removing abstraction in additional model scenarios. • Parameter sensitivity analysis can be undertaken to see determine uncertainty in the predictions.	• Additional modelling and scenario development will be required (higher costs).

The following project workflow for the options above is proposed:

1 Model scenario development (Options 2 and 3 only)
2 Run and process models (Options 2 and 3 only)
3 Model output analysis and visualisation.
4 Reporting.

Model choice

Based on a review of the available models, we propose to use the GWRC Model to undertake additional scenario modelling to support the Kāpiti Whaitua process. Advantages of using this model for scenario analysis include:

- Coverage of the entire region of interest.
- Representation of stream and wetland features (and relevant model outputs, i.e., fluxes) using appropriate model packages.
- The spatially resolved recharge calculation method that is more suitable for shallow hydrological processes.

Reporting

The project team will meet regularly and as required to discuss the progress of the modelling process. Where appropriate, members of the project team may attend other meetings/workshops (i.e., Whaitua meetings) to assist with understanding of the modelling process and interpretation of the results.

Final model scenarios and results will be presented in a technical report, to be produced by Jeremy Bennett (T+T), with input from other members of the project team.

6 Further analysis of existing model outputs

This would comprise analysis of the existing inputs and outputs from the GWRC and RRwGW models. Flow statistics will be derived from the inputs and outputs of both models, particularly for the points of interest outlined in Section 3. As both models are transient, hydrological changes can be estimated based on the spatial and temporal distribution of flows and fluxes throughout the transient model period.

The effect of hydrological changes will need to be extrapolated based on the existing models' inputs/outputs using assumed relationships between changes and effects. The RRwGW model already includes additional abstraction scenarios that will be useful for this option; however, this model only covers the Raumati and Waikanae groundwater zones and has not been developed to focus on shallow groundwater effects.

The estimated cost of this further analysis would be in the order of $7,000 - $10,000 and would take around a month to complete, pending the receipt of selected RRwGW model inputs and outputs (to be requested).

7 Additional scenario modelling using existing GWRC model

This option would involve the adaptation of the existing GWRC model to match the abstraction model scenarios undertaken with the RRwGW model. This would comprise a limited number of additional GWRC model runs undertaken using the existing Visual MODFLOW model files with modified abstraction rates.

The outputs of these models should provide insight into the effects of changing abstraction on the hydrology of the catchment. By using similar abstraction rates in the GWRC model as those used in the RRwGW model, a multi-model comparison can be undertaken for the Waikanae and Raumati groundwater zones. This should provide some additional information regarding the effect of model uncertainty on the predictions.

The estimated cost of additional scenario modelling for changes in abstraction only is between $15,000 - $20,000 and could take up to two months to complete. Initial scenario results could likely be provided to the Whaitua technical team within six weeks of commencing with this work.

8 Additional scenario modelling using converted GWRC model

This option would allow for a greater range of hydrological changes, and their effects (see Section 3), to be modelled. However, it would require additional model and scenario development time.

To complete additional scenario modelling, the following modelling activities are proposed:

1. Model conversion
2. Model scenario development
3. Run and process model scenarios.

These activities are outlined in the subsections below.

The estimated cost of additional scenario modelling for a range of hydrological changes is between $30,000 - $40,000 and could take three-four months to complete. Initial scenario results could likely be provided to the Whaitua technical team within six weeks of commencing with this work.

Model conversion

The item will comprise the conversion of the GWRC model to ensure that is able to meet the modelling objectives outlined in Section 3. The GWRC model was developed in a legacy version of Visual MODFLOW (a graphical user interface for the MODFLOW model software) and will require conversion into current modelling software formats.

The proposed scope of work for this stage includes:

- Conversion of the existing Visual MODFLOW and associated model files into format suitable for use with the FloPy python package for MODFLOW modelling. This will allow the GWRC model to be used more easily for scenario analysis and other purposes.
- Limited model runs to ensure the outputs of the converted models are in working order, consistent with existing model outputs, and suitable for model scenario analysis.

No recalibration of the model would be undertaken.

Model scenario development

To aid with the Whaitua decision-making process, we propose the use of a limited number of model scenarios. The scenarios may comprise an ensemble of models that explore parameter sensitivity, plausible hydrological scenarios, or a combination of both. The use of of model scenarios allows for relative comparison of different management regimes and the impact of uncertain climate and/or hydrological changes.

Each model scenario could comprise a combination of abstraction and forcing changes, including:

- Groundwater abstraction, based on with projected demand and management regimes proposed under KCDC's River Recharge with Groundwater (RRwGW) scheme.
- Changes in climate (total/extreme rainfall, evapotranspiration) based on a report[6] undertaken by NIWA for GWRC. These changes will affect land surface recharge and river flows.
- Changes to 'diffuse' groundwater impacts, including domestic well takes and low impact solutions from development (i.e., soakage, rainwater tanks).

For each scenario, the predicted impacts of climate change will be modelled based on the four representative concentration pathways (RCPs) outlined in the NIWA climate change report[6].

[6] NIWA, June 2017. Climate change and variability – Wellington Region. Prepared for GWRC. Maps accessed at https://mapping1.gw.govt.nz/gw/ClimateChange/

As outlined in Section 4, the model will be used as a basis for testing a range of scenarios. These scenarios will be developed in conjunction with the GWRC technical leads on the Kāpiti Whaitua committee, Mike Harkness and Rebecca Morris.

Selected long-term effects and associated numerical model parameter amendments required are listed in the table below:

Long-term effect	Model parameter change
Groundwater abstraction / water demand	Well abstraction rates based on water demand estimates predicted in the RRwGW model reporting
Groundwater recharge	Recharge calculations from estimates of changes to total rainfall and evapotranspiration predicted by NIWA[6]
Sea level rise	Changes to the constant head boundary condition in offshore model cells
Changing hydrology in the Waikanae and Ōtaki rivers	Amendment of the river boundary conditions to reflect predicted changes in flows.

Run and process model scenarios

Each model scenario will comprise the existing calibrated model parameters (i.e., aquifer and land surface recharge parameters), and the amended model scenario parameters/boundary conditions. A steady-state model with average boundary conditions will be run to get initial hydraulic heads. The transient model will then be run for the 19-year GWRC model period (July 1992 to 2011) with weekly stress periods. It would be possible to extend the model period to be consistent with the period of interest (i.e., 2030-2050, 2051-2100), but it is likely that critical hydrological behaviour will be captured in the shorter model period.

Once the scenarios have developed, the model scenario input files will be created and the model ensemble will be run. Model results will be post-processed, including data visualisation that will assist the Whaitua committee in their decision-making. We expect that additional model scenarios may be developed based on the results of preliminary modelling. Use of the FloPy structured modelling framework will facilitate additional model runs.

We also propose to undertake a comparison of model outputs between the GWRC model and the RRwGW model based on a consistent model input. This comparison will be for selected locations of interest, and based on consistent boundary conditions (i.e., groundwater abstraction). The model comparisons will provide an additional indicator of uncertainty between model predictions.

9 Project team

Name	Team role	Organisation	Contact
Penny Fairbrother	Project manager	GWRC	Penny.Fairbrother@gw.govt.nz
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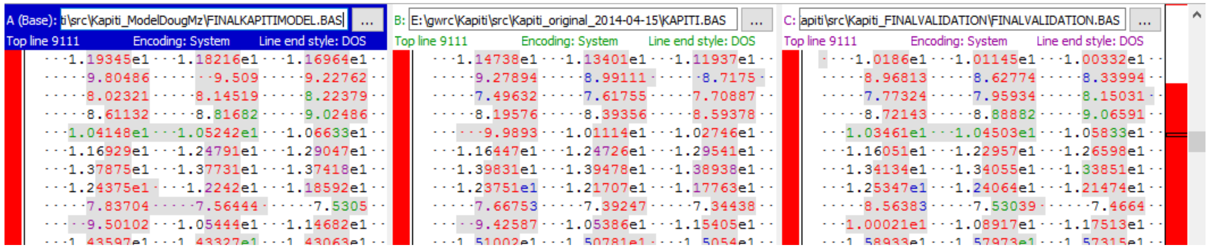
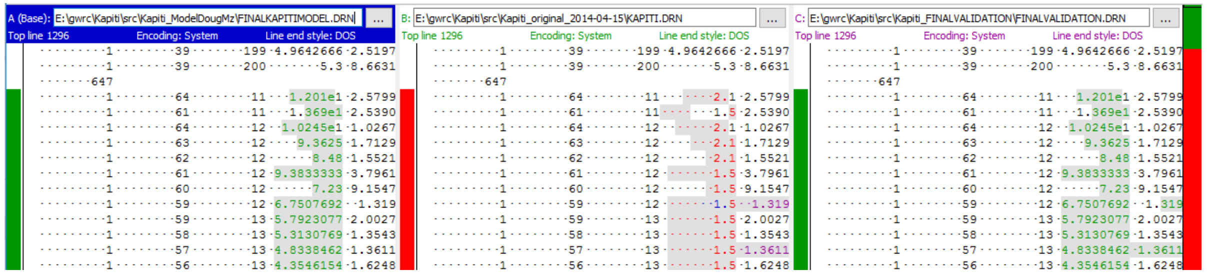
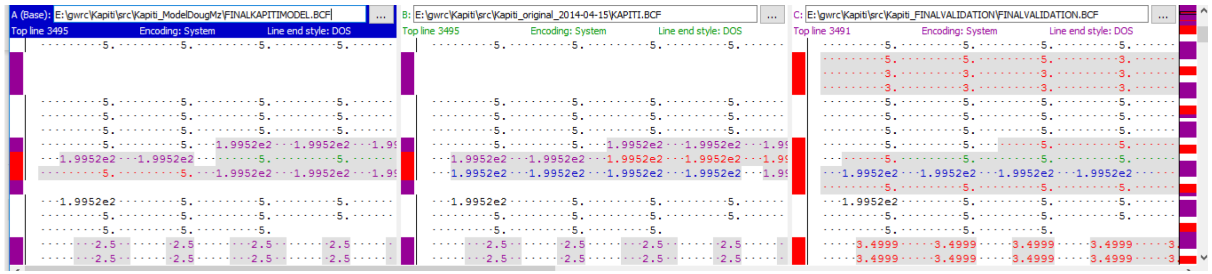
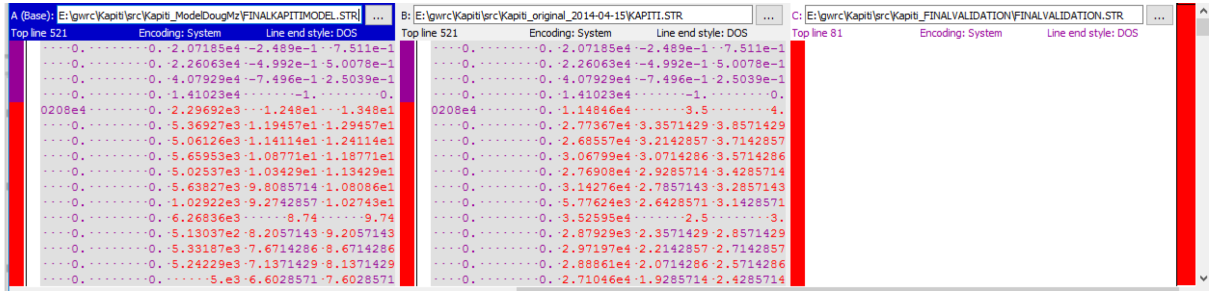
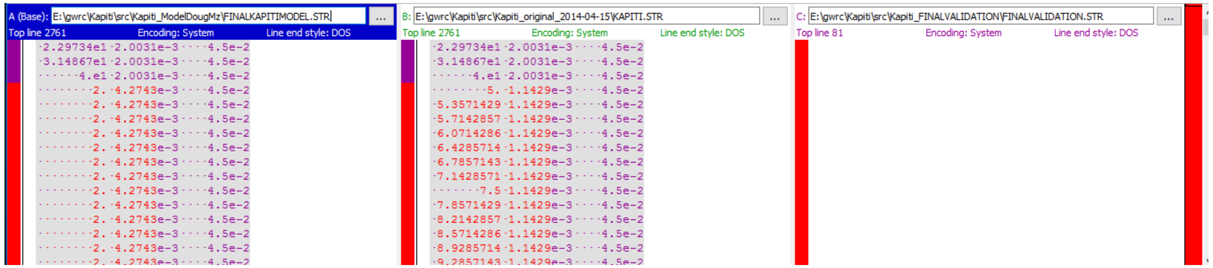
Jeremy Bennett	Groundwater modeller	Tonkin & Taylor	jbennett@tonkintaylor.co.nz

Appendix B: Model conversion

- **B1: Model source file differences**
- **B2: Model validation**

B1 Model source file differences

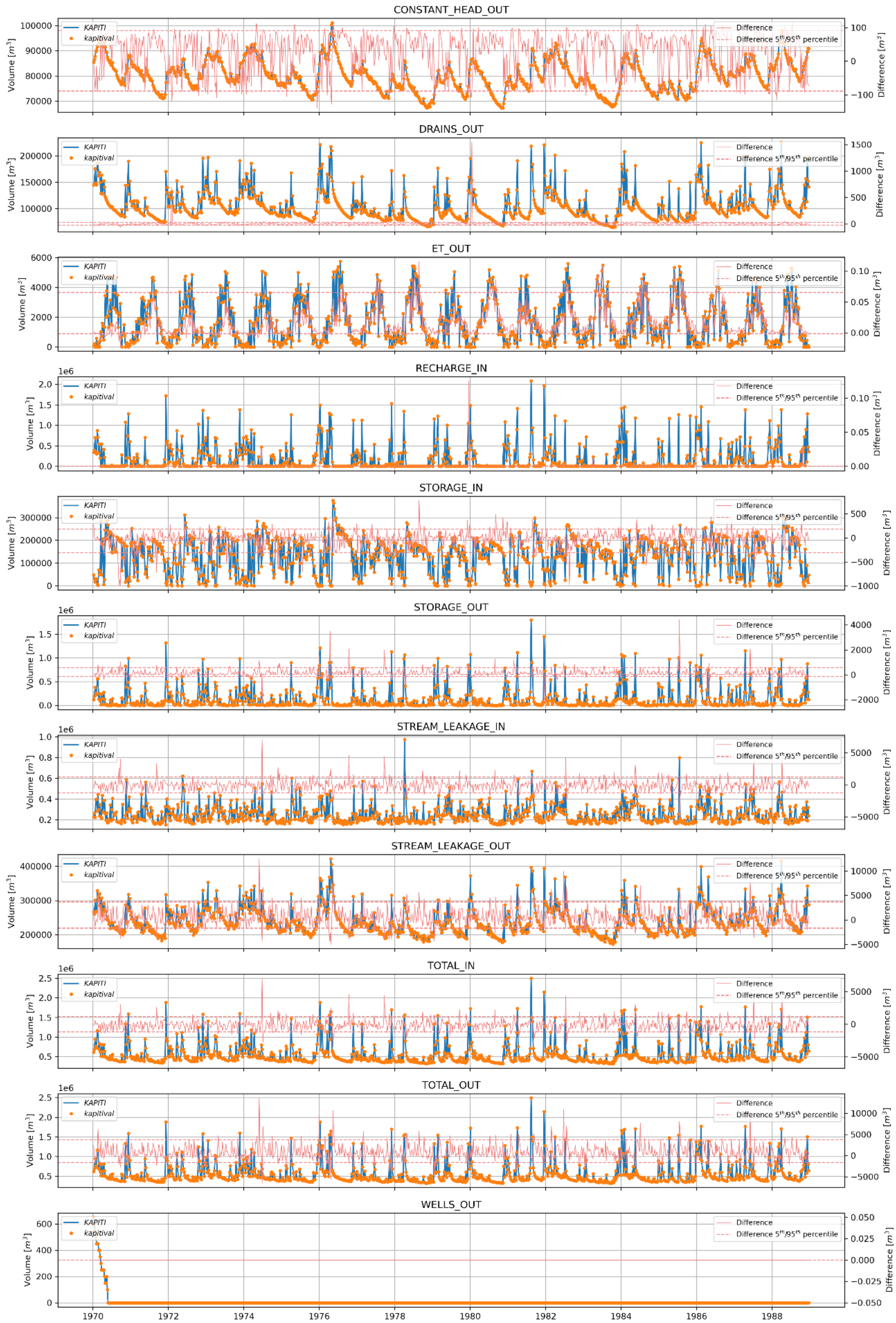
MODFLOW package	Difference to *FINALKAPITIMODEL*		Additional information
	KAPITI	***FINALVALIDATION***	
Discretisation (DIS)	No difference (15/4/2014)	Fewer time steps (26/9/2012)	1/10/2013
Basic (BAS)	Some differences in starting heads, generally within 0.3 m		
Drain (DRN)	Drain elevation is **very** different for 123 of 648 locations by up to 7 m	Fewer time steps	
Evapotranspiration (EVT)	No apparent difference		
Block-centred flow (BCF6)	No *wetdry* layer, minor differences in *storage* values	*Storage*, *vcont*, *wetdry* values different	
Recharge (RCH)	No difference (binary equal)	Fewer time steps	

MODFLOW package	**Difference to *FINALKAPITIMODEL***		**Additional information**
	KAPITI	***FINALVALIDATION***	
Stream (STR)	Differences in conductance, stream top/bottom elevations for some locations Difference in width, slope and roughness	Differences in conductance, input flows Missing *drain* values	 
Wells (WEL)	**Different**	**Different**	

B2 Model validation

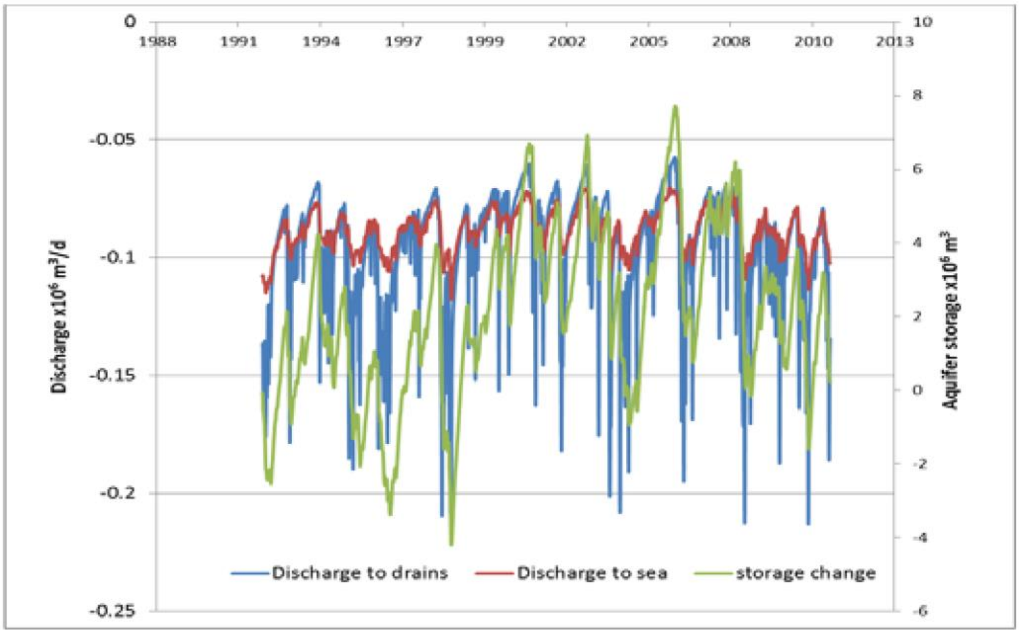
B2.1 Comparison of water budget time-series

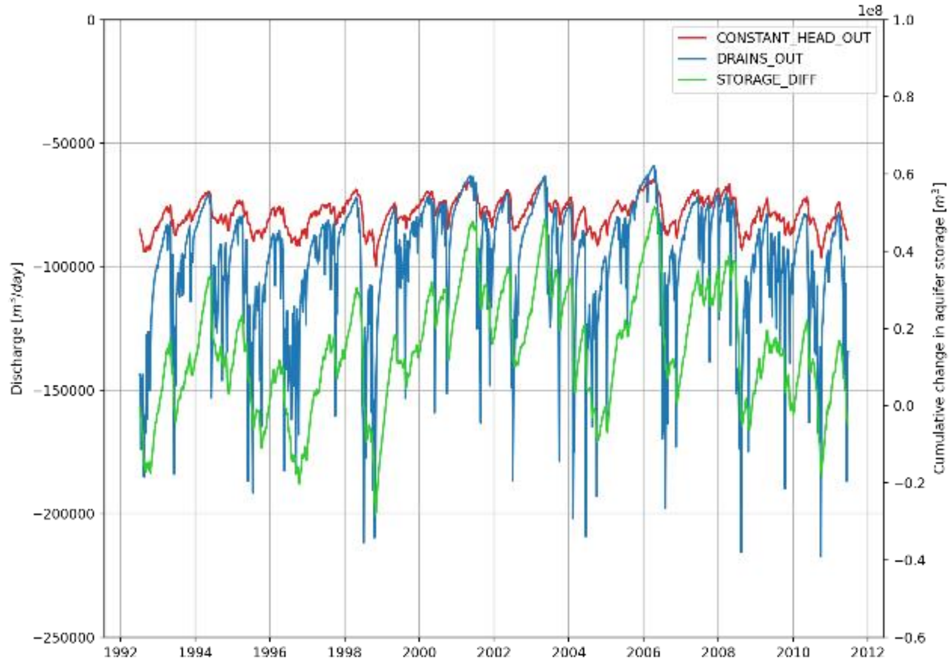
Comparison of water budget time-series between *Kapiti* and *kapitival* models. Note that right y-axis scale is different to left axis.



B2.2 Comparison of simulated catchment water balances

The figure below depicts a comparison of simulated catchment water balances from the original GWRC model[1] (Fig.78) and the converted model files





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