Heretaunga Aquifer Groundwater Model

Scenarios Report

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Environmental Science - Groundwater

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Executive summary

This report documents the scenarios that were run as part of a groundwater modelling study of the TANK catchments in the Hawke's Bay region of New Zealand. This report accompanies a Heretaunga Aquifer Model Development Report (Rakowski & Knowling, 2018), which described model set-up and calibration.

Key findings

The key findings of the modelling scenarios are:

Increases in groundwater pumping in the past, in particular irrigation pumping, have resulted in declines in groundwater levels and substantial reductions of flows in rivers and streams, especially during summer. Such declines are an expected response of the groundwater system to the additional pumping.

However, there are signs that the aquifer is reaching a new equilibrium and further substantial reductions in river flows will not continue, provided that the pumping abstractions do not increase further. Further increases in groundwater abstraction would result in further decline in groundwater levels and reduction in stream flows.

Uncertainty analysis was undertaken on this model, and it confirms these conclusions.

Modelling of mitigation options indicates that the mitigations used in the past to protect stream flows and groundwater levels, such as pumping bans and managed aquifer recharge provide only limited benefit. Stream augmentation of lowland streams is likely to be an effective measure to partially mitigate depletion resulting from current water use, but only as a short term measure during dry periods. It is not sustainable in the long term, and will not be enough if usage increases.

Additional detail on the model set up and on scenarios is summarised below.

Conceptual setting

The Heretaunga Plains overlie an extensive alluvial formation, on the east coast of the North Island of New Zealand. The Heretaunga Aquifer is a deep sedimentary basin underlying the Heretaunga Plains.

The Heretaunga Plains and surrounding valleys have a complex network of rivers, streams and drains that interacts with the underlying Heretaunga Aquifer System. The Ngaruroro River is the largest river in this network and originates in the mountains outside the Heretaunga Plains. As the Ngaruroro River enters the plains it begins losing water. These losses provides around two thirds of the recharge to the Heretaunga Aquifer System. The remaining groundwater recharge is from rainfall on the land surface.

Local springs, spring fed streams and artificial drains receive discharge from the aquifer. Groundwater pumping is a significant component of the water budget for the Heretaunga Aquifer System.

Groundwater model

MODFLOW-2005 was used to simulate groundwater flow under steady state and transient conditions. The model calibration covered the period from 1980 until 2015, with a monthly stress period. The model area is discretised into a 100 m x 100 m uniform grid, containing 87,594 active cells. The aquifer was discretised vertically into two model layers. Layer 1 represents the combined Holocene gravels and the underlying Last Glacial gravels. Layer 2 represents the deeper deposits of the main Heretaunga Aquifer, to a maximum depth of about 250 m.

Model boundary conditions include rivers, streams and springs, a coastal boundary, surface recharge and drainage, and groundwater pumping. The model represents spatial variability in the aquifer parameters.

Estimation of model parameters through calibration was performed using the industry-standard parameter estimation software PEST. Overall, more than 800 parameters and more than 6,000 observations were used in the model calibration. Due to long model run times and a large number of parameters, PEST runs had to be conducted using a high performance computing facility. The final calibrated model is able to replicate the observed dynamic of groundwater system (i.e. match seasonal and long term groundwater level changes, as well as observed spring flows and river losses). The model performance is suitable for simulating the effects of groundwater pumping on river flows, along with seasonal and long term changes of groundwater levels.

Scenarios report

This report includes descriptions of the prediction scenario methodology used (Section 2), descriptions of scenarios run (Sections 3 to 5), and uncertainty analysis (Section 6). The following sections summarise the scenario assessment.

Historical scenarios

The primary purpose of historical scenarios was to estimate the impact of current and past groundwater pumping on the aquifer, including effects on river flows and groundwater levels. Groundwater pumping (or abstraction) forms a major part (about 30% on average) of the Heretaunga Aquifer groundwater budget and has increased significantly since 1980. In particular this increase in abstraction has occurred for irrigation in summer. The historical scenarios were run with monthly stress periods from 1980 until 2015, with and without groundwater pumping.

Modelling indicates that river losses have increased in all major rivers analysed (the Ngaruroro, Tukituki, and Tūtaekurī rivers), and spring gains have declined in lowland streams (the Irongate, Karamu, Karewarewa, Mangateretere, Raupare, Tūtaekurī–Waimate streams). The increased groundwater pumping has caused reduced streamflow, particularly during summer. Modelling indicates that the most affected surface water body is the Ngaruroro River, with about 50% loss (depletion of about 1000 L/s) during the driest conditions. The Tukituki River and the Tūtaekurī River have been less affected.

A very large effect is also predicted in the spring-fed Karamu Stream, with over 1000 L/s depletion (over 60% of flow). However, in relative terms the largest loss in spring-fed streams was predicted in the Karewarewa Stream (more than 90% of natural flow - equivalent to about 340 L/s). Other streams also lost a significant portion of flow (between about 40% and 80%).

Modelling was also used to quantify the decline in groundwater levels as a result of groundwater pumping. The decline is generally larger in summer periods (on average about 2.5 m) than during winter (about 1 m). The areas most affected by drawdown are near large public water supply takes in Napier and, to a lesser degree in Hastings, where drawdown can exceed 4 m in the summer.

An additional scenario was used to estimate the effect of individual user groups on streamflow, which was achieved by switching off individual user groups and comparing modelled streamflow. Overall, about two thirds of the depletion effect in the summer can be attributed to irrigation pumping. Due to time delays associated with the relatively slow propagation of the drawdown that causes stream depletion, some of this effect can be seen long after the summer irrigation stops and sometimes continues into winter. Public water supply and industrial takes have a relatively constant effect on streamflow throughout the year.

Future scenarios

Several model scenarios were set-up for simulations 100 years into the future:

i. Repeated conditions

The aim of this scenario was to establish whether further decline in water levels and streamflow would occur if the current level of groundwater use and climate remained unchanged. Results indicated that further decline in water levels and streamflow would not occur if groundwater use was maintained at current levels, indicating that a new dynamic equilibrium had been established under these conditions.

ii. Increased pumping

This scenario was based on "repeated conditions" (ie, conditions modelled were the same as historical conditions), except groundwater pumping was assumed to increase in the future. The rate of increase was based on the observed rate of increase in the past. Although the modelled water use scenario may have been extreme, it is a useful indication of what could occur if the current increasing trend of abstraction continues.

This scenario results in significant future decline in streamflow and groundwater levels. This would lead to drying out of some streams and rivers, including the Ngaruroro River. Groundwater levels would also be affected, with additional drawdown of up to 5 m predicted. This magnitude of drawdown could lead to issues with saline intrusion, due to disappearance of artesian conditions near the coast. These results suggest that increased groundwater pumping under current climatic conditions is not sustainable.

iii. Dry climate scenario

The dry climate scenario repeats conditions (groundwater pumping, recharge, river levels) from the dry year 2012-2013 every year for the next 100 years.

Results indicate that when dry climatic conditions are repeated every year, groundwater levels and river flows remain at low levels, but there is not a long term declining trend, provided the groundwater pumping continues at the rates applied in 2012-2013 (90 million m^3/ year), which is about 20% higher than average pumping between 2005-2015 (76 million m^3/ year).

iv. Sensitivity to increases in pumping

To estimate the sensitivity of the aquifer to increases in pumping, a series of scenarios was run, with each scenario including a small increase in pumping, and the results were assessed in terms of trends in groundwater levels and groundwater contributions to surface water.

Results indicate that even a small increase in pumping will have negative effects on the surface water – groundwater exchange flux (and consequently on stream flows). A large reduction in pumping would be required to generate a meaningful improvement in lowland streamflow. Sensitivity of groundwater levels to pumping was estimated in aquifer specific capacity terms to be about 0.35 m water table decrease per 10% increase in pumping.

Overall conclusion from historical scenarios and future scenario

The historical scenario identifies that observed declining groundwater trends are a result of increasing groundwater abstraction. Modelling also indicates that surface water flows have been reduced by groundwater pumping. The future scenario with "repeated" conditions indicates that maintaining the current level of groundwater abstraction is expected not to result in further declines, under the current or the dry climatic scenarios. This means that the aquifer is currently at a dynamic equilibrium and groundwater mining would not occur if pumping was not permitted to increase. The current abstraction level may be considered "safe" in the sense that maintaining this abstraction level will not lead to further depletion of the aquifer under current or dry climatic scenarios. The observed declining trend in groundwater levels is caused by increases in pumping, rather than by slow mining of the aquifer from constant levels of pumping. Some of the trend observed in last 20 years can be attributed to the closing down of the Roy's Hill managed aquifer recharge scheme in 2008.

Additionally, this means that further increases of groundwater abstraction will lead to significant declines in groundwater levels and streamflow under current or dry climatic conditions, as demonstrated by the model scenarios. This means that, although the present aquifer abstraction is safe, significant future increases in pumping may lead to serious depletion of the aquifer.

Mitigation scenarios

Several scenarios were designed to assess the feasibility of various management options (mitigations). These scenarios included Managed Aquifer Recharge, Stream Augmentation, Pumping Bans, and combinations of these.

i. Managed Aquifer Recharge

A Managed Aquifer Recharge (MAR) scheme in the Heretaunga Plains was commissioned in 1988, to transfer water from the Ngaruroro River to recharge ponds near Roy's Hill. The purpose of the scheme was to prevent decline of groundwater levels in the Heretaunga Aquifer, although the effectiveness was doubted at the time, and the project was abandoned in 2008.

An early version of the model did not include the MAR scheme, and as a result the simulation of that region did not match observed data. When the MAR was incorporated, the model was able to represent water level dynamics in this area more effectively. In particular, modelled groundwater levels were more representative of the groundwater declines observed after the MAR scheme was discontinued.

Simulations with and without the MAR replenishment indicate that the scheme generated some local changes in groundwater levels and minor increases in spring flows, particularly during winter. Overall, the modelling indicates that benefits from the Roy's Hill MAR operation were relatively small. However, model calibration indicates that the model underestimates the effect of the MAR scheme on water levels, so it may also underestimate the effect of spring flows. Further refinement of model calibration, especially in the Roy's Hill area might be necessary to improve model predictions related to MAR, if there is a request to investigate this mitigation option further, despite modelling results indicating its limited effectiveness

ii. Effects of stream augmentation

Streamflow augmentation from groundwater involves pumping groundwater and discharging it to the stream to enhance streamflow. This strategy may be used to temporarily increase (or restore) streamflow, for example during periods of drought. However, if the augmentation flow is very large or is maintained for a long period, negative consequences may occur, such as lowering of groundwater levels (due to pumping) and decreased spring discharge (due to lower groundwater levels) in the augmented stream and potentially other streams.

A model scenario was set up to simulate augmentation of several streams (Raupare, Irongate, Karamu, Mangateretere, Karewarewa, Tūtaekurī–Waimate). Augmentation of the Ngaruroro River was not included in model simulations, as it would require excessively large (and probably infeasible) augmentation flows of over 700 L/s. Trigger flows (river flow below which augmentation is required) were proposed, and augmentation rates were calculated using flow records and trigger flows for the dry summer of 2012/2013. The largest augmentation rate is required for the Karamu (350 L/s), followed by the Irongate, Karewarewa and Mangateretere (about 80 L/s each) and the Raupare with about 6 L/s. No augmentation would be required for the Tūtaekurī-Waimate.

Overall, augmentation is effective in improving flows, except in the Karewarewa Stream, where augmentation is ineffective. However, negative effects of augmentation are predicted for all streams. The Ngaruroro River is not subject to augmentation, but some depletion of the Ngaruroro River is predicted to occur as a consequence of abstraction for lowland streamflow enhancement elsewhere. However, since this effect is relatively small in comparison to Ngaruroro River flow, it may be acceptable for stakeholders.

Augmentation is likely to be effective as a short term mitigation measure for low streamflows that are depleted from current groundwater use. However, augmentation is unlikely to be effective for mitigating the effects of increased groundwater allocation. Furthermore, selection of trigger flows should be balanced with the negative effects of augmentation resulting from higher trigger flows.

iii. Pumping bans

Groundwater pumping bans are currently used in the Heretaunga Plains to manage flow in surface water bodies during low flow periods. Groundwater takes that are currently classified as stream depleting are required to stop pumping when flow in the stream or river is less than a prescribed level (trigger flow, or cease take flow).

A scenario was designed to identify the benefit that these pumping bans have on river flow. The impact was estimated by running a model with and without a pumping ban and comparing the calculated interchange flux between surface water and groundwater from each model run.

Results indicate that pumping bans do generate some improvement of flow in the rivers and streams, but the benefits are relatively minor. This is mainly because pumping bans reduce total groundwater abstraction by only about 10%, and it takes time for pumping bans to manifest as increased streamflow.

The modelling demonstrated that the detrimental effects of pumping on a surface water body is not limited to pumping near the stream or river, but is caused by the cumulative effects of pumping from the entire aquifer over the long term. Consequently, protecting a river by pumping bans only near the river and perhaps only for a short term, as currently takes place in the Heretaunga Aquifer, is not a sufficient solution to mitigate stream depletion. Also, currently the burden of protecting streamflow lies with a relatively small number of groundwater users, even though the flows are affected by a much larger number of groundwater abstractions.

iv. Management scenarios

Thirteen management scenarios were run to investigate the effect of various management options for groundwater and surface water takes on river flow during a 17 year period (2015 to 2032). This was achieved by linking the MODFLOW model with a surface water SOURCE model. Scenarios required the use of daily stress periods.

Scenarios were defined using pumping assumptions (no pumping, estimated demand, maximum allocation for surface water), different ban triggers, different stream depletion management zones (current zone and new proposed zone 1), and the presence of augmentation.

Overall, the results indicate a relatively small effect for the analysed pumping scenarios, and little differences in effects between scenarios. The largest differences in effects on flow appear to be due to changes to trigger zones from the existing zones to proposed "zone 1". There are some differences in timing of flow recovery, and some increase in river flow in Tūtaekurī River for different trigger levels, but these changes are relatively small compared to the flow.

Overall, the results indicate that at selected trigger flows, augmentation is likely to be required for a large part of most irrigation seasons and at non-trivial rates in most locations. There is a negative effect of augmentation pumping on flow for some rivers, in particular the Tukituki, Karamu and Ngaruroro, but this effect is relatively small compared to typical summer flows.

Uncertainty Analysis

During model calibration, model parameters are adjusted to obtain the best match to observed data. In reality, the calibration process is non-unique, in that there may be many combinations of parameters that can provide an acceptable match to the calibration dataset. A consequence of this is that predictions provided by the model are uncertain.

Uncertainty analysis has been undertaken using PEST to apply the Calibration Constrained Monte Carlo method, which allows for assessment of predictive uncertainty. The first step of the analysis was to generate a collection of model parameter "realisations", which are parameter sets that produce a satisfactory match to observations. A total of 107 realisations was generated in this step, and selected model scenarios (Historical Scenarios and Future Scenarios) were than run for each model realisation. The final step requires compilation and analysis of the results.

The analysis indicated some spread in all types of key performance indicators (stream depletion, water levels, drawdowns). The analysis also showed there is some inadvertent bias in the original calibration/verification model parameter dataset that results in over- or under-prediction of pumping impacts on some rivers, compared to other model realisations.

However, the uncertainty analysis does not modify the conclusions of the analysis. Even when including uncertainty and bias, the results indicate there is significant impact from groundwater pumping on streamflow and groundwater levels historically and in the future.

1 Introduction

1.1 Regulatory background

Hawke’s Bay Regional Council (HBRC) is a local government body in New Zealand that has responsibility for developing policies and regulatory plans to ensure the sustainable management of resources within the region. HBRC is reviewing policy underpinning management of land and water resources in the TANK catchments (the collective acronym for the **T**ūtaekurī, **A**huriri, **N**garuroro and **K**aramu catchments). This catchment-wide approach to managing water and land includes groundwater resources underlying the Heretaunga Plains, and is intended to result in changes to the HBRC Regional Resource Management Plan (RRMP).

1.2 Conceptual setting

Heretaunga Plains is an alluvial formation, located on the east coast of the North Island of New Zealand, with an area of about 300 km^2. The Plains have been formed by sediments deposited by the Ngaruroro, Tukituki and Tūtaekurī Rivers (Dravid & Brown, 1997). The Heretaunga Aquifer is a deep sedimentary basin underlying the Heretaunga Plains. The Heretaunga Aquifer System includes the main aquifer and several connected peripheral valley aquifers.

On the Heretaunga Plains and surrounding valleys there are a number of rivers, streams and drains forming a complex network that interacts with the underlying Heretaunga Aquifer System. The Ngaruroro River is the largest river in this network and originates in the mountains outside of the Heretaunga Plains. As the Ngaruroro River enters the plains it begins losing water, which provides around two thirds of recharge to the Heretaunga Aquifer System. The remaining groundwater recharge is from land surface recharge: vertical movement of water to the saturated zone caused by the interception of rainfall and the irrigation of land over unconfined parts of the Heretaunga Aquifer System.

There are also springs, spring fed streams and artificial drains that receive discharge from the aquifer. These interactions are very important for understanding water resources of the Heretaunga Aquifer System and have been described by Dravid & Brown(1997) and more recently by Wilding (2018).

1.3 TANK plan change

In 2012, HBRC established a large stakeholder group with about 30 representatives from the wider community, to agree on a framework for managing land and water resources of the TANK catchments. The Group has met regularly and has considered presentations on new science to improve understanding of the ways that land and water use affects the TANK area. At the heart of this work is the TANK Group's commitment to keep rivers running healthily; including the availability of water supply to homes, swimming, fishing, cultural values, crop security, industry and other uses for water.

1.4 Groundwater model

A key part of the science programme was the development of surface water and groundwater models for the TANK catchments, to allow technically defensible groundwater and surface water allocation limits to be established. Work on these components commenced in 2015 and included a MODFLOW groundwater model that was developed to simulate the Heretaunga Plains gravel aquifer system and associated surface water resources. Conceptualisation of the Heretaunga hydrogeological system, along with details on the construction and calibration of the groundwater model, have been described by Rakowski and Knowling (2018).

Description of groundwater model and model calibration

MODFLOW-2005 was used to simulate groundwater flow under steady state and transient conditions. The model calibration covered the period from 1 July 1980 until 30 June 2015, with a monthly stress period. The model covers the area of the Heretaunga Plains and surrounding river valleys that are considered to contain aquifers in hydraulic connection with the Heretaunga Aquifer. The total active area is 506 km^2, which is larger than the Heretaunga Plains area of 300 km^2 because the model area includes valley aquifers and the offshore part of the aquifer (to allow for assessment of saline intrusion risks). The model area is discretised into a 100 m x 100 m uniform grid. The grid consists of 302 rows and 501 columns and the domain contains 87,594 active cells.

The aquifer was discretised vertically into two model layers. Layer 1 represents the combined Holocene gravels (mainly fan gravels where present in the unconfined area) and the underlying Last Glacial Gravels. Layer 2 represents the deeper deposits of the main Heretaunga, to a maximum depth of about 250 m.

Model boundary conditions include rivers, streams and springs, which are represented using the “River” boundary condition (RIV), with the main rivers using a variable river stage height. The Coastal boundary was represented as a line of “General Head Boundary” (GHB) cells, representing the head-dependent flow conditions. Land surface rainfall and/or irrigation recharge is represented by the “Recharge” (RCH) boundary condition. Pumping from the aquifer was simulated using the MODFLOW “Well” package (WEL). Diffuse drainage in the confined aquifer was represented using the “Drain” package (DRN).

Estimation of model parameter values (Kh, Kz, Sy, and Ss) and their spatial variability was performed using the industry-standard parameter estimation software PEST, applying the Pilot Points method to achieve a history-match to historical monitoring data. Overall, more than 800 parameters and more than 6,000 observations were used in the model calibration. Due to long model run times and a large number of parameters, PEST runs had to be conducted using a high performance computing facility. A total of nearly 50,000 processing hours was used during PEST runs. The final calibrated model is able to replicate the observed dynamic of groundwater system (i.e. match seasonal and long term groundwater level changes, as well as observed spring flows and river losses). The model has been independently reviewed as suitable for simulating the effects of groundwater pumping on river flows, along with seasonal and long term changes of groundwater levels, especially when the scenario differencing method is used to estimate the incremental impacts of management options.

Further details of the model set up are presented in the Heretaunga Aquifer Model Development Report (Rakowski & Knowling, 2018).

1.5 Content of this report

This report documents the predictive modelling scenarios that were simulated as part of the TANK groundwater modelling study. Section 2 describes the general methodology used in all modelling scenarios, while later Sections 3, 4 and 5 describe the setup and results from scenario modelling simulations, while Section 6 presents information on the uncertainty analyses for the scenario modelling results.

This report presents results from multiple scenario runs. The scenarios are listed in Table 1-1.

Table 1-1: Heretaunga Aquifer modelled scenarios

Scenario ID	Type	Report section no.	Description	From	To	Timestep
M3	Historical	3	Historical abstraction	1/07/1980	1/07/2015	Month
M3_zero	Historical	3	No abstraction	1/07/1980	1/07/2015	Month
M3_no_ind	Historical	3	No industrial abstraction	1/07/1980	1/07/2015	Month
M3_no_irr	Historical	3	No irrigation abstractions	1/07/1980	1/07/2015	Month
M3_no_PWS	Historical	3	No public water supply	1/07/1980	1/07/2015	Month
M4	Future	4.1	Historical abstraction/repeat conditions	1/07/1980	1/07/2115	Month
M4_incr	Future	4.2	Increasing abstraction	1/07/1980	1/07/2115	Month
M4_2012	Future	4.3	Dry conditions	1/07/1980	1/07/2115	Month
M4_perc	Future	4.4	Abstraction increase increments (-50%, -30%, -20%, -10%, 10%, 20%, 30%, 50%, 100%) 9 scenarios	1/07/2015	1/07/2035	Month
M3_no_AR	Mitigation	5.1	No artificial recharge (impact of artificial recharge by comparison with M3)	1/07/1980	1/07/2015	Month
AUGM_sim_recc	Mitigation	5.2	Augmentation-recommended case	1/12/2012	1/05/2013	Month
AUGM_sim_worst	Mitigation	5.2	Augmentation-worst case	1/12/2012	1/05/2013	Month
AUGM_base		5.2	Augmentation - base case (no augmentation flow)	1/12/2012	1/05/2013	Month
M5_d_sc8v2	Mitigation	5.3	Pumping ban	1/07/2015	1/07/2032	Day
M5_d_base	Management	5.4	Base	1/07/2015	1/07/2032	Day
M5_d_zero	Management	5.4	No pumping	1/07/2015	1/07/2032	Day
M5_d_sc8_z1	Management	5.4	Base_Case_Estimated_Demand	1/07/2015	1/07/2032	Day
M5_d_sc8v2	Management	5.4	Base_Case_Estimated_Demand_	1/07/2015	1/07/2032	Day
M5_d_sc9_z1	Management	5.4	Base_Case_Max_Allocation_zone1	1/07/2015	1/07/2032	Day
M5_d_sc9v2	Management	5.4	Base_Case_Max_Allocation_	1/07/2015	1/07/2032	Day
M5_d_sc10v2	Management	5.4	WCO_Estimated_Demand	1/07/2015	1/07/2032	Day
M5_d_sc11_z1	Management	5.4	NT_MF_70%_Habitat_Estimated_D	1/07/2015	1/07/2032	Day
M5_d_sc12_z1	Management	5.4	NT_MF_80%_Habitat_Estimated_D	1/07/2015	1/07/2032	Day
M5_d_sc13_z1	Management	5.4	NT_MF_90%_Habitat_Estimated_D	1/07/2015	1/07/2032	Day
M5_d_sc14_z1	Management	5.4	NT_MF_MALF_Estimated_Demand	1/07/2015	1/07/2032	Day
M5_d_sc16_z1	Management	5.4	N_MF_70%_T_MF_75%_Habitat_ED_	1/07/2015	1/07/2032	Day
M5_d_sc8.3	Management	5.4	Base_Case_Estimated_Demand_	1/07/2015	1/07/2032	Day
M5_d_sc16.1	Management	5.4	N_MF_70%_T_MF_75%_Habitat_ED_	1/07/2015	1/07/2032	Day
M5_d_sc18	Management	5.4	N_MF_80%_T_MF_90%_Habitat_ED_	1/07/2015	1/07/2032	Day

2 Methodology

2.1 Model version

All simulations were executed with calibrated model version HPM035, as documented by Rakowski and Knowling (2018). Specifically, all prediction scenarios use the verification model scenario as a basis, which was prepared after calibration was completed. This is referred to as the “M3” scenario, which uses monthly stress periods and covers the time period between 1980-2015.

2.2 Calculation of surface water – groundwater interaction.

The interactions between surface water and groundwater were calculated by processing the simulated flow outputs. Interchanges between surface water and groundwater were simulated in MODFLOW model using the “River” boundary condition. The model was set up to record the flow for every model cell. After the model run, the results were processed to calculate the total flux exchange between surface water and groundwater (SW/GW Q) for pre-defined sub-catchments (representative of river/stream sections), per model time step. The processing was completed using PEST utility program bud2hyd (Doherty, 2015). Sub-catchments used to calculate the SW/GW Q flux exchanges are shown in Figure 2-1. These definitions are based on model catchments used in a SOURCE surface water flow model (Diack & Williamson, 2018), with slight modifications to ensure spatial consistency with MODFLOW boundary conditions.
The SW/GW Q calculated for sub-catchments is suitable for input to the SOURCE model, which allows for linking of both models, as described in section 5.4.2

The SW/GW Q simulated for sub-catchments can be integrated to calculate the total SW/GW Q per river for a certain location (for example at a defined gauging station). In many cases this requires another calculation step, where the SW/GW Q from several sub-catchments is combined (for example, the Karamu consists of multiple tributary sub-catchments: Irongate, Karewarewa, Mangateretere). However, it is also useful to quantify the SW/GW Q in a given sub catchment (e.g. the flow contribution from groundwater to the Karamu mainstem excluding tributaries). To facilitate calculation of this combined flux exchange, or flux exchange per catchment, combined catchment groups were defined as shown in Figure 2-2.

The results are presented as time series of SW/GW Q flux exchange during the simulation time for defined rivers or catchments.

2.3 Flux exchange between surface water and groundwater vs river gain and loss

Typically, in groundwater modelling the boundary flux is given a positive value when water moves from the boundary to the aquifer and a negative value is it moves from the aquifer to the boundary. This convention was used in previous studies in the Hawke’s Bay area (Baalousha, 2012) and is used throughout this report. In this convention, river losses to aquifer have a positive value, and river gains (or spring flows) have a negative value (Table 2-1).

Table 2-1 Surface water groundwater flux vs river gain and loss

Flux exchange between surface water and groundwater	River gain/loss
Positive value	River loss
Negative value	River gain or spring flow

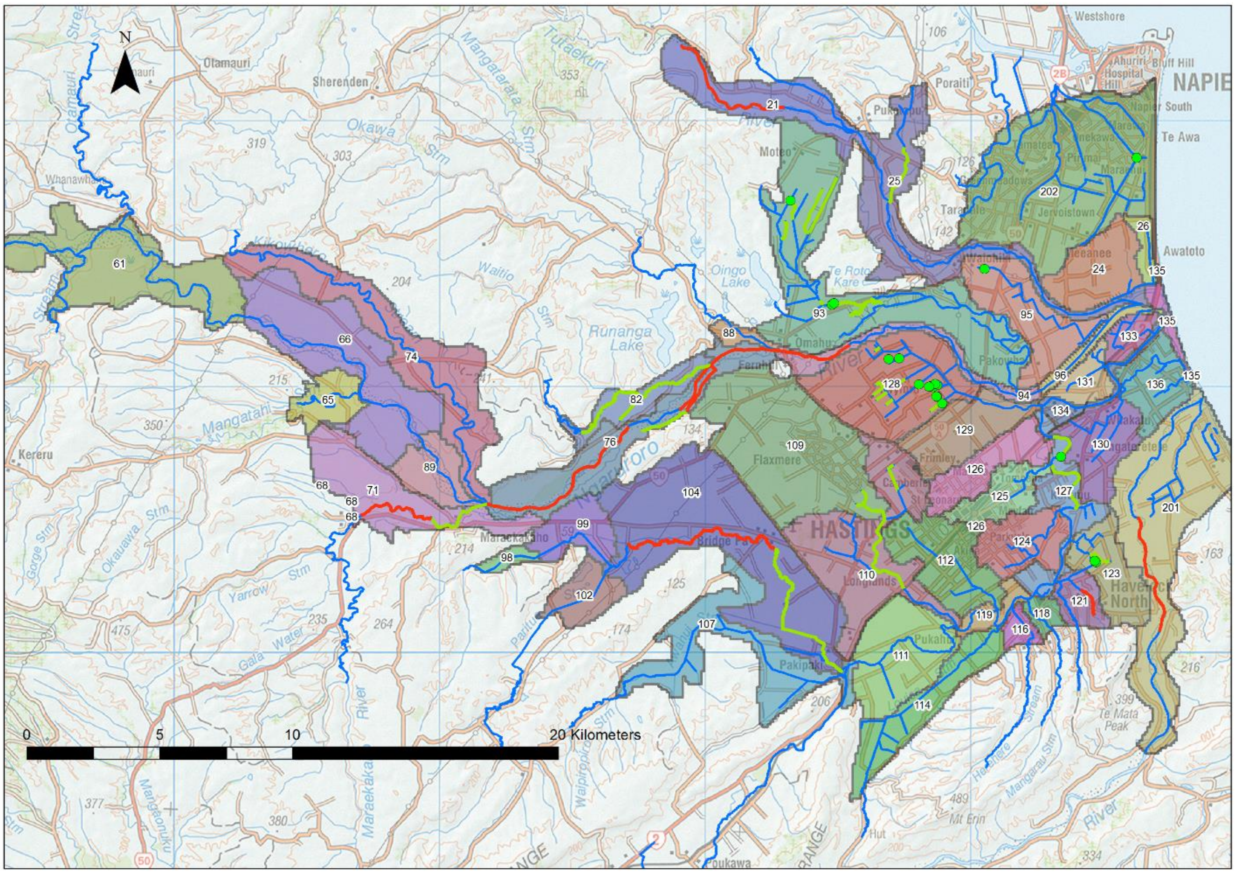

Figure 2-1: Catchments used for calculating surface water - groundwater exchanges. Catchments are shown with the various coloured regions, and include corresponding SOURCE catchment numbers (catchment numbers 201 and 202 are additional catchments that are not part of the SOURCE model but are part of the MODFLOW model). Gaining sections of rivers and point springs are shown in light green. Losing sections of rivers are shown in red. Conservative sections are shown in blue.

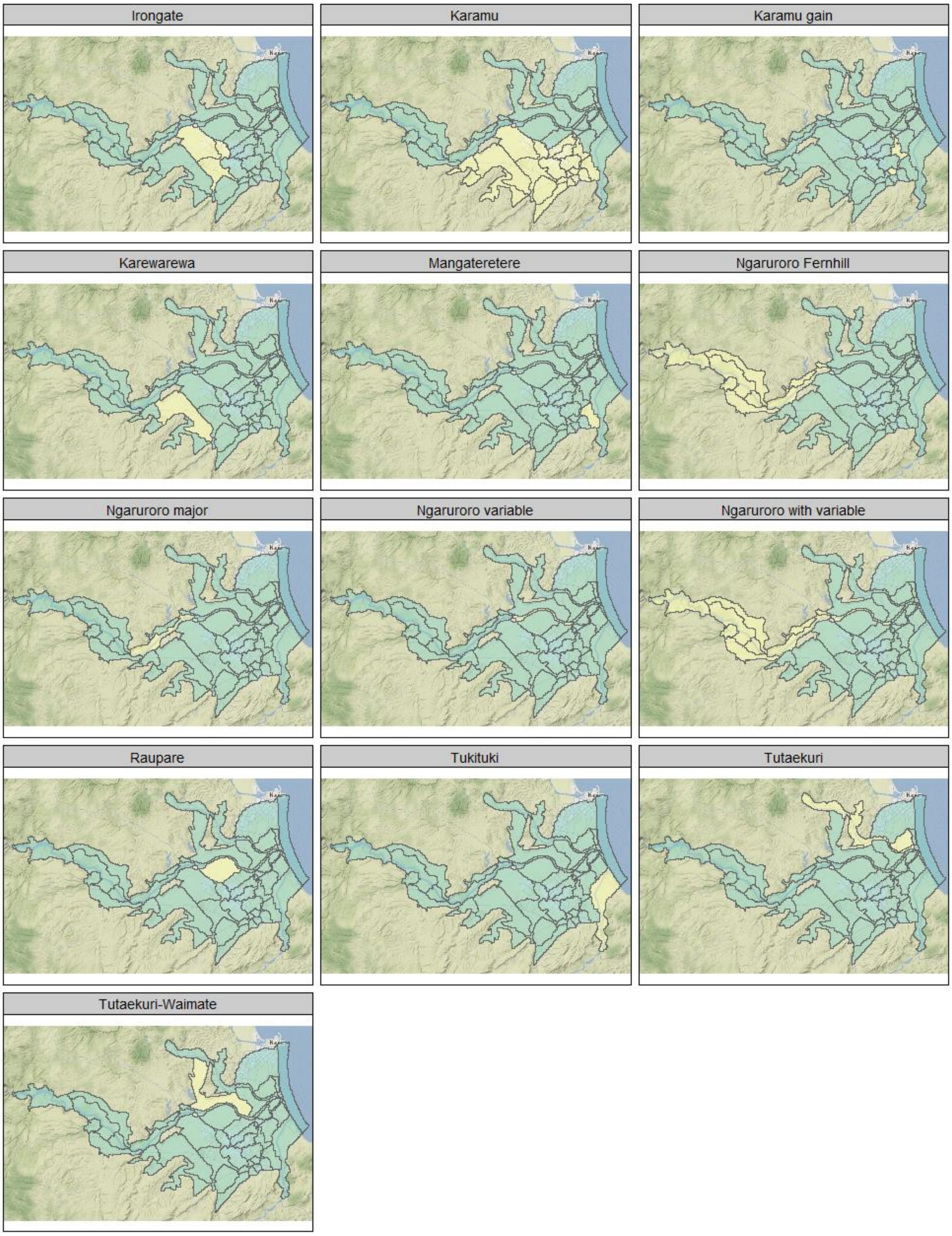

Figure 2-2: Zones used to calculate the flux exchange between groundwater and river flow. Pale yellow shows the catchments used to calculate the river flow effect per selected river reach or sub-catchment.

2.4 Calculating the effect of model perturbation

Perturbation is defined here as any hydrological change that has an effect on modelled groundwater flow. Perturbations may include groundwater pumping or change in rainfall recharge.

An effect is defined as an incremental change of groundwater flow for a perturbed model (scenario) in comparison to unperturbed (or base case) conditions. Examples of such effects may be a change of the surface water – groundwater exchange flux (SW/GW Q), or a change in groundwater level.

To calculate the effect of perturbation, a pair of models has to be run: one with and one without the perturbation (base case), followed by processing of model results (e.g. water levels and SW/GW Q flux exchange) and calculation of the difference between the model results. The pair of models has to be identical, except for the modelled perturbance (and in some cases initial conditions).

This modelled pair methodology requires a definition of unperturbed (base case) conditions specifically for calculation of the effect from a particular perturbation. For example, the technique can be used to calculate the effect of groundwater pumping on streamflow. In that case, the "base case" can be defined as a model with historical pumping, and the "scenario" may be defined as a model with no pumping. In another example, the effect of irrigation pumping may be separated from the other groundwater pumping, by defining "base case" as historic pumping, and "scenarios" as pumping without abstraction for irrigation.

2.5 Effect on surface water flow

The effect of groundwater pumping on stream or river flow (i.e. stream depletion) is calculated using the modelled pair (or scenario difference) methodology described in section 2.4 and the method for surface water – groundwater exchange flux (SW/GW Q) calculation described in section 2.2. The results are presented as time series of the perturbation effect for a defined catchment. The calculated effect can be interpreted as the incremental change in streamflow due to the perturbation, presented as a time series. For cases where the perturbation is groundwater pumping, this change can be interpreted as stream depletion due to pumping. In some cases, for example managed aquifer recharge when water is added to the aquifer, this effect may result in streamflow increases.

It should be noted that the "River" boundary condition used in the model does not allow for calculation of actual river flow. Rather, the "River" boundary condition allows for calculation of the exchange flux between a river and the aquifer (SW/GW Q). This flow can be interpreted as the total actual river flow only in some cases, where there is no surface water run-off and there are no inputs from upstream catchments. This is not the case for most catchments in the model domain, although some catchments such as Raupare and Irongate may meet these criteria during summer months.

To calculate the actual streamflow, these additional inputs must be accounted for and this was achieved by linking the MODFLOW and SOURCE models (section5.4.2**)**.

Alternatively, the modelled incremental effect (usually increased leakage due to groundwater pumping) can be applied to the recorded flow to estimate the perturbation effect on the streamflow.

Due to limitations in the way the "River" boundary condition works, in some cases the calculated SW/GW Q flux exchange may be unrealistic. For example, for extreme pumping scenarios the calculated exchange (in terms of stream leakage due to groundwater pumping) could be larger than the actual flow in the river. While this is physically impossible, it can occur in the model because the "River" boundary condition assumes an unlimited supply of river flow. Although this result is known to be unrealistic, it is likely to occur only in extreme scenarios and the result has value as an indicator of when the river is likely to become dry.

2.6 Effect on groundwater levels

The effect on groundwater levels is calculated using modelled pair methodology described in section 2.4, and by comparing calculated groundwater levels for both models. The difference between water levels calculated with both models (referred to as drawdown for pumping scenarios) can be reported as a hydrograph for each specified location, or as spatial distribution of the difference at specific times (a drawdown map in the case of pumping effect simulations).

3 Historical scenarios

3.1 Determining impact of Groundwater abstractions on the aquifer

3.1.1 Model setup

A primary purpose of historical scenarios was to estimate the impact of current and past groundwater pumping on an aquifer, for example river flows and groundwater levels. This was achieved by comparing a base case (historical pumping) scenario with a no pumping (naturalised) scenario. In this case, the perturbation is the removal of pumping, following the modelled pair methodology outlined in section 2.

This scenario is important because groundwater pumping is a significant component of the groundwater budget for the Heretaunga Aquifer System. Groundwater abstraction is mainly used for public water supply, industrial and irrigation uses, which together constitute about 95% of the total use. Smaller volumes of water are also abstracted for frost protection, stock water, and for domestic purposes.

The abstraction has significantly increased since 1980, until about 2005, when it showed signs of a developing equilibrium, as shown in Figure 3-1. The abstraction is characterised by high seasonality, mainly due to irrigation in the summer, as shown in Figure 3-2. Spatial distribution mapping shows large, concentrated abstractions for public water supply and industrial takes, in contrast to many generally smaller and relatively evenly distributed irrigation takes during the summer (Figure 3-3).

Managed Aquifer Recharge (MAR) operated in the Heretaunga Plains between 1998 and 2008. The purpose of the scheme was to redirect some Ngaruroro River water during high flows to recharge trenches and to increase aquifer recharge. This MAR scheme has been incorporated into the model (i.e. artificial recharge is simulated as an injection well).

The groundwater abstraction described above was incorporated into the groundwater model set-up. Model set-up for “base case scenario” is based on a model verification scenario, as described in section 5.4.4 of the Model Development Report (Rakowski & Knowling, 2018). This scenario is a transient model simulation run at a monthly stress period from 1980 to 2015, using historical stresses (pumping, recharge, river levels).

The “naturalised scenario” is identical to the base case scenario, except for different pumping:

- groundwater pumping (including artificial recharge) is switched off in the naturalised scenario,
- the naturalised scenario uses initial heads that were calculated using a steady state model without any pumping while base case scenario uses initial heads calculated using a steady state model with 1980 pumping; this is a best practice method, designed to ensure that the early time model results are not subject to re-equilibration due to antecedent conditions that are inconsistent with the scenario.

The effect of pumping is calculated as the difference between the “base case” (with pumping) and “naturalised” (without pumping) model scenarios. Because pumping is simulated using the “WEL” MODFLOW package, which also includes MAR, the effect calculated includes the effect of artificial recharge on flow.

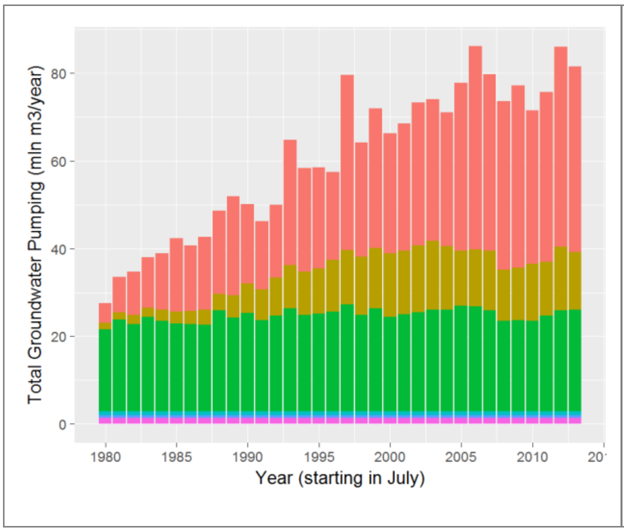

Figure 3-1: Annual groundwater abstraction from Heretaunga Aquifer System.

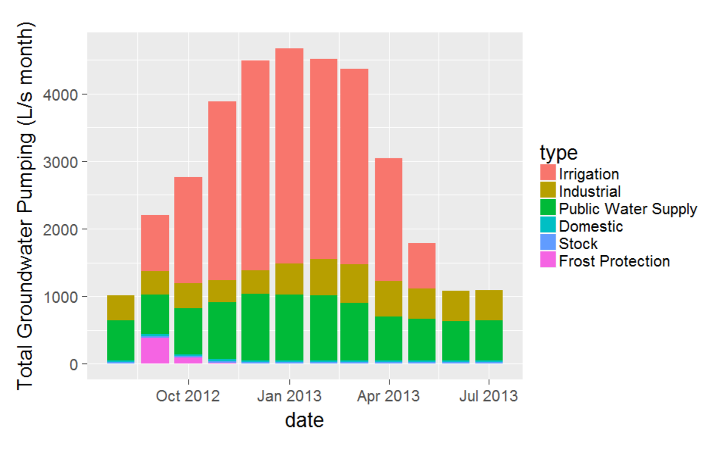

Figure 3-2: Monthly Groundwater abstraction during the 2012/2013 irrigation season.

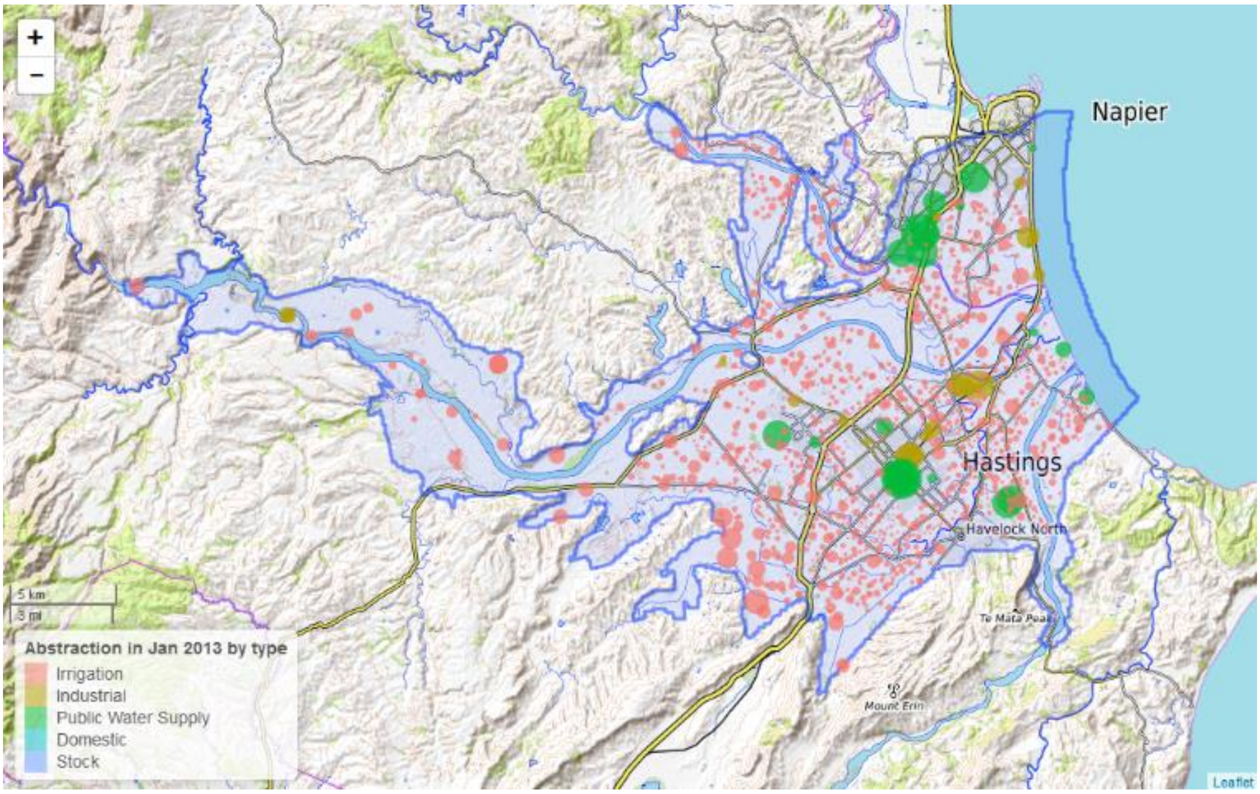

Figure 3-3: Distribution of groundwater pumping from the Heretaunga Aquifer System in January 2013 Dot area is proportional to take size, such that small domestic and stock water takes are indiscernible.

3.1.2 Streamflow

Main rivers

Surface water – groundwater exchange flux

The surface water – groundwater exchange flux (SW/GW Q) for the main rivers (Ngaruroro[1], Tukituki, and Tūtaekurī) is presented in Figure 3-5. For all rivers, this flux is positive (with some exceptions at a few times due to seasonal and sub-seasonal variability). A positive flux indicates loss of water from the river to the aquifer (river leakage). The plot shows both “naturalised” (no pumping) and “base case” (historical pumping) scenario exchange flux, and there is a noticeable difference in exchange flux between the scenarios. In most cases, as expected, the historical pumping base case scenario shows higher river losses due to pumping, which would result in lower river flows. Close examination of Figure 3-5 reveals that the “historical pumping” base case scenario shows decreased flux at certain times (and thus increased river flow). This effect is caused by the MAR scheme discussed in section 5.1.

The effect on river flow

The effect on river flow is shown in Figure 3-6 and Figure 3-7. Positive values indicate that river losses are greater in the “historical pumping” base case scenario than the naturalised scenario without pumping. Greater losses from a river to the aquifer results in less river flow (stream depletion). These plots show that:

- For all rivers the SW/GW exchange flux river losses increased (in turn resulting in declining river flow) because of groundwater pumping since 1980;
- The effects due to pumping (increase in river losses or flow depletion) are greatest during summer (Figure 3-7), which is due to larger pumping rates during the summer;
- For the Tukituki River and Tūtaekurī River, the summer losses increased since 1980, while winter losses did not change significantly. For the Ngaruroro River, winter losses increased along with summer losses.
- Figure 3-6 and Figure 3-7 show the incremental effects on SW/GW exchange flux due to groundwater pumping, indicating the maximum and minimum declines on the flows in the major rivers, summarised in Table 3-1.

Table 3-1 Approximate declines in river flow in major rivers between 2012 and 2015

	Maximum decline (summer)	Minimum decline (winter)
Ngaruroro River at Fernhill	1000 L/s	350
Tukituki River	650 L/s	200
Tūtaekurī River	150 L/s	<50

- In the Ngaruroro River, the river flow increased in the “historic pumping” scenario during some time intervals between 1997 and 2008. This is due to the MAR scheme (see section 5.1).

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[1] Note the figure represents Ngaruroro at Fernhill.

Flow depletion vs actual river flow

Maximum estimated flow depletion can be compared against typical recorded summer river flow to estimate the relative magnitude of flow change at the flow recorder locations on those rivers (Table 3-2). This method allows for quick comparison of overall effects on different rivers, without undertaking full flow naturalisation using complex surface water models. This quick comparison is possible by assuming that the maximum flow depletion typically occurs during the periods of low flow. Comparing the modelling results for SW/GW exchange flux to the recorded summer river flow allows the following quick/simple comparison: that the Ngaruroro River has been most affected by flow depletion and if this depletion did not occur, the flow in the river would be nearly doubled. The Tukituki River and the Tūtaekurī River have been less affected.

The flow depletion effect on the Ngaruroro River is further discussed in following sections.

Table 3-2: Maximum flow depletion against typical river flow.

Stream	Typical Summer River Flow L/s	Estimated maximum depletion L/s	Estimated flow without depletion L/s	% Flow loss
Ngaruroro	1100	933	2033	46%
Tukituki	2900	642	3542	18%
Tūtaekurī	2100	142	2242	6%

Ngaruroro River

Maximum change in losses

The change in losses during a dry season (summer 2012-2013) for the Ngaruroro River at Fernhill is shown in

Figure 3-8. This location is used because there is a gauging station at Fernhill which is used to trigger abstraction bans for irrigation takes, so it is important to know what the effect on pumping at this location is. Summer 2012-2013 was selected as this period is representative of extremely dry conditions and the effect on river flow is likely to be most significant.

Figure 3-8 shows that groundwater pumping induces increased losses (and consequently reduction in river flow) at Fernhill from about 400 L/s during the winter, to about 900 L/s at the end of the summer. This shows that the largest effect from pumping on SW/GW exchange flux is during the irrigation season, which coincides with the time when river flow is at its lowest.

Downstream of Fernhill there is a section of the Ngaruroro River, referred to as a variable loss section. In this section of the river further flow depletion can occur, of about 300 L/s maximum. The total depletion including the variable loss section is shown in Figure 3-9. This estimated maximum depletion is 1200 L/s at the end of the irrigation season.

Naturalised river flow

Figure 3-4 shows the recorded river flow and a “naturalised” river flow. The “naturalised” river flow was derived by adding the incremental effect of groundwater pumping to the recorded river flow. The incremental effect of groundwater pumping was calculated as the difference between the base case (“with pumping”) and the naturalised (“no pumping”) model scenarios. It can be seen that the estimated effect of pumping on Ngaruroro River is very significant. Model results suggest that in summer 2012-2013 nearly half of the natural river flow was lost as a result of groundwater pumping.

This method of flow naturalisation is useful for visualising effect of groundwater pumping on actual river flow, but it is a simple method that does not include effects of surface water pumping and the effect of abstraction bans. Full flow naturalisation that includes these factors was undertaken using a SOURCE model and is described in a separate report (Waldron, 2018).

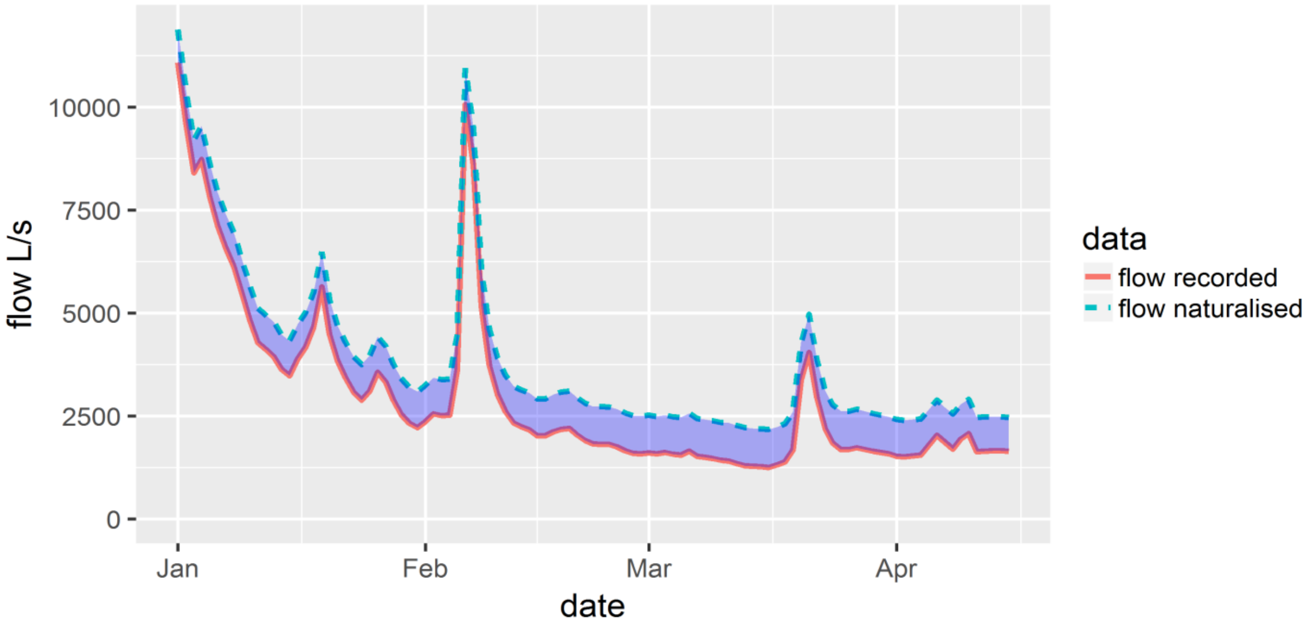

Figure 3-4: Ngaruroro at Fernhill in 2012**: recorded flow** compared to the simulated **naturalised flow.** Blue shading represents the incremental effect of river flow depletion due to groundwater pumping, calculated as the difference between the base case (“with pumping”) and the naturalised (“no pumping”) model scenarios.

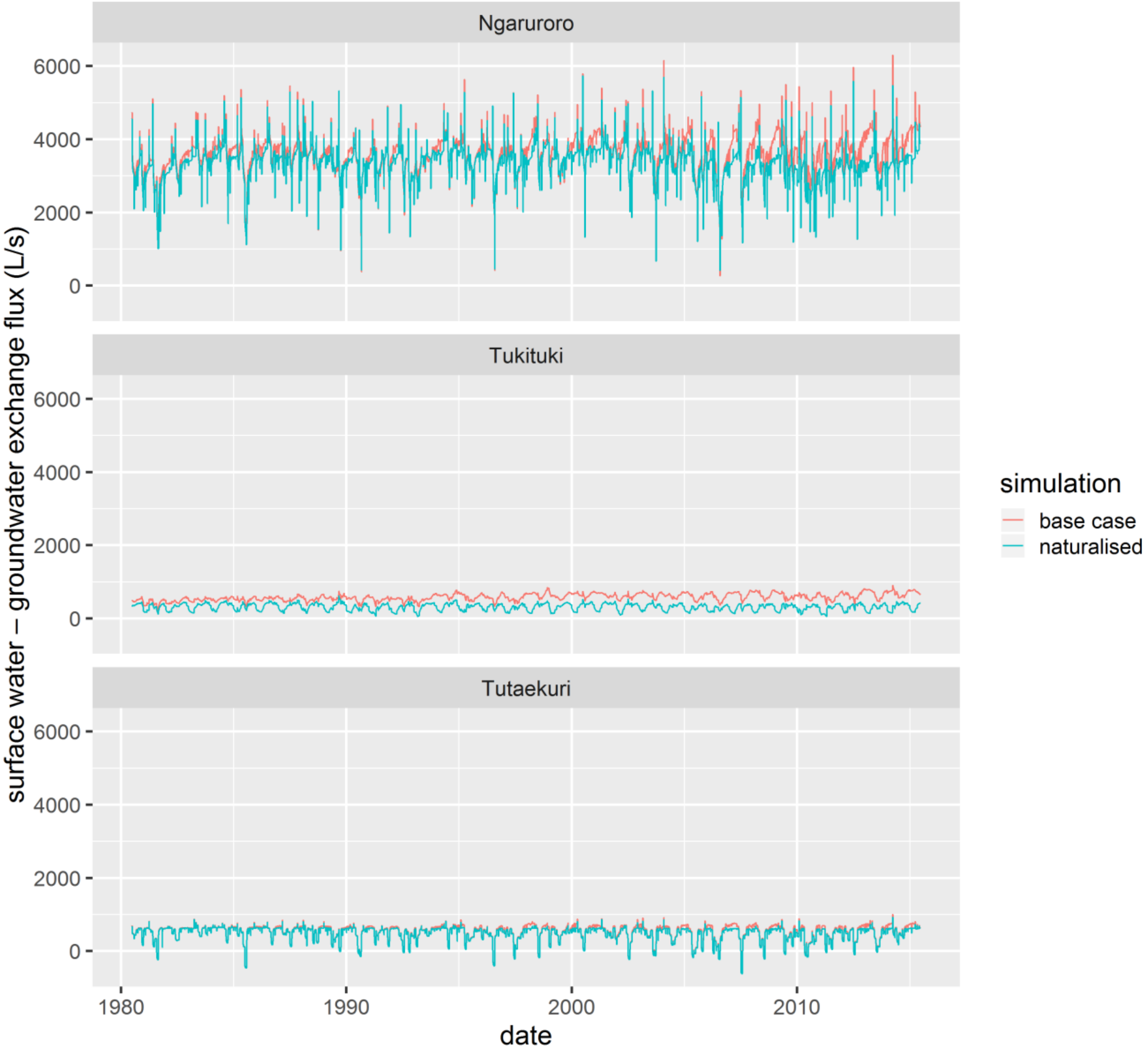

Figure 3-5: Surface water - groundwater exchange flux for base case and naturalised scenario for major rivers 1980-2015. Positive values indicate river loss to the aquifer. “Base case” scenario represents historical pumping including managed aquifer recharge. “Naturalised” scenario represents no pumping or artificial recharge. The flux for base case is usually higher than in “naturalised” scenario, due to additional river leakage induced by groundwater pumping. The exception is several occurrences in Ngaruroro River, where leakage in “base case” is lower, which is a result of Managed Aquifer Recharge (MAR). MAR results in increased groundwater levels which caused reduced river leakage.

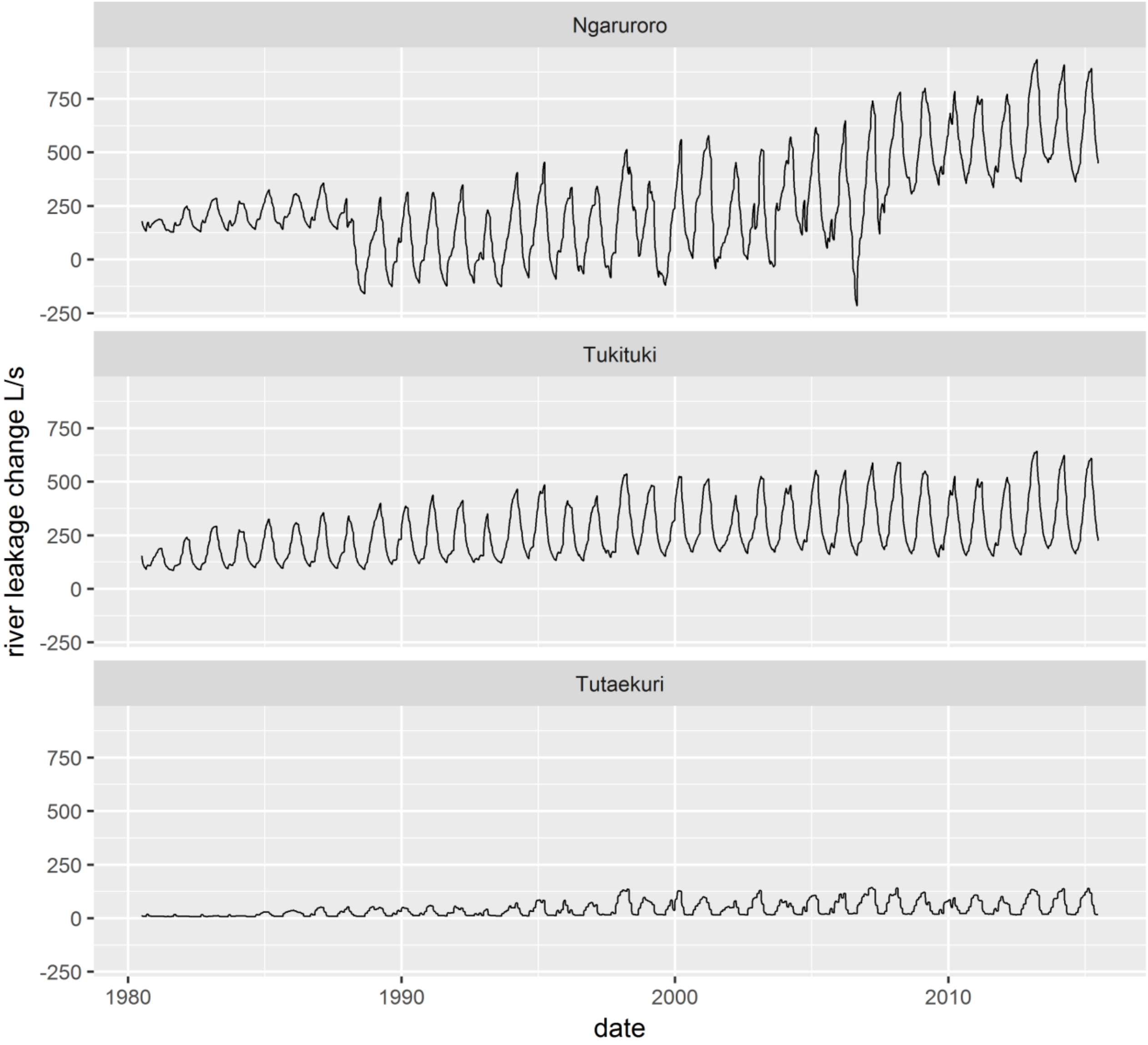

Figure 3-6: Incremental effect of groundwater pumping on river leakage for major rivers 1980-2015. Ngaruroro represents Ngaruroro at Fernhill. The incremental effect is calculated as the difference between the base case and naturalised scenarios, and is equivalent to a change of river loss. Positive values mean that river loss increases, resulting in a decline in river flow (stream depletion). Negative values mean that river loss decreases (river flow increases)

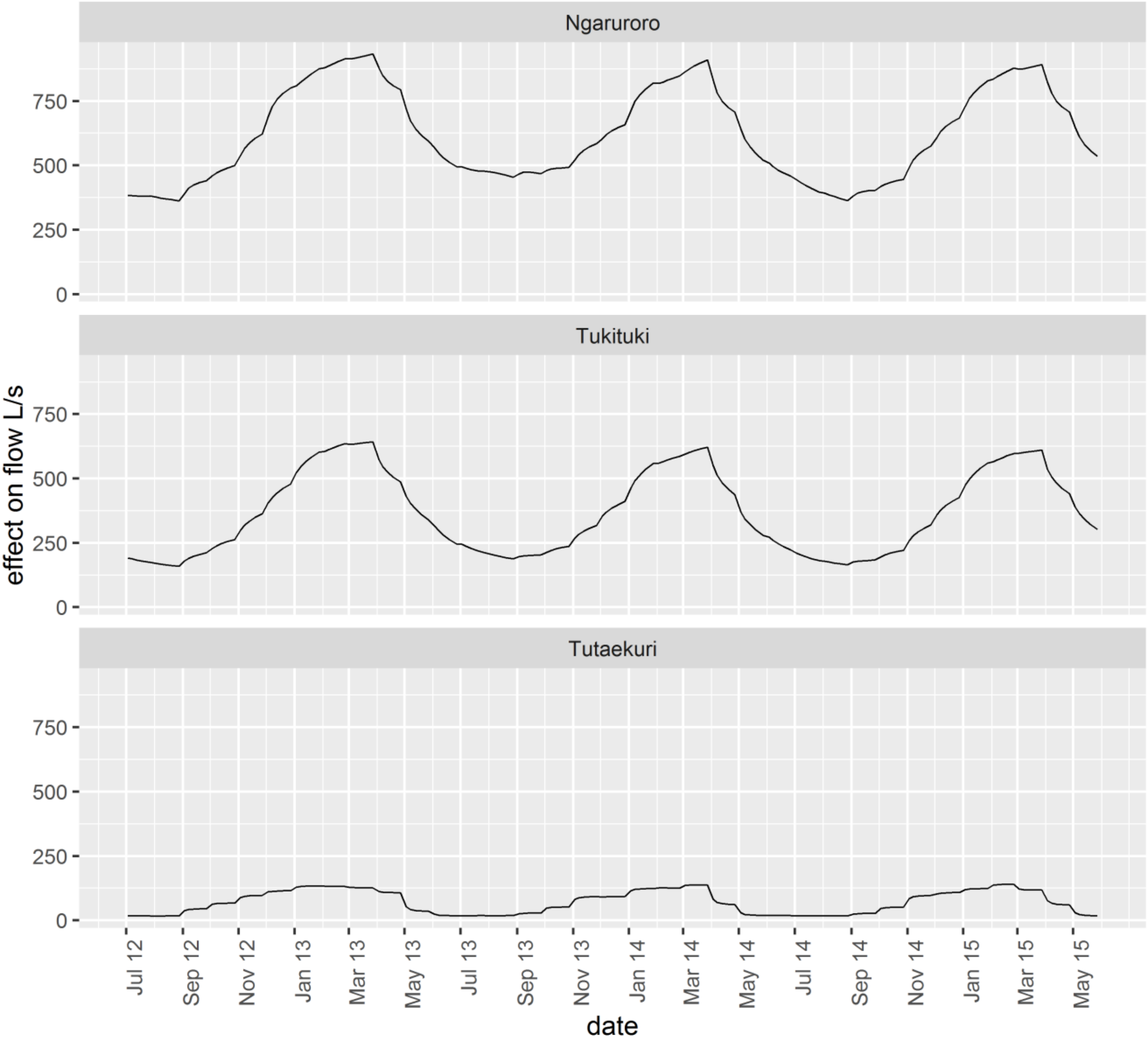

Figure 3-7: Seasonal incremental effect of groundwater pumping on river flow of major rivers 2012-2015. The incremental effect is calculated as the difference between the base case and naturalised scenarios, and is equivalent to a change in the river loss. Positive values mean that river loss increases, resulting in a decline in flow (stream depletion). This plot shows the detailed profiles for the last few years of the results shown in the previous figure.

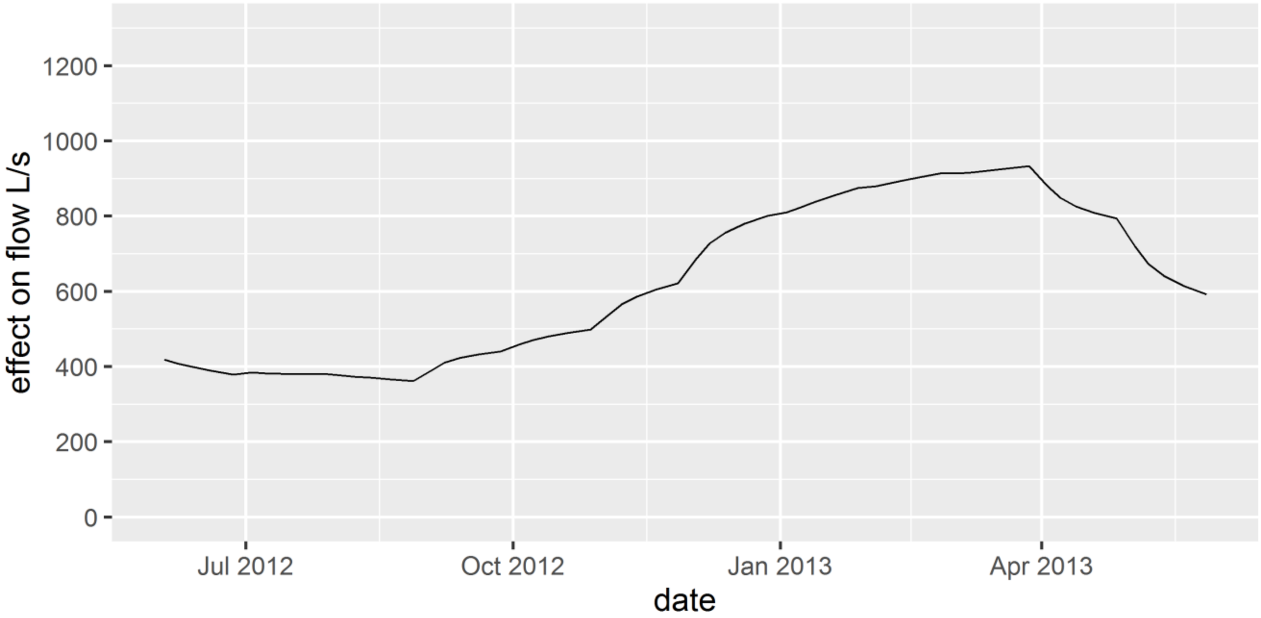

Figure 3-8: Incremental effect of groundwater pumping on Ngaruroro flow at Fern Hill during 2012/2013 drought. The incremental effect is equivalent to a change in river loss. Positive values mean that river loss increases, resulting in a decline in flow (stream depletion).

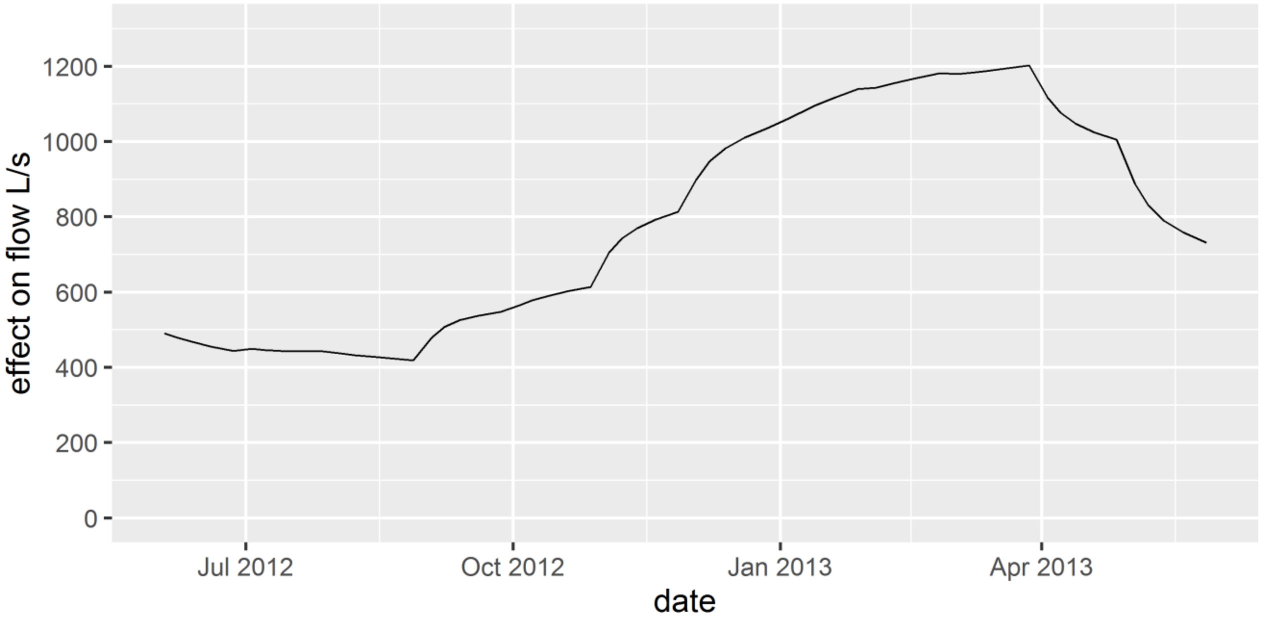

Figure 3-9:Incremental effect of groundwater pumping on total Ngaruroro flow during 2012/2013 drought. This includes the variable loss section of the Ngaruroro between Fernhill and the confluence with Tūtaekurī-Waimate, but excludes the Tūtaekurī-Waimate flows. The incremental effect is equivalent to a change in river loss. Positive values mean that river loss increases, resulting in a decline in river flow (stream depletion).

Spring fed streams

The surface water – groundwater exchange flux

The surface water – groundwater exchange flux (SW/GW Q) for the main spring-fed streams is shown in Figure 3-10 and Figure 3-11.

Negative values indicate flow from the aquifer to the stream (spring discharge).

This plot illustrates the seasonal variability in flows, with smallest spring discharge in the summer.

For all streams the naturalised (“no pumping”) scenario flows are noticeably larger than the historical (“with pumping”) scenario, and this difference appears to be increasing with time, consistent with the increasing groundwater pumping (Figure 3-1).

The effect on streamflow (change in spring discharge or stream depletion)

For all streams, results indicate significant effects of pumping on SW/GW Q (Figure 3-12 and Figure 3-13). For spring fed streams, increased values (i.e. values becoming less negative) of SW/GW Q mean that spring discharge declines, resulting in reduced streamflow.

Karewarewa Stream shows the most significant change – SW/GW Q exchange flux in the “historical” scenario becomes positive (which indicates that the stream dries out) during summers in recent years, as observed in the field (Wilding, 2018). This is not observed in the “naturalised” scenario, which indicates that the stream would not become dry under the natural conditions.

For all springs the effect of pumping on streamflow is increasing with time.

The effect of pumping also shows seasonal variability for all springs (Figure 3-14 and Figure 3-15). For Tūtaekurī-Waimate, Karewarewa and Raupare the pumping effect is largest during the summer (similarly to major rivers). This is expected, as pumping during the summer is the largest.

For other streams (Karamu, Irongate, Mangateretere) the seasonal pattern is more complex. During the winter the effect is low (similar to other streams and major rivers) but then it increases during the spring. However, the effect becomes smaller again during the summer (December to May), increases again in May, and then declines in the winter.

This model behaviour is due to some artefacts that do not reflect physical reality. As explained in the model development documentation (Rakowski & Knowling, 2018, section 4.4.1), some springs have been modelled using time-variable river conductance, to account for the observed non-linear relationship between spring flow and groundwater level. The conductance is set to lower values during summer for these springs, and allows for model calibration for both summer in winter conditions. The side effect of this set up is a higher calculated depletion effect during the winter, and a step-change in calculated effect during transition from winter to summer. In reality this change in effect is likely to be more gradual. The calculated step change of effect between winter and summer can be therefore treated as an artefact of the model, but it is not considered to impact on model ability to predict the effect during the summer or winter.

Flow depletion vs actual river flow

Maximum estimated flow depletion can be compared against typical recorded summer river flow to estimate the relative magnitude of flow change (Table 3-3). This method allows for quick comparison of the overall effect on different rivers, without undertaking full flow naturalisation.

The largest change in spring discharge is in Karamu stream, which loses over 1000 L/s of flow as a result of groundwater pumping. This represents a large portion of streamflow, which in the summer can be less than 600 L/s.

Other streams also appear to be significantly affected by groundwater pumping, with large portions of flow lost due to pumping.

The largest decline relative to streamflow occurred in Karewarewa stream (over 90% lost).

The least affected relative to streamflow is Tūtaekurī-Waimate stream, with 20% decline.

Table 3-3: Maximum flow depletion against typical river flow for spring fed streams.

Stream	Typical Flow L/s	Estimated depletion in February 2013 L/s	Estimated naturalised flow	% Flow Loss
Irongate	168	272	440	62%
Karamu	575	1107	1682	66%
Karewarewa	25	341	366	93%
Mangateretere	46	253	299	85%
Raupare	402	242	644	38%
Tūtaekurī -Waimate	1831	435	2266	19%

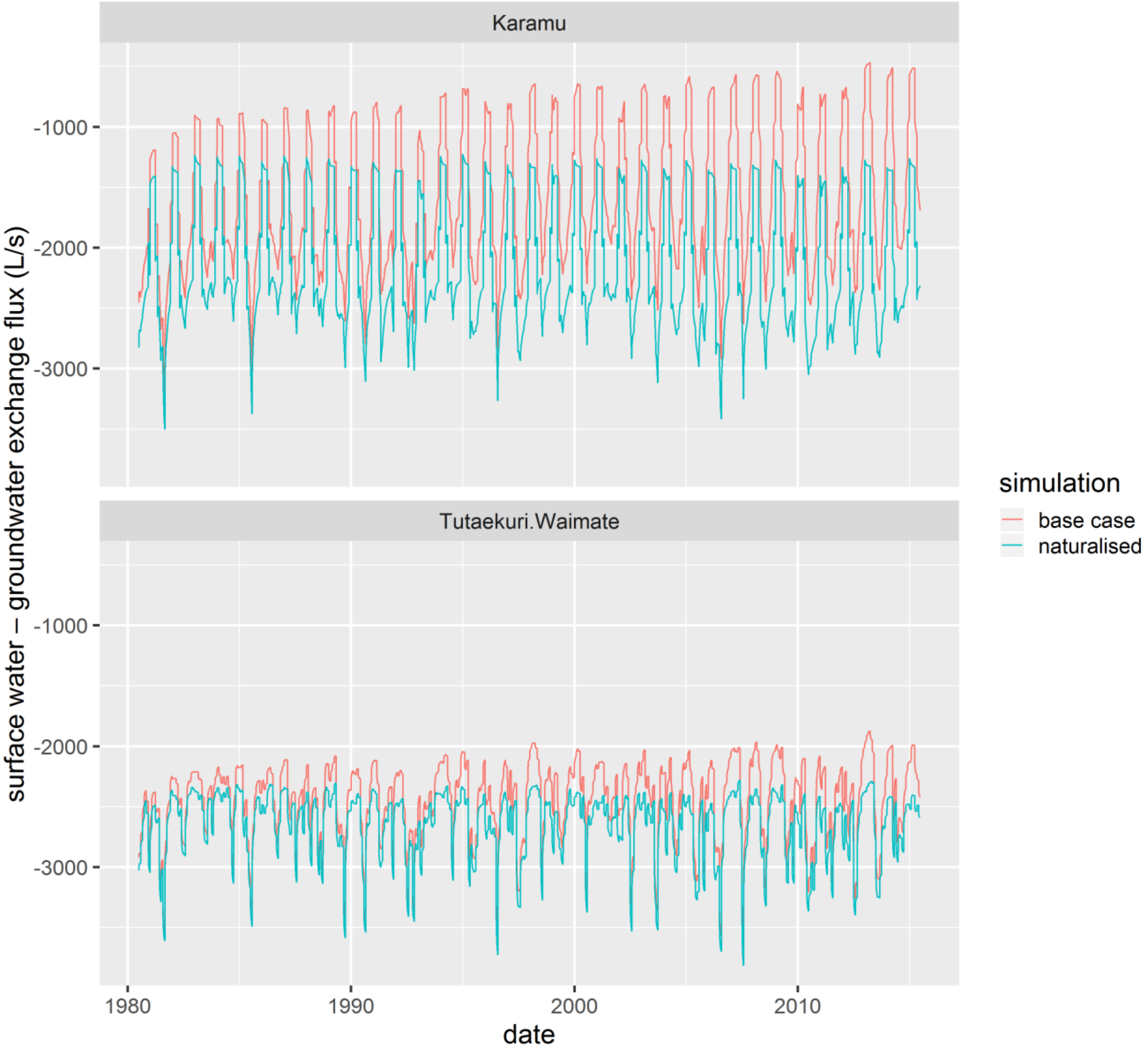

Figure 3-10: Surface water - groundwater exchange flux for base case and naturalised scenario for major spring-fed streams 1980-2015 (part1). Negative values indicate streams gaining water from aquifer. “Base case” scenario represents historical pumping including managed aquifer recharge (hence the reduced gaining stream conditions due to pumping). “Naturalised” scenario represents no groundwater pumping or managed aquifer recharge.

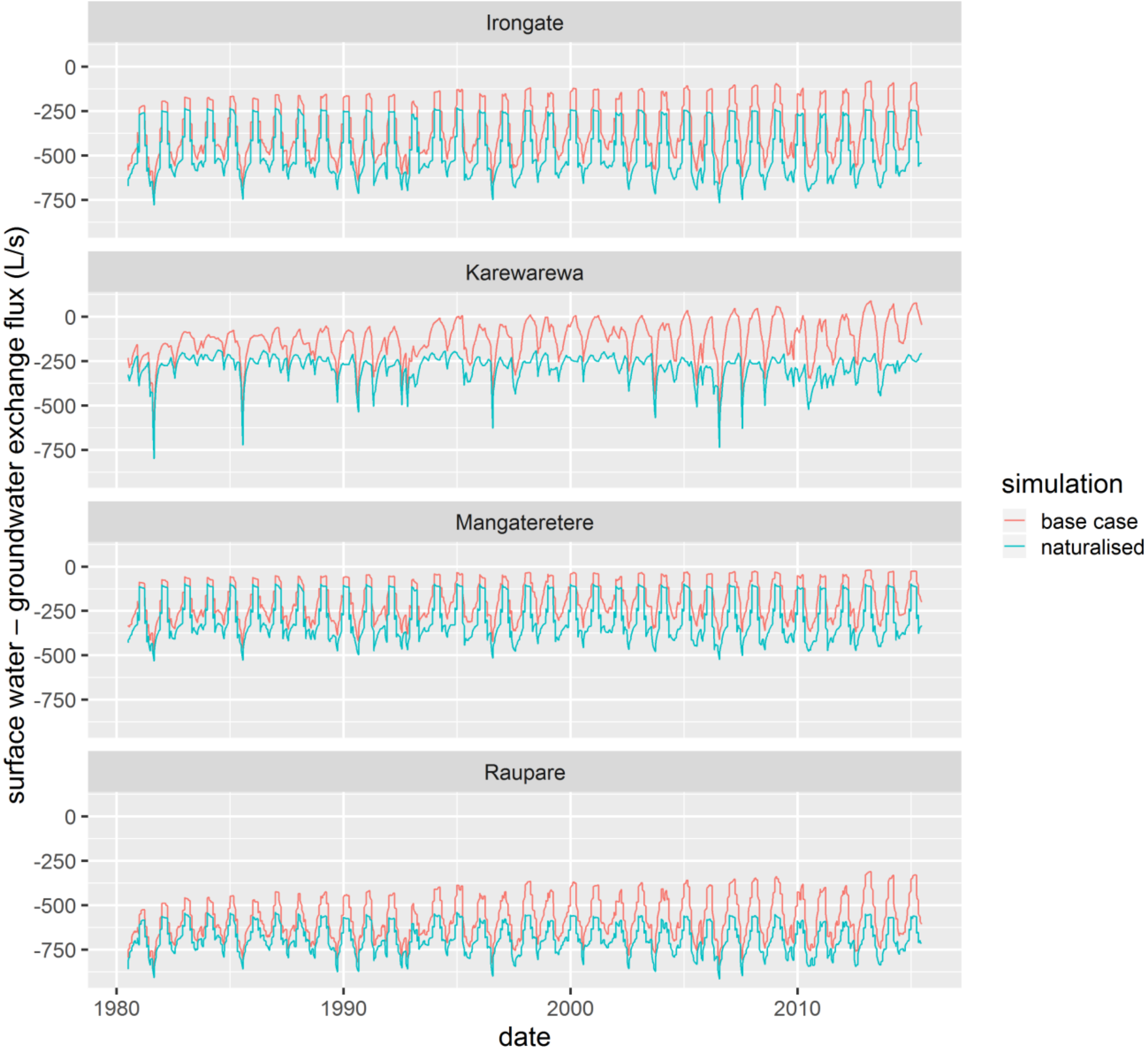

Figure 3-11: Surface water - groundwater exchange flux for base case and naturalised scenario for major spring-fed streams 1980-2015 (part2). Negative values indicate streams gaining water from the aquifer, positive values indicate streams losing water to the aquifer. “Base case” scenario represents historical pumping including managed aquifer recharge (hence the reduced gaining stream conditions generally due to pumping; and for Karewarewa, a change from gaining to losing for significant periods). “Naturalised” scenario represents no pumping or managed aquifer recharge.

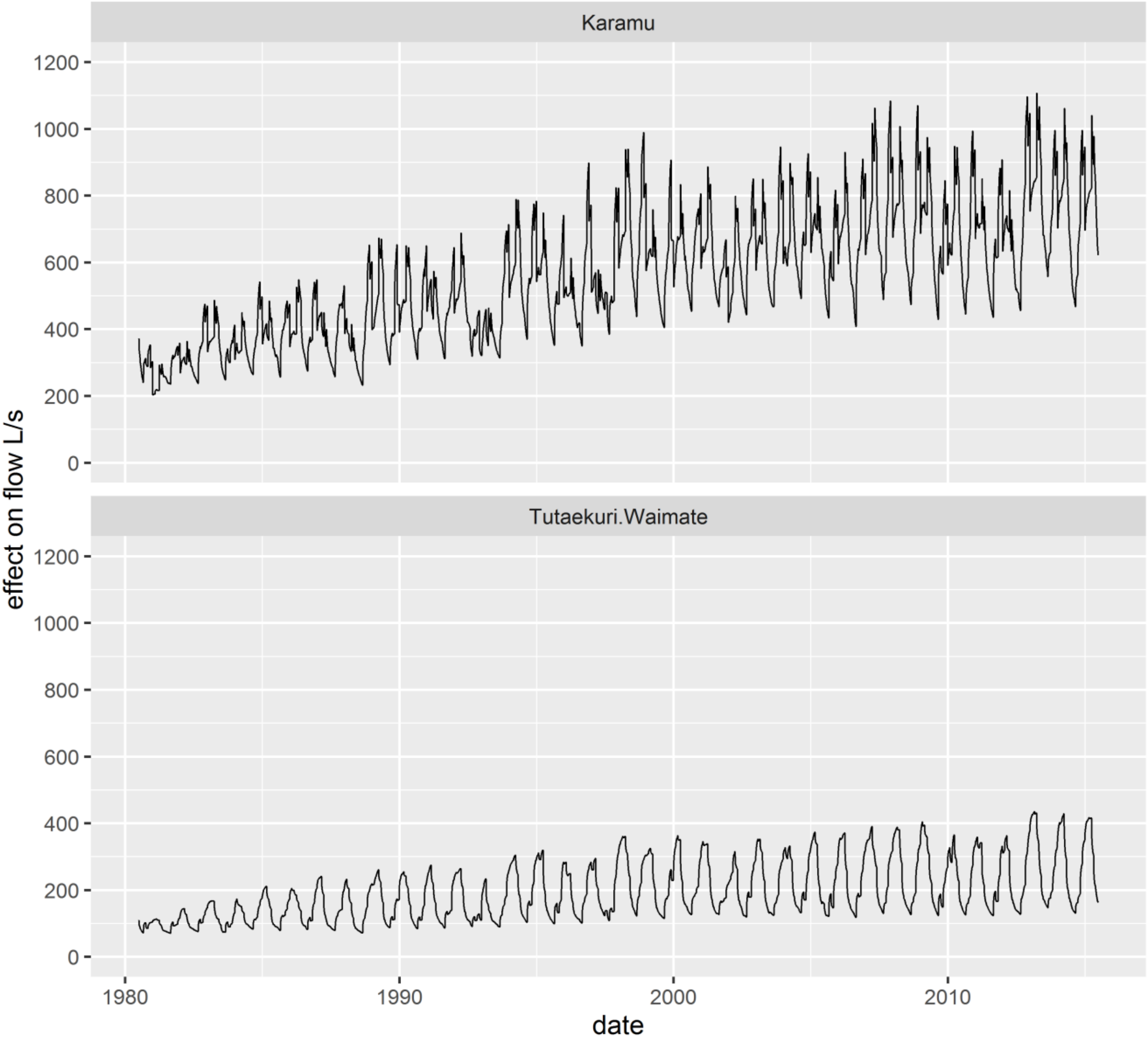

Figure 3-12: Incremental effect of groundwater pumping on major spring-fed streamflow 1980-2015 (part1). For spring fed streams the incremental effect is equivalent to a change of spring discharge, or a change in stream gain. Positive values mean that spring discharge declines, resulting in decreased streamflow (stream depletion). The incremental effect is clearly increasing with time, consistent with increasing groundwater pumping.

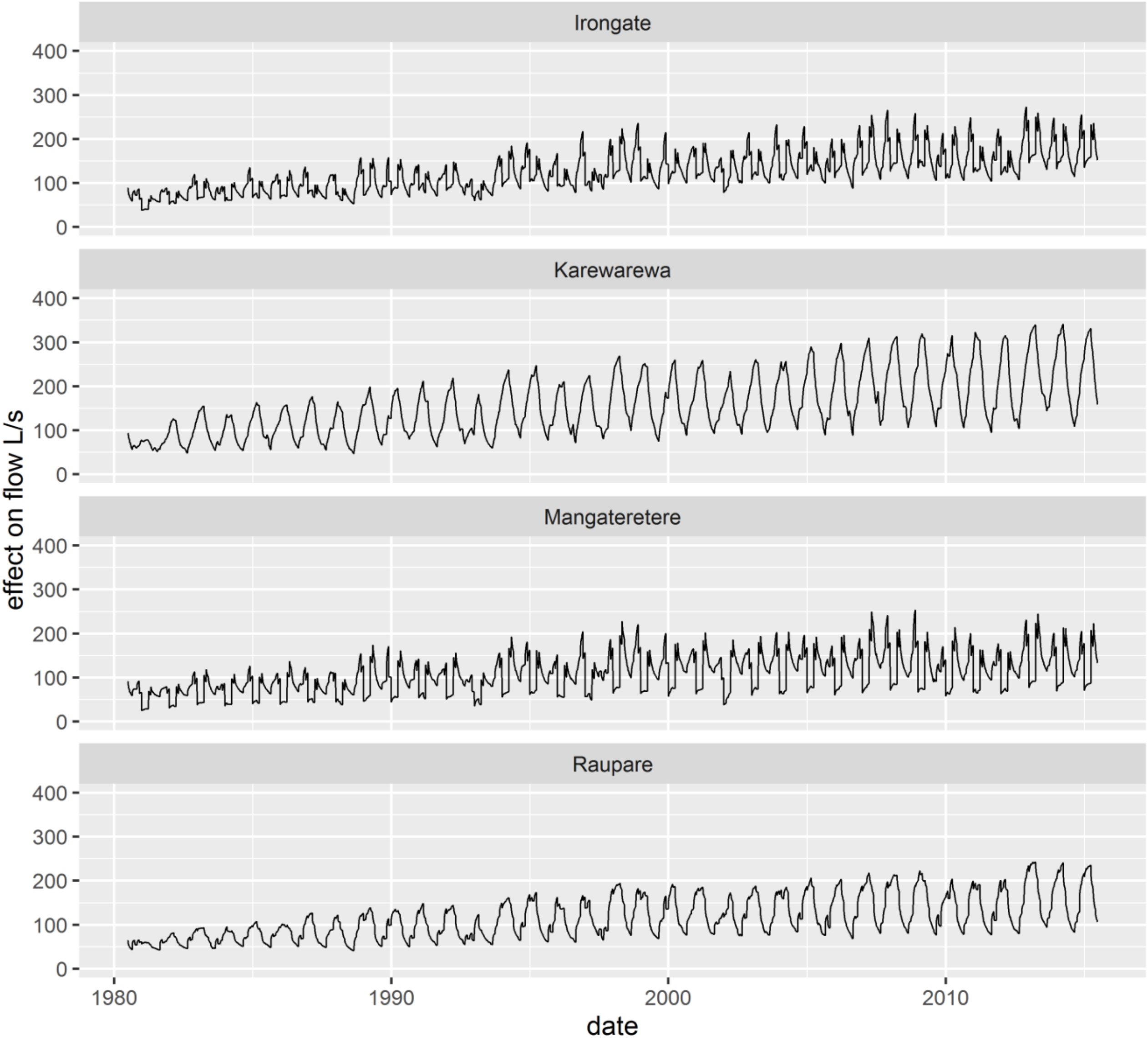

Figure 3-13:Incremental effect of groundwater pumping on river flow for major spring-fed streams 1980-2015 (part2). For spring fed streams the incremental effect is equivalent to a change of spring discharge, or a change in stream gain. For Karewarewa, which may switch from losing to gaining, this may result in stream depletion. Again, the effect is increasing with time.

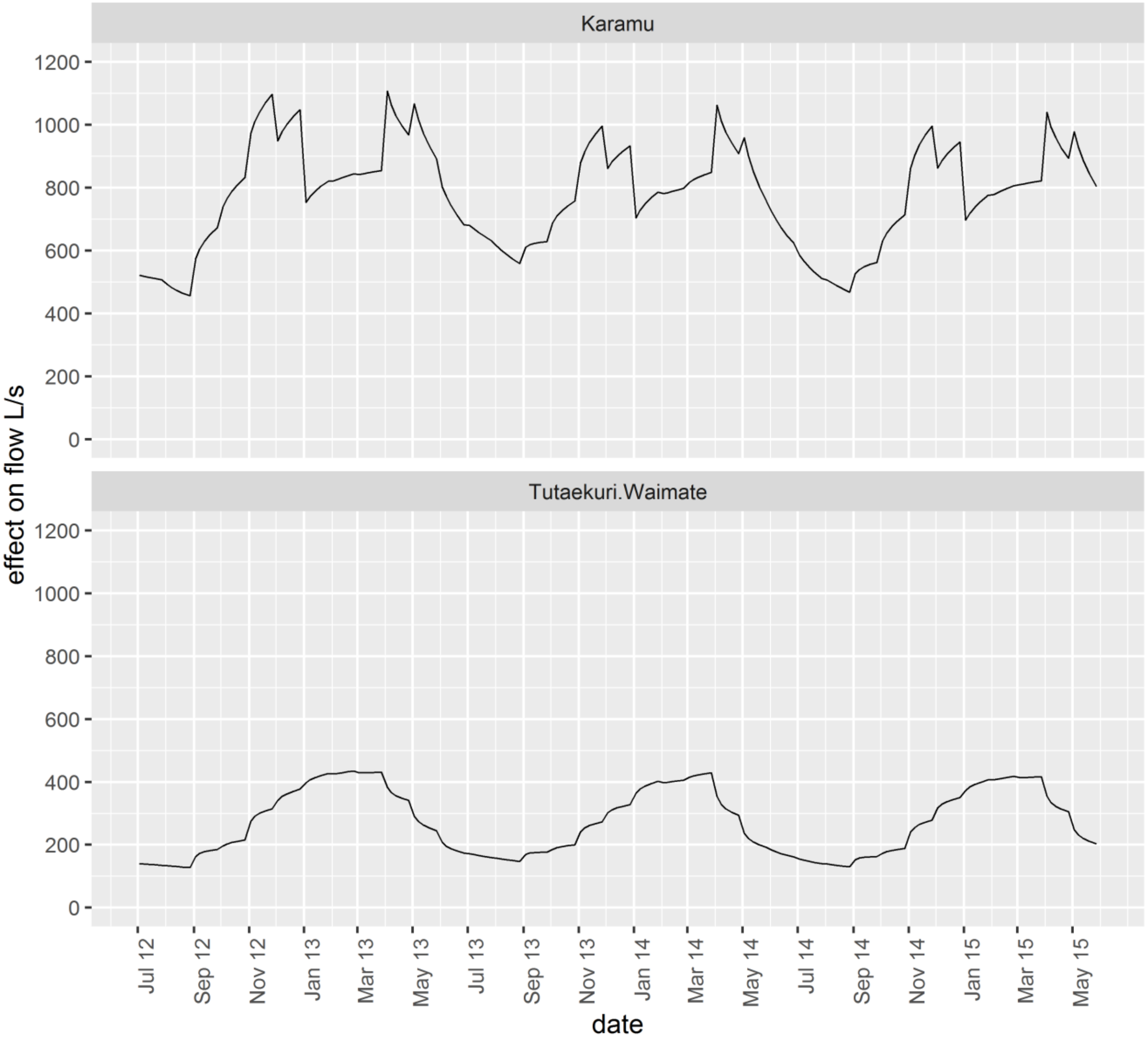

Figure 3-14 Incremental s effect of groundwater pumping on SW/GW exchange flux for spring fed streams 2012-2015 (part1). For spring fed streams the incremental effect is equivalent to a change of spring discharge, or a change in stream gain. Positive values mean that spring discharge declines, resulting in decreased streamflow (stream depletion). The visible abrupt decline in effect for Karamu stream between December and May is a model artefact resulting from the use of time-variable stream conductance (see page 32 for explanation).

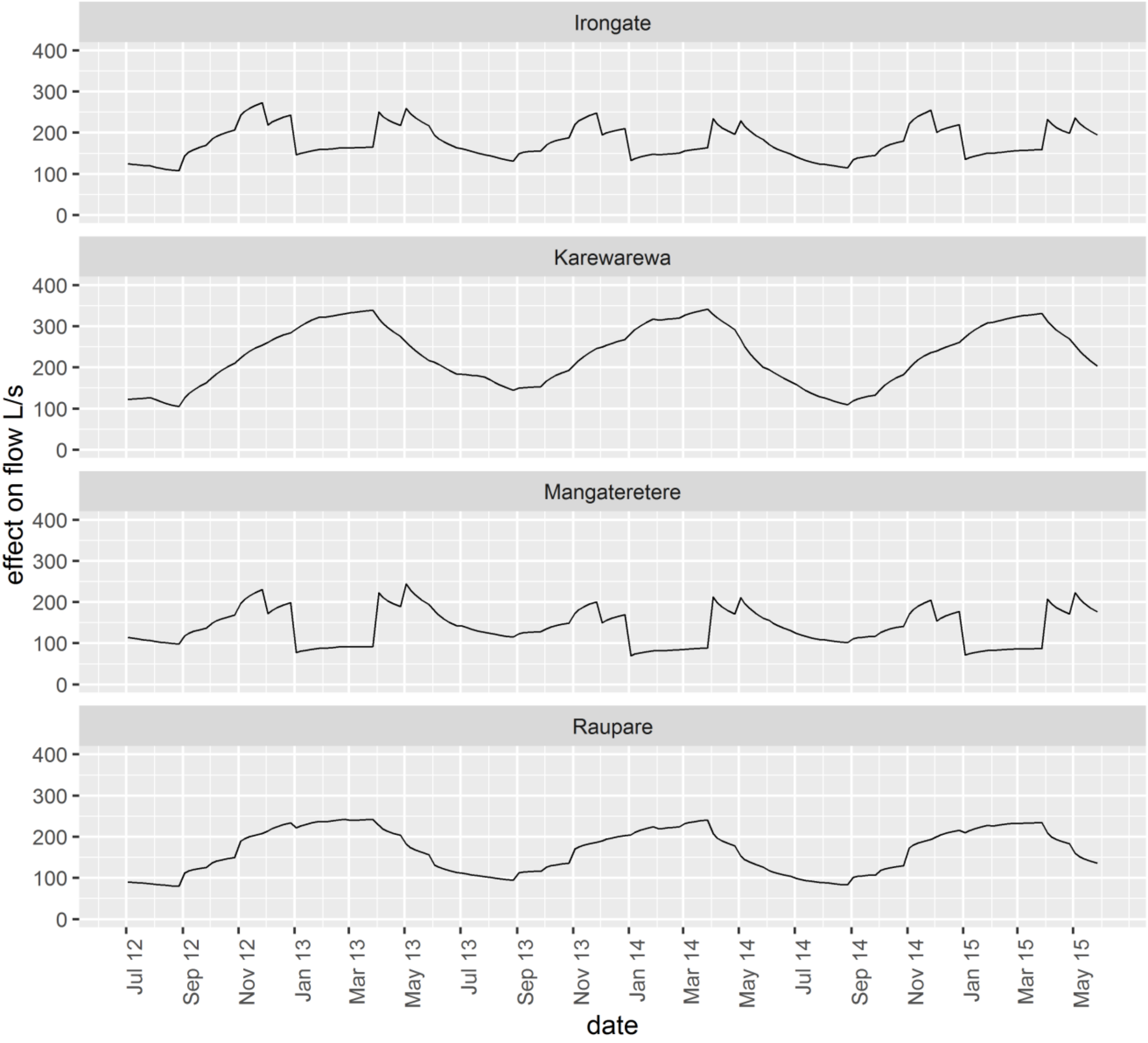

Figure 3-15: Incremental seasonal effect of groundwater pumping on SW/GW exchange flux for spring fed streams 2012-2015 (part2). For spring fed streams the incremental effect is equivalent to a change of spring discharge, or a change in stream gain. The visible abrupt decline in effect for Irongate and Mangateretere streams between December and May is a consequence of time-variable stream conductance (see text for explanation).

Effect per user type

The effect of groundwater pumping on streamflow is caused by the combined impact of pumping by thousands of groundwater users. The main user groups, responsible for 95% of total use, are irrigation, public water supply and industry. These users have different use patterns, with irrigation being highly seasonal and only occurring during the summer, whilst public water supply and industrial users pump at a relatively constant rates throughout the year.

The model was used to estimate the effect of different user groups' contribution to the overall flow depletion effect throughout the year. The base case scenario was constructed using all historical pumping data. For each scenario, perturbation was simulated by removal of pumping by a user group. For example, the impact of irrigation users was identified by running the model after removing abstraction for irrigation from the pumping dataset, calculating the exchange flux between surface water and groundwater, then comparing this flux with that calculated for the base case (which includes all pumping). The difference between calculated flows identifies the amount of stream depletion caused by that user group.

Results are presented for main rivers and spring fed streams, for the irrigation year 2012-2013 (Figure 3-16 to Figure 3-18).

Results show that for all rivers and spring-fed streams, the stream depletion effect from public water supply and industrial users is relatively constant throughout the year (as expected).

The effect from irrigation users is variable throughout the year, with much larger stream depletion observed in the summer (as expected). In summer the effect of irrigation on river flow dominates the effect from other users for all rivers and streams (e.g. about two thirds of Ngaruroro river depletion during summer is a consequence of pumping for irrigation).

The effect from irrigation pumping is delayed in comparison to the pumping itself (this “lag time” effect is expected in groundwater systems). For example, maximum flow depletion in the Ngaruroro River is observed in April, whilst the maximum pumping occurs in January. This delay causes stream depletion to occur after irrigation pumping ceases in June and continues to be observed throughout winter. For the Ngaruroro River, the delayed effect from irrigation pumping is similar in magnitude to the combined effect of other users, even at the end of the winter in August.

The effect per user varies for different rivers and streams. The delayed stream depletion effect from irrigation pumping is similar for the Tukituki River, but less obvious for lowland streams including the Raupare, Mangateretere, Irongate and Tūtaekurī-Waimate. The Tūtaekurī River is affected mostly by irrigation, with only minor effects from other user groups. This is likely caused by geographic separation of the Tūtaekurī River losing reach from the rest of Heretaunga Plains.

The apparent abrupt reduction of the effect of pumping during the summer for some streams is discussed in a previous section.

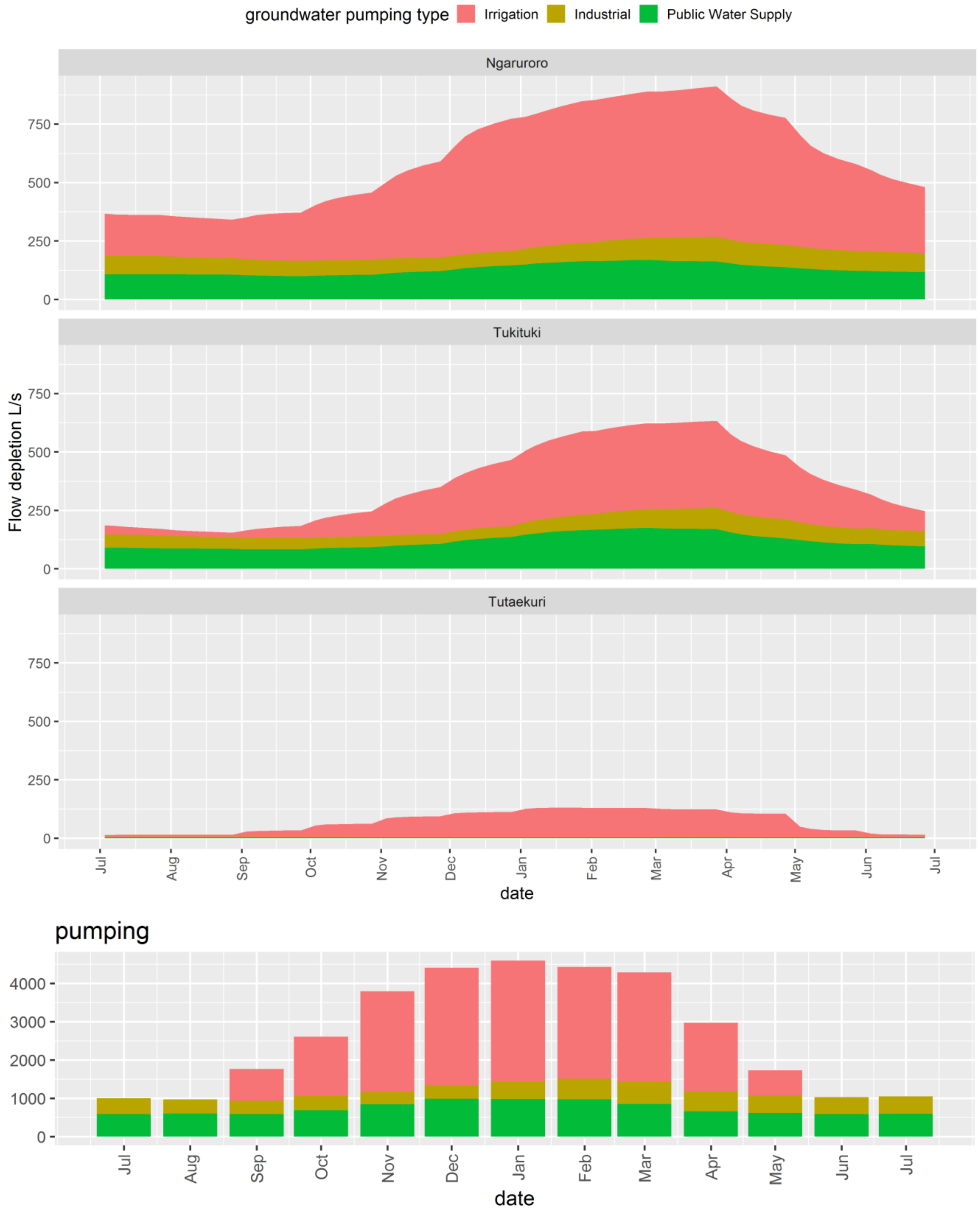

Figure 3-16: Flow depletion per user type in 2012-2013 irrigation year for major rivers. Pumping from groundwater L/s per user type (for largest users) is also shown.

Figure 3-17: Flow depletion per user type in 2012-2013 irrigation year for spring fed streams (part 1). Pumping from groundwater (L/s) for the largest user groups is also shown. The visible abrupt changes between December and May is a consequence of time-variable stream conductance (see page 32).

Figure 3-18: Flow depletion per user type in 2012-2013 irrigation year for spring-fed streams (part 2). Pumping from groundwater (L/s) for the largest user groups is also shown. The visible abrupt changes for some streams between December and May is a consequence of time-variable stream conductance (see page 32).

3.1.3 Groundwater levels

Groundwater levels simulated for the base case (“historical pumping”) and naturalised (“no pumping”) scenarios, for selected bores, are shown as hydrographs in Figure 3-20 to Figure 3-22. Bore locations and sequences for presentation in the hydrographs are shown in Figure 3-19. All hydrographs generally use the same vertical scale for ease of comparison. That is, hydrographs show a 10 m range of groundwater levels, except two cases where this was not possible (see figure captions).

Simulated groundwater levels for the “historical pumping” scenario are generally lower than for the “no pumping” scenario, except bore 15005 (as described below). The difference in groundwater levels between the scenarios appears to become larger with time in all bores, although there are recent signs of a developing equilibrium. The discrepancy varies for different bores, indicating variable levels of impact from groundwater pumping.

Both scenarios show seasonal variation of groundwater levels, with lower groundwater levels occurring during summer periods. However, the “historical pumping” scenario shows larger amplitudes of seasonal variations, and the amplitude increases over time (although there are recent signs of a developing equilibrium). Winter groundwater levels appear relatively constant through time, whilst summer groundwater levels appear to continue to decline. This is consistent with the relatively stable groundwater pumping during the winter since 1980, whilst summer pumping has been increasing until about 2005, when it showed signs of a developing equilibrium (Figure 3-1). Hydrographs for one season (2012/2013) are presented in Figure 3-23 and, in the “historical pumping” scenario, minimum groundwater levels can be seen to occur around March.

In the “no pumping” scenario, groundwater levels appear to remain in a dynamic equilibrium (i.e. they show seasonal variations but not long term changes). Exceptions are bores located in the upper Ngaruroro valley (5023, 3453), which show long term changes that were first recognised during model calibration (Rakowski & Knowling, 2018). A possible reason for this model behaviour was identified as an impact of pumping. However, it is now obvious that this behaviour is observed in both pumping and no pumping scenarios, so it cannot be interpreted as a consequence of pumping. The reason for this behaviour in the Ngaruroro valley has not yet been identified, but in general, the model is less reliable outside of the main Heretaunga Plains area due to less data being available.

Groundwater drawdown (the difference between the “historical” and “no pumping” scenarios) is presented as hydrographs in Figure 3-24. There are differences in pumping responses between the bores, but in all cases increasing drawdown is apparent. Drawdown in summer is generally larger than in winter (median drawdown in the summer is 2.5 m and median drawdown in the winter is 0.95 m). The smallest drawdown responses are visible near the losing reach of Ngaruroro River (bores 15005 and 10371), presumably due to the presence of substantial river recharge, and in the Moteo Valley. Negative drawdown (increase in water level) is visible in bore 15005 between 1990 and 2010, due to the effect of managed aquifer recharge. Maximum drawdown occurs around March and smallest drawdowns were identified around August in most of the locations (Figure 3-25).

Spatial distribution of drawdown is presented in Figure 3-26 (summer) and Figure 3-27 (winter). Drawdown occurs in both winter and summer throughout the plains, with larger drawdown in the summer. There are clear patterns of spatial distribution of drawdown. Areas near losing sections of major rivers (Ngaruroro, Tukituki, Tūtaekurī) are least affected by drawdown, which is less than 0.5 m in both summer and winter.

Areas most affected by drawdown appear to be near large public water supply takes in Napier and to a lesser degree in Hastings, where drawdown can exceed 4 m in the summer.

Drawdown in the western part of the model, upstream of Maraekakaho is not presented, as drawdown predictions for this area are considered unrealistic.

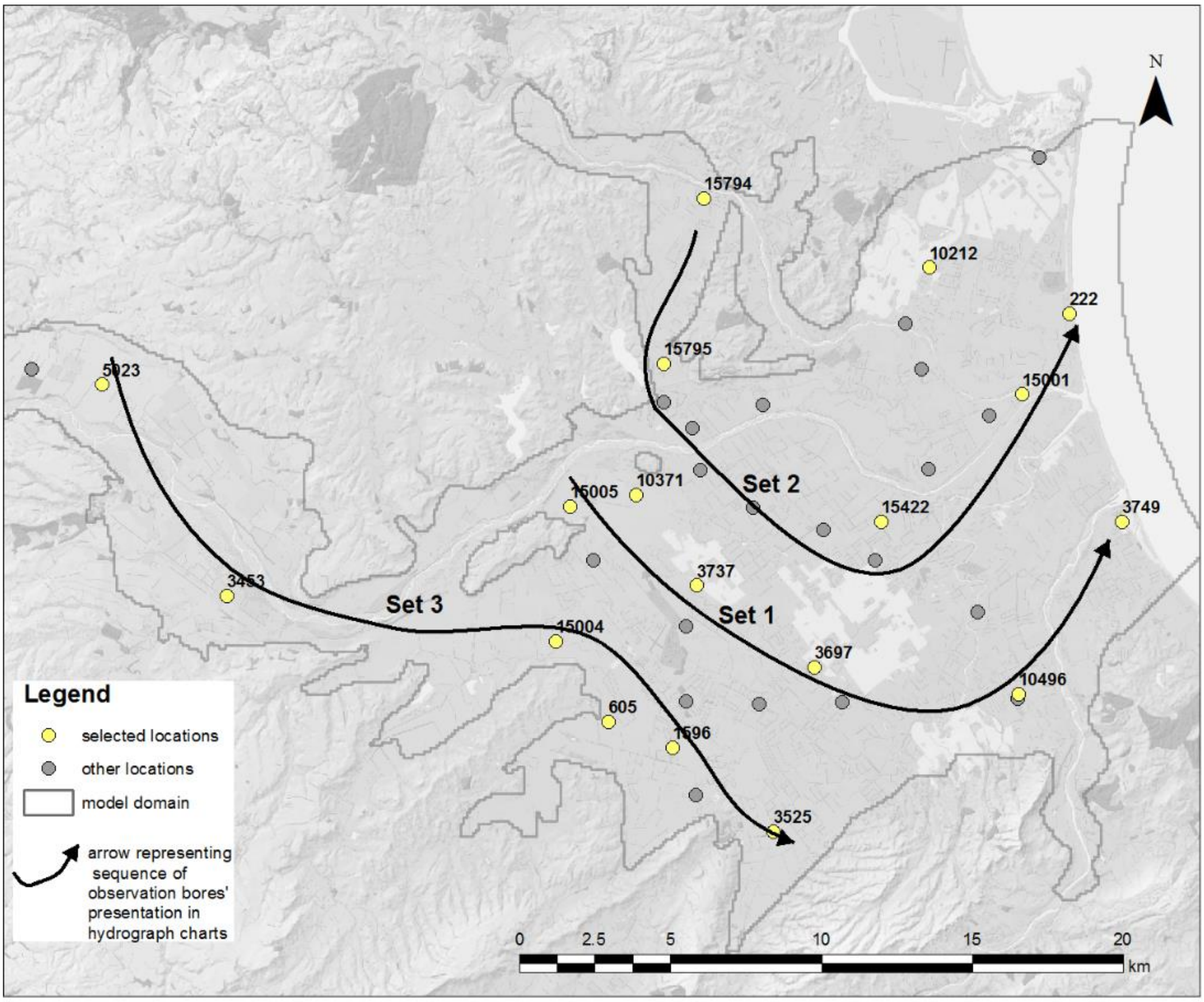

Figure 3-19: Locations of selected observation bores. Arrows show the sequences of hydrograph presentation in Figure 3-20, Figure 3-21 and Figure 3-22.

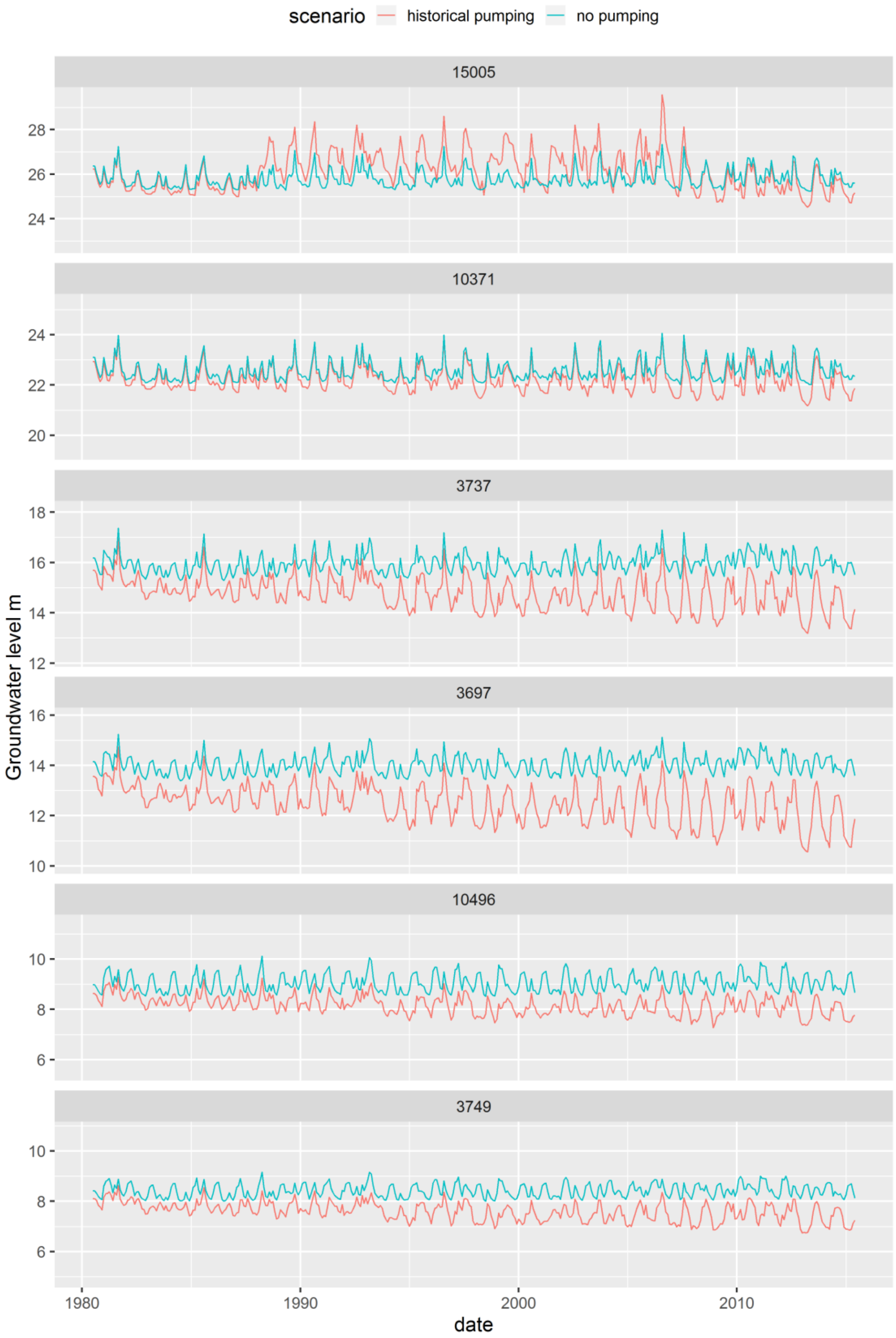

Figure **3**-**20**: Hydrographs of simulated groundwater levels (masl) in Heretaunga Aquifer. Set 1 of bores identified in Figure 3-19 (Fernhill-Flaxmere-Hastings-Havelock North-Haumoana)

Figure 3-21: Hydrographs of simulated groundwater levels (masl) in Heretaunga Aquifer. Set 2 of bores identified in Figure 3-19 (Tūtaekurī Tūtaekurī-Waimate-Napier-Awatoto).

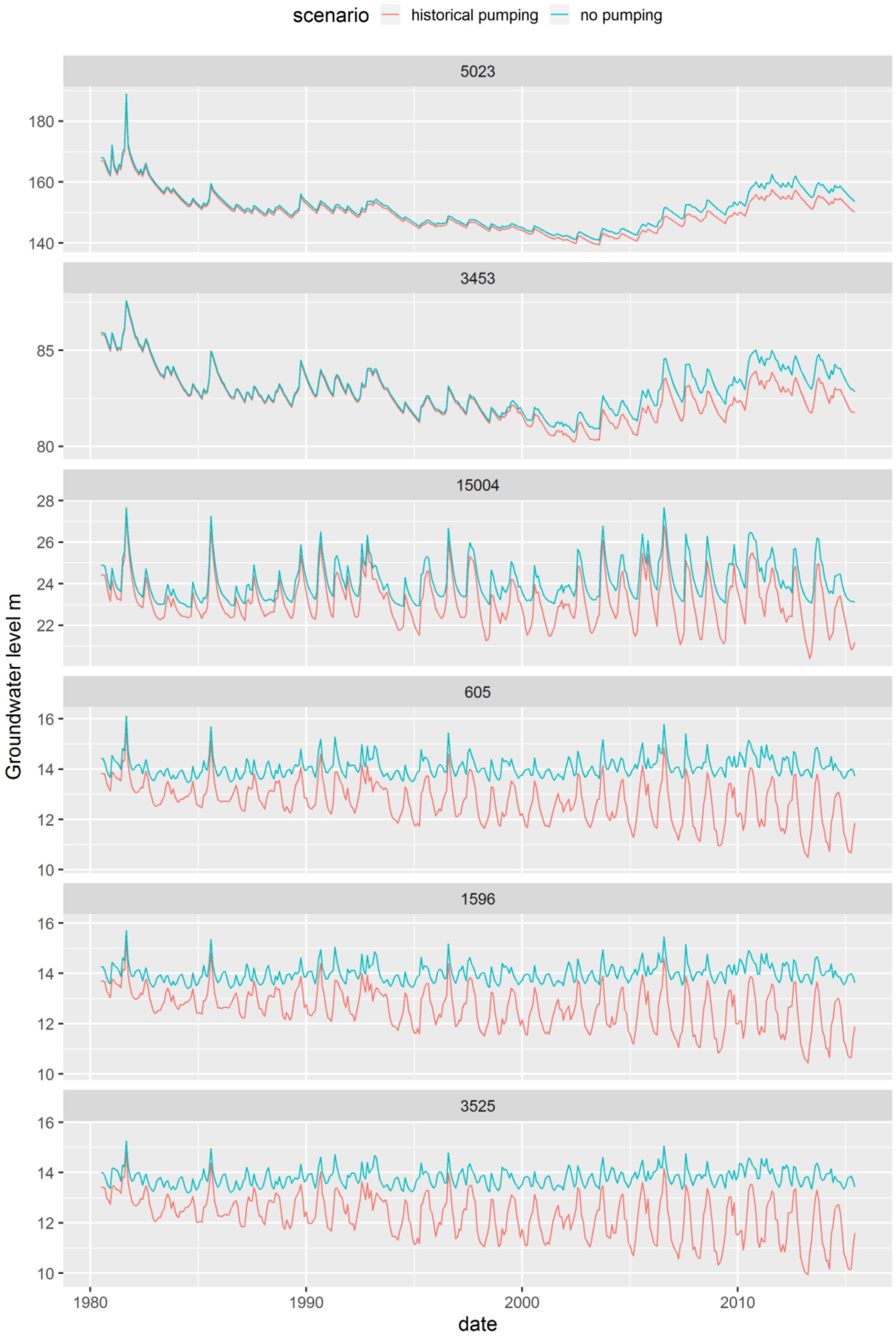

Figure 3-22: Hydrographs of simulated groundwater levels (masl) in Heretaunga Aquifer. Set 3 of bores identified in Figure 3-19 (Kikowhero-Maraekakaho - Bridge Pa - Pakipaki). Note that bores 5023 and 3453 show a greater range of groundwater levels

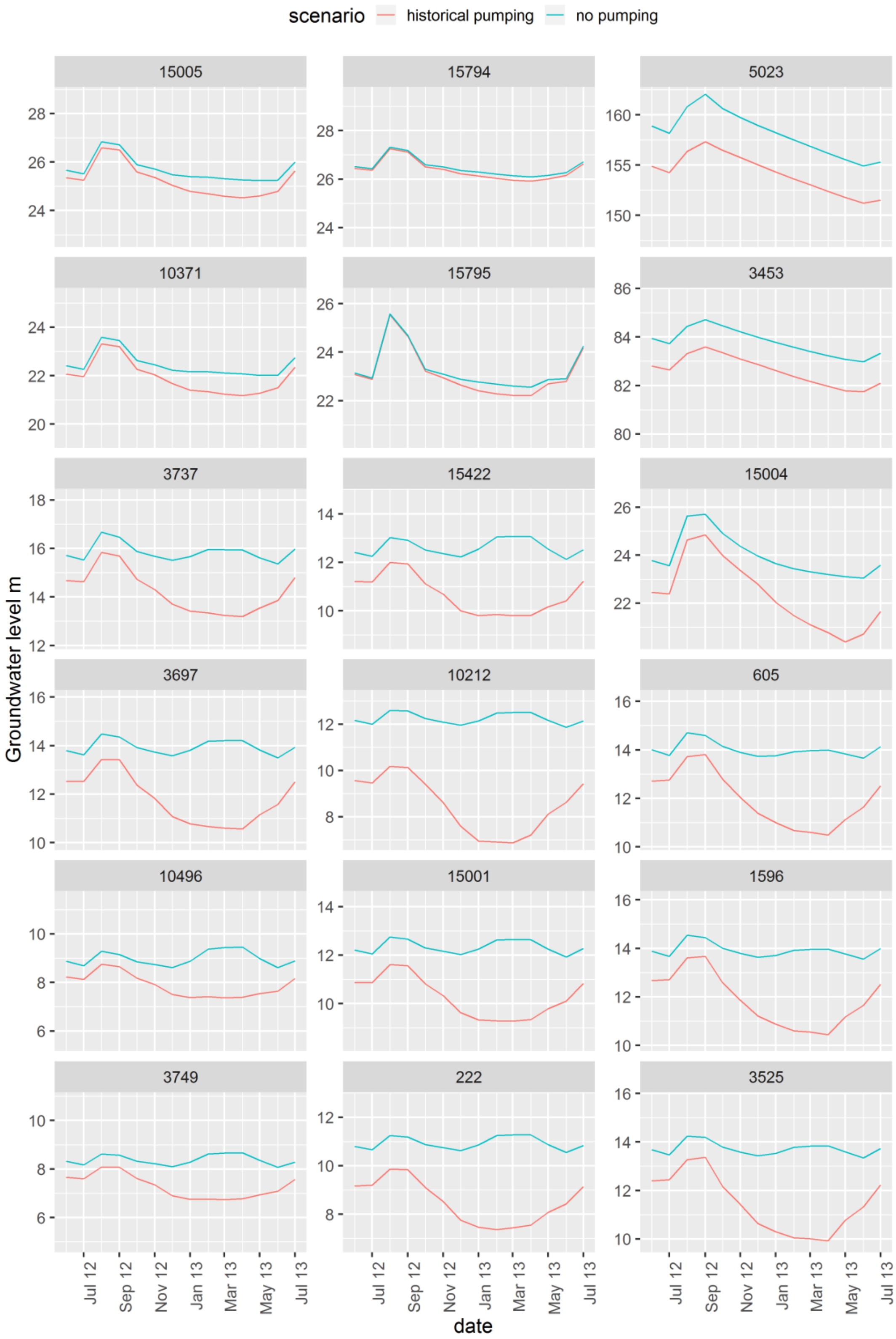

Figure 3-23: Hydrographs of simulated groundwater levels (masl) in the Heretaunga Aquifer during 2012-2013. Bore numbers are shown above each plot and bore locations are identified in Figure 3-19

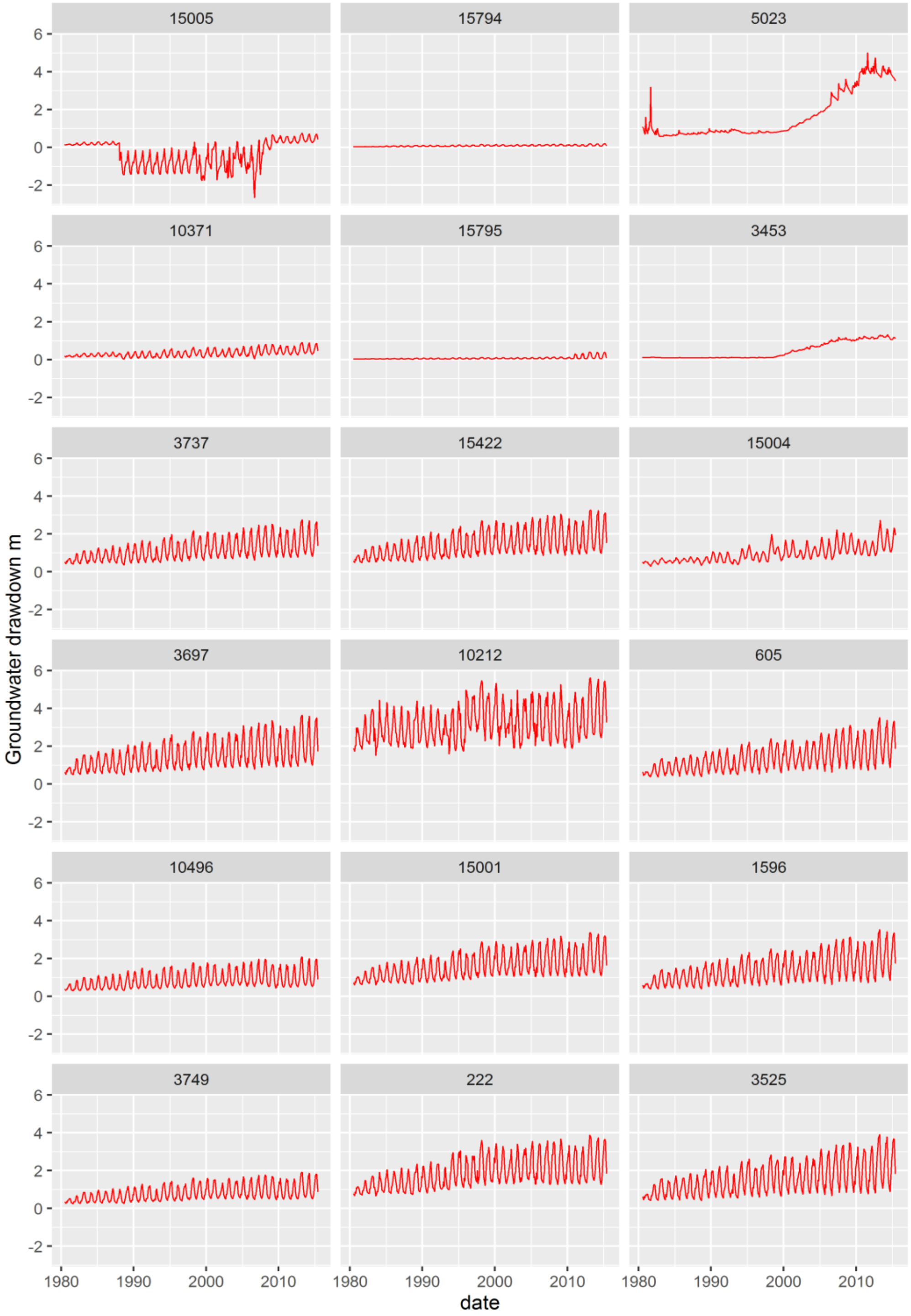

Figure 3-24: Hydrographs of simulated groundwater drawdown for selected locations. Positive numbers indicate decline in groundwater level in relation to the "no pumping" scenario (note the increasing trend in drawdown due to increasing pumping, with recent signs of a developing equilibrium). Negative numbers indicate increases in groundwater level (e.g. bore 15005 shows an increase as a consequence of MAR). Bore numbers are shown above each plot and bore locations are identified in Figure 3-19.

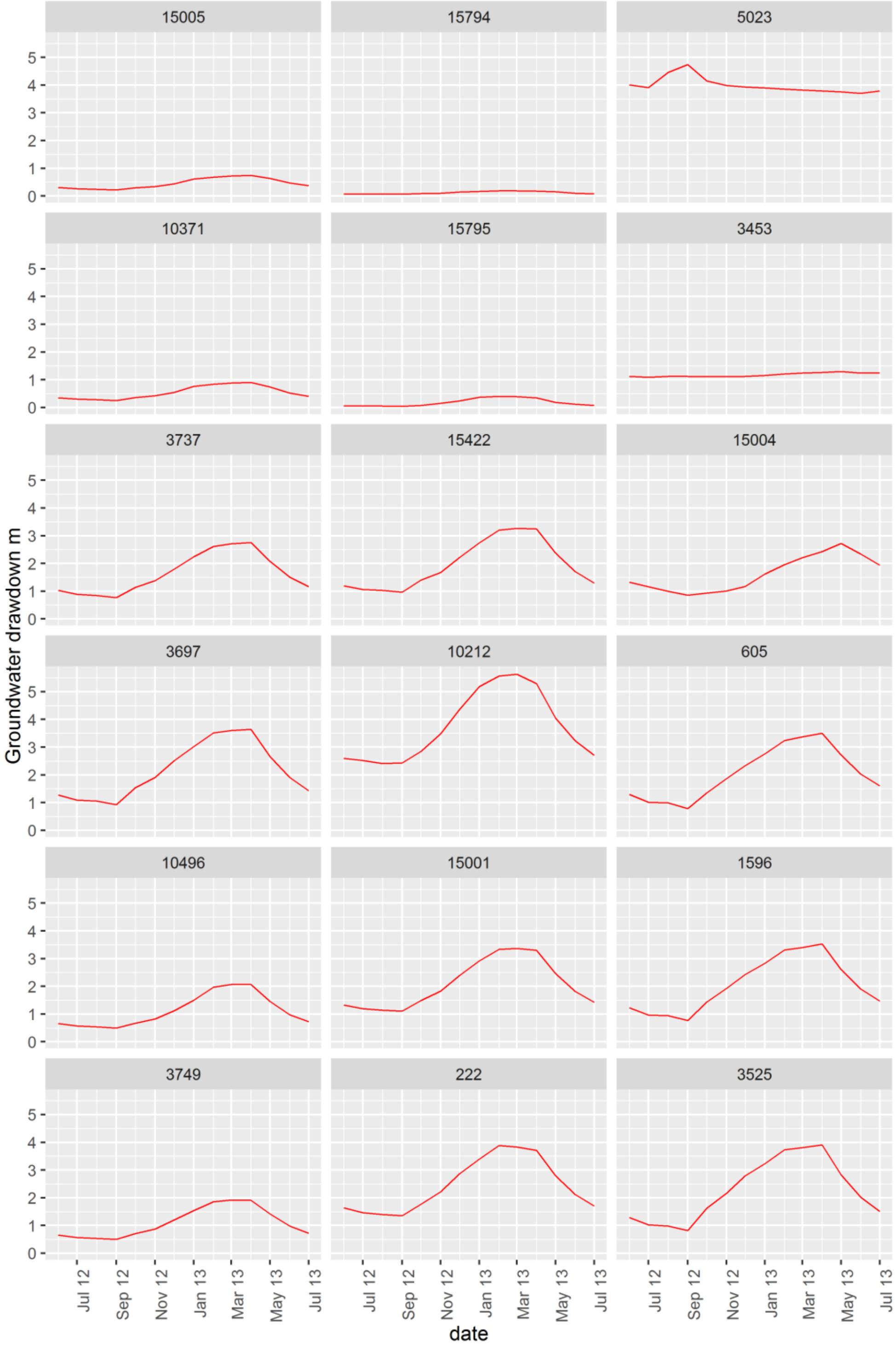

Figure 3-25: Hydrographs of simulated groundwater drawdown for selected locations in 2012/2013. Positive numbers indicate decline in groundwater level in relation to the "no pumping" scenario. Bore numbers are shown above each plot and bore locations are identified in Figure 3-19.

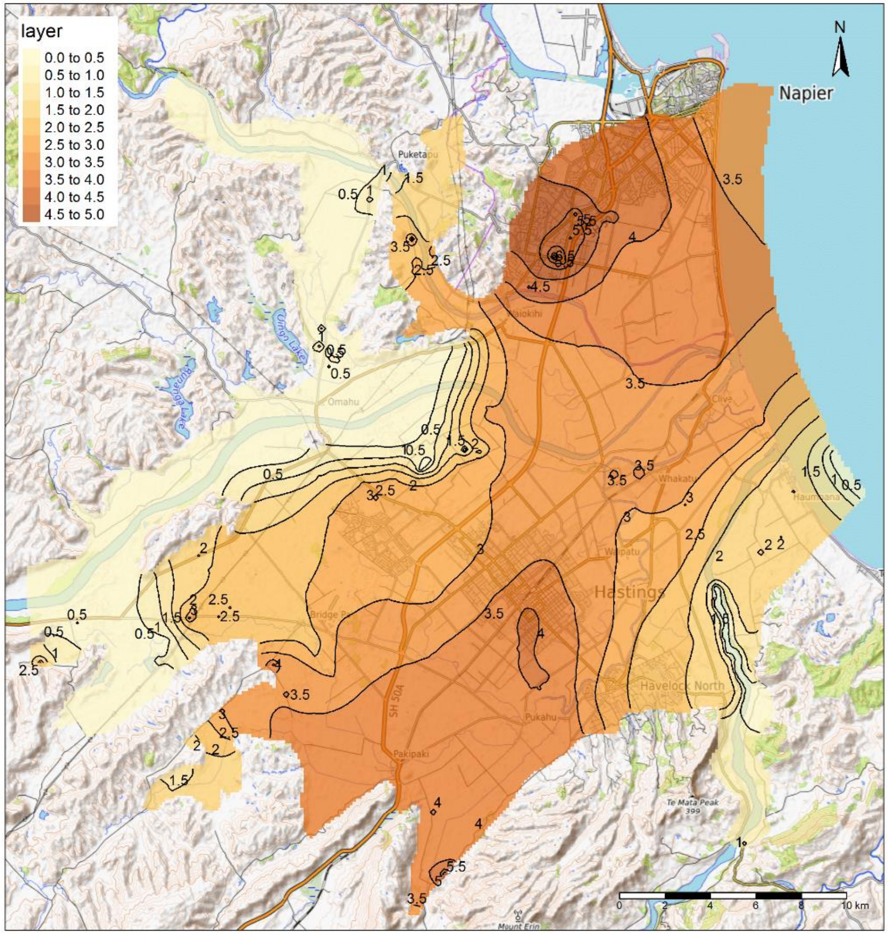

Figure 3-26: Groundwater drawdown (m) in Heretaunga Aquifer during summer (March 2013).

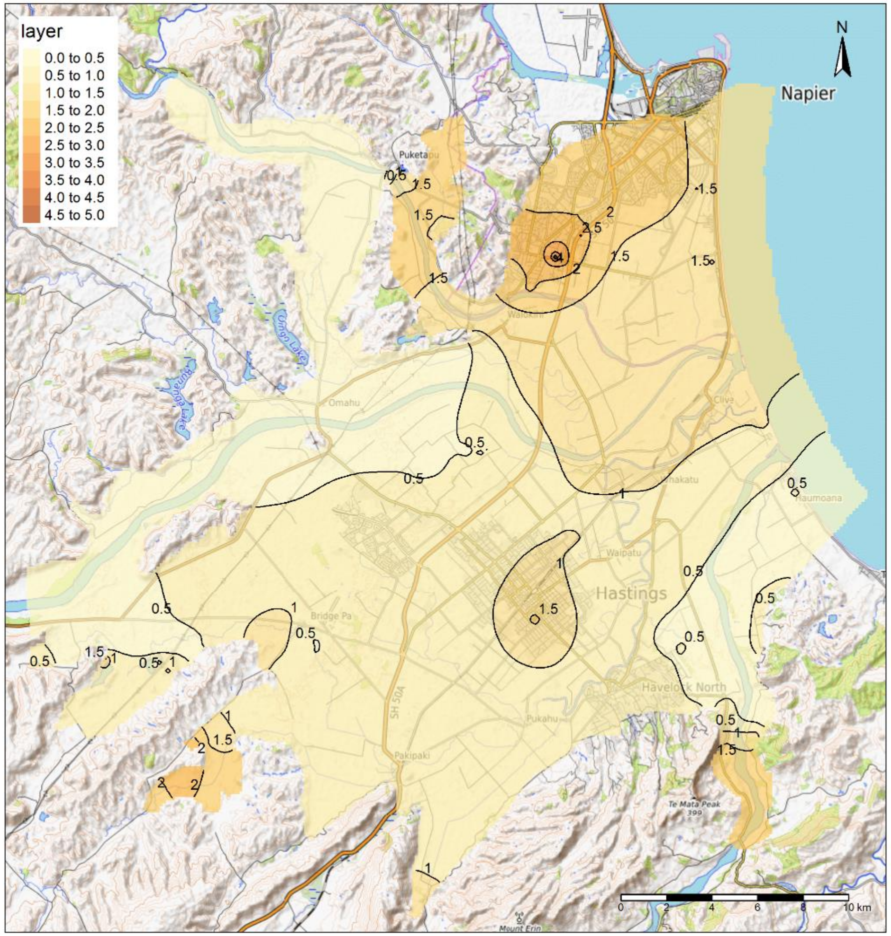

Figure 3-27: Groundwater drawdown (m) in Heretaunga Aquifer during winter (August 2012).

4 Future scenarios

Three model scenarios were set-up for 100 year simulations. The scenarios are based on the historical monthly scenario, projected into the future.

4.1 Repeated conditions

4.1.1 Scenario set-up

This scenario is based on using the last 10 years of model stresses (recharge, pumping, and river levels) and repeating them 10 times to represent a 100 year scenario. The aim of this scenario is to establish what would happen if the current level of groundwater use and climate remained unchanged (i.e. to investigate whether further declines in water levels and/or streamflow would occur). This scenario is also used as a reference for investigations of increasing pumping and dry climate scenarios, as reported in later sections.

4.1.2 Scenario results

The results indicate that if the current conditions of groundwater use and climate remained unchanged, further decline in water levels (Figure 4-8) and streamflow (Figure 4-5 to Figure 4-7) would not occur. This indicates that the aquifer is presently developing a dynamic equilibrium.

4.2 Increased pumping

4.2.1 Scenario set-up

This scenario is similar to “repeated conditions”, except that groundwater pumping is assumed to increase in the future. The rate of increase is based on the observed rate of increase in the past. The past pumping rate has been increasing (Figure 4-1). The change in groundwater use varies from year to year, but when analysed by decade, a clear pattern emerges (Figure 4-2): Public water supply has been stable for the past three decades, industrial use has been stable for the past two decades, and irrigation has been increasing. When irrigation use is analysed separately, the rate of increase is about 10 Mm^3 per decade (Figure 4-3). A modelling scenario was set up, assuming the same seasonal and yearly pattern of groundwater use as in 2005-2015 but, assuming continued increase of irrigation use at a rate of 10 Mm^3/decade over next 100 years (Figure 4-4). This increase may be unrealistic, but the scenario is valuable as it enables exploration of a potentially extreme groundwater use case based on observed recent trends.

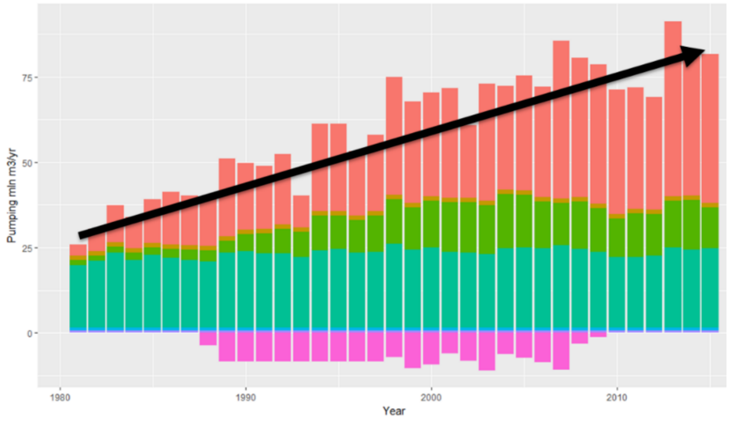

Figure 4-1: **Changes in groundwater use.**

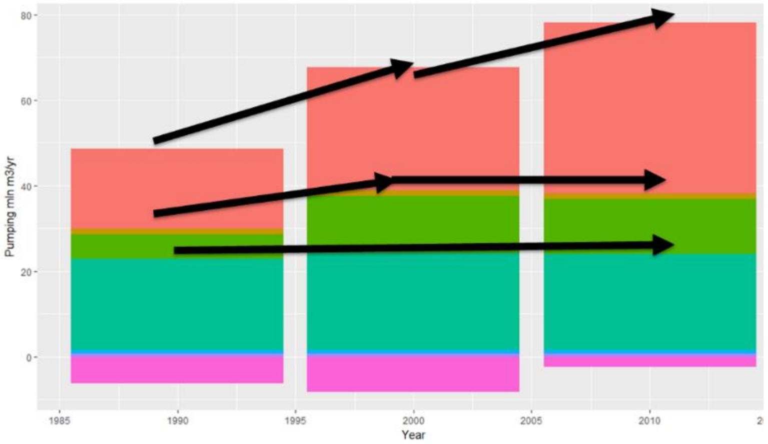

Figure 4-2: **Decadal changes in groundwater abstraction for all users.**

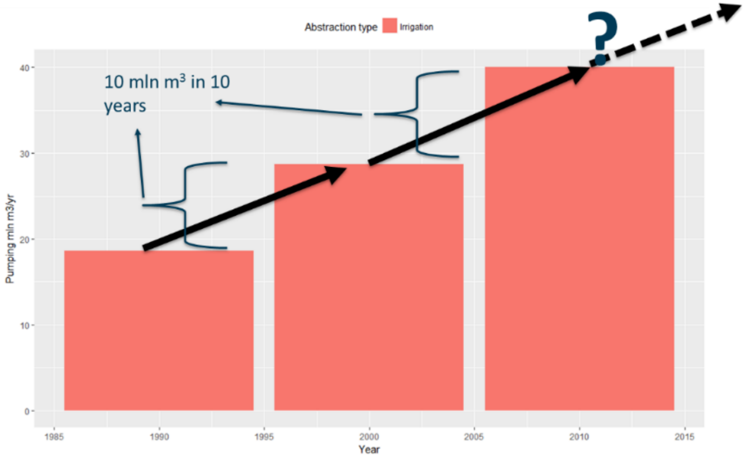

Figure 4-3: **Decadal changes in groundwater use for irrigation.**

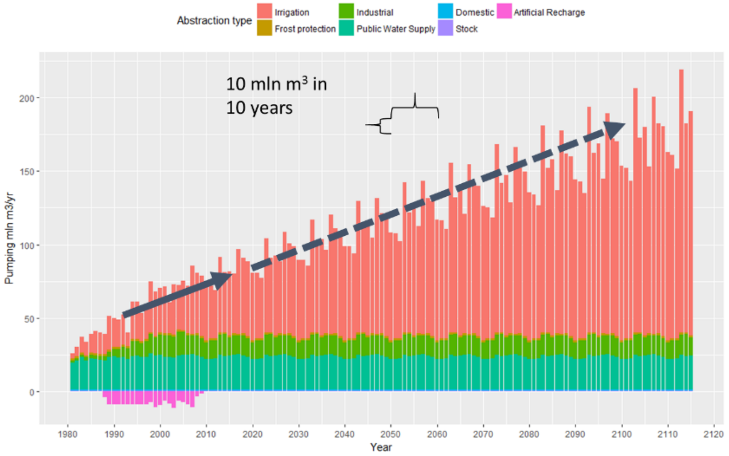

Figure 4-4: **Increasing groundwater use dataset.** Irrigation use is assumed to keep increasing at 10 Mm^3/decade rate, but following the same seasonal and annual pattern as in the 2005-2015 period

4.2.2 Scenario results

The results indicate significant declines of streamflow and groundwater levels would be expected in the future, if the rate of groundwater pumping keeps increasing (Figure 4-5 to Figure 4-8). If the current trend of increasing groundwater use continues, this would lead to drying out of some streams and rivers. For example, Mangateretere Stream would be dry around 2030. By about 2050, the Ngaruroro River would lose an additional 1000 L/s of water which would result in river flow ceasing during dry periods (as the Ngaruroro River flows have been as low as 1000 L/s in the past). The groundwater levels would also be affected, with additional drawdown of up to five metres predicted. Such high drawdown could lead to issues with saline intrusion, due to loss of artesian conditions. Even smaller additional drawdown may lead to issues with access to water for some users that rely on artesian pressures.

This modelled scenario may be considered extreme in relation to future water use. For example, the predicted change in groundwater conditions is so large that some streams would switch from gaining to losing. Due to a boundary condition used in the model (MODFLOW RIV), this means that the result becomes unrealistic at that point. For example, in reality, the Mangateretere Stream could not become losing if flow ceases (as there would be no water to be lost from the river). However, even with these limitations the model provides a clear indication of potential threats to the groundwater flow regime and gives an estimate of when these changes could be expected to occur.

4.2.3 Model limitation and confidence in results

This modelled scenario may be considered extreme in relation to future water use. In some cases (e.g. Mangateretere and Irongate) the lowest spring flow may become positive, which indicates that stream ceased flow, or becomes losing and starts providing aquifer recharge. In reality streams as Mangateretere would dry out and would not provide aquifer recharge, but the MODFLOW “RIVER” boundary condition allows for continued aquifer recharge (although this recharge is relatively small in comparison to overall water budget, about 100 L/s for Mangateretere, which means that it is unlikely to have a major impact for the overall water budget of the aquifer). Similarly, the Ngaruroro River, which is a losing river shows losses increasing by about 1000 L/s, which would indicate near complete drying of the river during low flows. In reality, this would result in loss of river recharge to the aquifer, and reduction of effect on the river (e.g. the impact on the river would decline if river flow becomes very small and would reduce to zero if river dries out). However, the model uses “RIVER” boundary condition, which will, due to its limitations, continue providing river recharge. This means that in such extreme cases, the model under-predicts the impact on the aquifer, and over predicts impacts on river. This is a known limitation of the model that was recognised during model development. Despite this, the results remain useful and fulfil modelling objectives (such as assessing impact of different abstraction strategies) as they can indicate with high confidence the level of pumping that will cause a significant change in surface-water and groundwater exchange flux.

4.3 Dry climate scenario

4.3.1 Scenario setup

The dry climate scenario uses conditions (e.g. groundwater pumping, recharge, river levels) from the very dry hydrological year 2012-2013 and repeats these conditions via simulation every year for the next 100 years.

4.3.2 Scenario results

Results are presented in Figure 4-5 to Figure 4-8. When simulating dry climatic conditions, repeated every year, groundwater levels and river flows remain at low levels, but there is not a long term declining trend.

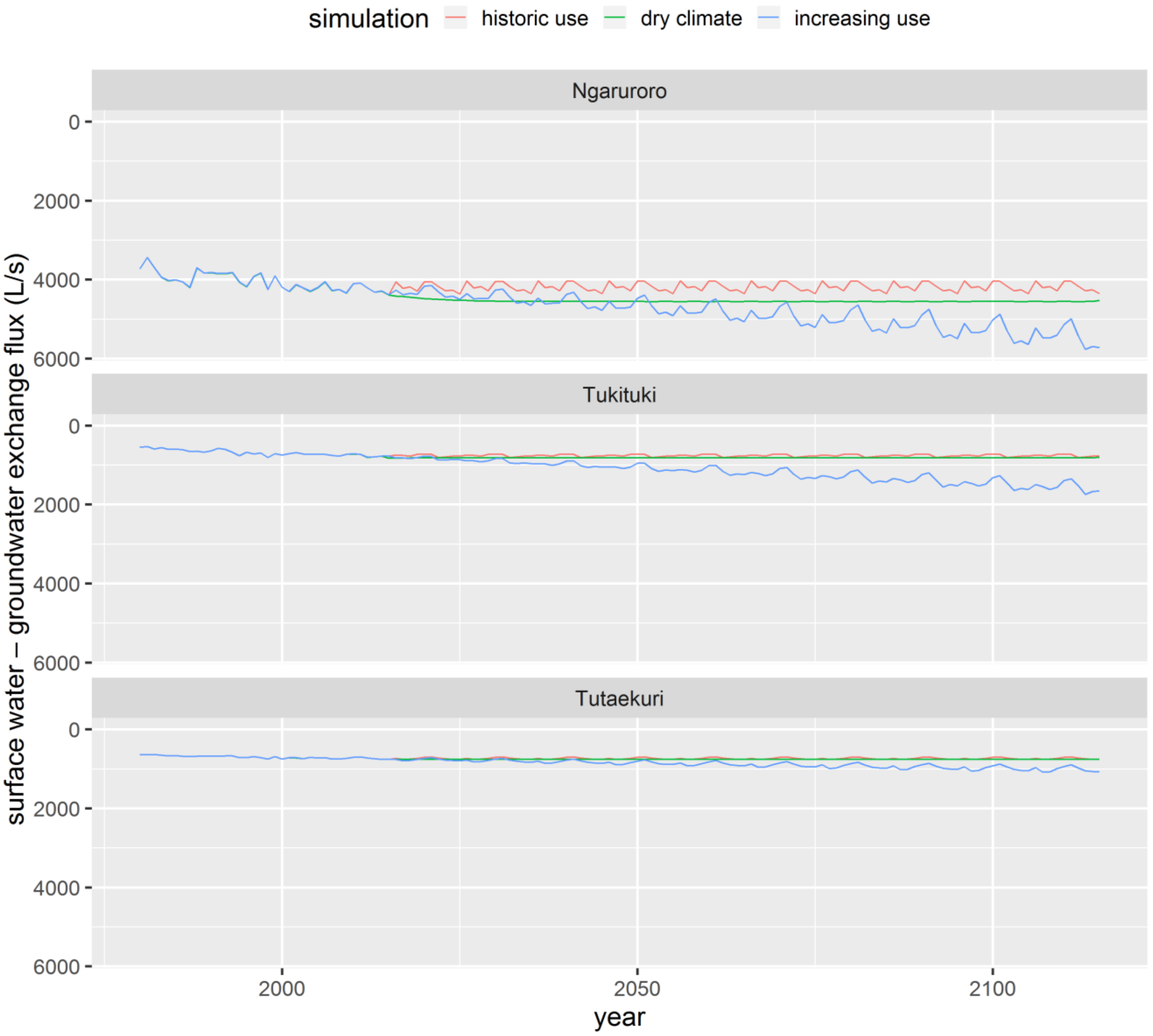

Figure 4-5: Predicted Groundwater-surface water exchange flux for future scenarios (part 1). Positive values indicate river loss. Lowest yearly surface water–groundwater exchange fluxes in any year are shown. The green line (dry climate scenario) is invariable because in each year the same climatic and pumping conditions are repeated.

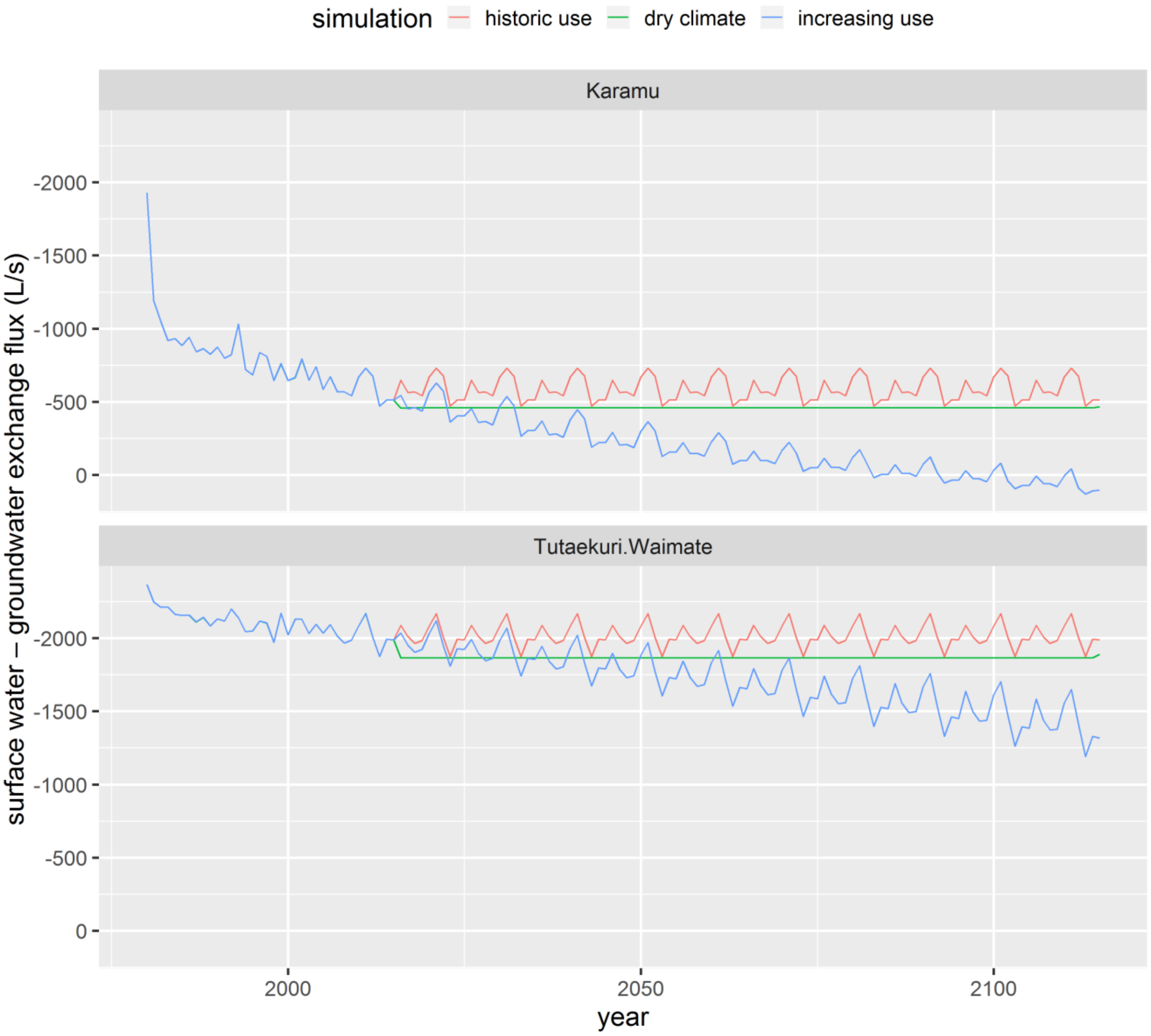

Figure 4-6: Predicted Groundwater-surface water exchange flux for future scenarios (part 2). Lowest yearly flux (least negative surface water–groundwater exchanges in any year) are shown. The green line (dry climate scenario) is invariable because in each year the same climatic and pumping conditions are repeated.

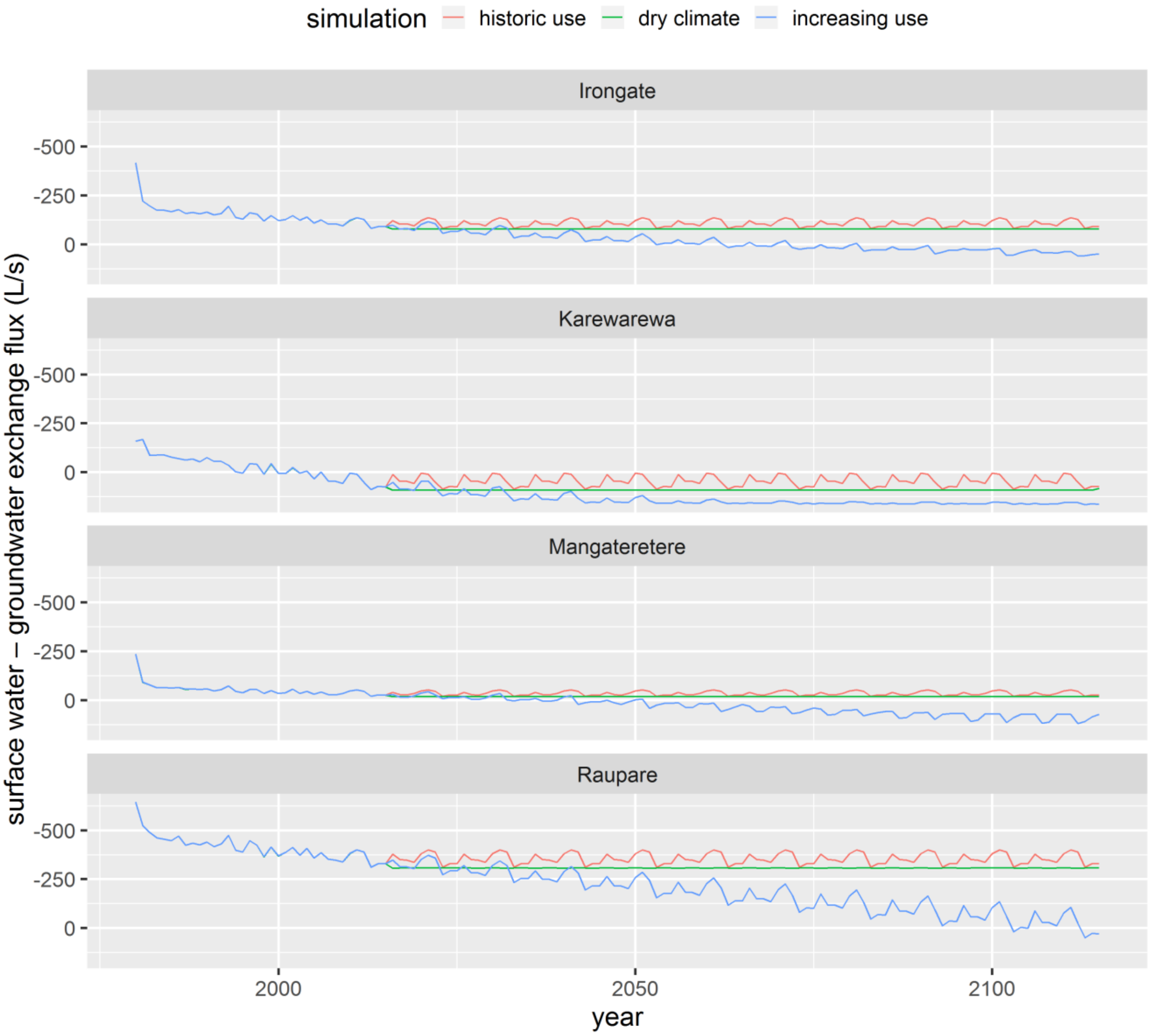

Figure 4-7 Predicted Groundwater-surface water exchange flux for future scenarios (part 3). Positive values indicate river loss. Lowest yearly flux (least negative surface water–groundwater exchanges in any year) are shown. The green line (dry climate scenario) is invariable because in each year the same climatic and pumping conditions are repeated.

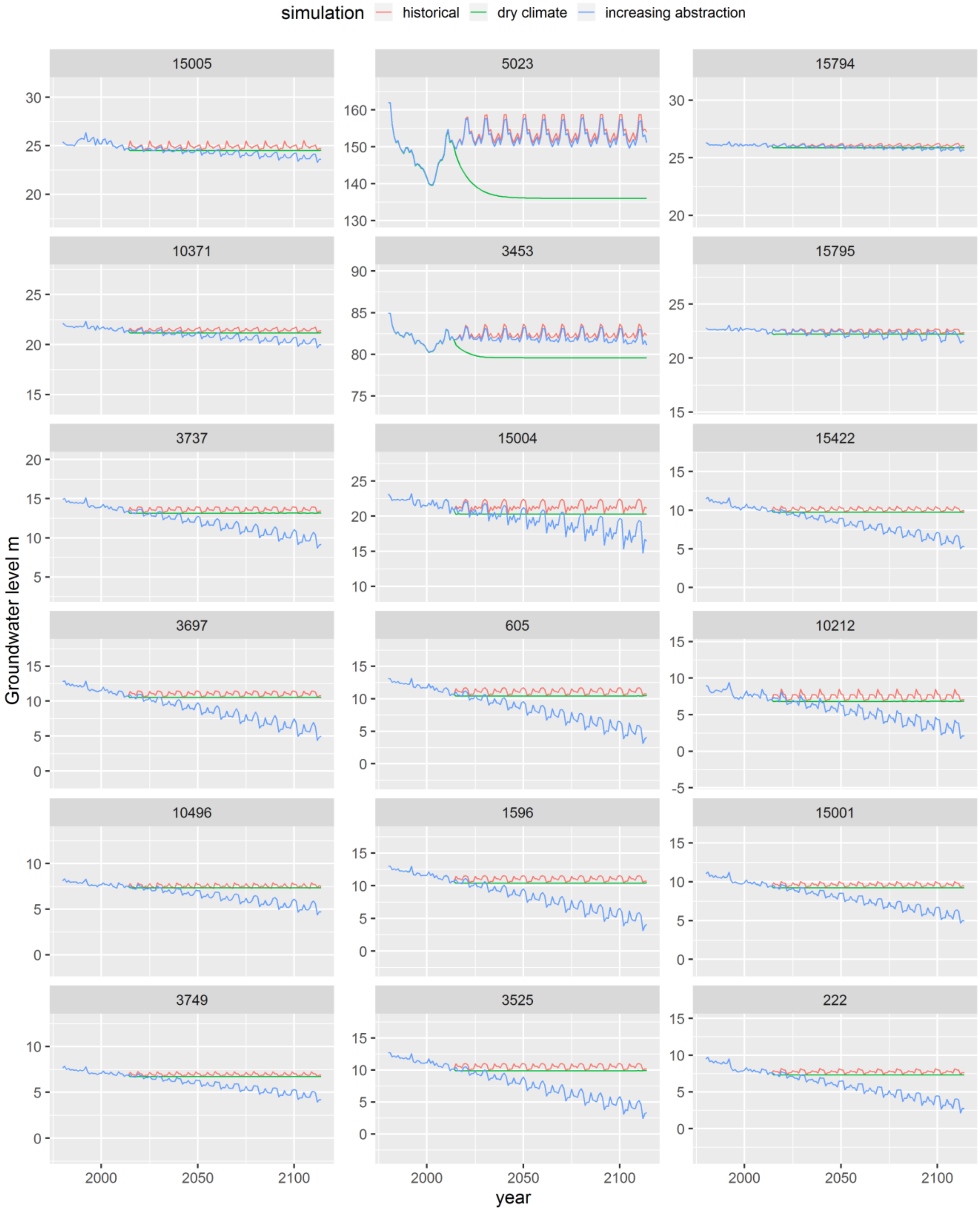

Figure 4-8: **Predicted minimum yearly groundwater levels for future scenarios**

4.4 Sensitivity to increases in pumping

4.4.1 Scenario setup

The increasing pumping scenario indicated large changes to the aquifer system in response to large increases in pumping. The question arose about what happens to the aquifer system when pumping increases or decreases by a small fraction, for example 10% or 20%? This may be thought of as testing the sensitivity of the aquifer to changes in pumping. This knowledge would be valuable in decision making, for example in establishing an abstraction (or allocation) limit for the aquifer.

To establish the sensitivity of the aquifer to pumping, a series of model scenarios was set up. The previous modelling indicated a fast response to change and rapid stabilisation at a new dynamic groundwater level (e.g. dry climate scenario and historical pumping scenario resulted in stabilised conditions). Because the response was fast, these new sensitivity scenarios used a 20 year simulation duration. The set up was similar to the historical pumping scenario, but with historical data from 2005-2015 repeated two times and groundwater pumping increased or decreased in each scenario by a set fraction. The scenarios explored the following percentage changes in pumping, relative to current pumping: -50%, -30%, -20%, -10%, +10%, +20%, +30%, +50%, +100%.

4.4.2 Scenario results

The scenario results were processed to obtain groundwater levels and surface water – groundwater flows as for other scenarios.

Groundwater levels for selected bores (222, 3697 and 3737 – see Figure 3-19 for locations) under each scenario are plotted in Figure 4-9. Each incremental increase of groundwater pumping results in further declines in groundwater levels; and decreased pumping results in increased groundwater levels. January 2025 was selected to be representative of low groundwater conditions (Figure 4-9) and used for more detailed comparisons. Groundwater levels calculated for the selected bores, under each scenario during January 2025, are plotted against percentage changes in pumping (Figure 4-10). Groundwater levels at each location exhibit similar sensitivity to changes in pumping, and the relationship between groundwater level and changes in pumping can be approximated using a straight line. For other locations, the slope of the line is similar and represents approximately 0.35 m groundwater level response per 10% change in pumping.

Surface water - groundwater exchange flux was calculated for each scenario, and the spring flows in a selected period (which corresponds to low flow and high impact period) were analysed in the same way as groundwater levels – as described in the previous paragraph. The response of surface water - groundwater exchange flux to changes in pumping is similar to the response of groundwater levels (Figure 4-11). The relationship in most cases is linear, but for some streams there is some divergence from the linear response (e.g. Karewarewa).

In some cases (Mangateretere and Irongate) the lowest spring flow become positive, which indicates that the stream ceases to flow, or becomes losing. This has been discussed in section 4.2.3.

Results are also summarised in Table 4-1, which shows the percentage of streamflow loss per percentage of groundwater pumping increase. Table 4-1 is colour coded to indicate when the decrease of streamflow is greater than 25%, greater than 50%, or is 100% (i.e. the stream is dry).

Figure 4-10, Figure 4-11 and Table 4-1 show that even minor increases in groundwater pumping will have some negative effect on streamflow and groundwater levels. On the other hand, a minor reduction of abstraction (e.g. 10%) may not be sufficient to increase streamflow to desired levels.

For example, the minimum flow requirement for Karamu Stream at Floodgates is 1100 L/s and the lowest recorded flow during summer 2013 was 750 L/s, so the flow deficit is 350 L/s. However, the estimated flow increase in Karamu from 10% decrease of groundwater pumping is only 60 L/s. Furthermore, it may be challenging to achieve a 10% reduction of groundwater pumping throughout the Heretaunga Plains, due to the economic and social value of groundwater for industry, municipal drinking water supplies and irrigation to support primary production. To reduce stream depletion in Karamu Stream by 350 L/s would require a 50% reduction of groundwater pumping (see Table 4-2 for estimated streamflow responses following changes in groundwater pumping).

The method presented above has some limitations, for example:

- Extreme weather may make impacts even worse than those simulated
- Local impact is not considered (e.g. the analysis considered a uniform increase in pumping in existing locations – a large increase in pumping in a specific location, such as a new large irrigation take close to the spring fed stream, may result in greater local impact on this stream)
- Modelling uncertainty increases for simulations of extreme stress.

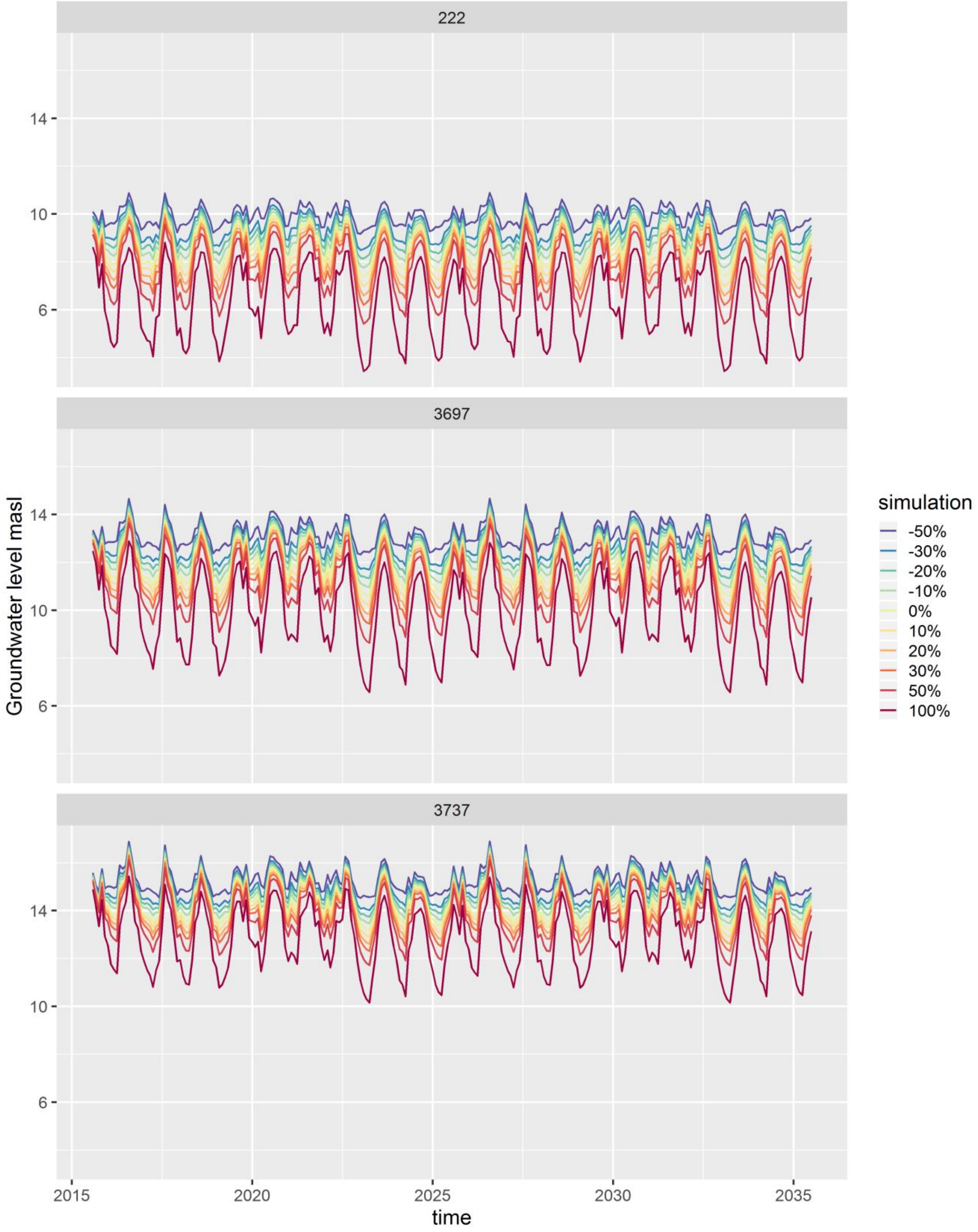

Figure 4-9: Groundwater levels for selected locations under scenarios with decreased and increased pumping. Bore numbers are above each plot and the bore locations are shown in Figure 3-19. Units for groundwater levels (GWL) are metres above mean sea level (masl).

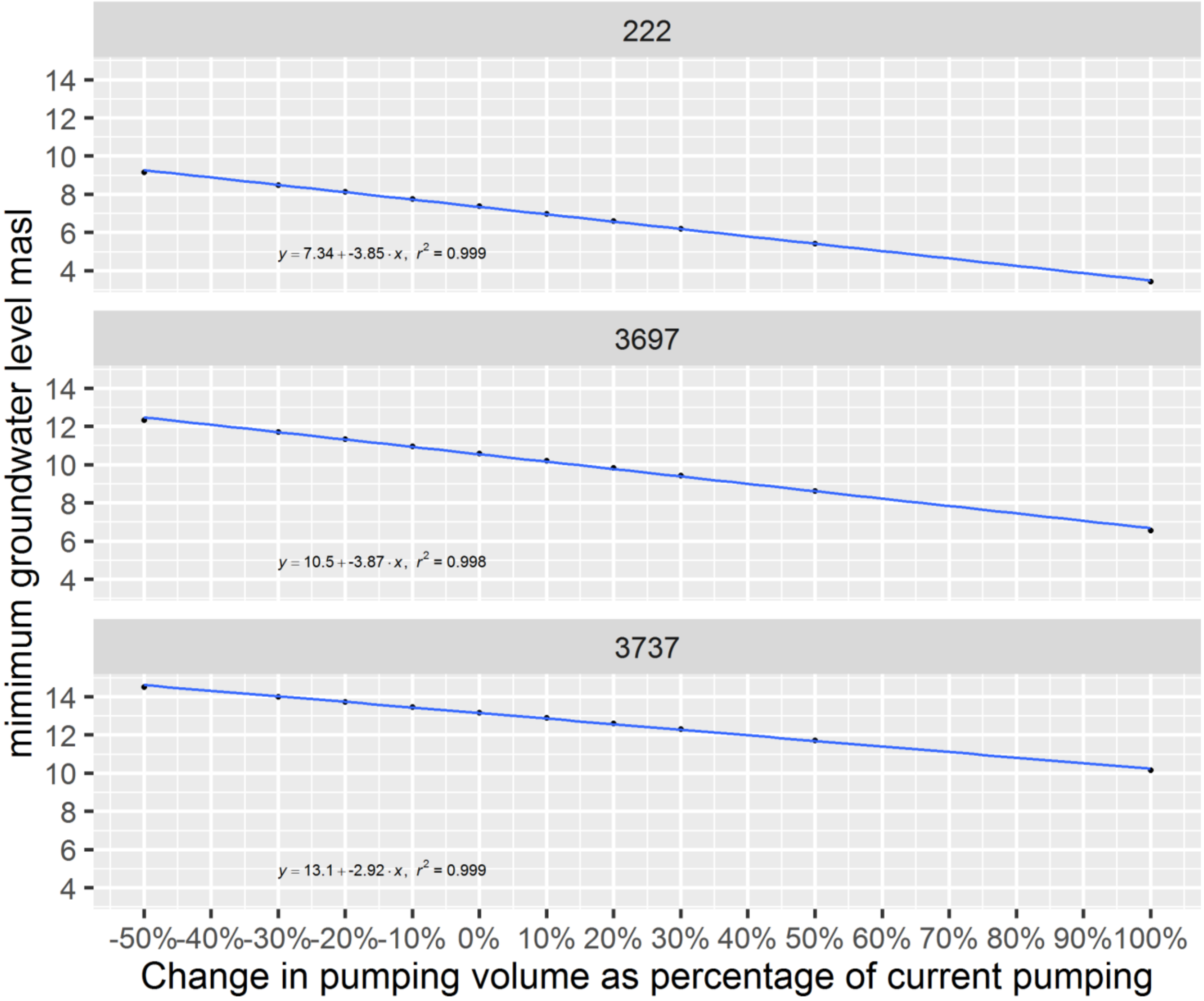

Figure 4-10: Sensitivity of groundwater levels to pumping variation. The charts show simulated groundwater levels at the end of January 2025 (which is a period representative of very low groundwater levels) for each selected bore, under scenarios of increased and decreased pumping. The relationship between groundwater levels and change in pumping can be approximated using straight lines (blue). Units for groundwater levels are metres above mean sea level (masl)).

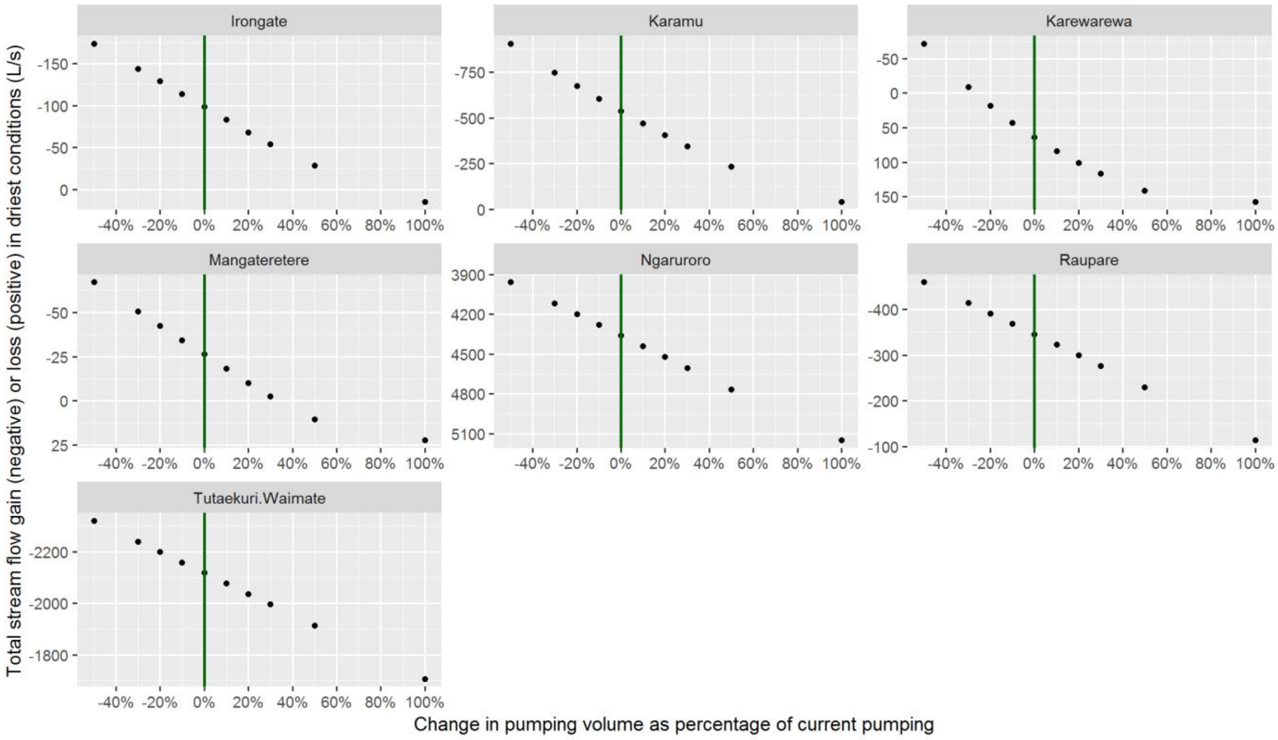

Figure 4-11: Sensitivity of surface water - groundwater exchanges to changes in pumping.

Table 4-1: Sensitivity of streamflow (as percentage of current flow) to pumping changes. Ngaruroro is the Ngaruroro River at Fernhill. The Karamu represents the gaining section of the lower Karamu River and does not incorporate effects on tributaries including Irongate, Karewarewa and Mangateretere (which are shown separately).

stream	-100%	-50%	-30%	-20%	-10%	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Raupare	66%	33%	20%	13%	7%	0%	-7%	-13%	-20%	-27%	-34%	-40%	-47%	-54%	-60%	-67%
Irongate	152%	76%	46%	31%	15%	0%	-15%	-31%	-45%	-58%	-71%	-80%	-89%	-97%	-106%	-115%
Mangateretere	310%	155%	93%	62%	31%	0%	-31%	-61%	-90%	-115%	-139%	-148%	-157%	-167%	-176%	-185%
Karamu(gains in main stem	49%	24%	15%	10%	5%	0%	-5%	-10%	-15%	-20%	-25%	-30%	-35%	-40%	-45%	-50%
Karewarewa	423%	211%	113%	71%	33%	0%	-31%	-57%	-82%	-100%	-119%	-124%	-130%	-135%	-140%	-145%
Ngaruroro *	82%	41%	24%	16%	8%	0%	-8%	-16%	-25%	-33%	-41%	-49%	-57%	-65%	-73%	-81%
* % base on 1000 L/s river flow																

>25% flow lost	25 % flow added
>50% flow lost	50 % flow added
dry	100 % flow added

Table 4-2: Sensitivity of streamflow (as flow change in L/s) to pumping changes. Ngaruroro is the Ngaruroro River at Fernhill. The Karamu represents the gaining section of the lower Karamu River and does not incorporate effects on tributaries including Irongate, Karewarewa and Mangateretere (which are shown separately).

stream	-100% *	-50%	-30%	-20%	-10%	0%	10%	20%	30%	50%	100%
Raupare	227	114	68	46	23	0	-23	-46	-69	-116	-232
Irongate	150	75	45	30	15	0	-15	-31	-45	-70	-113
Mangateretere	82	41	24	16	8	0	-8	-16	-24	-37	-49
Karamu.gain	234	117	70	47	23	0	-23	-47	-71	-118	-239
Karewarewa	272	136	73	46	21	0	-20	-37	-52	-77	-93
Ngaruroro	1060	530	318	212	106	0	-107	-213	-321	-536	-1053

5 Mitigation scenarios

In earlier sections it was demonstrated that groundwater pumping from the Heretaunga Aquifer had caused a reduction in groundwater levels and a significant change to surface water – groundwater exchange flux and thus stream flows in Heretaunga Plains, including potential stream depletion during the irrigation season.

There are management options (mitigations) that could be used to protect the stream flow and groundwater levels from further declines. Options discussed in this section include Pumping Bans, Stream Augmentation and Artificial Recharge. The first two of these are currently used in some parts of the aquifer, and in the past Artificial Recharge was also used. This section describes modelling simulations that were designed to test various mitigations and review their effectiveness.

Sections 5.1 to 5.3 describe scenarios to test effectiveness of Pumping Bans, Stream Augmentation and Artificial Recharge.

Section 5.4 describes several mitigation scenarios, that may consist of one or more management options, and include different assumptions about these options (e.g. different trigger flows for pumping bans). These scenarios were run for a longer simulation period lasting several irrigation seasons. The simulations were loosely coupled with SOURCE model simulations.

5.1 Artificial recharge

5.1.1 Scenario background

A Managed Aquifer Recharge (MAR) scheme in the Heretaunga Plains was commissioned in 1988 and transferred water from the Ngaruroro River to recharge ponds near Roy’s Hill, at an average rate of about 300 L/s before the scheme was abandoned in 2008 (Gordon, 2009). The location of the recharge scheme is shown in Figure 5-1. The purpose of the scheme was to prevent decline of groundwater levels in the Heretaunga Aquifer.

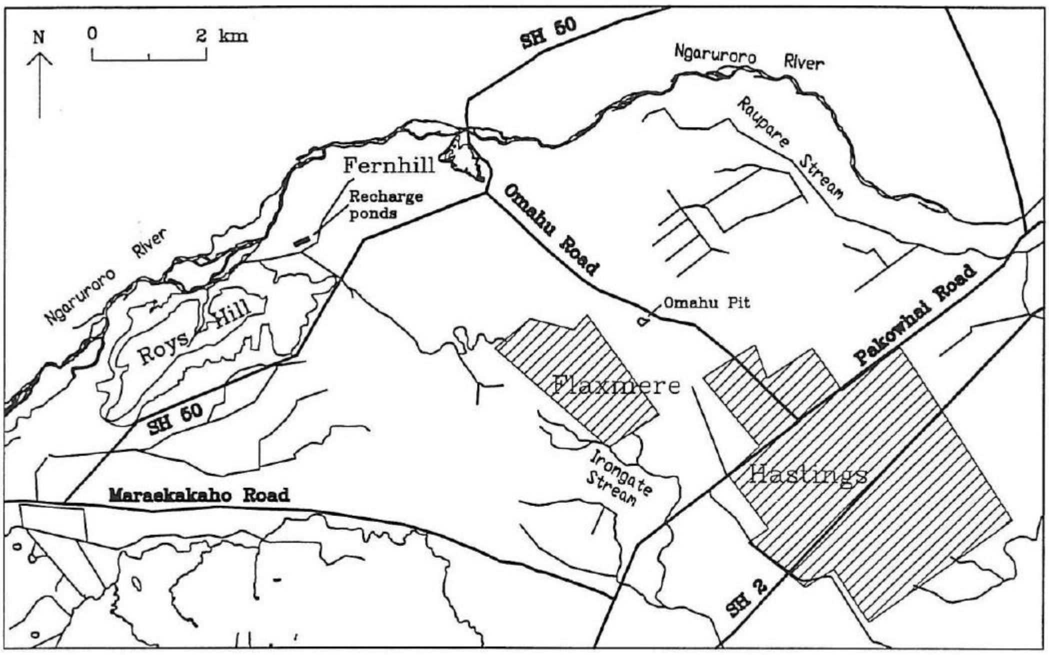

Figure 5-1: Location of the Roy’s Hill Managed Aquifer Recharge scheme (After Gordon, 2009b)

5.1.2 Scenario set-up

During model calibration, the MAR scheme was initially not included in the model set up. However, without it, the model failed to achieve a match to observed groundwater level changes and long term trends in some locations: particularly at locations close to the recharge scheme. The recharge was then incorporated using positive rate injection wells, as part of the MODFLOW WEL package.

After artificial recharge was incorporated, the model was able to represent water level dynamics in this area much better, in particular at bore 15005 (Figure 5-2). However, the model seems to underestimate the extent of the impact of the recharge scheme. For example, the groundwater level observation at bore 10356 and 10371 indicate some impact of the artificial recharge, because recorded groundwater levels are higher before 2008 (when the scheme was abandoned) than after this time. However, the model does not fully simulate the scheme impact at those locations.

5.1.3 Scenario results

Simulations with and without MAR indicate that the scheme has caused some local changes in groundwater levels (Figure 5-2). The model also indicates some minor increases in spring flows as a consequence of the MAR scheme. For example, there is less than 5 L/s increase in modelled summer flows for the spring fed Irongate and Raupare streams, located relatively close to the recharge scheme. The effect of the MAR scheme is larger during the winter, when artificial recharge rates are larger due to sustained water availability from persistently higher flows in the Ngaruroro River.

There is also some effect of the MAR scheme on Ngaruroro River flows, which increased by about 50-100 L/s during the summer, and by about 300L/s during the winter when the scheme was active. This effect on Ngaruroro River flow at Fernhill is comparable to the actual rate of artificial recharge during the 2002/2003 irrigation season (Figure 5-6). The source of MAR water is the Ngaruroro River itself, so the results indicate that the artificial recharge water effectively reduces the amount of leakage from the Ngaruroro River in this area. During the 2002/2003 irrigation season, the average recharge rate was 200 L/s, and the effect on Ngaruroro River flow was 170 L/s, which means that 85% of the recharged water was effectively “not lost” from the Ngaruroro River.

The simplistic interpretation that the artificial recharge water “returns” to the Ngaruroro River is not strictly correct, as most of the water does not physically “return” to the River (in terms of actual molecules of water). Instead, artificial recharge causes a localised increase in water levels, which in turn reduces the head gradient between the losing section of the river and the aquifer, which causes the rate of river loss to decrease. This effect might have some benefit for the river during low flows, although it appears that this effect is relatively small (only about 50 L/s in driest conditions), as there is a small delay in this effect occurring. For example, river flow may be higher for some time after the recharge was stopped, presumably due to time taken for the groundwater mound to subside. Figure 5-6 shows this delay to be relatively short, as after about a month from change of recharge rate the effect on the river seems to stabilise.

5.1.4 Discussion of results

Overall, the modelling indicates that the benefit from operation of the Roy’s Hill MAR scheme is relatively small, with only minor increases in flow of the spring-fed streams. However, model calibration indicates that the model underestimates the effect of the artificial recharge on groundwater levels, so it may also underestimate the effect of spring flows. Further refinement of model calibration, especially in the area of the artificial recharge, might be necessary to improve model predictions related to artificial recharge, if there is a request to investigate this mitigation option further, despite modelling results indicating its limited effectiveness.

The model can be used (if it is suitably refined) to test different scenarios of artificial recharge (e.g. different rates and locations of the recharge scheme). Such runs undertaken with an earlier version of the model indicated only limited benefit from the artificial recharge scheme, even if the scheme was operating at higher recharge rates. The results are not reported here, as the model parameters have been updated since the scenarios were run, and the results are outdated.

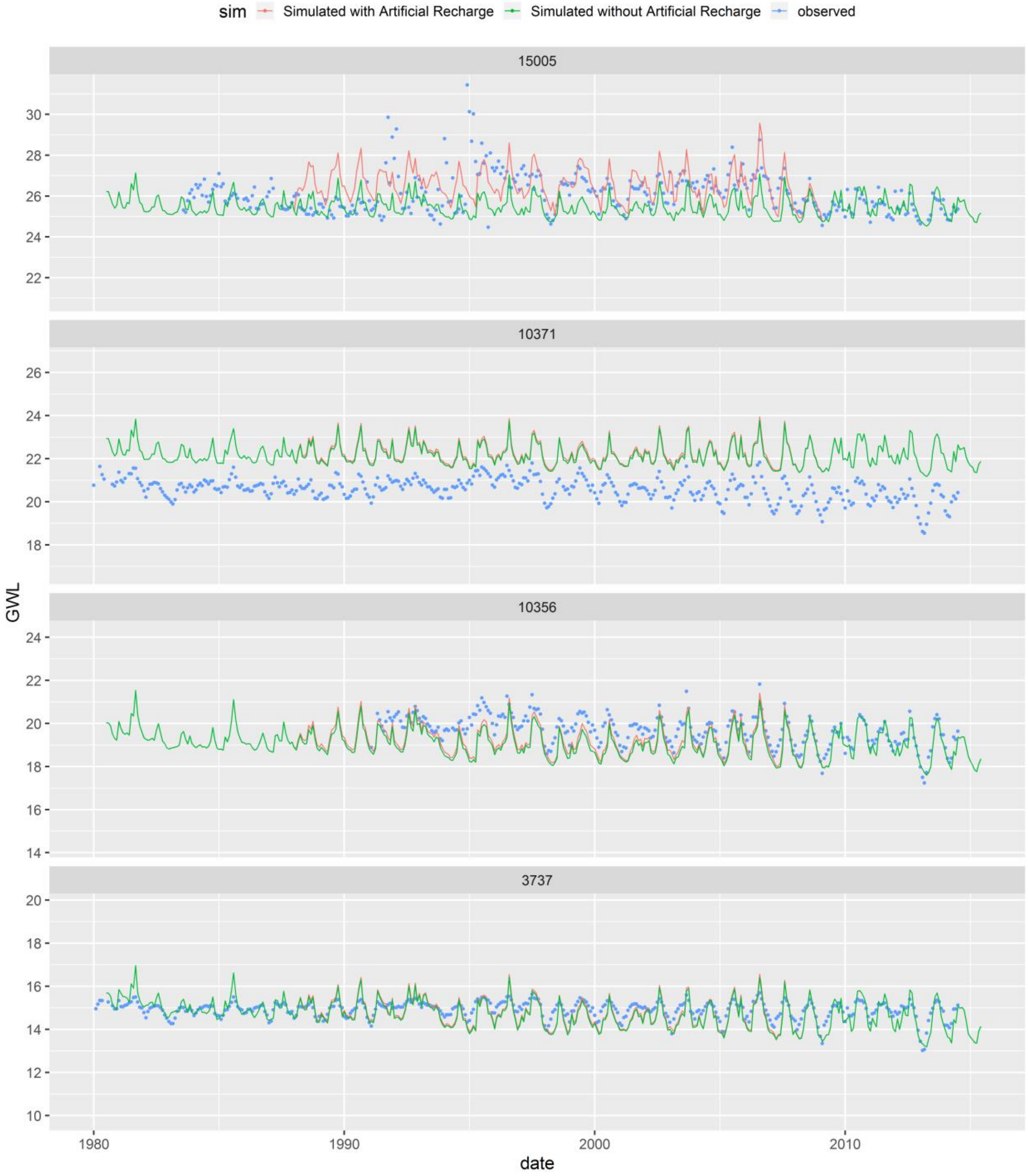

Figure 5-2: Hydrographs of simulated (with and without Managed Artificial Recharge) and observed groundwater levels near the MAR site. Groundwater levels (GWL) are elevations in metres above mean sea level (masl)

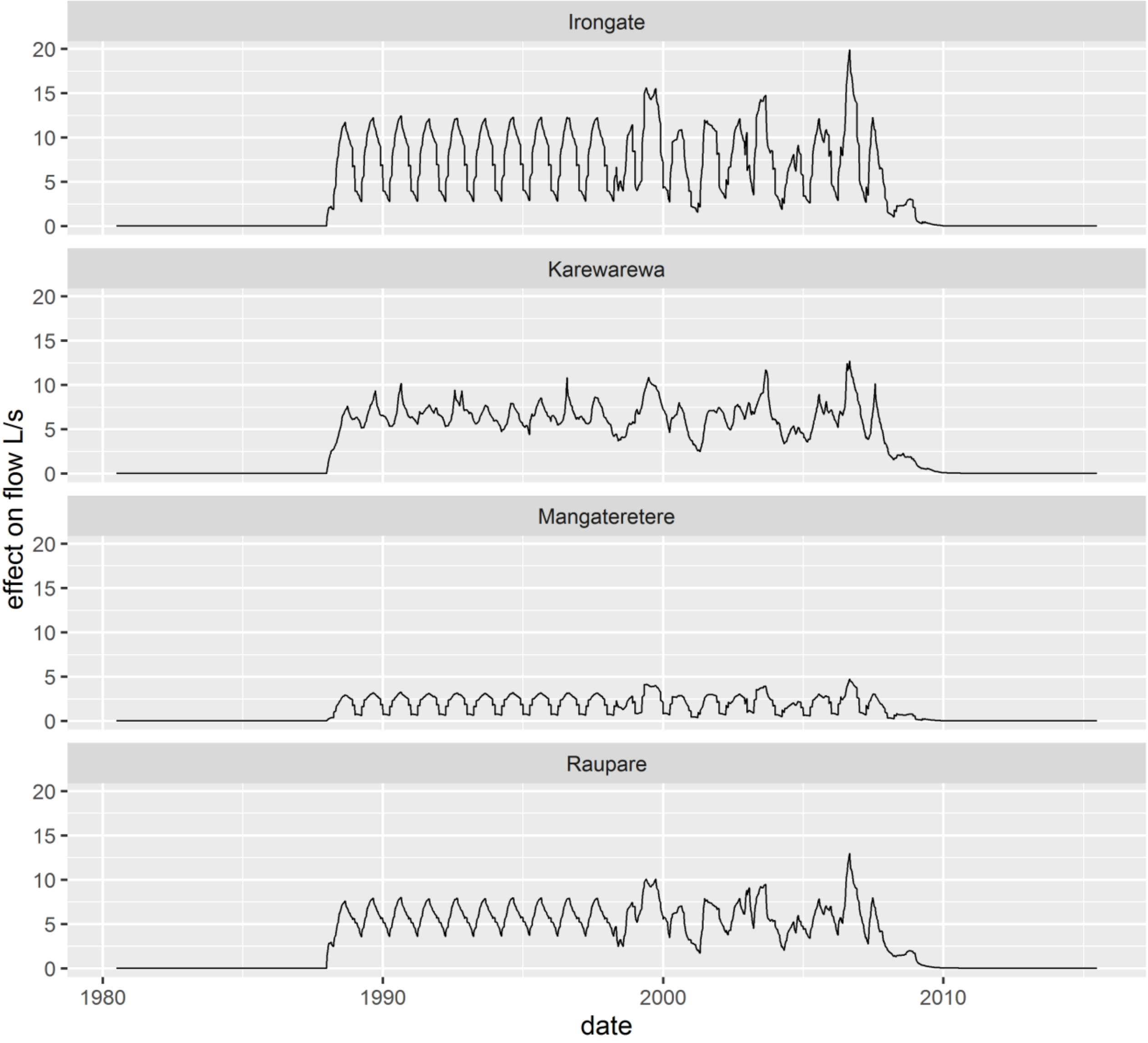

Figure 5-3: Effects of the Roy’s Hill MAR scheme on streamflow (part1).

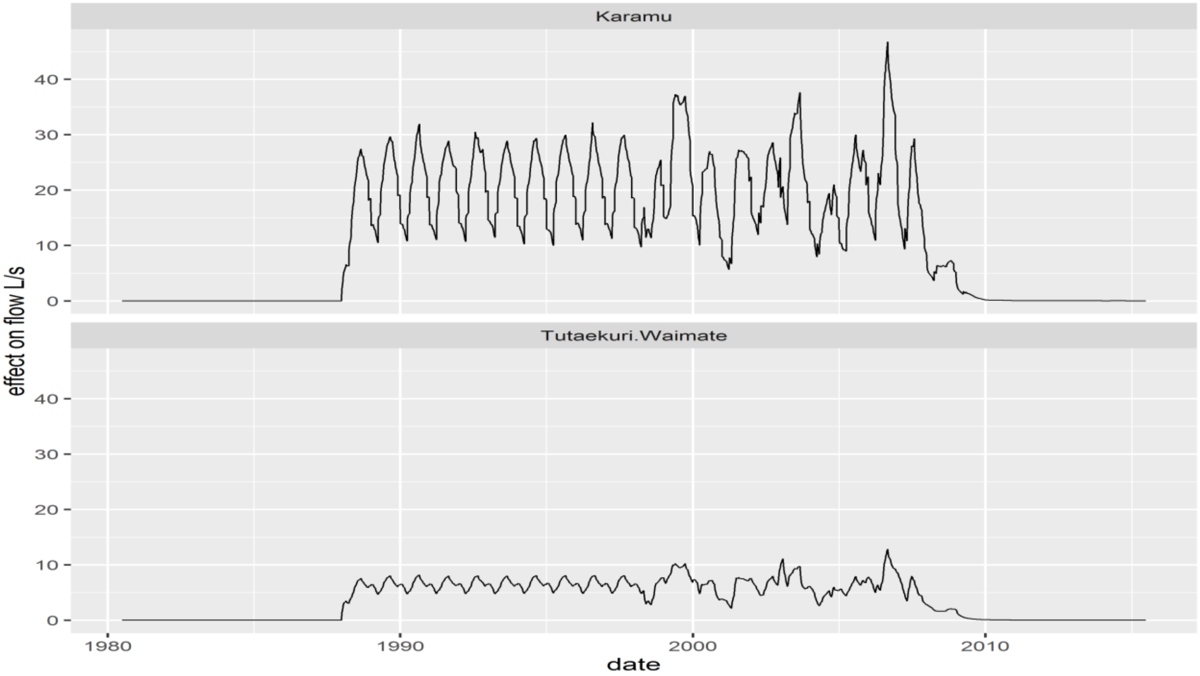

Figure 5-4: Effects of the Roy's Hill MAR scheme on streamflow (part 2).

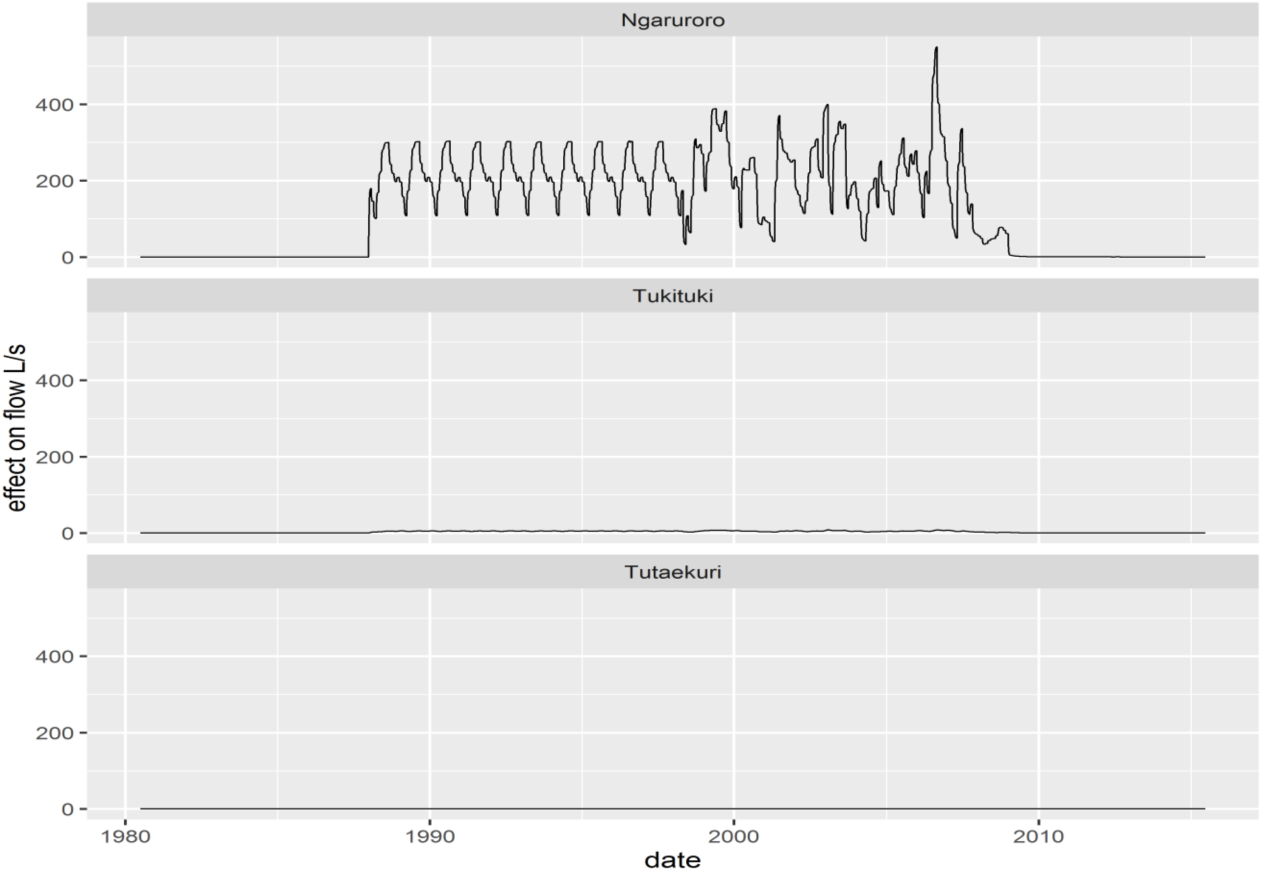

Figure 5-5: Effects of the Roy's Hill MAR scheme on streamflow (part 3).

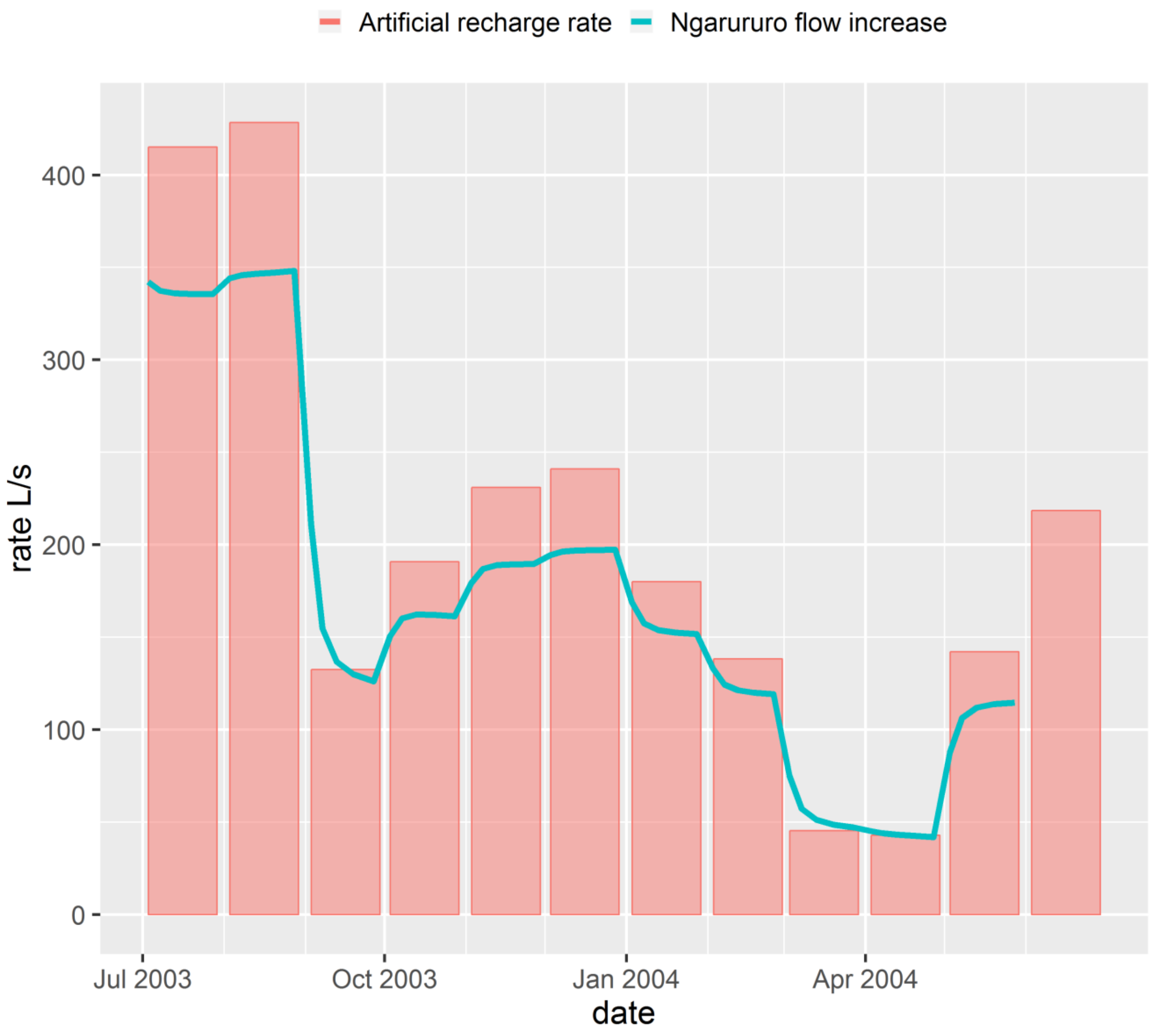

Figure 5-6: Recharge rates from the Roy's Hill MAR scheme and effects on Ngaruroro River flow during the 2002/2003 irrigation season. Bars show recharge rates. Line shows the effects on flow for the Ngaruroro River at Fernhill.

5.2 Effect of stream augmentation

5.2.1 Scenario background

Streamflow augmentation from groundwater is a strategy that involves pumping groundwater from the aquifer and discharging it to the stream to supplement streamflow (Figure 5-7). Such a strategy could be used to temporarily increase (or restore) streamflow, for example during periods of drought. Adding water to the stream is defined here as a “positive effect” of augmentation.

However, augmentation pumping may also have negative effects. Abstraction of groundwater would normally lead to lowering of groundwater levels. If the augmented stream is hydraulically connected to the aquifer that is used for pumping, this would in turn lead to decrease in streamflow (negative effect of augmentation). However, this depleting effect might be delayed or distributed in the wider aquifer. This could make augmentation a viable strategy to temporarily increase streamflow.

Augmentation would typically be undertaken in close vicinity to a stream that needs augmentation, to minimise pumping and transfer costs. However, the effect of pumping may have a negative effect not only on the augmented stream, but also on other, more distant streams connected to the aquifer. If augmentation pumping occurs for multiple streams at the same time, there may also be a combined effect.

There are also some positive effects from augmentation, beyond improved streamflow. The value of the stream for supporting aquatic ecosystems is dependent on flow to maintain adequate oxygen levels (Wilding, 2016). Oxygen levels also are dependent on water temperature (Haidekker, 2016). Both temperature and oxygen levels can be improved when augmentation from groundwater is undertaken. This is because groundwater is typically cooler than surface water during the summer (when augmentation is typically required), and the augmentation system can be easily configured so that augmentation water becomes aerated and oxygen rich before discharging to the stream. Such a system has been successfully implemented by Twyford Irrigators group for Raupare stream (Twyford Irrigators *et al.*, 2018).

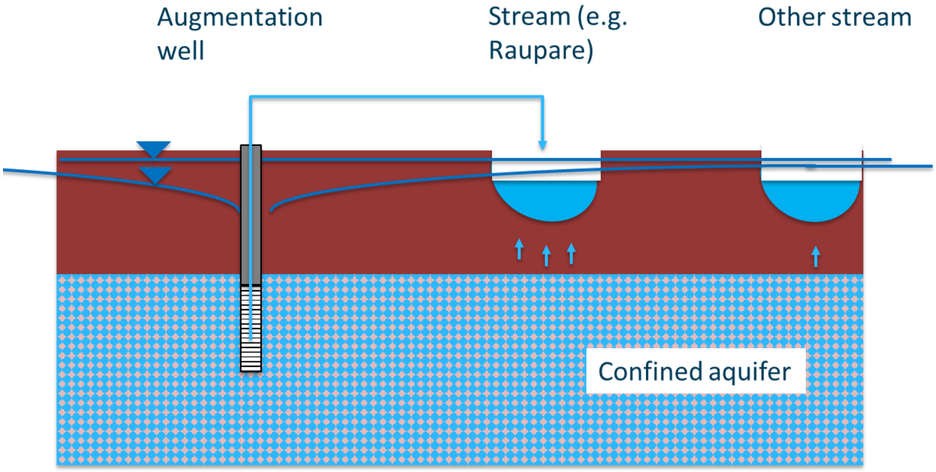

Figure 5-7: Schematic of stream augmentation from groundwater.

The effect of augmentation pumping on streamflow, including a combined effect of augmentation of multiple streams can be estimated using a groundwater model. A model scenario was set up to allow for this assessment.

5.2.2 Augmentation scenario set-up

To set up the stream augmentation scenario, the following was required:

a) **Identification of streams that require augmentation**

The following streams have been identified as possibly requiring augmentation:

Raupare, Irongate, Karamu, Mangateretere, Karewarewa, Tūtaekurī – Waimate

The Ngaruroro River was not considered in the assessment as the augmentation flow required was considered infeasible.

b) **Choosing augmentation trigger flow** (i.e. streamflow below which augmentation starts); refer Table 5-1.

Table 5-1: Augmentation trigger flows (L/s). Worst case triggers are based on existing minimum flows for these streams.

Stream	Recommended Trigger	Worst case Trigger	Recommended Trigger Rationale
Karamu	1000	1100	Exceeds 30% oxygen
Raupare	300	300	Multi-scenario exceeds 40%
Mangateretere	61	100	40% oxygen
Karewarewa	45	75	Velocity trigger
Tūtaekurī-Waimate	1200	1200	Existing minimum flow
Irongate	100	160	40% oxygen upper reach, velocity trigger lower reach

c) **Selecting pumping location for augmentation**

Preliminary locations for augmentation wells were selected (Figure 5-8). For Karamu, three locations were needed due to high required augmentation rates (see point d). Note that these site locations are preliminary, for initial assessment of augmentation potential. Locations are arbitrary and are located at the top of active losing or gaining reaches in each stream. No other criteria (such as accessibility, ground conditions, aquifer properties) were considered. Detailed design of the augmentation scheme will require identification of suitable augmentation sites. The augmentation scheme may require construction of additional wells, or may utilise existing wells.

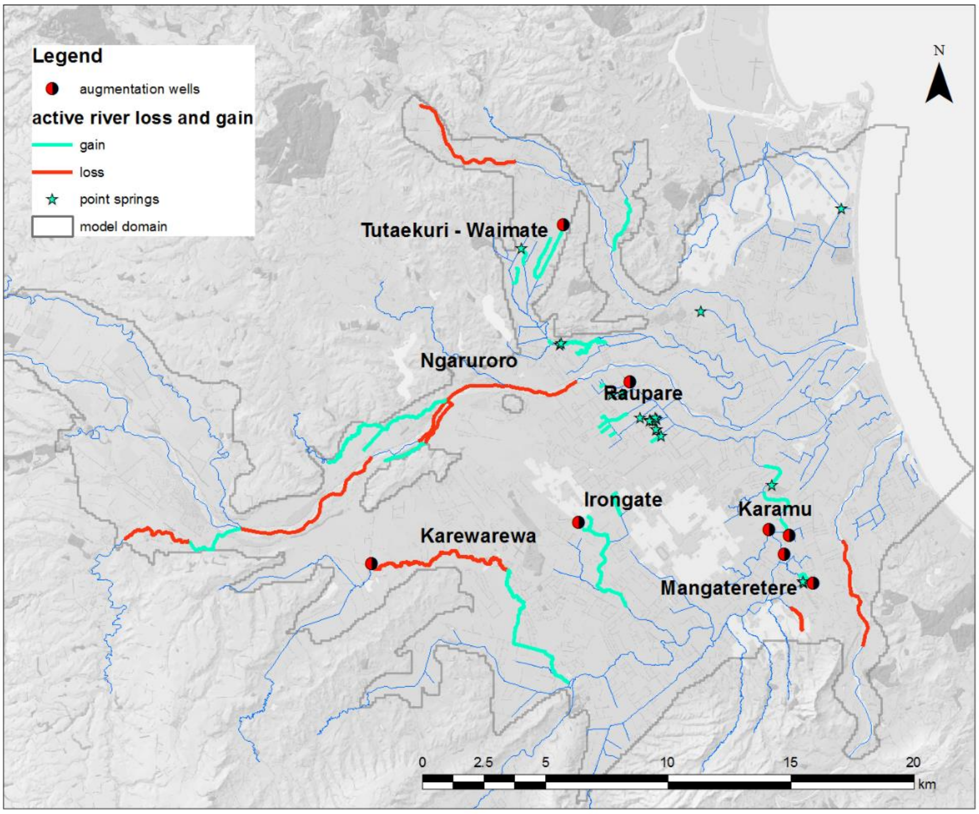

Figure 5-8: **Selection of augmentation well locations.**

d) Selecting a representative period of time to make an assessment:

A dry summer 2012/2013 was used as a representative period for calculation.

e) Calculated augmentation rates, based on trigger flows and flow records from selected time periods

Augmentation rates for each stream were calculated by subtracting trigger flow from actual flow on days when actual river flow was below the trigger flow (Figure 5-9 and Figure 5-10). The model stress period was monthly, so the daily rates were then aggregated into average monthly rates (Table 5-2 and Table 5-3). Monthly augmentation rates for each river were then included in the model scenarios by including additional pumping wells in selected locations. In the case of the Karamu, the need for augmentation can be reduced by augmentation of its tributaries - the Irongate, Mangateretere and Karewarewa streams - and this reduction was applied to augmentation rates in the model scenario.

For the selected trigger levels, the Tūtaekurī-Waimate will not require augmentation. Augmentation requirements for the Raupare are relatively small. The Ngaruroro River was included in calculations to visualise when the flow drops below current minimum flow and calculate required augmentation flows, but augmentation of the Ngaruroro River was not included in model simulation, as it would require excessively large (and probably not feasible) augmentation flows (over 700 L/s).

Excluding Ngaruroro, the most significant water supply is required for the Karamu stream, which may require a maximum of 350 L/s and may require augmentation during most of the irrigation season. This is a very significant augmentation requirement, and it will form nearly half of the total augmentation requirement for selected streams.

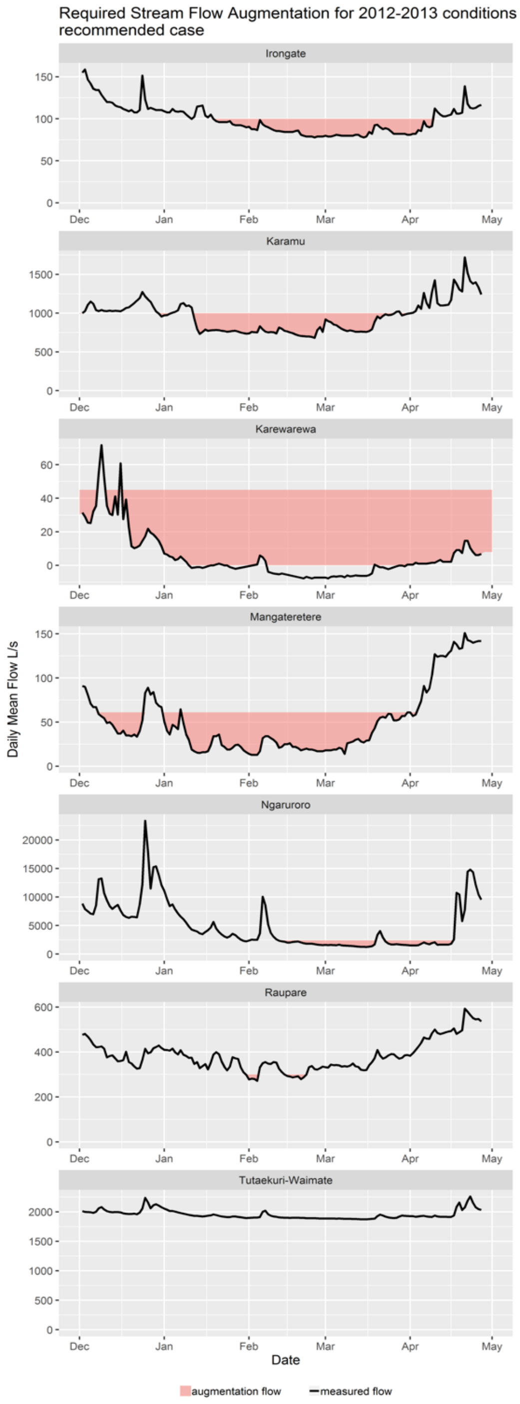

Figure 5-9: Calculation of required streamflow augmentation for recommended trigger flows.

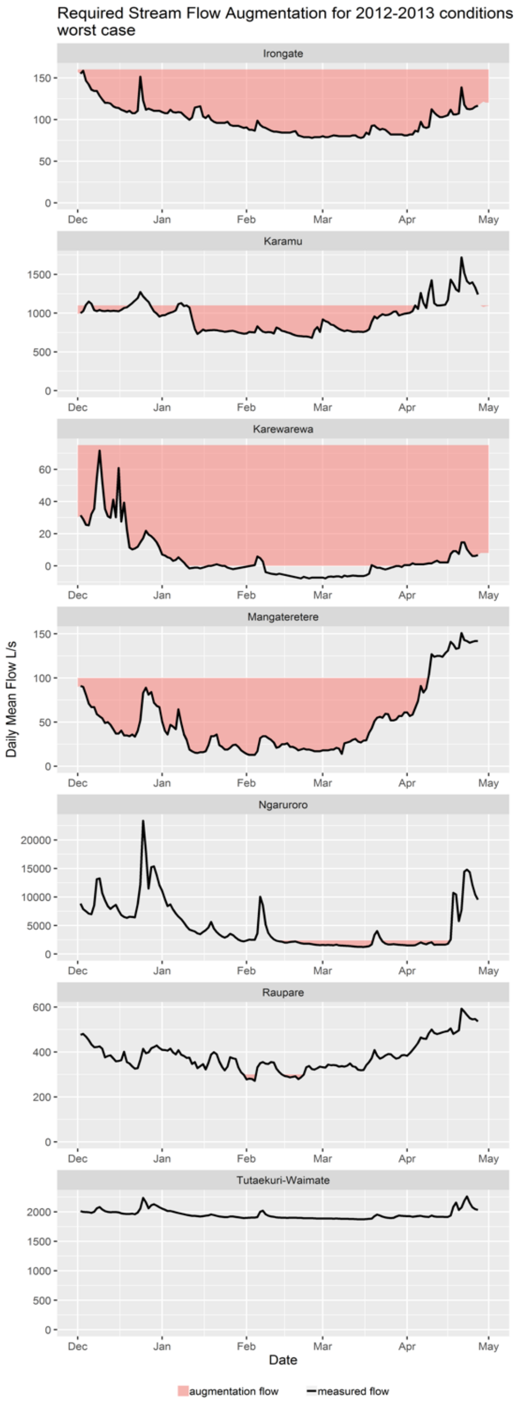

Figure 5-10: Calculation of required streamflow augmentation for worst case trigger flows.

The line shows recorded river daily mean flow. Red shading indicates the when actual flow drops below trigger flow. The trigger flow is represented by the top of the red shading

Table 5-2: Calculated required augmentation rates for "recommended" trigger (L/s).

month	Irongate	Karamu	Karewarewa	Mangateretere	Ngaruroro	Raupare	Tūtaekurī-Waimate
Dec	0.0	1.9	18.4	9.6	0.0	0.0	0.0
Jan	2.3	147.2	43.3	32.3	8.3	0.0	0.0
Feb	15.1	249.7	44.1	39.3	270.6	6.1	0.0
Mar	17.4	126.0	45.0	23.9	767.7	0.0	0.0
Apr	3.8	0.0	40.0	0.2	361.9	0.0	0.0
May	0.0	0.0	37.0	0.0	0.0	0.0	0.0

Table 5-3: Calculated required augmentation rates for "worst case" trigger (L/s).

month	Irongate	Karamu	Karewarewa	Mangateretere	Ngaruroro	Raupare	Tūtaekurī-Waimate
Dec	36.5	46.4	46.5	40.7	0.0	0.0	0.0
Jan	57.8	230.2	73.3	71.2	8.3	0.0	0.0
Feb	75.1	349.7	74.1	78.3	270.6	6.1	0.0
Mar	77.4	224.7	75.0	62.9	767.7	0.0	0.0
Apr	55.1	12.6	70.0	7.4	361.9	0.0	0.0
May	39.7	3.6	67.0	0.0	0.0	0.0	0.0

Model configuration:

The model was based on historical scenario runs, except that:

- The time period modelled includes only 5 monthly stress periods in the selected time period from December 2012 to April 2013;
- Starting conditions are based on modelled conditions at the end of November 2013;
- Selected augmentation wells are included.

5.2.3 Scenario results

Model results were processed to calculate surface water and groundwater exchange flux as for other scenarios (Figure 5-11). Subsequently, the negative effect of augmentation pumping (reduction in stream flows) was calculated by comparing results with a model run without augmentation. Results indicate that there are some negative effects on streamflow caused by augmentation pumping.

The calculated negative effect is cumulative – it is the combined effect of pumping from all augmentation wells. The largest effect is on the Karamu stream – up to 120 L/s of loss. Maximum augmentation benefit for the Karamu is 350 L/s, so it means that overall effectiveness of augmentation (ratio between stream flow increase and augmentation pumping) is about 65%. A modest effect is also seen in the Ngaruroro River (30 to 60 L/s comparing to actual flow >1000L/s), which is not augmented, but nevertheless it experiences a negative impact from augmentation pumping in other locations.

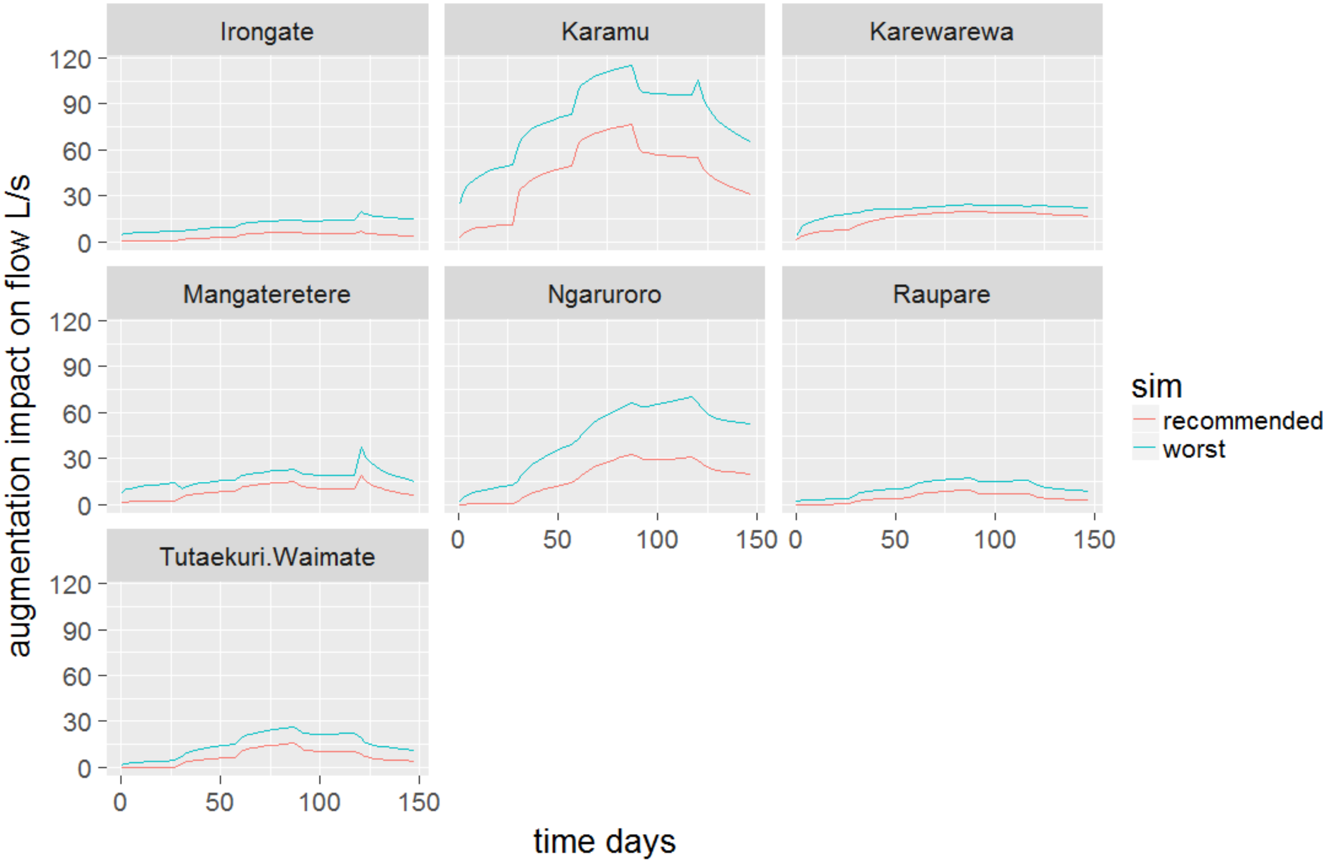

Figure 5-11: Effect of augmentation pumping on streamflow for selected stream and rivers. Diagrams show the effect, defined as reduction in stream flows (result of reduction in groundwater inflows or increased leakage to groundwater), following augmentation pumping from groundwater. “Sim” refers to 2 simulations tested (recommended and worst case scenarios as per Table 5-1)

The limitation of the boundary condition used in the model to simulate stream and river flow (MODFLOW “RIVER”) is that the actual river flow is not calculated, instead only surface water – groundwater exchange flux is calculated. This means that the effect on river flow needs to be calculated outside of the model. This can be done by using measured river flow and adding the incremental effect of the SW/GW exchange flux. This was achieved using Equation 5-1 (Figure 5-13 and Figure 5-14, Table 5-4).

Overall, augmentation is effective in improving flow, except for the Karewarewa stream, where augmentation is of limited effectiveness, although there are some negative impacts from augmentation. Most affected will be the Ngaruroro River, which is not subject to augmentation, but this effect is relatively small compared to flow.

A model limitation is that the augmentation rate cannot be calculated dynamically during the simulation on basis of stream flow (the MODFLOW code used does not permit a simple recursive arrangement), with the rate specified at the start of the simulation on basis of stream flow observation. However, the negative effect of augmentation means that streamflow could decline further during the simulation, which would mean that higher augmentation volume could be required (e.g. augmentation with 100 L/s would lead to additional 5 L/s loss in the stream, which would result in additional augmentation requirements, and so on). This means that the actual augmentation requirement is likely to be larger than predicted (e.g. 10% - 20% larger typically, and more than 100% larger for Karewarewa). It is difficult to give an exact estimate, as this requires iterative use of the model to evaluate the recursive augmentation requirement (e.g. the model has to be run multiple times each time the augmentation rate is reassessed). In the case of the Karewarewa, the estimate is subject to additional uncertainty resulting from relatively poor hydrogeological understanding. In practice, the augmentation rate could be easily adjusted depending on streamflow.

The potential negative effects of augmentation also include lowering groundwater levels. This effect was assessed in several bores (Figure 5-12). Maximum groundwater level decline in these bores as a result of augmentation is predicted to be minor, with 0.15 m for the recommended case and 0.25 m for worst case However, this effect may be larger locally in the vicinity of augmentation bores, depending on local aquifer properties.

5.2.4 Discussion of results

Overall, the results indicate that augmentation is a technically feasible method to protect streamflow during periods of low flow. Despite this, there are some associated negative consequences, which increase in magnitude if higher augmentation flows are required. If high trigger flows are selected, or if water use in the aquifer becomes greater, the augmentation required will also increase, resulting in significant negative effects. At some point the impacts from augmentation may outweigh the benefits. For very high augmentation rates limitations of the model mean it is likely to be inaccurate, although this could be improved in future if required.

In summary:

- Augmentation is likely to be effective as a short term mitigation measure for low streamflow depletion resulting from current water use.
- Augmentation is likely to be inadequate to mitigate the effects of increasing water allocation.
- Trigger flows for augmentation should be selected considering the negative effects. For example, for choosing a trigger for the Karamu of 1000 L/s or 1100 L/s requires significant augmentation volumes. It may be beneficial to select a lower trigger flow to minimise the negative effects of augmentation.

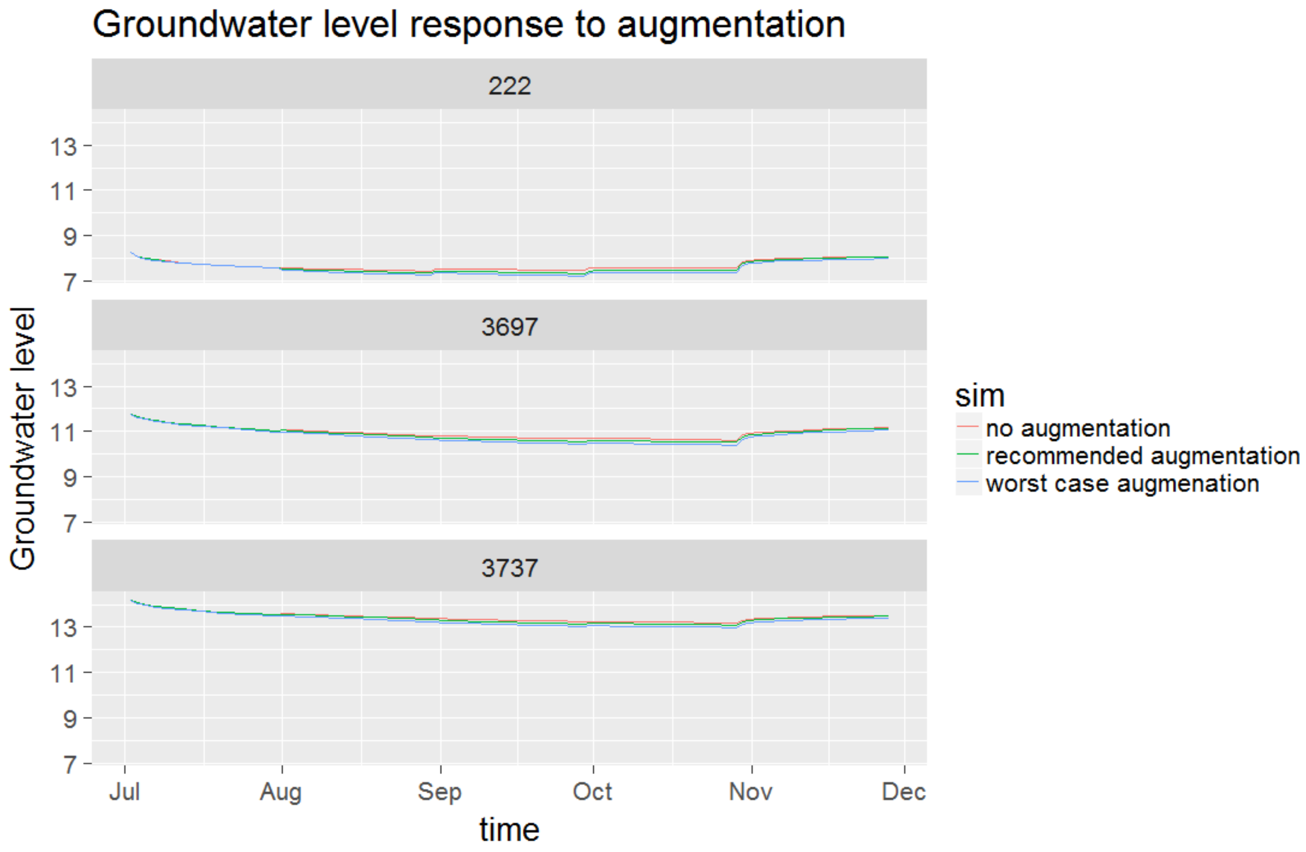

Figure 5-12: Effect of augmentation of groundwater levels.

Equation 5-1: Calculation of augmented river flow.

$$Q_{with\ augmentation} = Q_{measured} + Q_{augmentation\ pumping} - Q_{combined\ effect\ of\ augmentation\ on\ flow}$$

Where:

$Q_{with\ augmentation}$	New augmented streamflow
$Q_{measured}$	Actual river flow (without augmentation),
$Q_{augmentation\ pumping}$	Augmentation pumping rate – water pumped from the aquifer into a selected stream for a given streamflow, estimated from trigger flows and measured flows
$Q_{combined\ effect\ of\ augmentation\ on\ flow}$	Modelled combined negative effect on flow in selected streams from augmentation pumping from all augmentation locations

Table 5-4: Augmentation - discussion of results.

Stream	Results
Irongate	In both cases augmentation is able to sustain the flow in the stream just below the trigger level.
Karamu	In both cases augmentation significantly improves the flow.
Karewarewa	In both cases flow improves, but the negative impacts from augmentation results in only about 50% improvement.
Mangateretere	In both cases augmentation is effective in significantly improving the flow.
Ngaruroro	Ngaruroro is not augmented, but does experience decline in flow as a result of augmentation pumping where the negative effect of augmentation is small in relation to flow and indiscernible on a chart.
Raupare	Raupare has very small limited need for augmentation. There is some effect visible from augmentation in other areas, but this effect is small.
Tūtaekurī-Waimate	Tūtaekurī-Waimate is not augmented (as flow remains about trigger flow), and the effect from augmentation in other areas is very small in comparison to flow.

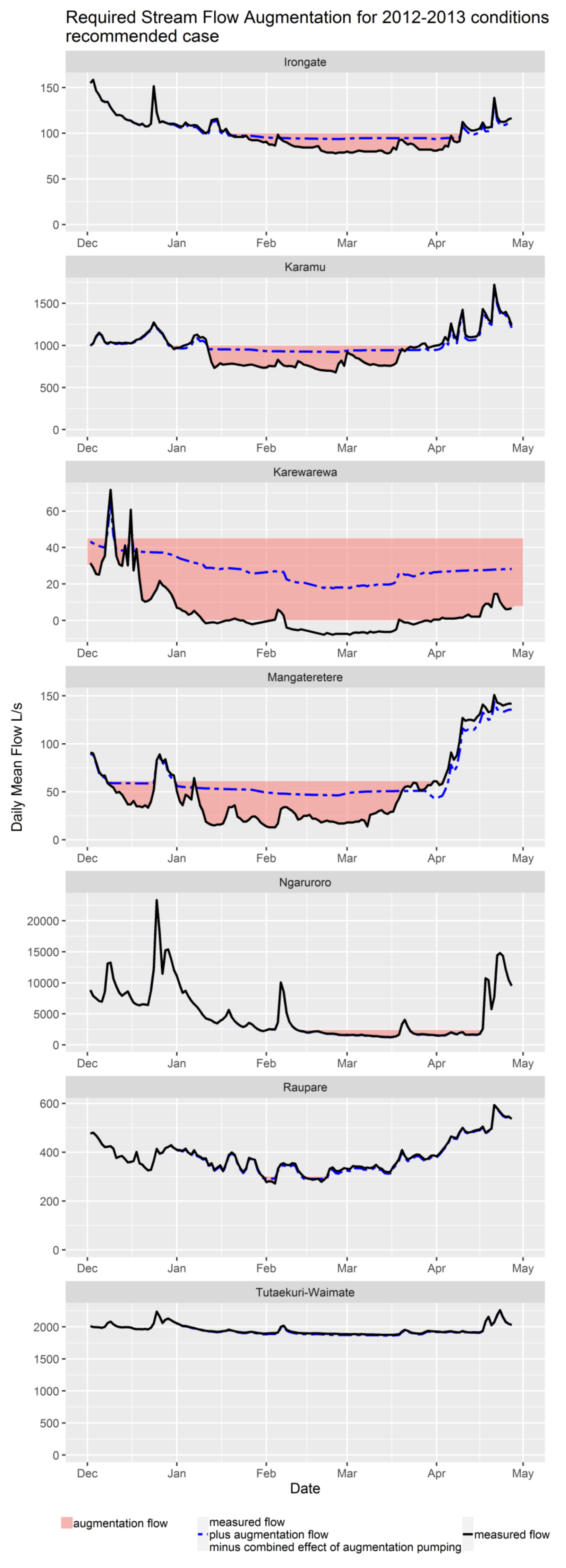

Figure 5-13: Streamflow with and without augmentation - recommended case.

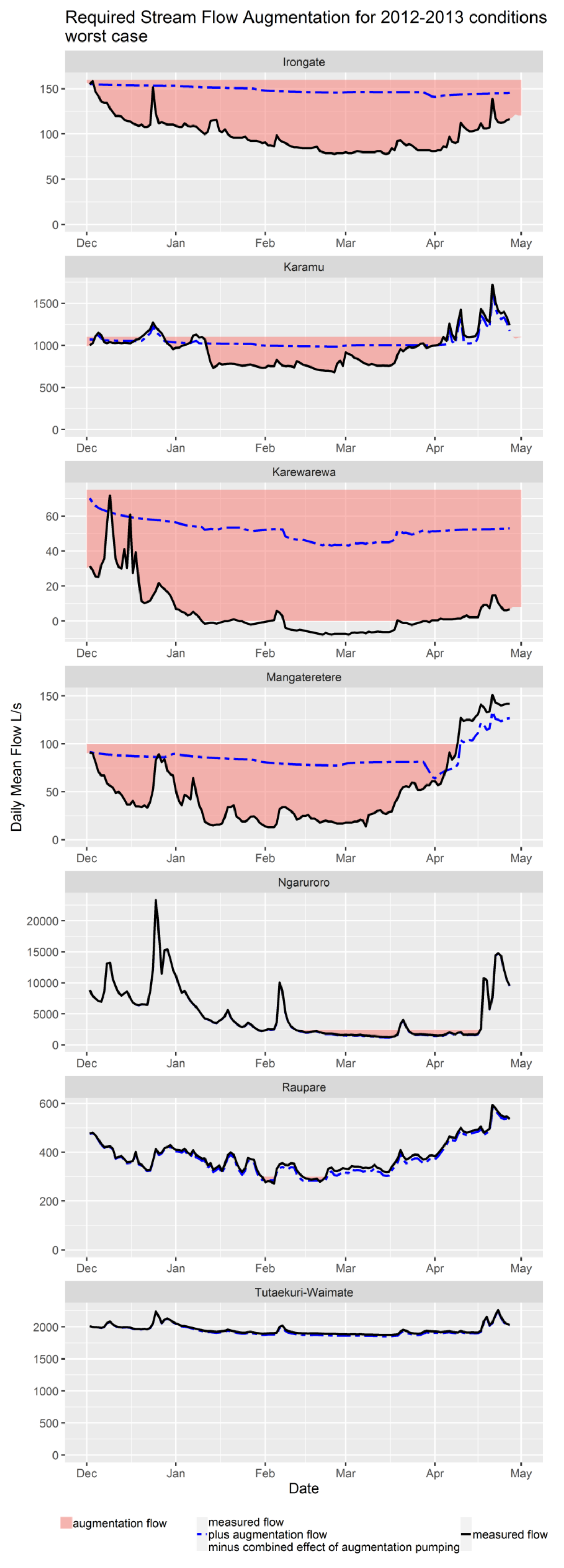

Figure 5-14: Streamflow with and without augmentation - worst case.

The black line shows recorded river daily mean flow. The blue line represents augmented streamflow. This is calculated by adding calculated augmentation flow (water that is pumped out from aquifer to the river) to measured streamflow, and subtracting the calculated combined augmentation effect. Red shading indicates when measured flow drops below trigger flows. Trigger flows are represented at the top as red shading

5.3 Effect of pumping bans on flow

5.3.1 Scenario background

Pumping bans are a method that is used on the Heretaunga Plains as a mitigation measure to maintain river flow during low flow periods. When flow in rivers drops below a prescribed level (trigger flow, or cease-take flow), groundwater takes identified in a resource consent as depleting that river are required to stop pumping. Ceasing pumping has a positive effect on river flow. On the Heretaunga Plains several rivers are protected by pumping bans, including the Ngaruroro and the Raupare, but only selected takes on the Heretaunga Plains are subject to pumping bans.

The initial scenario, developed using an older version of the model, was run using monthly stress periods, with an arbitrary start to the pumping ban, and including only one trigger flow site. More recently, a further scenario was completed, using the calibrated version of the model and with more realistic trigger flows based on actual consent conditions, with a daily stress period and calculated ban periods.

The latter scenario was intended to investigate the effect of pumping bans (from both groundwater and surface water) on flow statistics during a 17 year long model run until 2032, which was achieved by linking the model with the surface water SOURCE model. The scenario was run as part of a number of scenarios, described in Section 5.4. A selected dry period during this scenario (2029-2030), was included as the climatic equivalent of the dry year 2012-2013, and was used to visualise the effectiveness of pumping bans.

5.3.2 Scenario set-up

A scenario was designed to estimate the impact pumping bans have on river flow, by running a model both with and without a pumping ban and comparing the calculated surface water and groundwater exchange flux.

The scenario used in the assessment is based on the “repeated conditions” scenario (see page 53), but the time discretisation was changed to a daily stress period. This was necessary to accommodate daily changes to pumping bans. Input data for boundary conditions remain discretised in monthly intervals (e.g. recharge rates are constant for every day of a particular month), with the only exception being the irrigation pumping, which was varied daily (but the total each month was the same as in the monthly version of the model).

Input data

Ban index

The surface water model SOURCE was used to produce daily river flows, to calculate when pumping bans are introduced at each trigger site. In the analysed period, 4 trigger sites were considered, 2 on the Ngaruroro River and 2 for the Raupare stream (other trigger sites, such as Tūtaekurī River sites were not in ban during this period). These data are compiled into a “ban index”, which is a time series for each trigger site, indicating when the ban is active (Figure 5-16, second chart from top).

The SOURCE simulation that produced the flows required input from the MODFLOW model, which was provided from the MODFLOW run without pumping bans - for details refer to SOURCE report (Waldron, 2018).

Location of bores subject to bans

Pumping bores subject to pumping bans were identified and assigned a trigger flow site (Figure 5-15).

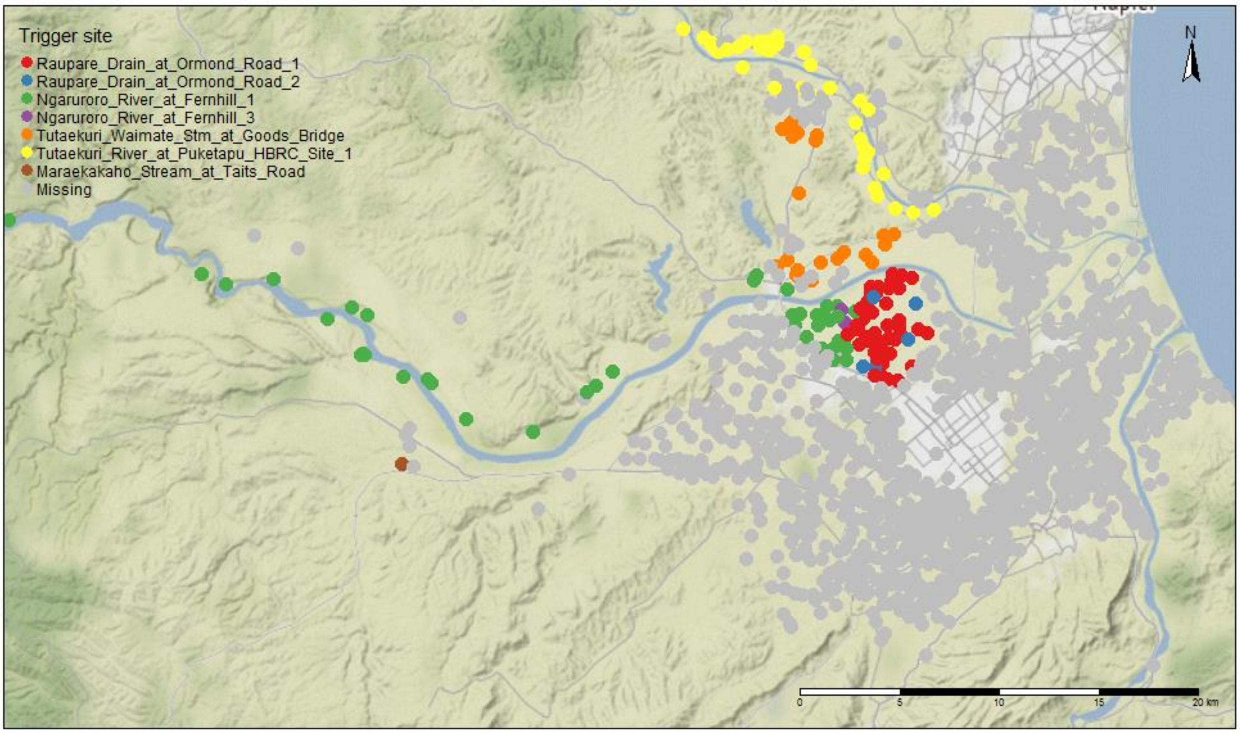

Figure 5-15: Location of bores classified by their trigger sites. The "Missing" class indicates no trigger site (no restriction).

Groundwater pumping input data

The ban index, and location of pumping bans was combined with original (no ban) irrigation pumping data to produce a new dataset for the "pumping ban" scenario. Due to the size of the dataset (daily time series for over 1400 bores, multiple ban sites) this new dataset and MODFLOW WEL file was produced using an R script.

In this scenario, pumping bans have little visible effect on total abstraction volumes from the aquifer until mid-February, when ban conditions are applied to the Ngaruroro, and persistent (rather than intermittent) ban conditions are applied to the Raupare, giving a maximum reduction in total pumping of about 500 L/s (Figure 5-16).

5.3.3 Scenario results

Results indicate the largest effects are seen for the Ngaruroro River, resulting in about 40 L/s flow improvement. However, this improvement takes about a month to be fully visible in the river. Raupare flow is improved by about 25 L/s, and the improvement seems to appear more quickly. A similar response is seen for the Tūtaekurī-Waimate. Other rivers and streams show even less effect on flow improvement from a pumping ban, but streamflow improves slightly even in streams that are not subject to protection by pumping bans.

These improvements are relatively small in relation to actual streamflow. When these improvements are added to observed streamflow (and thus represent improved flow) in the drought period of February 2012-2013, the difference is hardly discernible from measured flow (Figure 5-17). Also, the improvement in flow is unlikely to be sufficient to reverse the decline in river flows, and at best it can slow down the decline.

When maximum improvement in flow is compared with mean flow in this period, Raupare flow improves by 8% and Ngaruroro by only 2% (Table 5-5).

Table 5-5: Estimated flow improvement due to groundwater pumping ban (L/s).

Stream	Mean flow 15 Feb 2012 to 15 Mar 2013	Maximum flow difference	Proportional flow change
Raupare	322.0	26.8	8.3%
Irongate	79.8	3.3	4.2%
Mangateretere	21.5	0.6	2.9%
Ngaruroro	1676.0	38.2	2.3%
Karamu	772.0	8.3	1.1%
Tūtaekurī - Waimate	1888.0	19.8	1.1%

5.3.4 Discussion of results

Overall results indicate that pumping bans do improve river and stream flows, but this effect is relatively minor. However, it has been shown in the “Historical Scenario” (Section 3.1) that the overall effect of pumping by all users is large. This apparent paradox can be explained by the fact that users subject to a ban constitute a relatively small proportion of all aquifer users. Reduction in pumping caused by the ban is only about 500L/s of a total of 3500 L/s in all irrigation takes. Total use in this period (including public water supply and industrial takes) is about 4500 L/s, which means that pumping bans reduce groundwater use by only about 10%. Another aspect is timing, as it takes time for the effect to manifest itself in river flows. Even if all pumping in the Heretaunga Aquifer stopped, it would take several months for the aquifer to recover fully, and consequently for the flows to recover fully.

This suggests that the detrimental effect on a river due to pumping is not limited to pumping near the river, but instead is caused by a combined effect of pumping from the entire aquifer. Because of this, protecting a river by putting in place pumping bans only near the river, as currently takes place in the Heretaunga Aquifer, is not sufficient to restore the river. Also, currently the burden of protecting river flows lies with a relatively small number of consent holders, even though the flow is affected by much larger number of users of the aquifer.

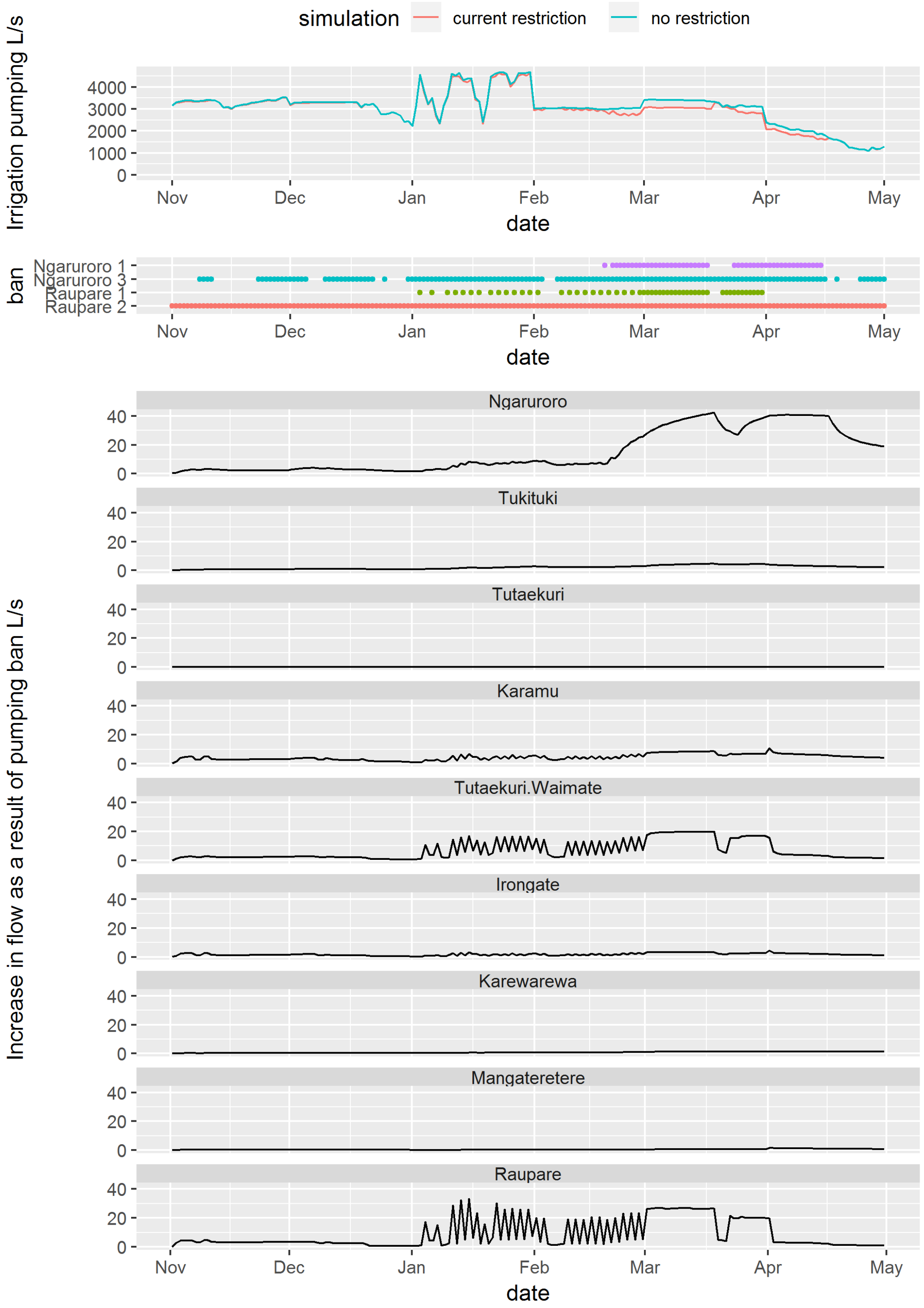

Figure 5-16: Pumping rates, pumping bans and effect on river flows in summer 2012/2013. The upper chart shows pumping rates with and without bans in place (irrigation only). The second chart down shows the point when sites reach a trigger (coloured points indicate that a ban is in place, absence of points indicates it is not on ban). The remaining charts show an increase in river flows as a result of pumping bans.

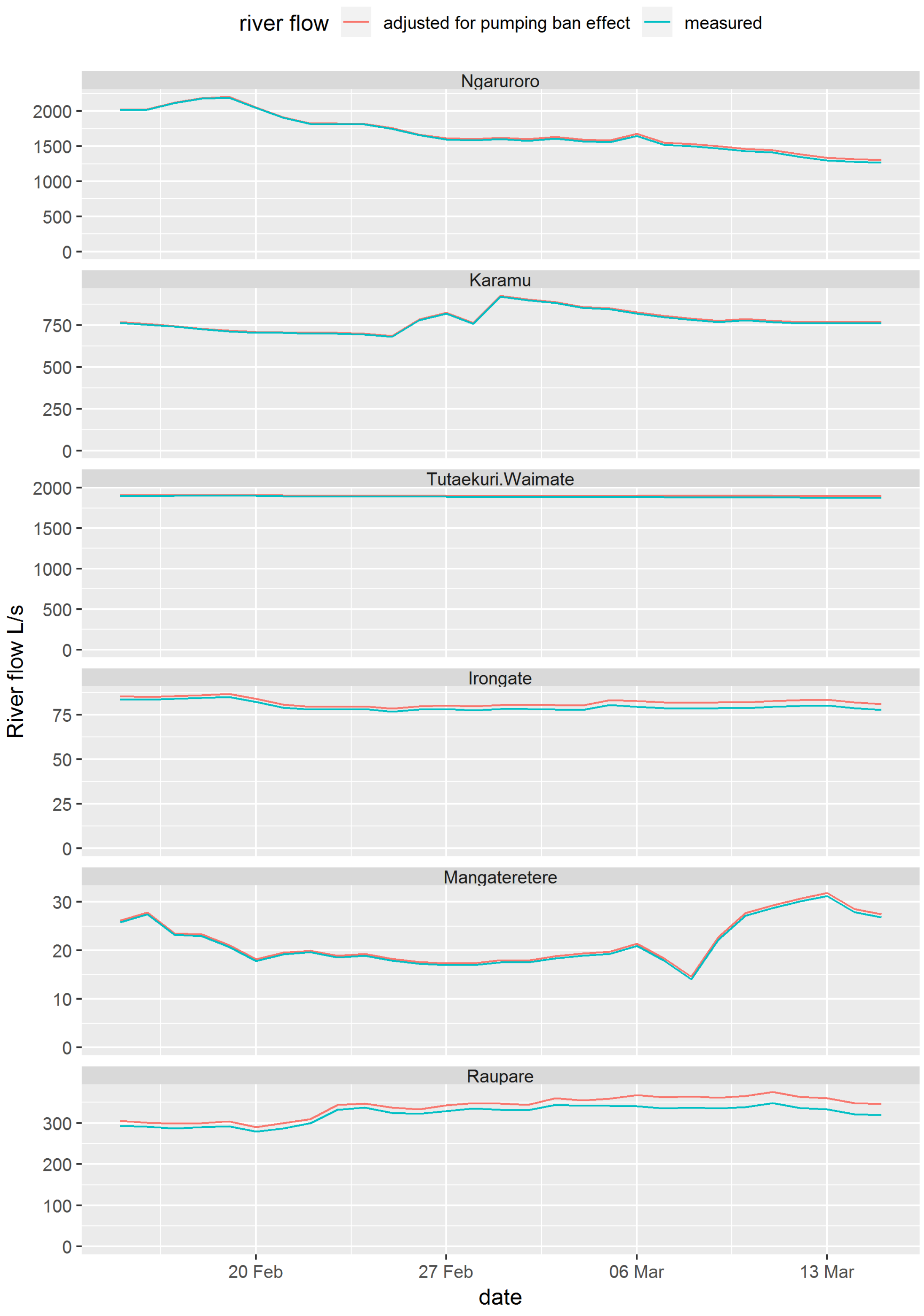

Figure 5-17: River flows with and without bans in February/March 2012. The predicted effects of the bans are added to measured river flows to visualise the relative effect of the ban. Karewarewa flow is negative because this flow is correlated on measurements from other sites.

5.4 Management scenarios

5.4.1 Scenario background

Several combined management scenarios – including various pumping ban strategies and flow augmentation - were run to investigate the effect on river flows of various management options for groundwater and surface water takes. The period modelled was 17 years long, up to 2032, which was achieved by linking the model with surface water SOURCE model.

5.4.2 Linking of SOURCE and MODFLOW

This linking of surface water (SOURCE) and groundwater (MODFLOW) models was necessary, since each of the models on its own is unable to simulate the dynamics of both surface and groundwater flow (

Table 5-6).

The SOURCE model domain is much larger than the MODFLOW domain (Figure 5-19), because it includes surface water catchments upstream of the Heretaunga Plains. This larger domain allows for simulation of surface water runoff from the entire catchment, and thus simulation of river flows. However, SOURCE is not able to fully simulate surface water – groundwater exchange flux or changes to the exchange flux (for example, due to groundwater pumping) within the Heretaunga Plains, and this has been accomplished using the MODFLOW model. MODFLOW can simulate the exchange flux, but it does not simulate full river flow, and consequently is unable to simulate timings of pumping bans or of augmentation pumping (which depend on river flows).

This means that SOURCE and MODFLOW models have to be run in a sequence (Figure 5-18). The first step is a “base scenario”: The MODFLOW model is run to calculate river losses and gains, and these results are then passed to the SOURCE model, which can calculate river flows. Calculations can then be made on when pumping bans or augmentation should be undertaken.

A “mitigation scenario” was also developed, where MODFLOW was run with pumping bans/augmentation, and calculated river losses and gains were passed on to SOURCE, which calculated new river flows. These flows may result in new timings for pumping bans and augmentation pumping, which means the “mitigation scenario” may need to iterate several times to converge on a solution. Due to the complex setup of both models and long run times, only one iteration was run. Finally, SOURCE calculates flow statistics, such as Q95, reliability of supply etc. A final “naturalised scenario” was also run, with no groundwater or surface water pumping.

Calculation of river flows and losses is undertaken for each SOURCE catchment (Figure 2-1), as described in Section 2.2.

Table 5-6: MODFLOW and SOURCE model capability.

Process/result	MODFLOW	SOURCE
Run off from surface water catchment	no	yes
Surface flow losses and gains to from groundwater	yes	No, only as input from MODFLOW or data
Surface water flows	No, only as exchange with groundwater	Yes, with input from MODFLOW
When pumping bans are implemented	No, need timing from surface water	yes
Changes to flow losses and gains as a result of groundwater pumping bans and augmentation of river flow	yes	No, only as input from MODFLOW
Total flow	SOURCE, with input from MODFLOW	
Flow statistics (e.g. duration of low flow, duration of ban, reliability of supply)	SOURCE, with input from MODFLOW	

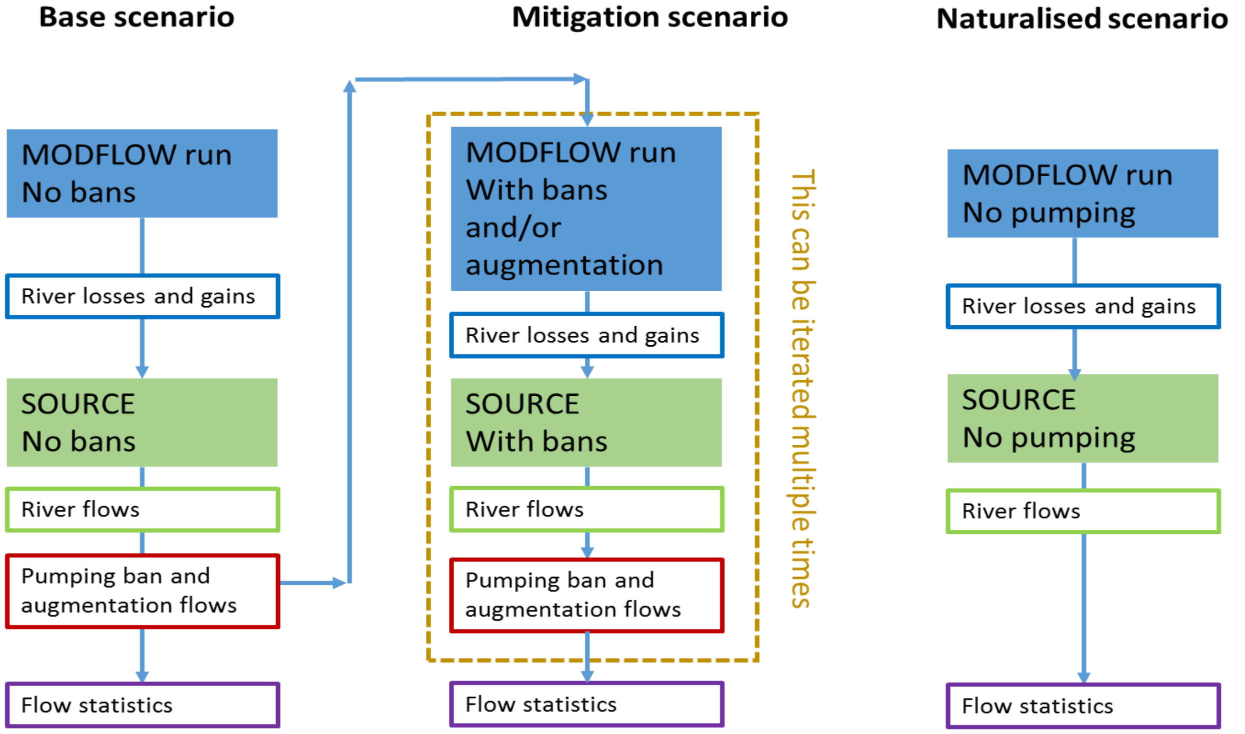

Figure 5-18: Linking MODFLOW and SOURCE.

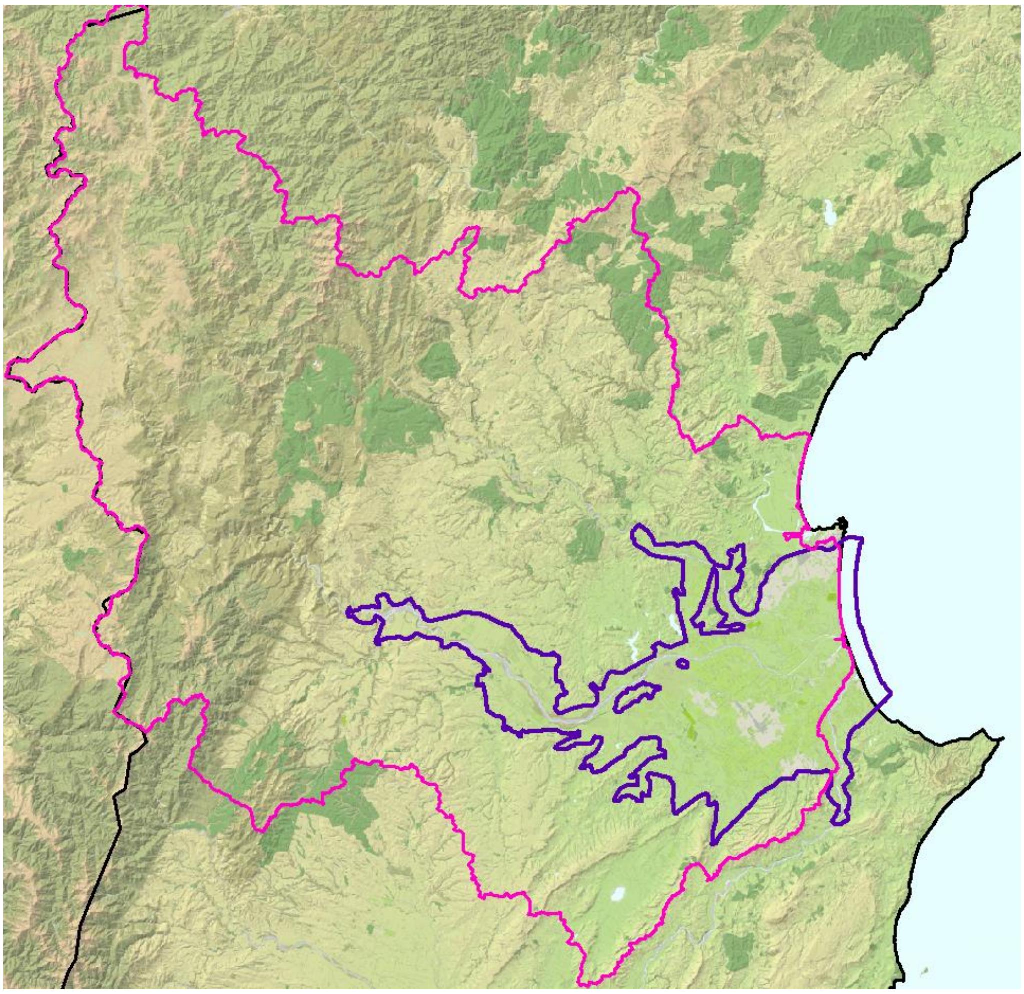

Figure 5-19: Study area (pink – surface water model and TANK catchment model boundary, blue – Heretaunga Aquifer System boundary)

5.4.3 Scenario setup

The scenarios include various set up characteristics (Table 5-9). The scenarios are defined by following variables:

- **Pumping assumption:**
    - Estimated demand:

      This represents irrigation demand calculated assuming current land use, and climatic conditions the same as 1998-2015, and other uses such as public water supply and irrigation repeating use during the period 1998-2015
    - No pumping
    - Maximum allocation of surface water, and estimated demand for groundwater
- **Ban triggers** – ban triggers are river flows below which pumping is restricted. The triggers are based on:
    - Proportion of habitat at MALF (Mean Annual Low Flow)

  - WCO (Water Conservation Order) specified triggers
  - Current triggers - trigger flows defined in current consent conditions
- **Management zones** – these define which bores are subject to bans during restriction:
  - Existing zones classify bores as stream depleting under existing rules (see Figure 5-15)
  - Zone 1 means bores result in stream depletion estimated to be over 90% after 7 days of pumping, using a groundwater model (Stream Depletion Zones Modelling report to be prepared in 2018), and extended to include additional 400 m buffer around some rivers (Figure 5-24).
- **Augmentation pumping** – three scenarios include augmentation pumping. Trigger flows for augmentation are based on the "worst case" (see Section 5.2). When augmentation pumping takes place, abstraction bans do not apply for groundwater takes linked to streams that are being augmented.

For further detail about the scenarios, refer to the SOURCE report (Waldron, 2018).

5.4.4 Pumping rate change for scenarios

Variables discussed in Section 5.4.3 (pumping assumption, ban triggers, management zones, and augmentation pumping) result in different pumping volumes between scenarios, as pumping bans and augmentation pumping are triggered

Pumping bans

Differences due to pumping bans for the dry summer of 2013 are presented in Figure 5-20, and statistics for maximum achieved reduction are presented in

Table 5-7. Overall, the changes to pumping rates are relatively small, with a maximum reduction of about 350 L/s, which is about 10% of total irrigation abstraction. The largest difference is for scenarios with a current restriction regime. The differences between different scenarios are also relatively small. The largest difference appears to be the result of using different management zones.

Table 5-7: **Reduction in groundwater abstraction per scenario.**

	Max abstraction reduction	Max abstraction reduction	Median abstraction reduction	Median of max abstraction reduction
	Mm^3/year	L/s	Mm^3/year	L/s
M5_d_sc8_z1	0.3	85	0.01	14
M5_d_sc8v2	1.3	351	0.18	71.7
M5_d_sc9_z1	0.3	85	0.02	39
M5_d_sc9v2	1.3	351	0.22	155
M5_d_sc10v2	1.6	351	0.29	245
M5_d_sc11_z1	0.3	133	0.02	38.5
M5_d_sc12_z1	0.5	143	0.03	46.9
M5_d_sc13_z1	0.6	143	0.05	77.2
M5_d_sc14_z1	0.7	198	0.12	94
M5_d_sc16_z1	0.4	143	0.02	38.5
M5_d_sc8.3	0.2	54	0.01	21.7
M5_d_sc16.1	0.3	111	0.03	50.3
M5_d_sc18	0.4	111	0.05	93.5

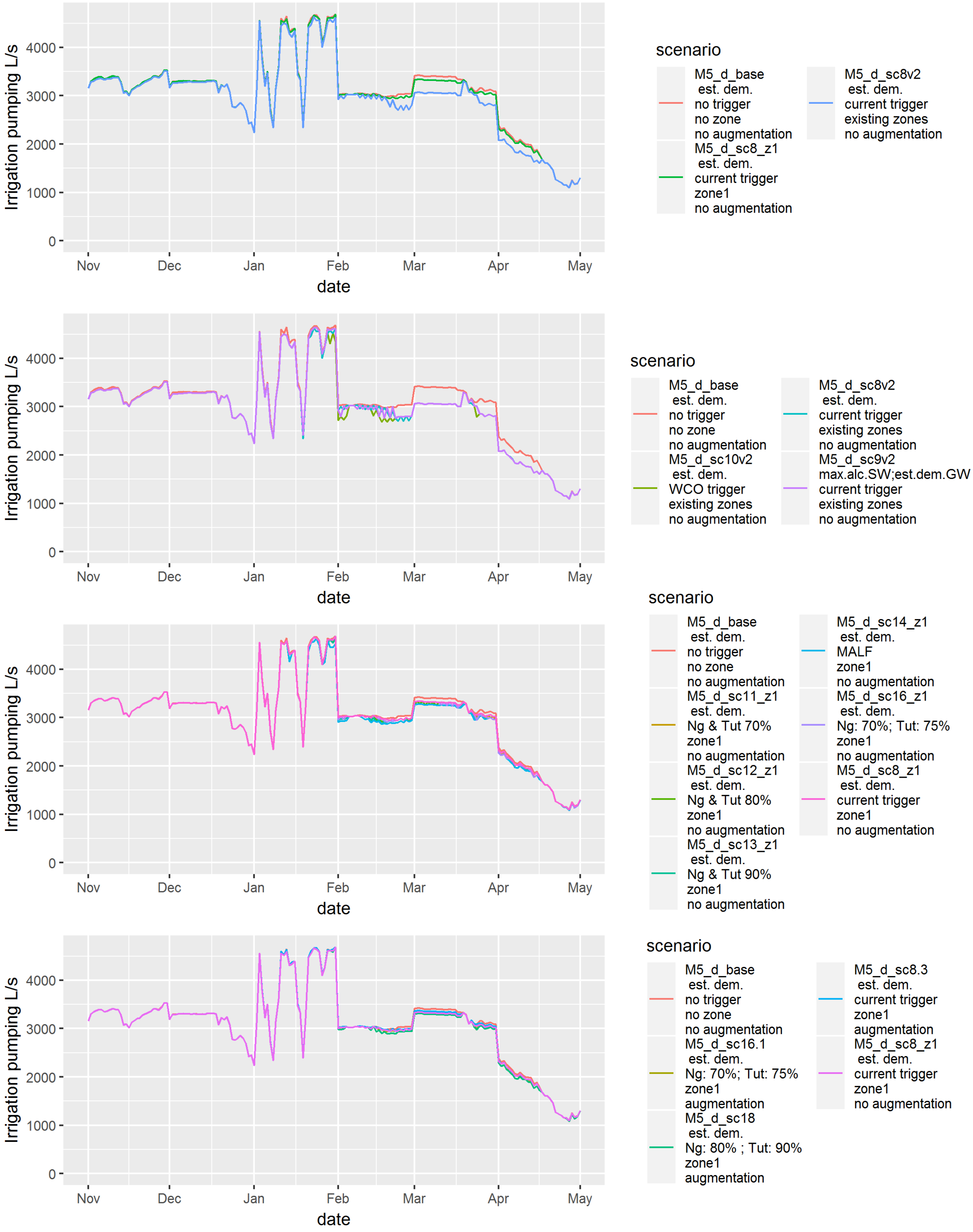

Figure 5-20: Irrigation pumping .Values are for a period of summer 2032, equivalent to the dry summer of 2013 Augmentation pumping is excluded.

Augmentation flows:

Scenarios 8.3_SDZ1, 16.1_SDZ1, and 18.0_SDZ1 included stream augmentation. Previous augmentation simulations (described in Section 5.2) included only one season and were focused on the effects of augmentation on streamflow, and the overall feasibility of augmentation. Simulations described here included augmentation and pumping bans, so the effects of augmentation cannot be fully separated out from effect of pumping bans on the flow. However, these simulations are long term, covering 2015-2032, which allows for assessment of longer term augmentation needs, for example to assess how often, at what rate, and for how long augmentation pumping will be required in each year.

Augmentation rates are variable throughout the year and between different years (Figure 5-21). The highest requirement for augmentation is in Karamu Stream, the lowest in Raupare Stream.

Total augmentation is 5 Mm^3/year at the maximum, and 2 Mm^3/year average (Figure 5-22), which is relatively small compared to the maximum total use of about 90 Mm^3/year. The required duration of augmentation is variable between seasons and streams (Figure 5-23). The Raupare stream has the shortest augmentation duration, and Mangateretere stream the longest. The statistics for duration and rate of augmentation are presented in Table 5-8. The probability of needing augmentation in any given year is around 90% for all streams except the Raupare, which has a 50% probability of needing augmentation. The median duration of augmentation is over two months for all streams except Raupare.

The differences between Scenarios 8.3_SDZ1, 16.1_SDZ1, and 18.0_SDZ1 are very small, and only 8.3_SDZ1 is shown.

Overall, the results indicate that at selected trigger flows the augmentation in likely to be required nearly every year, for a large part of the irrigation season, and at a considerable rate in most locations.

As the augmentation is likely to have some negative consequences (5.2), it may be advisable to consider lower augmentation trigger flows to minimise reliance of augmentation pumping with high rates for extended periods of time.

Table 5-8: Augmentation statistics.

Stream	Maximum number of augmentation days	Median number of augmentatio days	Mean augmentation rate	Maximum augmentation rate	Probability of augmentation in any year	Max yearly	Mean yearly
	d	d	L/s	L/s		Mm^3/year	Mm^3/year
Irongate	125	67	22.9	74.8	89%	0.51	0.17
Karamu	90	66	131	343	89%	2.08	0.80
Karewarewa	177	87.5	41	82.5	100%	1.08	0.35
Mangaterete	194	128	49.4	110	94%	1.09	0.63
Raupare	88	3.5	5.39	43.2	50%	0.25	0.05
Total			**250**	**654**		**5.02**	**2.00**

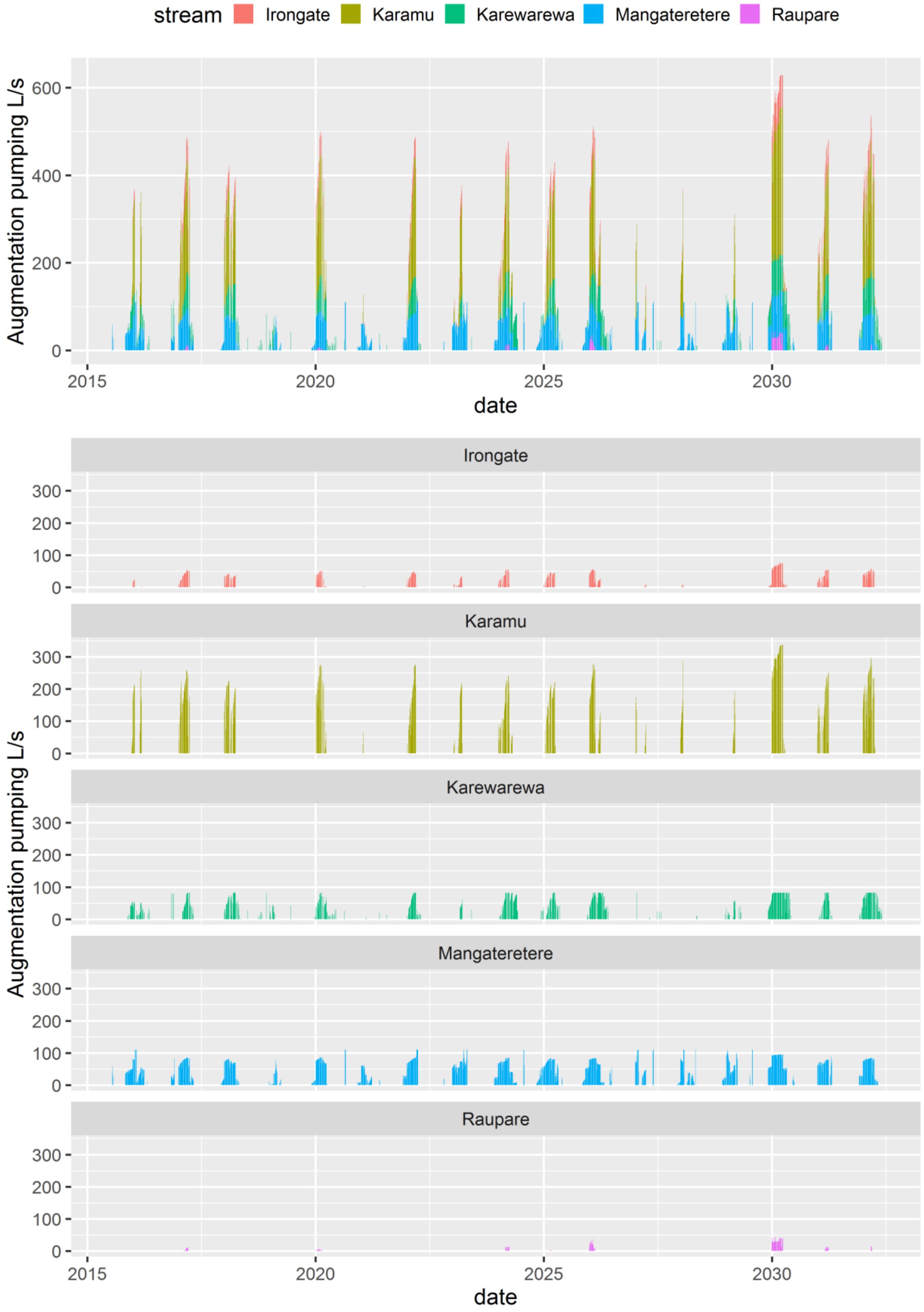

Figure 5-21: Daily augmentation requirements.

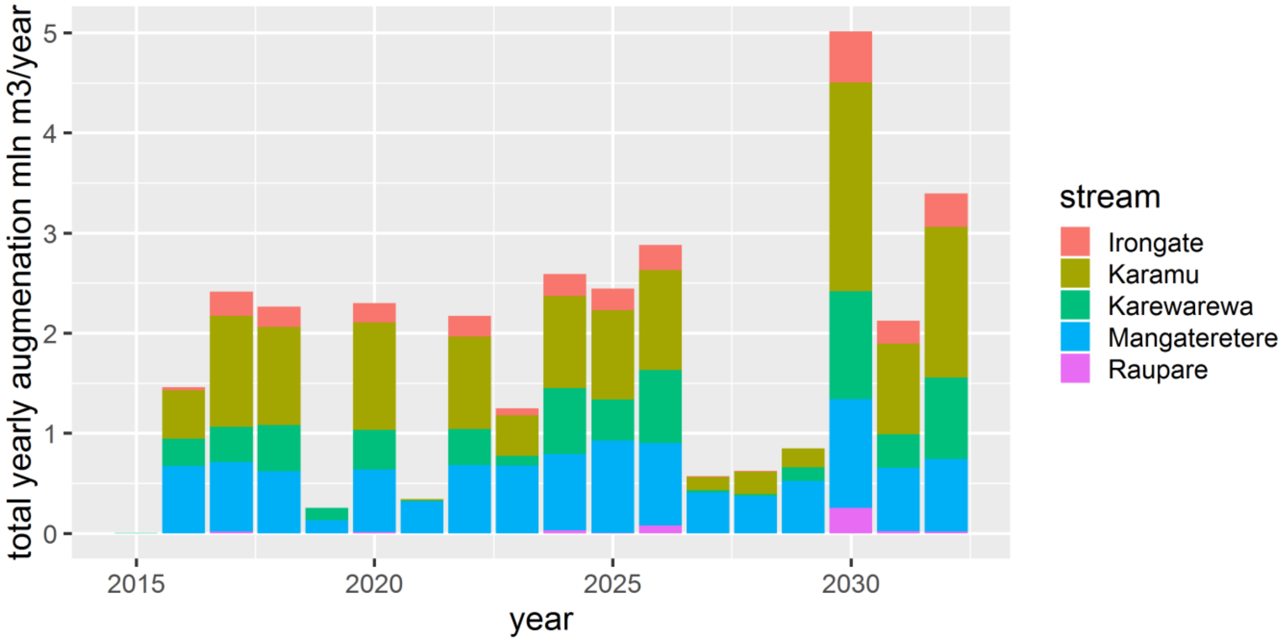

Figure 5-22: Total yearly augmentation requirement.

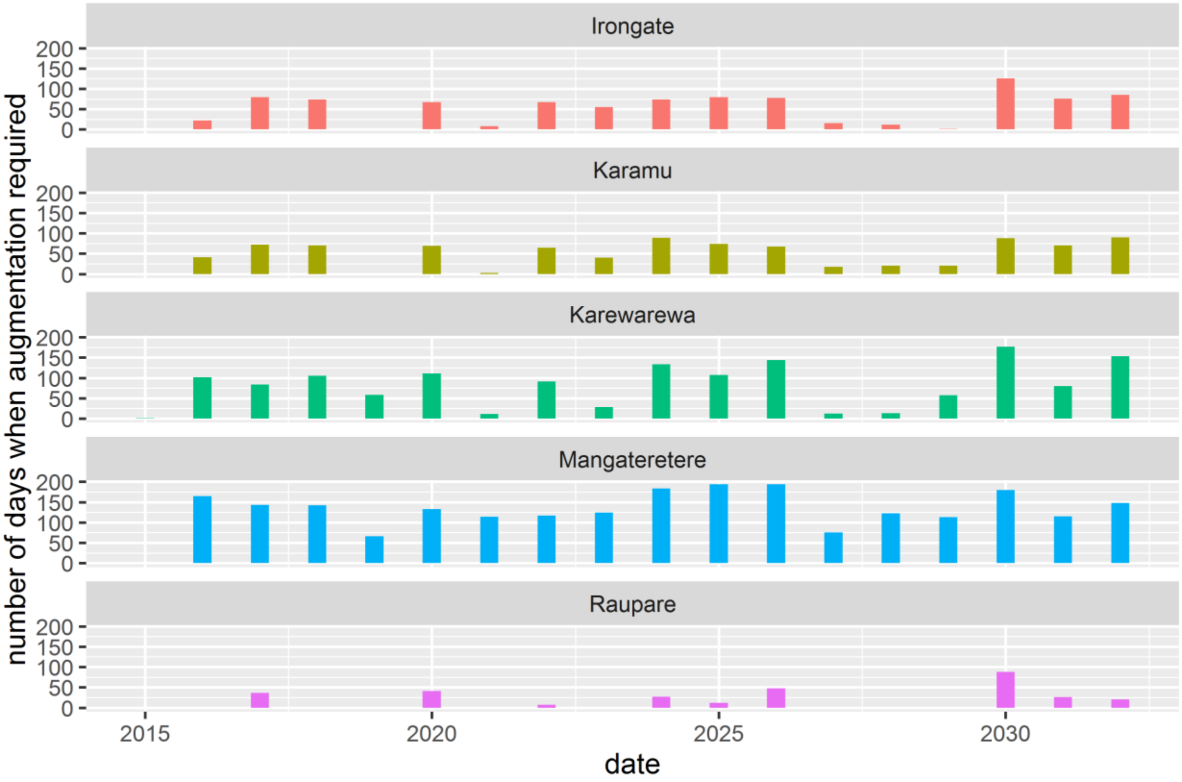

Figure 5-23: Augmentation duration per season.

Table 5-9: Management scenarios.

MODFLOW ID	Source ID	Pumping	ban trigger		Management zones	Augmentation
			Ngaruroro	Tūtaekurī		
M5_d_base	8.1	Estimated demand			n/a	no
M5_d_zero	7.1	No pumping			n/a	no
M5_d_sc8_z1	8.1_SDZ1	Estimated demand			Zone1	no
M5_d_sc8v2	8.1_SDC	Estimated demand	Current trigger		Existing zones	no
M5_d_sc9_z1	9.2	Maximum allocation surface water estimated demand groundwater	Current trigger		Zone1	no
M5_d_sc9v2	not run	Maximum allocation surface water estimated demand groundwater	Current trigger		Existing zones	no
M5_d_sc10v2	10.0	Estimated demand	WCO trigger		Existing zones	no
M5_d_sc11_z1	11.0_SDZ1	Estimated demand	70% Habitat at MALF		Zone1	no
M5_d_sc12_z1	12.0_SDZ1	Estimated demand	80% Habitat at MALF		Zone1	no
M5_d_sc13_z1	13.0_SDZ1	Estimated demand	90% Habitat at MALF		Zone1	no
M5_d_sc14_z1	14.0_SDZ1	Estimated demand	MALF		Zone1	no
M5_d_sc16_z1	16.0_SDZ1	Estimated demand	70% Habitat at MALF	75% Habitat at MALF	Zone1	no
M5_d_sc8.3	8.3_SDZ1	Estimated demand	Current trigger		Zone1	yes
M5_d_sc16.1	16.1_SDZ1	Estimated demand	70% Habitat at MALF	75% Habitat at MALF	Zone1	yes
M5_d_sc18	18.0_SDZ1	Estimated demand	80% Habitat at MALF	90% Habitat at MALF	Zone1	yes

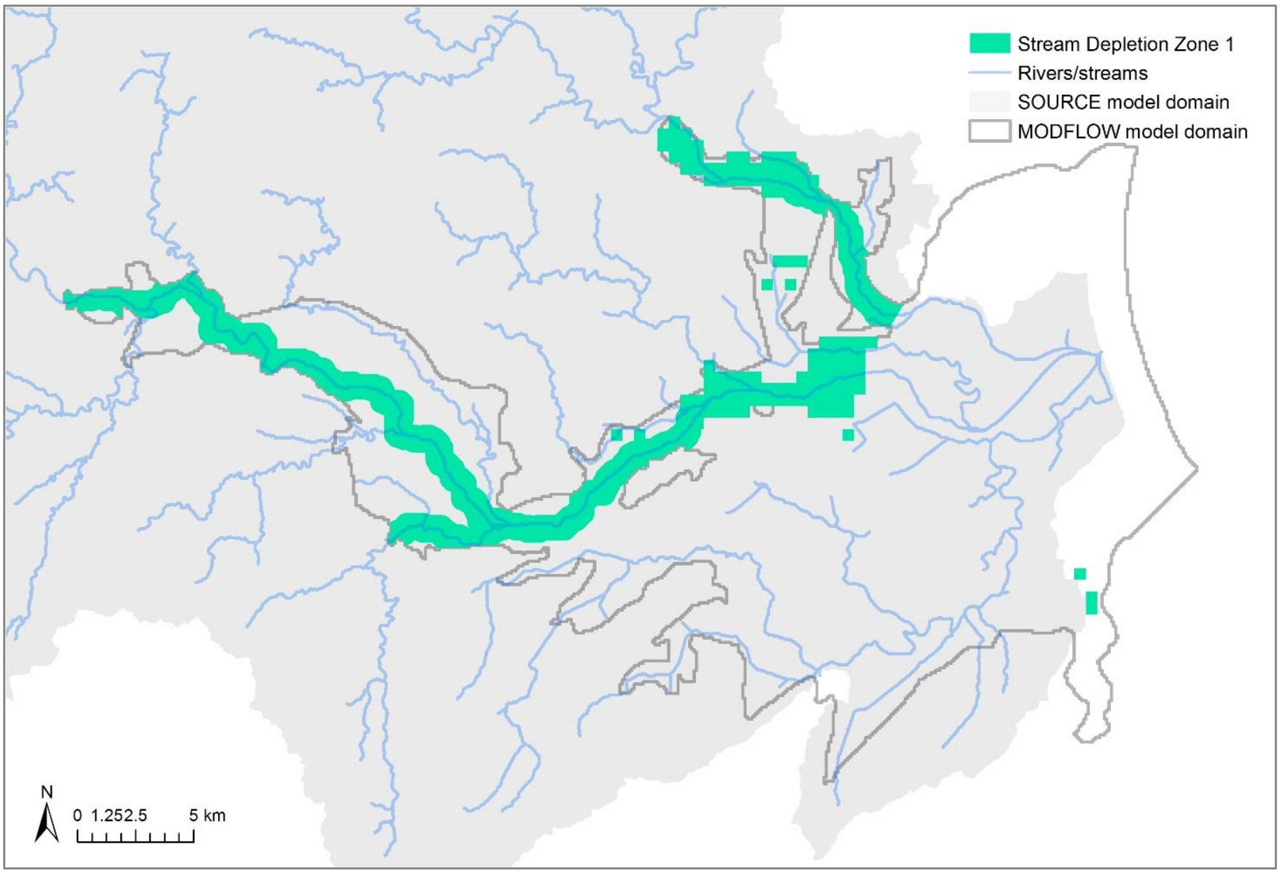

Figure 5-24: Groundwater Stream Depletion Zone 1.

5.4.5 Scenario results

Results of scenario runs on flow statistics are presented in the SOURCE report (Waldron, 2018). Below are presented only the results related to groundwater flow.

Impact on river flows

Differences in groundwater pumping resulting from different management scenarios affect the surface-water/groundwater exchange flux. Pumping bans result in increased spring flow, and a decrease in river losses for losing rivers. Pumping groundwater for augmentation has an opposite effect. These effects, for a dry period equivalent to the summer of 2012-2013, are shown on Figure 5-25 to Figure 5-29.

Figure 5-25 compares a scenario using existing trigger zone with a scenario that uses zones. The scenario with zone 1 results in more flow recovery compared to existing zones, however the recovery is relatively small in both cases. The jagged line visible for both scenarios is a result of oscillation caused by the abstraction ban. When the ban is triggered, resulting flow recovery allows the ban to be lifted the following day, and pumping resumes. This in turn causes flow reduction and triggering of a ban, and the cycle repeats.

Figure 5-26 shows the difference between trigger levels (current trigger sc8v2 and sv9v2 against WCO trigger sc 10v2) for existing management zones. Higher flow trigger levels result in much earlier onset of bans, and consequently higher river flows, particularly for the Ngaruroro River. However, this additional increase is relatively minor, with a maximum of 20L/s more flow, and only about 10L/s more flow when river flows are lowest. The difference between sc8v2 and sv9v2 is that sc9.2 uses maximum allocation pumping for surface water abstractions, which results in earlier occurrence of pumping bans, but this has a very minor effect on flows.

Figure 5-27 compares scenarios with different trigger levels for zone 1. There is little difference between the scenarios, except at Tūtaekurī, and some difference at Ngaruroro. The difference is related to the onset of the pumping ban. There is also some increase in Tūtaekurī flow, by up to about 70 L/s for the most conservative scenario.

Figure 5-28 compares scenarios for different trigger levels with augmentation (including current trigger levels without augmentation). It shows decrease in streamflow in some streams, largest for Tukituki, Karamu and Ngaruroro, which is a result of augmentation pumping. Decrease in Karamu flows would be more than offset by pumping of the augmentation water into Karamu (see section 5.2). Flow decreases in Ngaruroro and Tukituki are relatively small (50 and 100 L/s respectively) in comparison typical summer flow (Q95 for these rivers is 4200 and 5700 respectively).

Figure 5-29 shows all of the analysed scenarios using same scale, to allow for easy visual comparison of the effect of mitigation options on streamflow between all of the scenarios. Overall the impact of analysed mitigation pumping scenarios is relatively small:

- The largest effect appears to be due to the changes to the trigger zone from existing to zone 1;
- There are some differences in timing of flow recovery, and some increases in river flow in Tūtaekurī River for the different trigger levels, but these are relatively small compared to flow.
- There is a negative effect of augmentation pumping on flow for some rivers, in particular to Tukituki, Karamu and Ngaruroro, but this is effect will be mitigated by Augmentation in Karamu, and is relatively small in comparison to typical summer flow in Tukituki and Karamu.

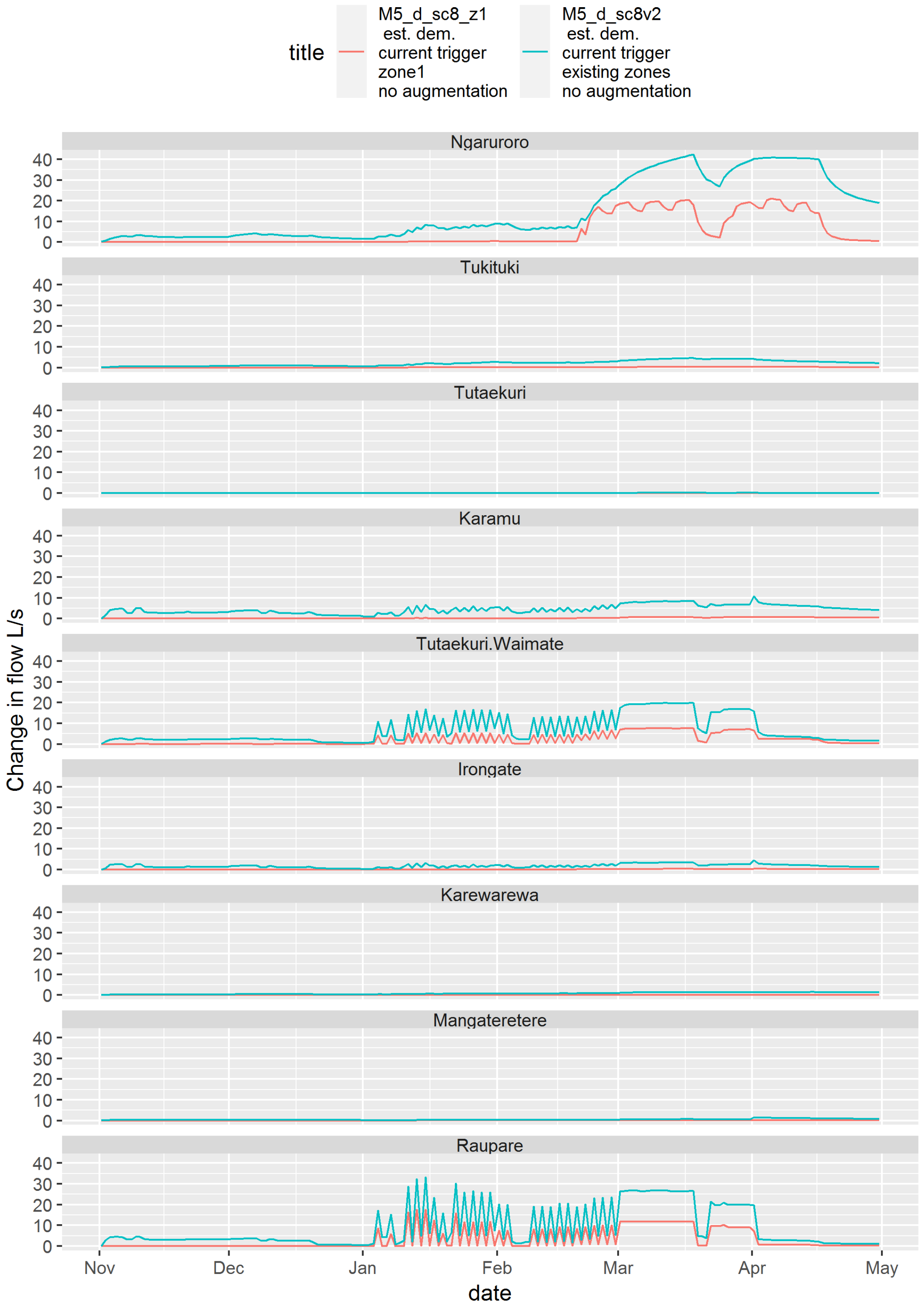

Figure 5-25: Impact of groundwater pumping bans on river flows (part 1.) Comparison between scenario using current trigger levels, but different zones: sc 8v2 uses current zones, sc8_z1 use proposed Zone 1. Positive values: increase in flow.

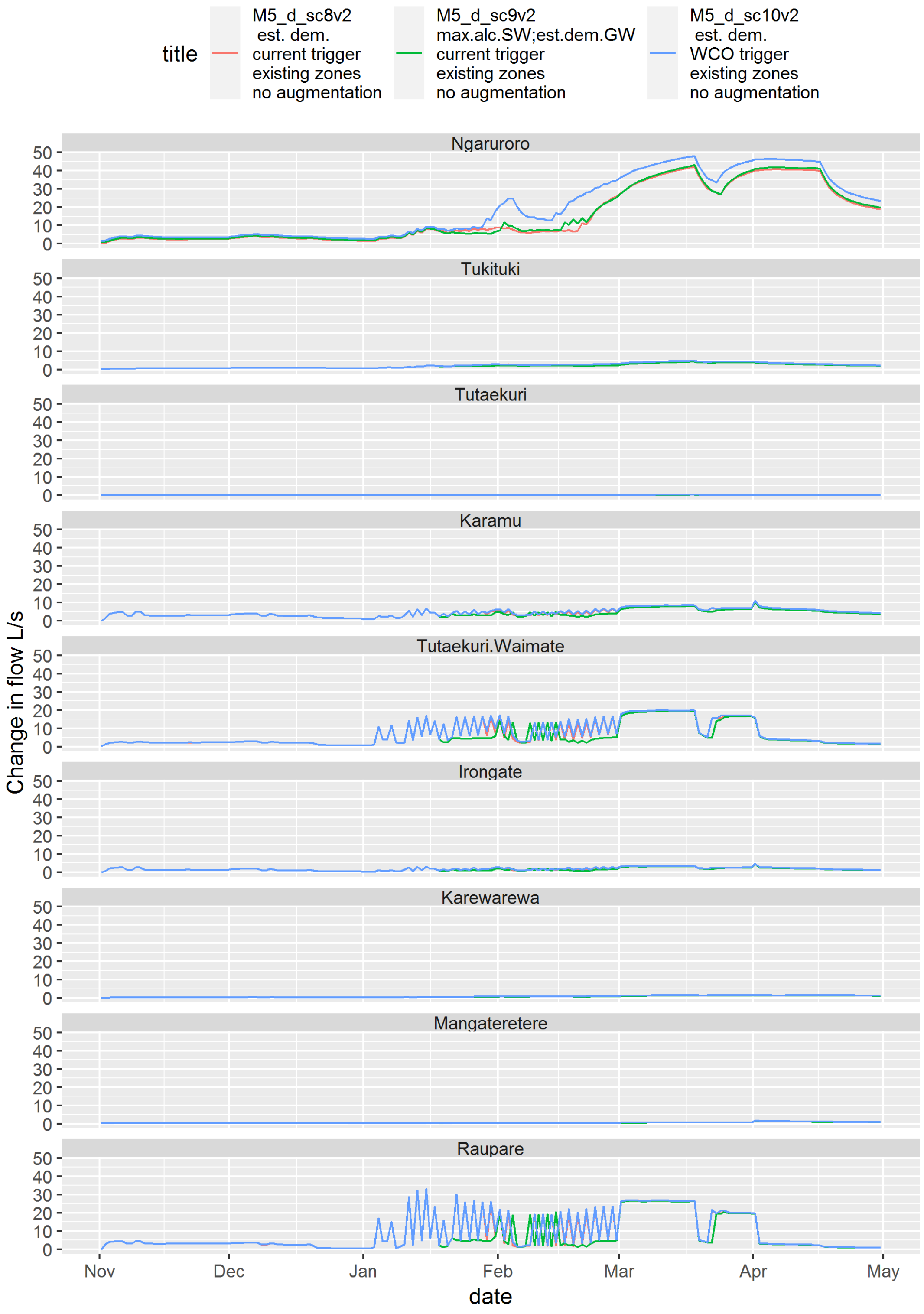

Figure 5-26: Impact of groundwater pumping bans on river flows (part2). Impact of different trigger levels (current trigger sc8v2 and sv9v2 against WCO trigger sc 10v2) for existing management zones. Difference between sc8v2 and sv9v2 is that sc9.2 uses maximum allocation pumping for surface water abstractions, which results in earlier occurrence of pumping bans. Positive values indicate increases in flow.

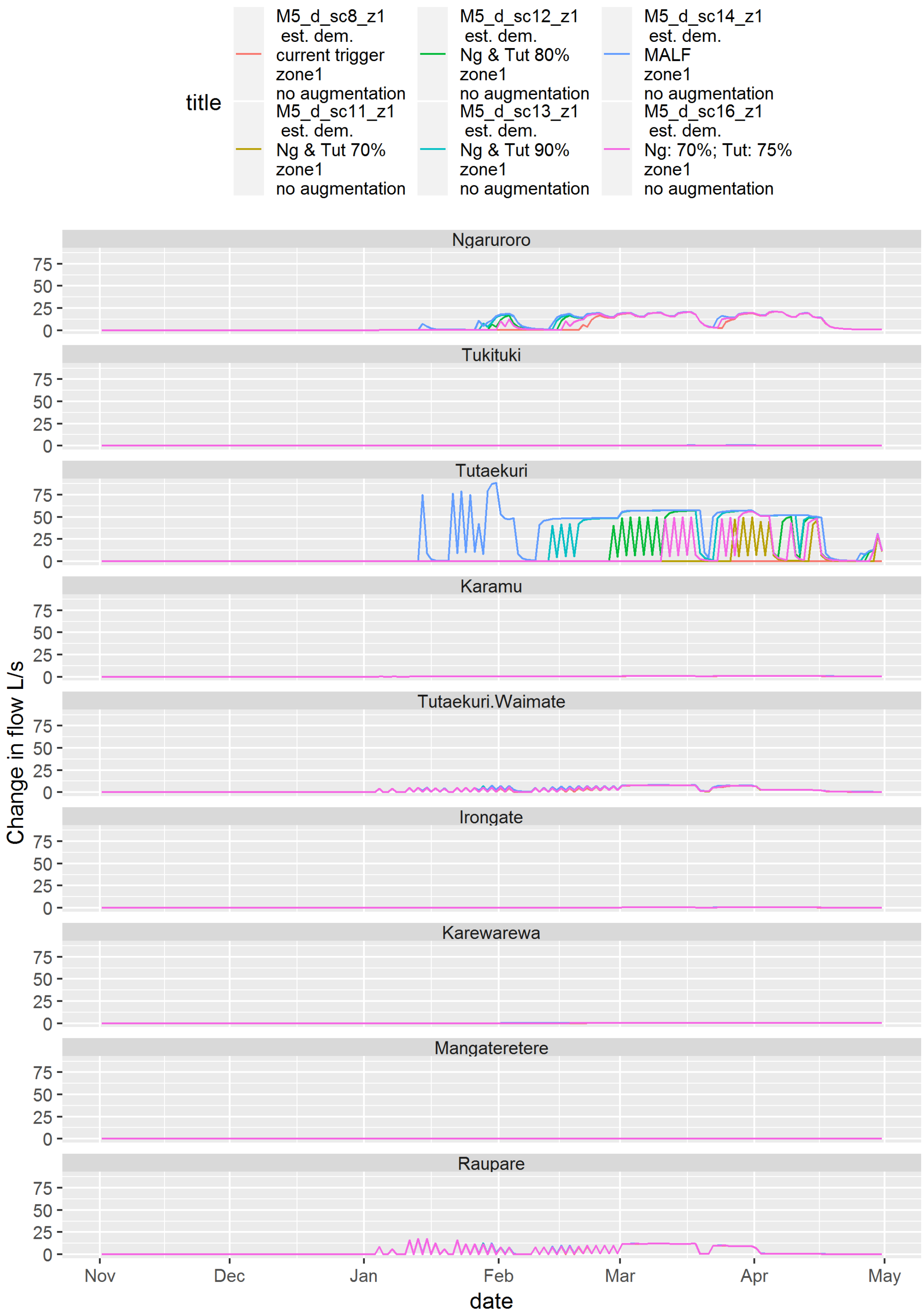

Figure 5-27: Impact of groundwater pumping bans on river flows (part3). Scenarios compare different trigger levels for zone 1. Positive values indicate increases in flow.

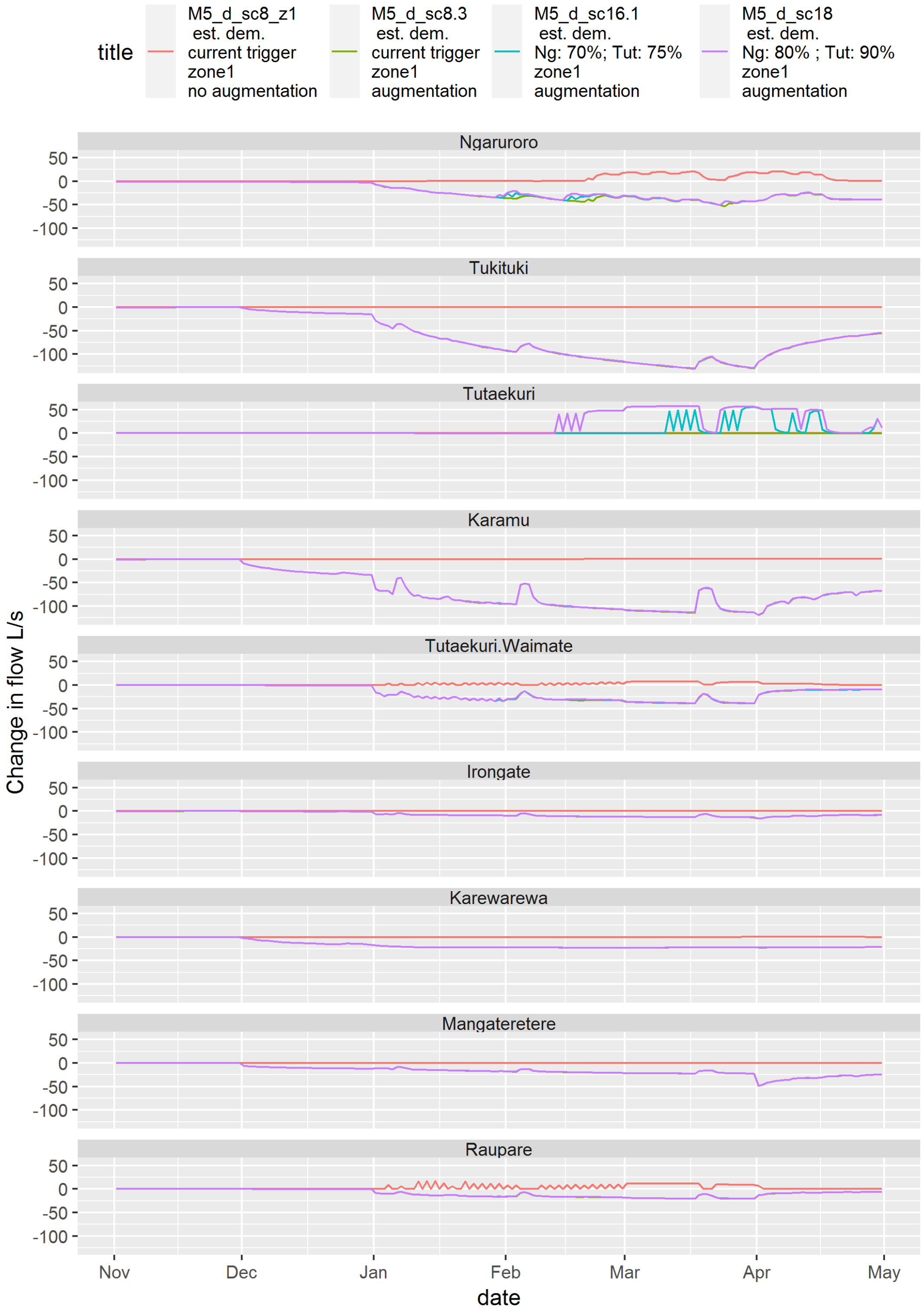

Figure 5-28: Impact of groundwater pumping bans and augmentation on river flows (part 4). Scenarios compare different trigger levels. Positive values indicate increases in flow, negative values show decreases in flow (note that in most cases decreases caused by augmentation pumping are more than offset by pumping into the stream, except streams that are not augmented, eg. Tukituki and Ngaruroro, this chart does not include positive effects).

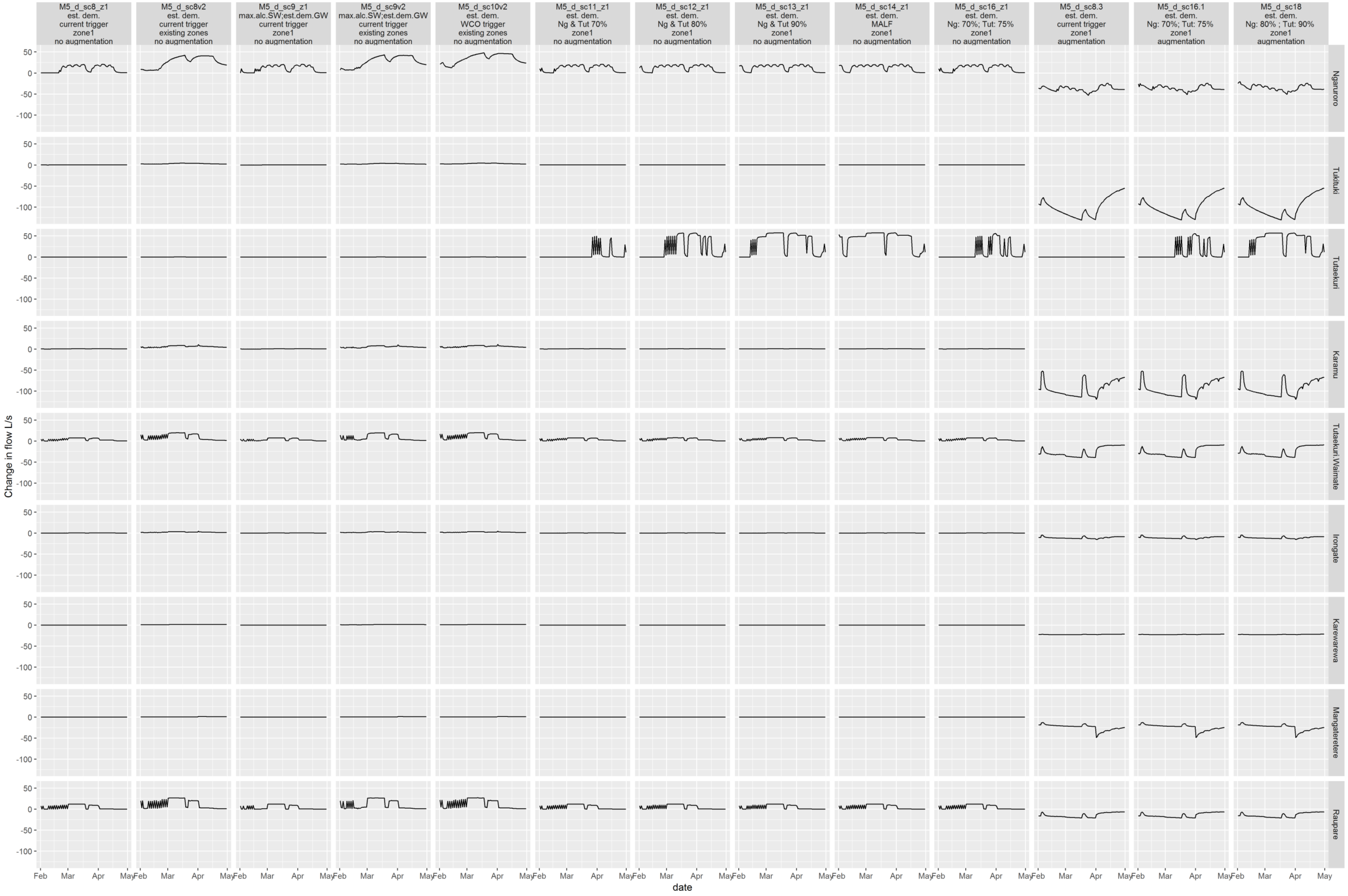

Figure 5-29: Impact of mitigation measures on river flow, all scenarios. Positive values indicate increases in flow, negative values show decreases in flow (note that in most cases decreases caused by augmentation pumping are more than offset by pumping into the stream, except streams that are not augmented, eg. Tukituki and Ngaruroro, this chart does not include positive effects). Est.dem. – estimated demand; Max.alc – maximum allocation; NG – Ngaruroro; Tut – Tūtaekurī, %% indicates trigger flow as proportion of habitat at MALF.

6 Uncertainty analysis

6.1 Methodology

During model calibration, model parameters were adjusted to obtain the best match of model outputs to observed data. This set of model parameters that fit calibration criteria can be defined as a solution of model calibration. This process has been described by Rakowski and Knowling (2018). In reality, most calibration problems are non-unique, which means that there are many combinations of parameters that can provide an acceptable match of model outputs to the observed data. Although these parameter sets may provide similar matches to the calibration dataset, model predictions run with the various parameter sets may differ significantly. This is because some of the model parameters are not well constrained by available observations, and yet they may have an impact on model prediction. Consequently, there is uncertainty associated with model predictions.

Uncertainty analysis has been undertaken using PEST (Doherty, 2016) to apply the calibration constrained Monte Carlo method, which allows for assessment of predictive uncertainty.

The first step of this uncertainty analysis was to generate a collection of model parameter “realisations”, which are parameter sets that produce a satisfactory match of model outputs to observations. Details of this process are described by Knowling (2018). In the process, additional model observations were used to help constrain the calibration and reduce non-uniqueness, such as groundwater age and nitrite concentrations (not just groundwater level). Following this process, 107 parameter sets (realisations) were identified.

The second step of uncertainty analysis was to use these realisations to generate specific model predictions. For example, predicting future groundwater levels required generation of a separate model for each realisation or parameter set, and assuming a repeat of the 2005-2015 climatic conditions and with assumptions of no pumping, historical pumping or increased pumping, as described in subsequent sections. Each model was then run, and groundwater level predictions were analysed. Because of the differences in model parameters, predicted groundwater levels may be different for each realisation and this variability is an indication of prediction uncertainty. The variability (and uncertainty) will be specific to a particular model simulation and prediction. For example, uncertainty for groundwater level predictions may depend on the specific prediction scenario (e.g. which part of the aquifer where abstraction is occurring and at what rate), and may be different in various areas of the model (e.g. where the groundwater level is measured).

The second step was also undertaken using PEST methodology, which allows for generation of predictive models using parameters sets derived in step 1, and combining of model results. The uncertainty analysis was run for selected scenarios, including Historical Scenarios (as described in section 3), and Future Scenarios assuming “Historical Use” and “Increasing Use”(Section 4), and included assessment of Stream Depletion effects. Details of the predictive scenario set ups using are reported by White (2018).

The third step of the uncertainty analysis involved processing of model results and is described in this chapter. This included Historical Scenarios and Future Scenarios. Stream Depletion Zone modelling uncertainty assessment will be described in a separate report.

6.2 Results

6.2.1 Historical scenario M3

Stream depletion

Stream depletion was calculated for each river using the same method described in section 3.1.2, for each of the realisations.

Stream depletion assessments were conducted for the 35-year period 1980-2015 of climate and pumping conditions (includes the dry 2012-13 year) for all 107 realisations, and results of the recent 3 year period (2012-2015) is presented in Figure 6-1. A separate line is displayed for each realisation, which represent the various solutions of stream depletion calculations based on the multiple realisations. Generally, all realisations show similar patterns of seasonal variation in stream depletion, but there are some differences in magnitude. Blue shading represents the stream depletion range that that is predicted by 90% of realisations (quantile range 5% to 95%), which can be interpreted as the “most likely” range of stream depletion. The result reported originally (as discussed in section 3.1.2) is presented as a red line “series 0”. In most cases red lines fall within the “most likely” range. In the case of Ngaruroro River (at Fernhill) the red line prediction is at the top of this range. This is visible in Figure 6-2, which presents the “most likely” range along with the original result and the median of all realisations.

Presentation of all realisations for a full simulation duration is difficult, as a large number of lines representing realisations results makes the charts unreadable. Instead, only the “most likely” range (plus original simulation and mean) is presented (Figure 6-3). The pattern of stream depletion variability since 1980 is similar for all simulations, showing a gradual increase in stream depletion for all streams and some changes in seasonal effects, but there are also significant differences between the realisations. For example, Tūtaekurī-Waimate shows significant variability in summer, with estimated depletion of between 400 and 800 L/s. Relatively small variability is visible for Ngaruroro stream depletion and this is likely to be a result of model parameters being constrained effectively by available observations.

Results for Ngaruroro in the dry year 2012-2013 are presented in Figure 6-4, following the same format as Figure 6-1. Figure 6-4 shows results for stream depletion of the Ngaruroro River at Fernhill (labelled Ngaruroro) and for the Ngaruroro River including the variable loss section (labelled Ngaruroro2). Notably, the results show that when the variable reach is included, the original prediction is in the middle of the “most likely” range. Overall, the prediction indicates a “most likely” range of about 220 L/s depletion for the summer 2013, which corresponds to about 30% of all estimated depletion effects.

Detailed statistics of stream depletion for all rivers, for the end of March 2013 are presented in Table 6-1. As already indicated, the “most likely” range is defined as between 5th and 95th percentile and included 90 percent of all predictions. A relative percentage range (in Table 6-1 labelled as *% 90 percentile range*) is a ratio of this “most likely” range to the mean, and allows for comparison of prediction variability between different rivers. Another useful measure of variation is the interquartile range, defined as the range between the 25th and 75th percentiles, which represents half of the results. This range can also be expressed as the relative percentage range for comparison with different rivers.

Standard deviation is a common measure of variation in a group and is shown in Table 6-1. The standard deviation is also expressed as a percentage of the coefficient of variation (the CV is the ratio of standard deviation to the mean), which also allows for comparison of variation between different rivers.

These measures of variation indicate different levels of variability for different rivers. The coefficient of variation is 9% for the Ngaruroro River, and 58% for Mangateretere Stream. This reflects a larger level of uncertainty related to stream depletion predictions for Mangateretere Stream. When all zones are considered, the coefficient of variation is only 4%. Overall, the statistics indicate some variability (i.e. not a wide range), with relative interquartile ranges between 12% and 48% (5% for all streams).

Histograms can be used to visualise the distribution and variability of results (Figure 6-5). To enable comparison between different rivers, the histograms show a ratio of stream depletion to mean stream depletion for each group. For example, the results for the Ngaruroro River are much closer together than for the Karewarewa Stream, indicating less variability of the stream depletion in the Ngaruroro River.

Variability of results between the realisations is an indicator of prediction uncertainty. The larger the variability, the higher the prediction uncertainty. This means that the results of stream depletion calculations are less uncertain for Ngaruroro than for other streams.

Despite the fairly limited range of uncertainty characterised above, all realisations indicate a significant stream depletion effect due to historical groundwater pumping, and that this effect is increasing, although there are signs of a developing dynamic equilibrium in recent times.

Groundwater levels

Groundwater levels and water level changes at selected observation points were also recorded for every realisation, using the same methodology and locations as described in section 2.

Predicted water levels for realisations show a range of variability, depending on location (Figure 6-6 to Figure 6-8). For example, bore 3737 shows small variability, with a total range of 1 m in March 2013, compared to bore 15794, which had a total range of 3 m in March 2013. Statistics for all measurements in March 2013 are presented in Table 6-2. Overall, despite this variability, realisations appear to replicate the seasonal and long term pattern of the original simulation in most cases. For example, at bore 3737 all realisations indicate an increasing interval of summer-winter variations and a decline in summer water levels.

In some cases, realisations are closer to observed values than the original model solution, for example at bore 10371 (observed water levels are shown by the green line).

The differences in predicted water levels for each realisation in the dry 2012-2013 year are shown in Figure 6-9. The order of presentation follows that presented in Figure 3-19, broadly east to west for each presented column. All bores are shown with a common vertical range (except bore 5023), which allows the variability to be directly compared. Comparison of variability between bores reveals the higher variability occurs near recharge areas (bores 15006 and 10371), at Moteo valley (15794, 15795) and in the upper Ngaruroro valley (5023, 3453). This is consistent with previous findings related to uncertainty in these areas (Rakowski & Knowling, 2018).

Groundwater drawdown (the difference between water levels with and without pumping) was also calculated for all realisations (Figure 6-10 to Figure 6-12). Visual assessment generally indicates less variability in drawdown compared to absolute groundwater levels, except for bore 5023 located in the upper Ngaruroro valley. All realisations indicate drawdown increases over time. In 2012-2013 all locations have increasing drawdown, with high variability in the upper Ngaruroro valley (as for groundwater level predictions), but less variability in the Moteo Valley and near to recharge areas (which is the opposite pattern with absolute groundwater levels). The reason for this is not clear, but is probably due to the impact of the Ngaruroro River on groundwater levels. Statistics for all measurements in March 2013 are presented in Table 6-2.

6.2.2 Future scenarios

Future scenarios assuming “historic use” and “increasing use”, as described in section 4, were also rerun through all realisations.

Streamflow

The highest river losses and lowest stream gains in each year, typically occurring at the end of the summer, are shown on Figure 6-14 to Figure 6-16. Variability between different realisations is shown as shading, which represents the “most likely” results between the 5th and 95th percentiles. Dashed lines represent the original predictions. All realisations indicate stabilised flows for the historic scenario and declining flows for the increasing use scenario.

Variability between realisations remains stable for the “historic use” scenario, but appears to increase for the “increasing use” scenario, indicating increasing uncertainty, including uncertainty in the rate of streamflow decline in response to the assumed increasing pumping.

The original run (the M3 verification model scenario for 1980-2015 as described in section 4) is represented as a dashed line. For the Ngaruroro River (for the major river losing reach to Fernhill), the original (M3) predicted river loss is close to the lowest predicted river loss from among all realisations, all of which meet the calibration criteria. This indicates that there is an inadvertent bias in the calibration/verification model parameter dataset that results in relatively low river loss compared to other realisations (see also previous discussions about model non-uniqueness at section 6.1, and about river losses and gains at section 2.2). This essentially means that it is more likely that the actual surface water / groundwater exchange flux would be higher than predicted by the original M3 scenario (i.e. the original run under-predicts the decline in river flows as a result of increased pumping in the future , and the other scenario results indicate the potential amount of under-prediction).

It is important to note that this inadvertent bias is apparent only for the mainly losing reach of the Ngaruroro River to Fernhill. As shown in Figure 6-4, when the Ngaruroro variable loss section between Fernhill and the confluence with the Tūtaekurī-Waimate is included (but not including the Tūtaekurī-Waimate itself), this inadvertent bias is no longer apparent, and the original M3 predicted river loss almost matches the median of all scenarios.

The Tūtaekurī-Waimate shows similar effects, but this time in relation to river gains (Figure 6-15), in that the originally predicted spring flows are close to the highest in all realisations (i.e. the highest amount of river gain from groundwater).

A more complex process of surface-groundwater flux exchange is apparent for the gaining streams under the increasing abstraction scenario, especially for the Raupare, Irongate, Karamu and Tūtaekurī-Waimate. As shown in the results for the Karamu and Tūtaekurī-Waimate (Figure 6-15), the original (M3) result is initially around the middle of the results for all scenarios (and remains there for the historic use scenario). However, as the increasing use scenario proceeds, the river gaining conditions gradually reduce (i.e. the negative values on the plots of the surface – groundwater exchange flux tend towards zero), and the original (M3) result becomes more aligned with either the highest or the lowest river gains, depending on the river. The Karamu and the Raupare reach zero river gain by about 2075, and then show some losing character, with the original M3 run plotting close to the lowest predicted flows. The original M3 predicted spring flows for the Tūtaekurī-Waimate, however, tends to align with the highest river gain fluxes as abstraction increases, while the Irongate aligns with the lowest river gains and then the lowest river losses as the drawdown effects develop with increasing abstraction.

Groundwater levels

The lowest groundwater levels in each year, typically occurring at the end of the summer, are shown in Figure 6-17. Variability between different realisations is shown as shading, which represents results between the 5th and 95th percentiles. Dashed lines represent the original predictions.

All realisations indicate stabilized groundwater levels for the "historic use" scenario, and declining groundwater levels for "increasing use" scenario.

Variability between realisations remains stable for the "historic use" scenario, but appears to increase for the "increasing use" scenario, indicating increasing uncertainty, including uncertainty in the rate of groundwater level decline in response to increased pumping.

6.3 Summary of uncertainty analysis

Uncertainty analysis undertaken for selected model scenarios allows estimation of how reliable the model predictions are. The analysis indicates some spread in all types of results (stream depletion, water levels, drawdowns). While the uncertainty does not alter the conclusions of the analysis, it does provide information on the effects of uncertainty that can support decision-making.

This analysis concludes that, even when including uncertainty, there have been significant impacts due to groundwater pumping on streamflow and groundwater levels historically. In the future these stream depletion effects are expected to continue at around the same magnitude under current abstraction and climatic conditions, but to increase for scenarios of future increases in groundwater pumping.

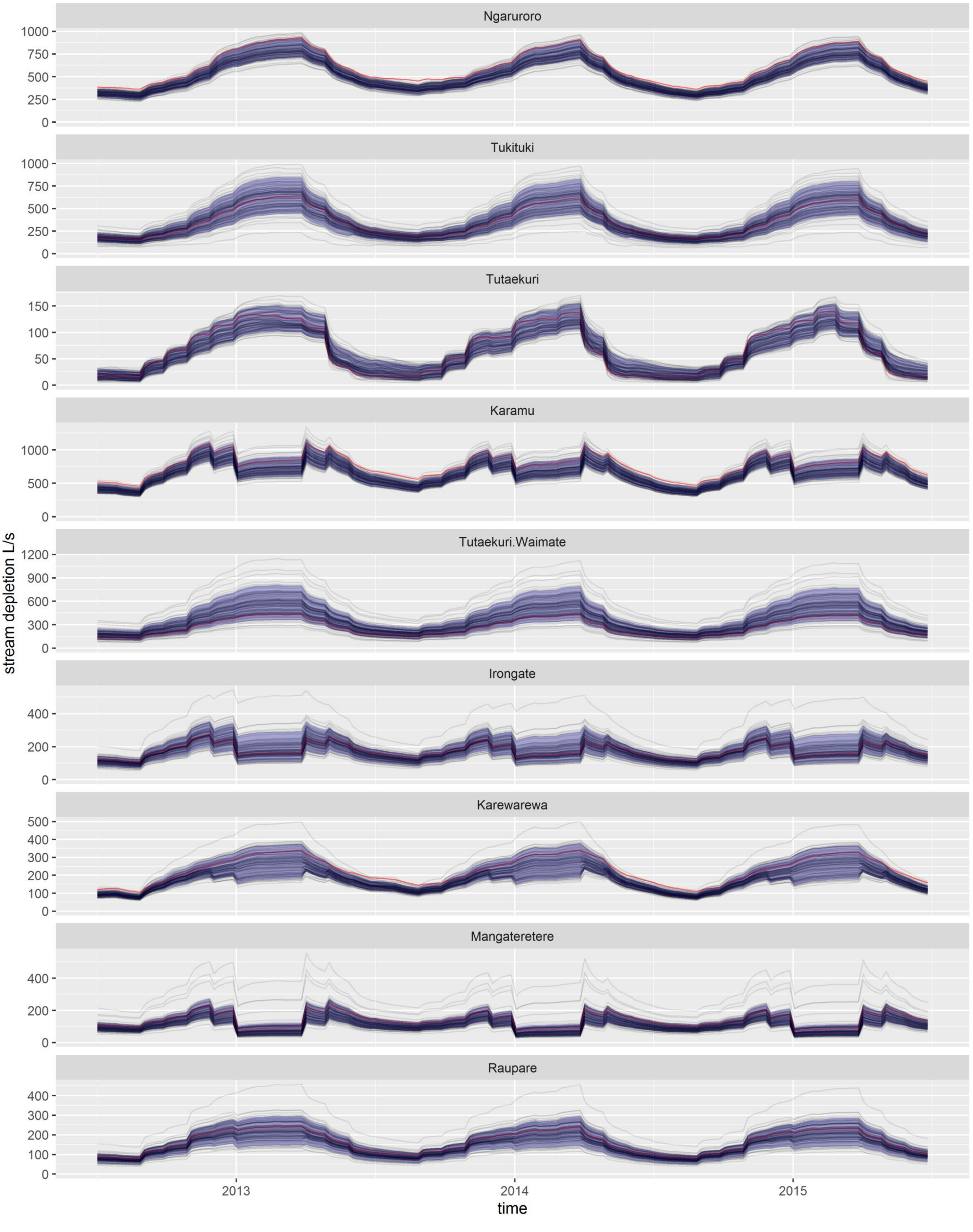

Figure 6-1: Historical scenario M3 uncertainty results – stream depletion 2012-2015 for all realisations. Blue shading indicates results between 5th and 95th percentiles. Red series "0" represents originally reported calibrated result. Grey lines represent other 107 realisations

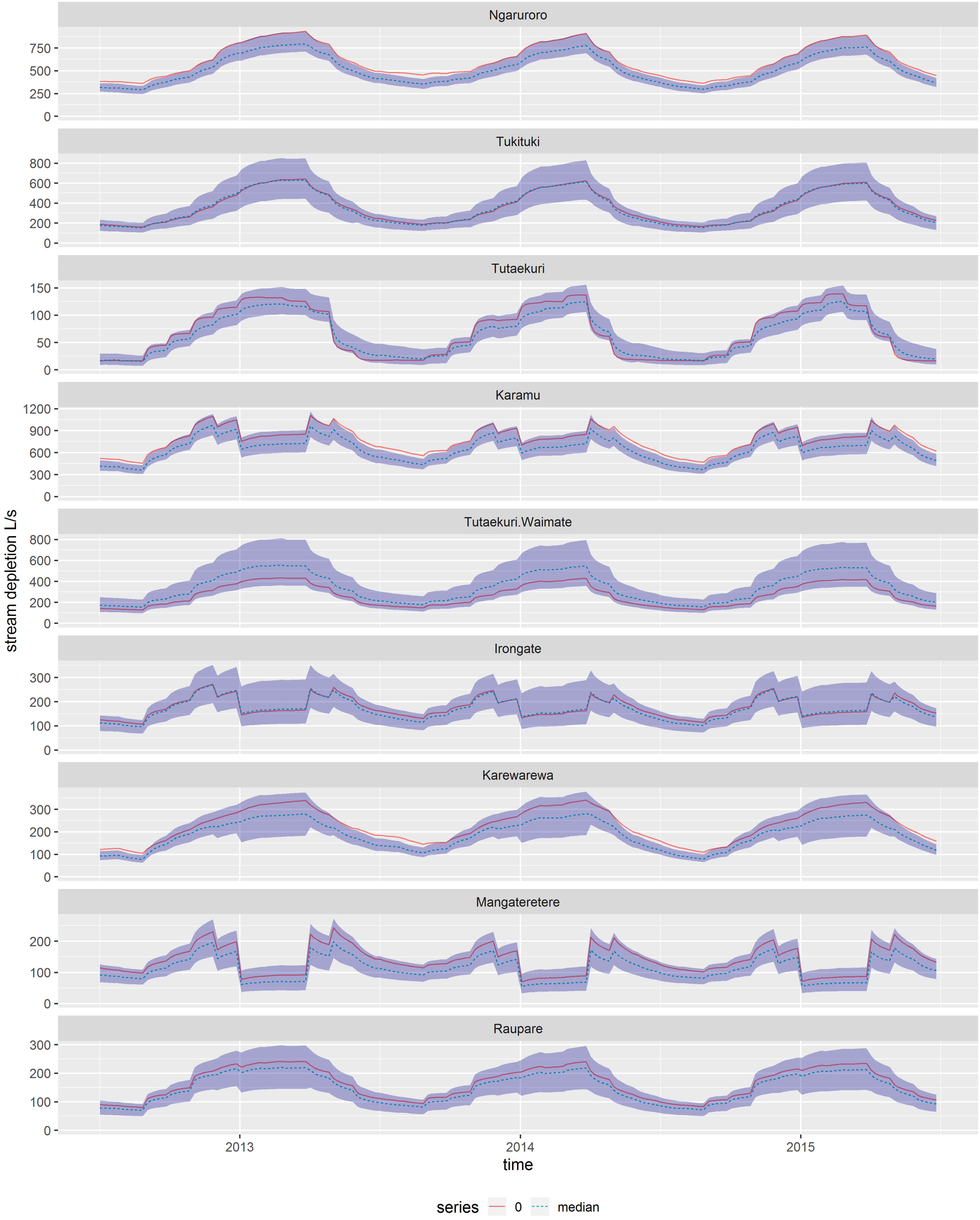

Figure 6-2: Historical scenario M3 uncertainty results – stream depletion 2012-2015. Blue shading indicates results between 5th and 95th percentiles. Dashed blue series “median” represents median prediction. Red series “0” represents originally reported calibrated result.

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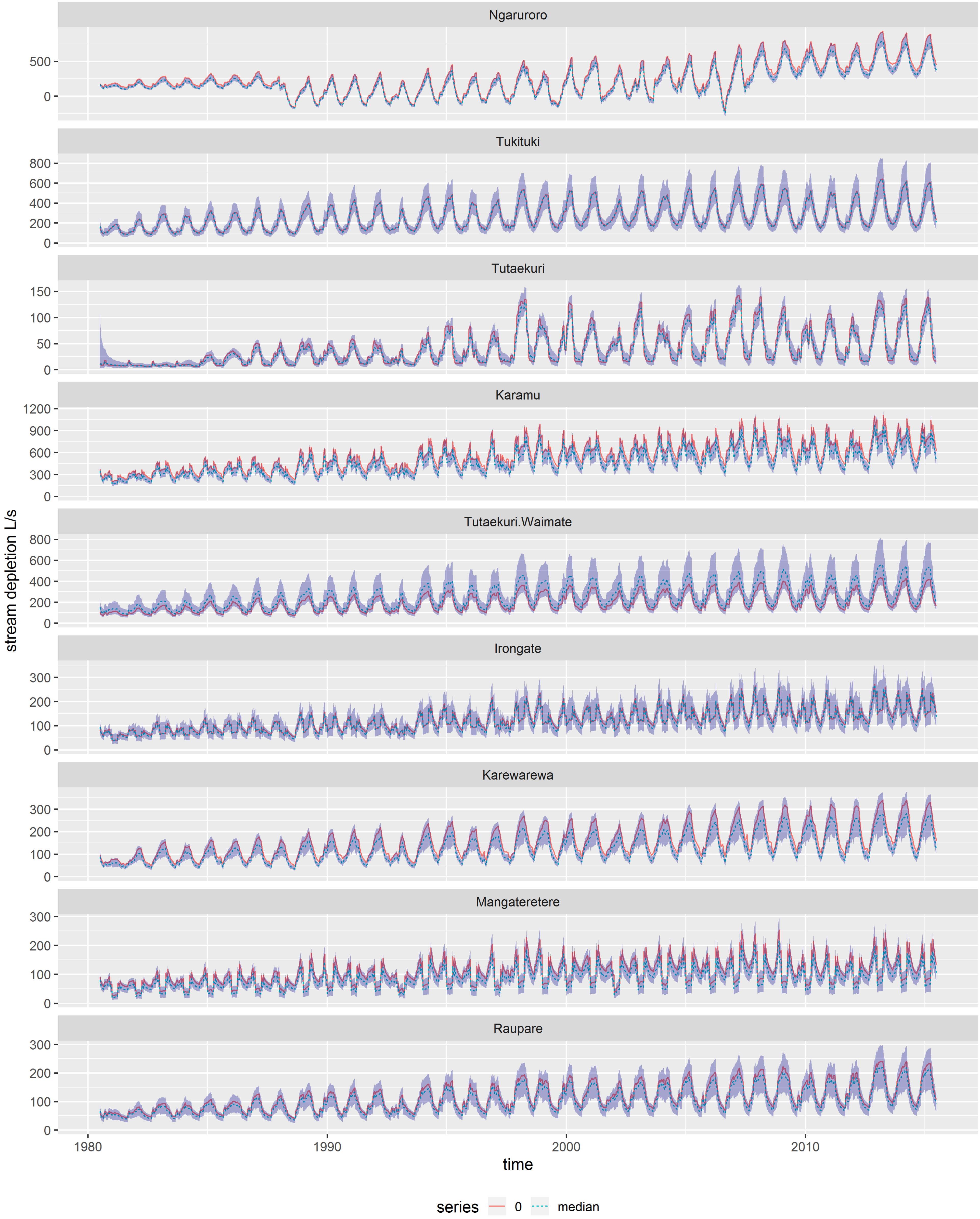

Figure 6-3: Historical scenario M3 uncertainty results – stream depletion 1980-2015. Blue shading indicates results between 5th and 95th percentiles. Dashed blue series "median" represents median prediction. Red series "0" represents originally reported calibrated result.

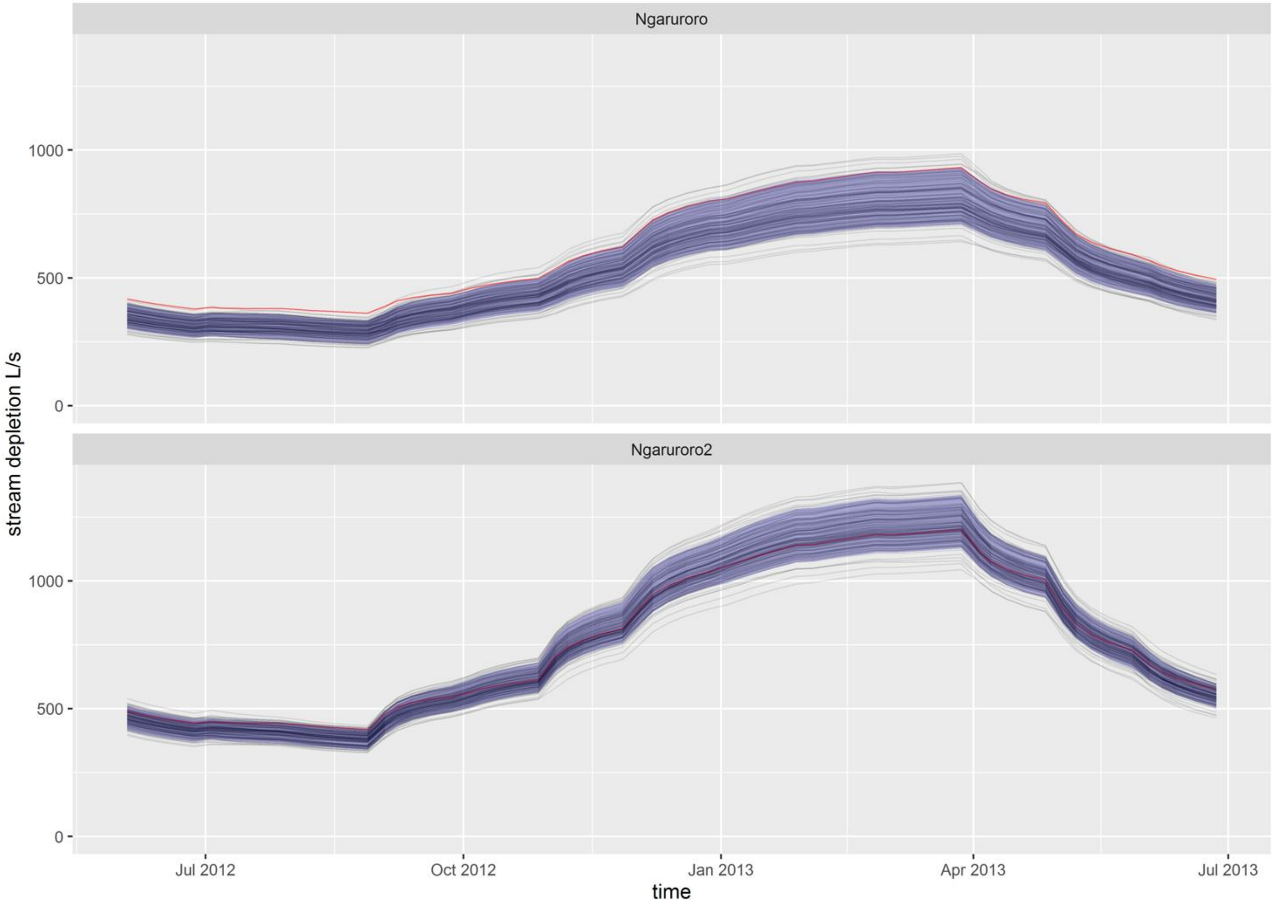

Figure 6-4: Historical scenario M3 uncertainty results – stream depletion in dry year 2012-2013. Blue shading indicates results between 5th and 95th percentiles. Red series "0" represents originally reported calibrated result. Grey lines represent other 107 realisations. Ngaruroro (top chart) refers to Ngaruroro at Fern Hill, Ngaruror2 includes variable loss section of Ngaruroro between Fernhill and confluence with Tūtaekurī-Waimate, but excludes Tūtaekurī-Waimate.

Table 6-1: Statistics for stream depletion for March 2013 for all realisations. The coefficient of variance is calculated by dividing the standard deviation by the mean. Ngaruroro represents Ngaruroro at Fernhill

	Ngaruroro	**Tukituki**	**Tūtaekurī**	**Karamu**	**Tūtaekurī -Waimate**	**Irongate**	**Karewarewa**	**Mangateretere**	**Raupare**	**All zones**
max	985.7	992.3	168.3	1069.6	1132.5	509.9	497.4	381.2	456.8	3869.2
min	641.7	232.4	92.1	529.8	265.1	99.4	160.6	34.7	116.4	3095.7
median	792.7	630.3	115.7	723.6	548.3	171.0	278.7	70.2	219.2	3497.3
mean	808.4	627.7	120.6	734.8	559.2	182.6	276.4	79.6	223.6	3495.7
percentile 95	931.2	846.5	148.2	906.8	799.5	292.3	375.2	122.9	297.3	3694.9
percentile 05	711.5	443.2	100.1	601.5	360.1	108.9	182.3	41.8	145.3	3280.8
percentile 75	854.4	706.4	133.6	792.9	625.7	209.9	316.7	92.5	250.0	3584.6
percentile 25	759.5	534.0	109.8	663.9	455.1	150.1	227.4	54.4	193.0	3404.9
standard deviation	72.2	130.0	15.6	99.9	144.6	59.1	62.2	46.4	49.8	129.3
total range	344.0	759.9	76.2	539.8	867.3	410.5	336.8	346.6	340.4	773.4
90 percentile range	219.7	403.3	48.1	305.2	439.3	183.4	192.9	81.1	152.0	414.1
interquartile range	95.0	172.4	23.9	129.0	170.6	59.8	89.3	38.1	57.0	179.6
%total range	43%	121%	63%	73%	155%	225%	122%	435%	152%	22%
% 90 percentile range	27%	64%	40%	42%	79%	100%	70%	102%	68%	12%
% interquartile	**12%**	**27%**	**20%**	**18%**	**31%**	**33%**	**32%**	**48%**	**25%**	**5%**
% coefficient of variation	9%	21%	13%	14%	26%	32%	23%	58%	22%	4%

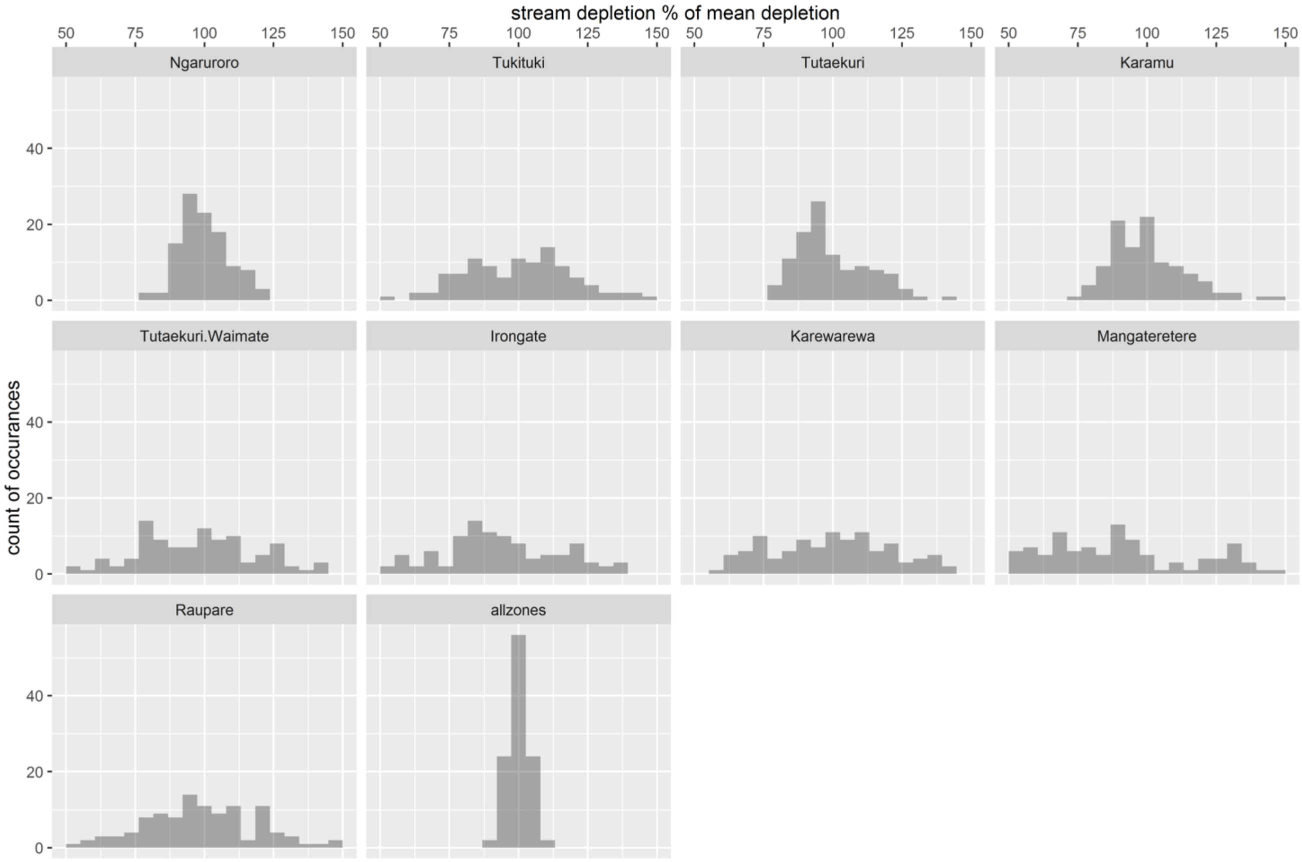

Figure 6-5: Histograms of relative stream depletion between in March 2013 for each river. Relative stream depletion is defined as a ratio of stream depletion and mean stream depletion for all realisations for each river. Wide histograms (e.g. Karewarewa) indicate large differences between realisations, narrow histograms (e.g. for all zones) indicate little difference between realisations. All zones indicate net stream depletion in the entire model domain. X-axis is truncated at 50% and 150%, so extreme results are not shown.

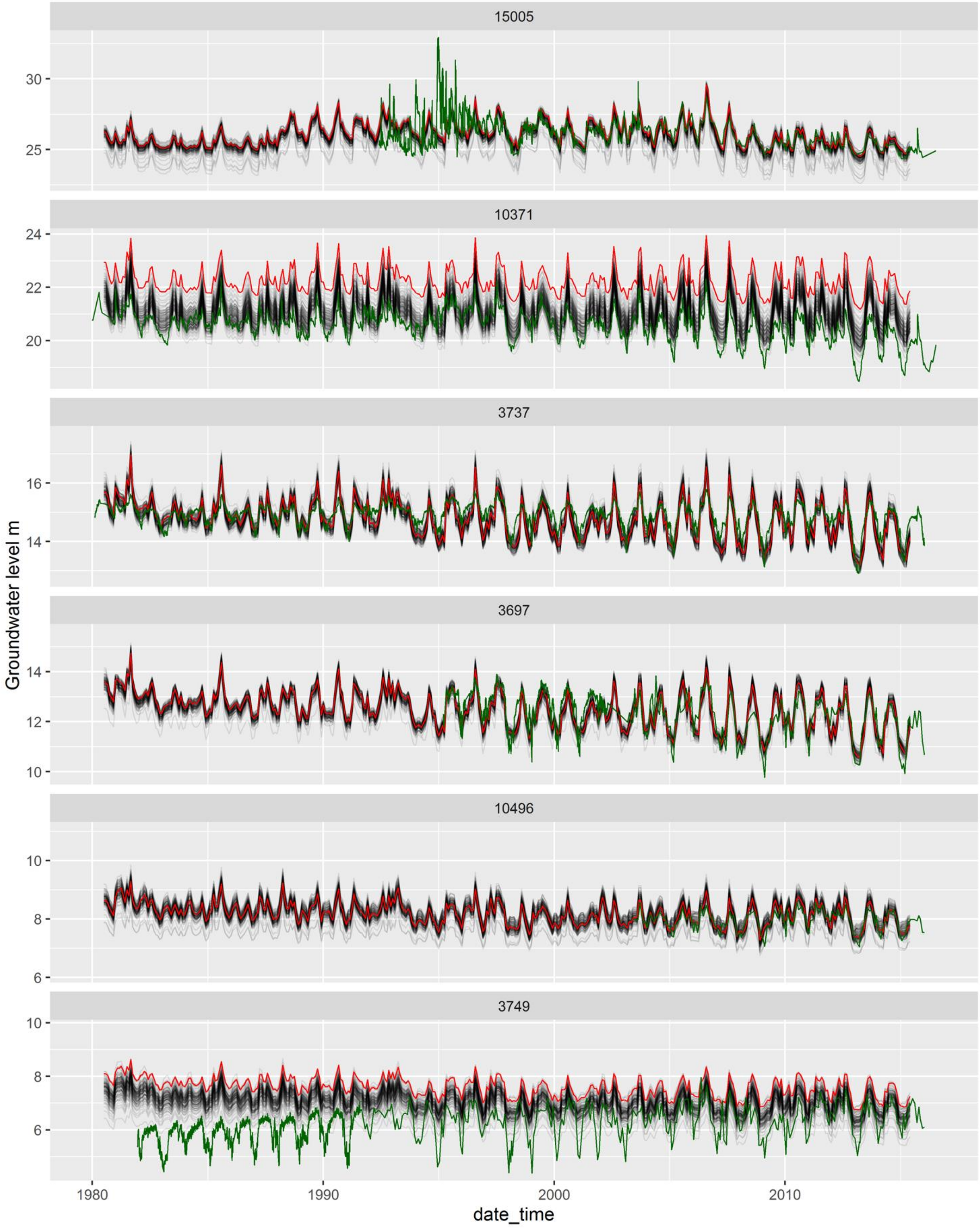

Figure 6-6: Selected groundwater for each realisation, part 1. Red represents original predictions. Green represents observed values.

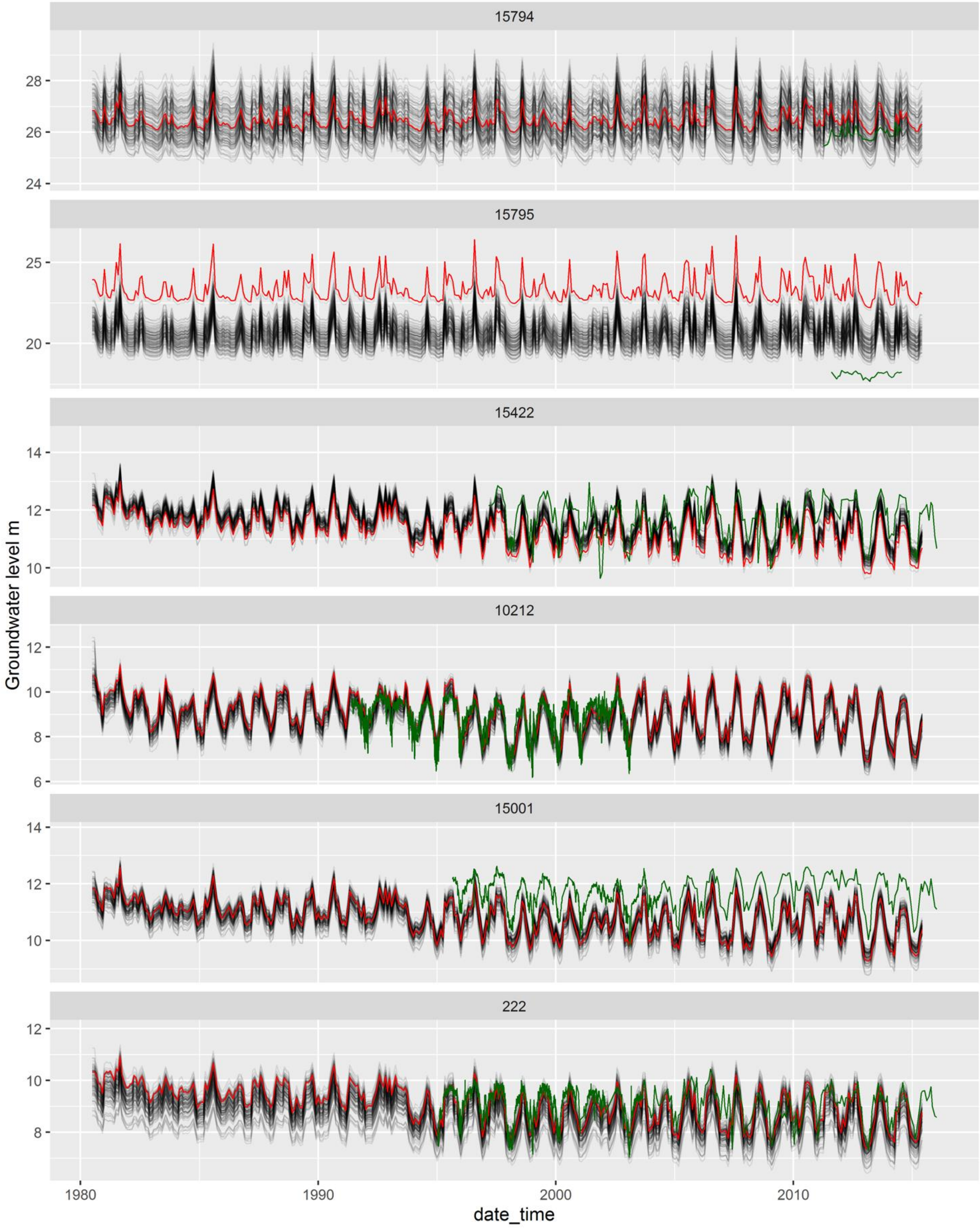

Figure 6-7: Selected groundwater for realisations part 2. Red represents original predictions. Green represents observed values.

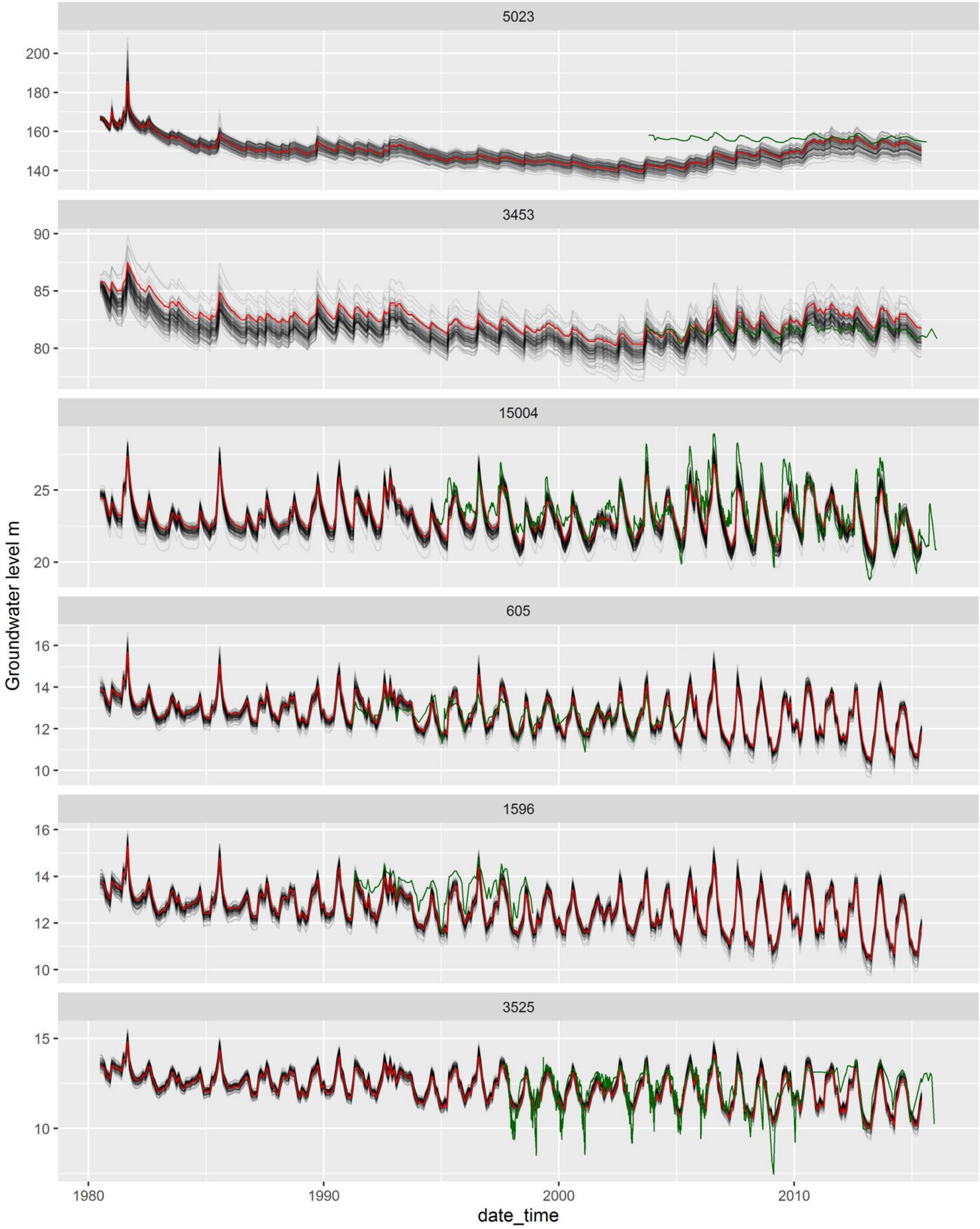

Figure 6-8: Selected groundwater for realisations part 3. Red represents original predictions. Green represents observed values.

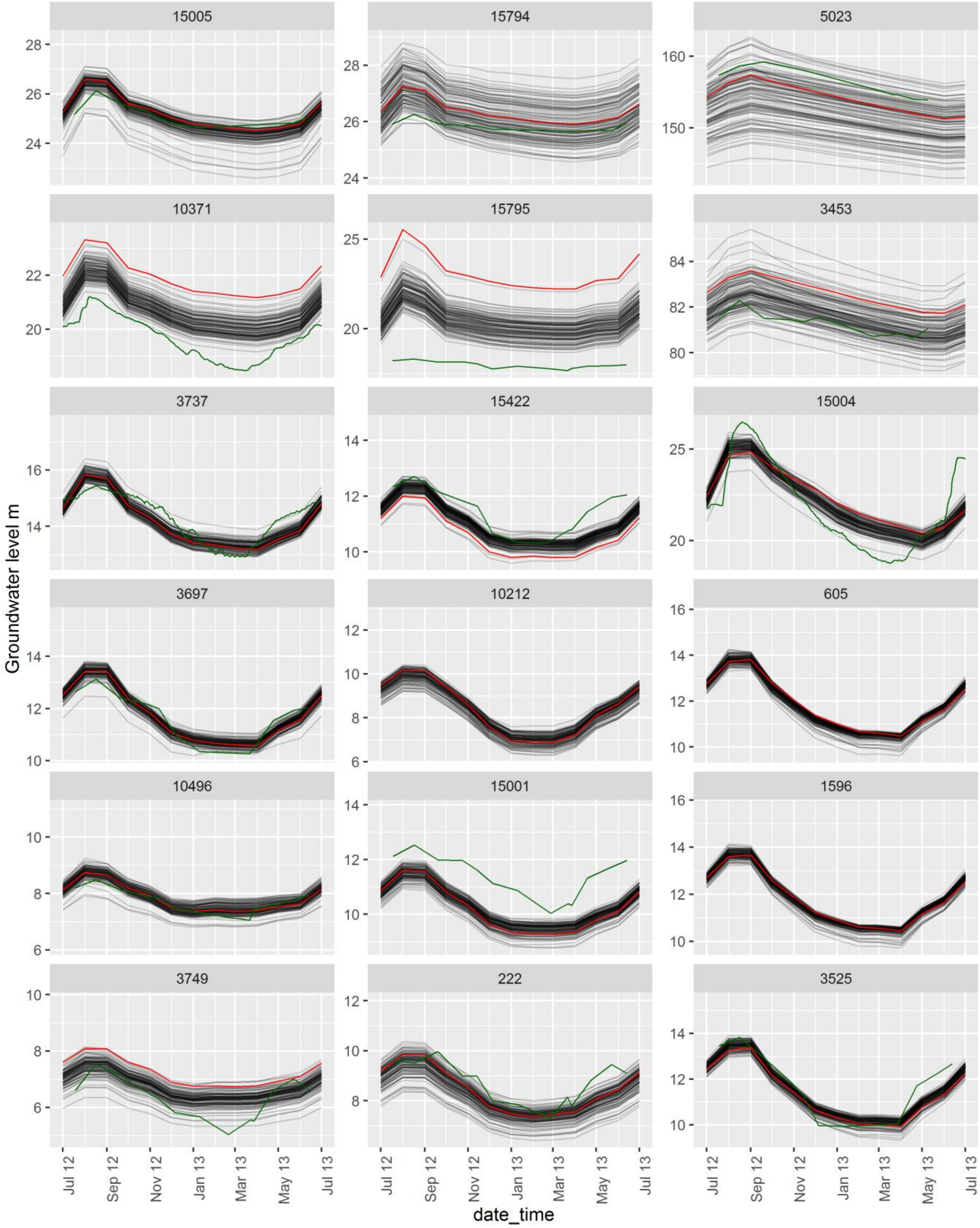

Figure 6-9: Selected groundwater levels for realisations in 2012-2013 Red represents original predictions. Green represents observed values.

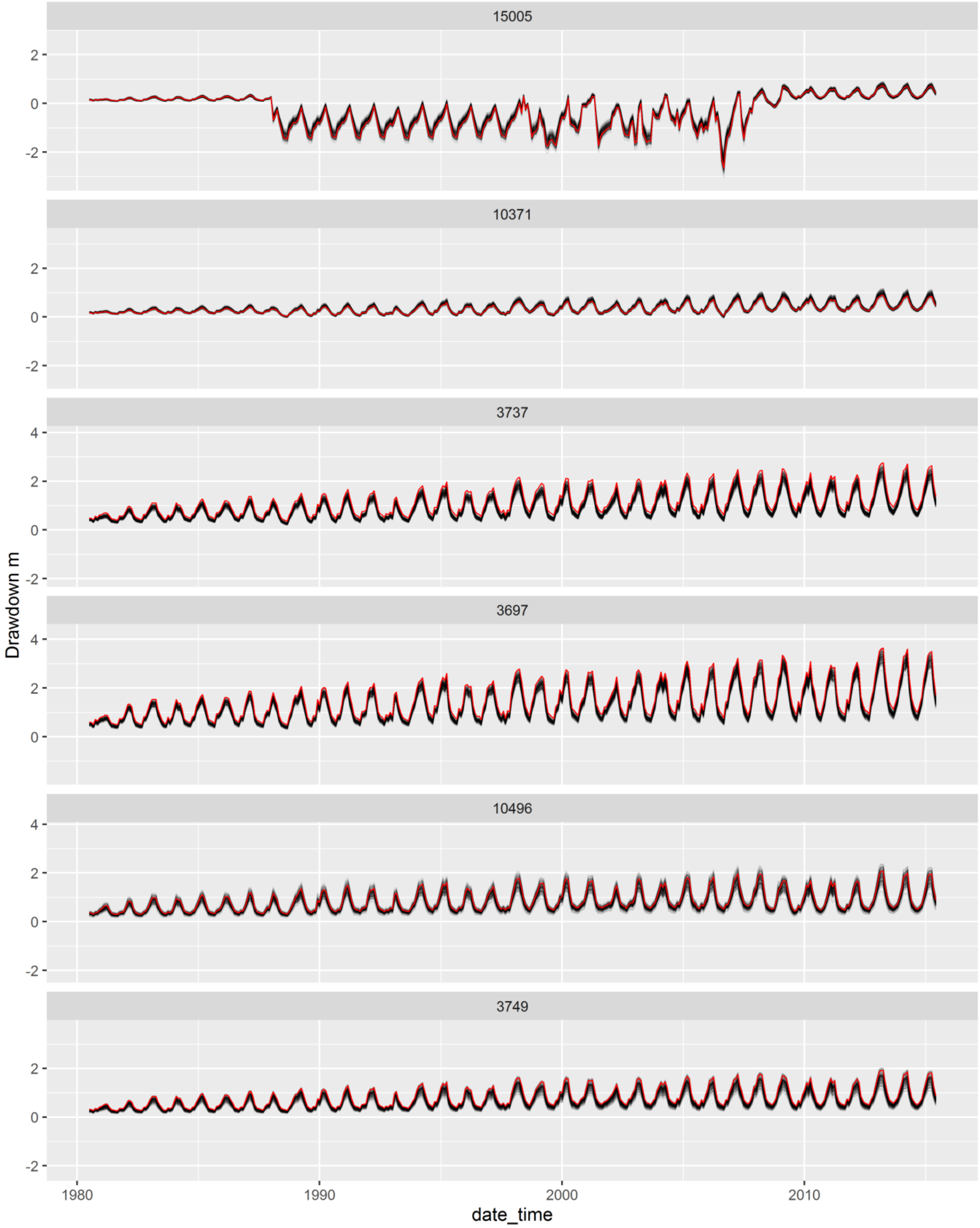

Figure 6-10: Drawdown in selected locations for realisations part 1. Red represents original predictions.

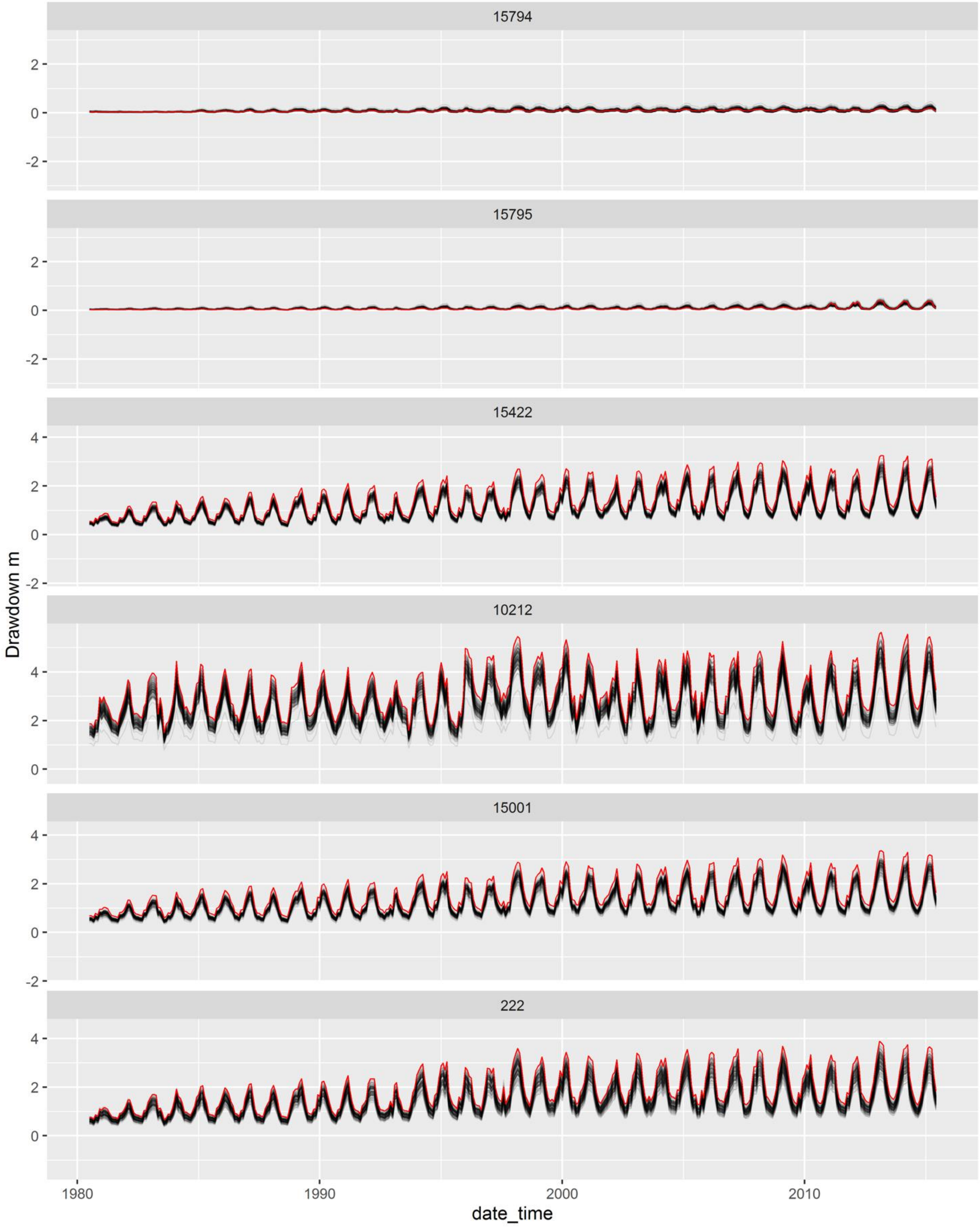

Figure 6-11: Drawdown in selected locations for realisations part 2. Red represents original predictions.

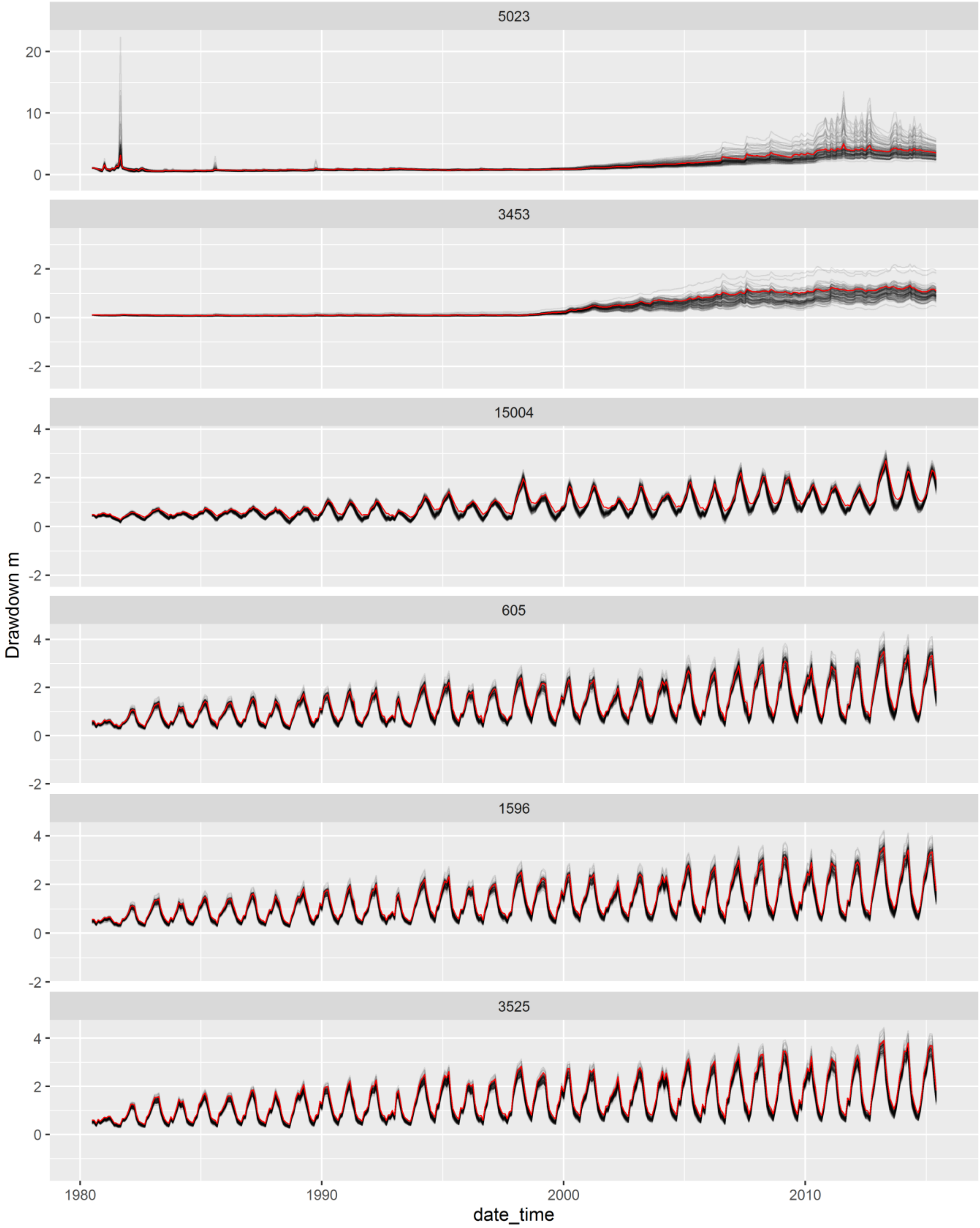

Figure 6-12: Drawdown in selected locations for realisations part 3. Red represents original predictions.

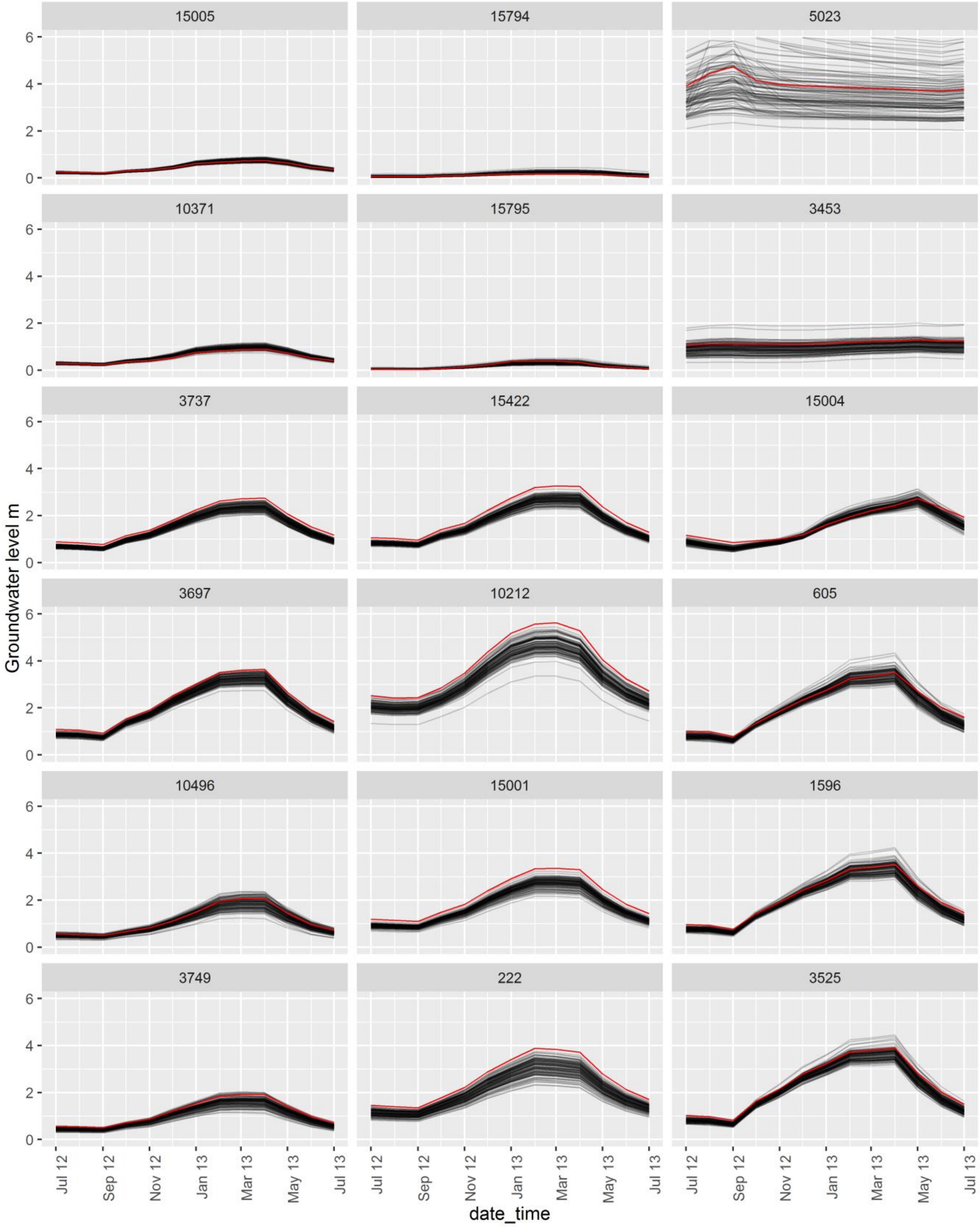

Figure 6-13: Drawdown in selected locations for realisations in 2012-2013. Red represents original predictions.

Table 6-2: Head and Drawdown statistics for March 2013 for all realisations.

Head																		
bore	**15005**	**10371**	**3737**	**3697**	**10496**	**3749**	**15794**	**15795**	**15422**	**10212**	**15001**	**222**	**5023**	**3453**	**15004**	**605**	**1596**	**3525**
max	24.9	21.2	13.9	11.0	7.8	6.9	27.5	22.2	10.7	7.9	9.9	8.2	157.3	83.2	20.9	10.6	10.6	10.4
min	22.6	19.2	12.9	10.3	6.9	5.4	24.6	18.7	9.7	6.6	8.8	6.5	143.7	79.4	19.2	9.6	9.7	9.3
median	24.4	20.0	13.3	10.6	7.4	6.3	25.8	19.9	10.3	7.3	9.5	7.5	151.4	81.0	20.3	10.4	10.5	10.1
mean	24.3	20.0	13.3	10.6	7.4	6.3	25.8	19.9	10.3	7.3	9.5	7.5	151.1	81.1	20.3	10.4	10.4	10.1
percentile 95	24.7	20.6	13.5	10.9	7.8	6.7	26.9	20.9	10.5	7.7	9.7	7.9	155.5	82.1	20.8	10.6	10.6	10.3
percentile 05	23.9	19.6	13.0	10.4	7.2	5.9	24.9	18.9	10.0	6.8	9.1	6.9	146.6	80.2	19.9	10.0	10.0	9.7
percentile 75	24.5	20.2	13.4	10.7	7.6	6.5	26.4	20.2	10.4	7.5	9.6	7.7	153.2	81.5	20.6	10.5	10.5	10.2
percentile 25	24.2	19.7	13.2	10.5	7.3	6.2	25.4	19.4	10.2	7.1	9.4	7.3	149.3	80.7	20.1	10.4	10.4	9.9
standard deviation	0.4	0.4	0.2	0.2	0.2	0.3	0.6	0.6	0.2	0.3	0.2	0.3	2.9	0.6	0.3	0.2	0.2	0.2
total range	2.3	2.0	1.0	0.8	1.0	1.6	3.0	3.5	1.0	1.3	1.1	1.7	13.6	3.8	1.7	1.0	0.9	1.1
90 percentile range	0.9	1.0	0.6	0.5	0.6	0.8	2.0	1.9	0.5	0.8	0.6	0.9	9.0	2.0	1.0	0.6	0.6	0.6
interquartile range	0.3	0.5	0.3	0.2	0.3	0.3	1.0	0.8	0.2	0.4	0.3	0.4	4.0	0.8	0.4	0.1	0.1	0.3
%total range	10%	10%	7%	7%	13%	25%	11%	18%	10%	18%	11%	22%	9%	5%	9%	10%	9%	11%
% 90 percentile range	4%	5%	4%	5%	8%	13%	8%	10%	5%	11%	7%	13%	6%	2%	5%	6%	6%	6%
% interquartile	1%	2%	2%	2%	4%	5%	4%	4%	2%	5%	3%	5%	3%	1%	2%	1%	1%	3%
% coefficient of variation	1%	2%	1%	1%	3%	4%	2%	3%	2%	4%	2%	4%	2%	1%	2%	2%	2%	2%

Drawdown

bore	**15005**	**10371**	**3737**	**3697**	**10496**	**3749**	**15794**	**15795**	**15422**	**10212**	**15001**	**222**	**5023**	**3453**	**15004**	**605**	**1596**	**3525**
max	0.90	1.18	2.75	3.65	2.36	2.00	0.44	0.50	3.25	5.29	3.30	3.72	7.13	1.97	2.85	4.34	4.24	4.45
min	0.62	0.75	2.03	2.73	1.21	1.11	0.13	0.19	2.26	3.14	2.11	2.20	2.07	0.52	2.13	2.92	2.89	3.20
median	0.76	0.98	2.37	3.27	1.88	1.63	0.22	0.30	2.68	4.40	2.69	2.96	3.42	1.07	2.41	3.42	3.39	3.66
mean	0.76	0.98	2.36	3.27	1.87	1.61	0.23	0.30	2.67	4.42	2.68	2.95	3.66	1.07	2.42	3.42	3.39	3.66
percentile 95	0.87	1.13	2.61	3.57	2.26	1.94	0.33	0.40	2.93	4.94	2.97	3.40	5.63	1.36	2.68	3.81	3.76	4.03
percentile 05	0.66	0.86	2.13	2.99	1.51	1.26	0.16	0.22	2.35	3.95	2.29	2.41	2.50	0.77	2.21	3.06	3.04	3.32
percentile 75	0.81	1.03	2.47	3.41	2.04	1.73	0.26	0.34	2.81	4.66	2.82	3.18	4.07	1.19	2.51	3.60	3.56	3.80
percentile 25	0.72	0.92	2.26	3.13	1.68	1.47	0.19	0.26	2.56	4.20	2.56	2.73	3.02	0.94	2.31	3.22	3.18	3.47
standard deviation	0.06	0.08	0.15	0.19	0.24	0.19	0.05	0.06	0.19	0.33	0.21	0.31	0.98	0.22	0.14	0.26	0.25	0.24
total range	0.28	0.43	0.72	0.92	1.15	0.89	0.31	0.31	0.99	2.15	1.19	1.51	5.06	1.46	0.72	1.42	1.34	1.26
90 percentile range	0.21	0.26	0.48	0.58	0.76	0.67	0.16	0.18	0.58	0.99	0.67	0.99	3.13	0.59	0.46	0.75	0.72	0.71
interquartile range	0.09	0.12	0.21	0.28	0.36	0.25	0.07	0.07	0.25	0.45	0.26	0.45	1.04	0.26	0.20	0.37	0.39	0.32
%total range	36%	44%	30%	28%	61%	55%	136%	102%	37%	49%	44%	51%	138%	136%	30%	42%	40%	34%
% 90 percentile range	27%	27%	20%	18%	40%	42%	72%	60%	22%	22%	25%	34%	85%	55%	19%	22%	21%	19%
% interquartile	12%	12%	9%	9%	19%	16%	28%	24%	9%	10%	10%	15%	29%	24%	8%	11%	11%	9%
% coefficient of variation	8%	9%	6%	6%	13%	12%	23%	19%	7%	7%	8%	11%	27%	20%	6%	8%	7%	7%

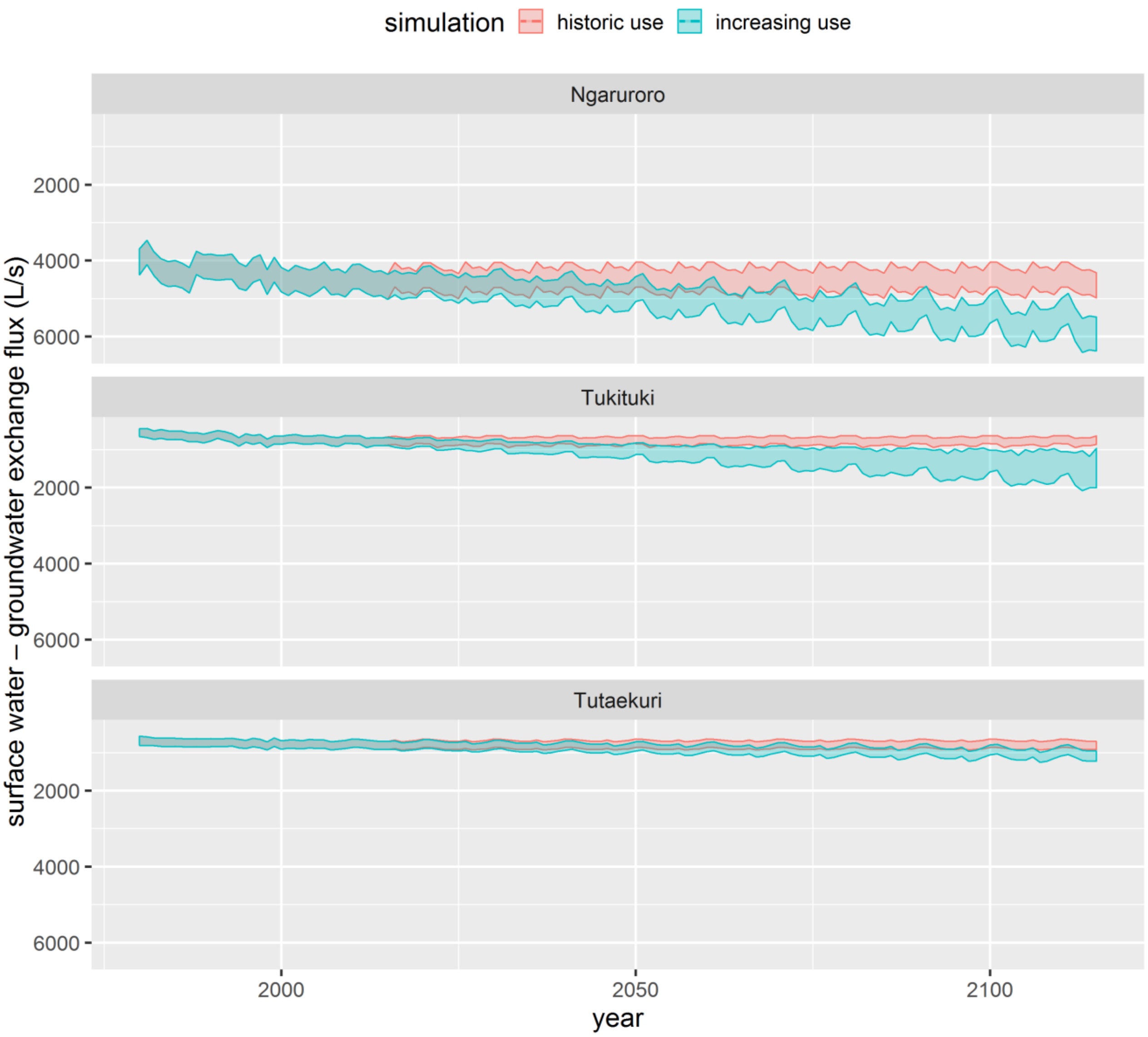

Figure 6-14: Surface water - groundwater exchange flux for all realisations for 100 years simulation for major rivers. Showing "historical use" and "increasing use" simulations. Dashed line represents original prediction. Shading represents 5th and 95th percentile of predictions.

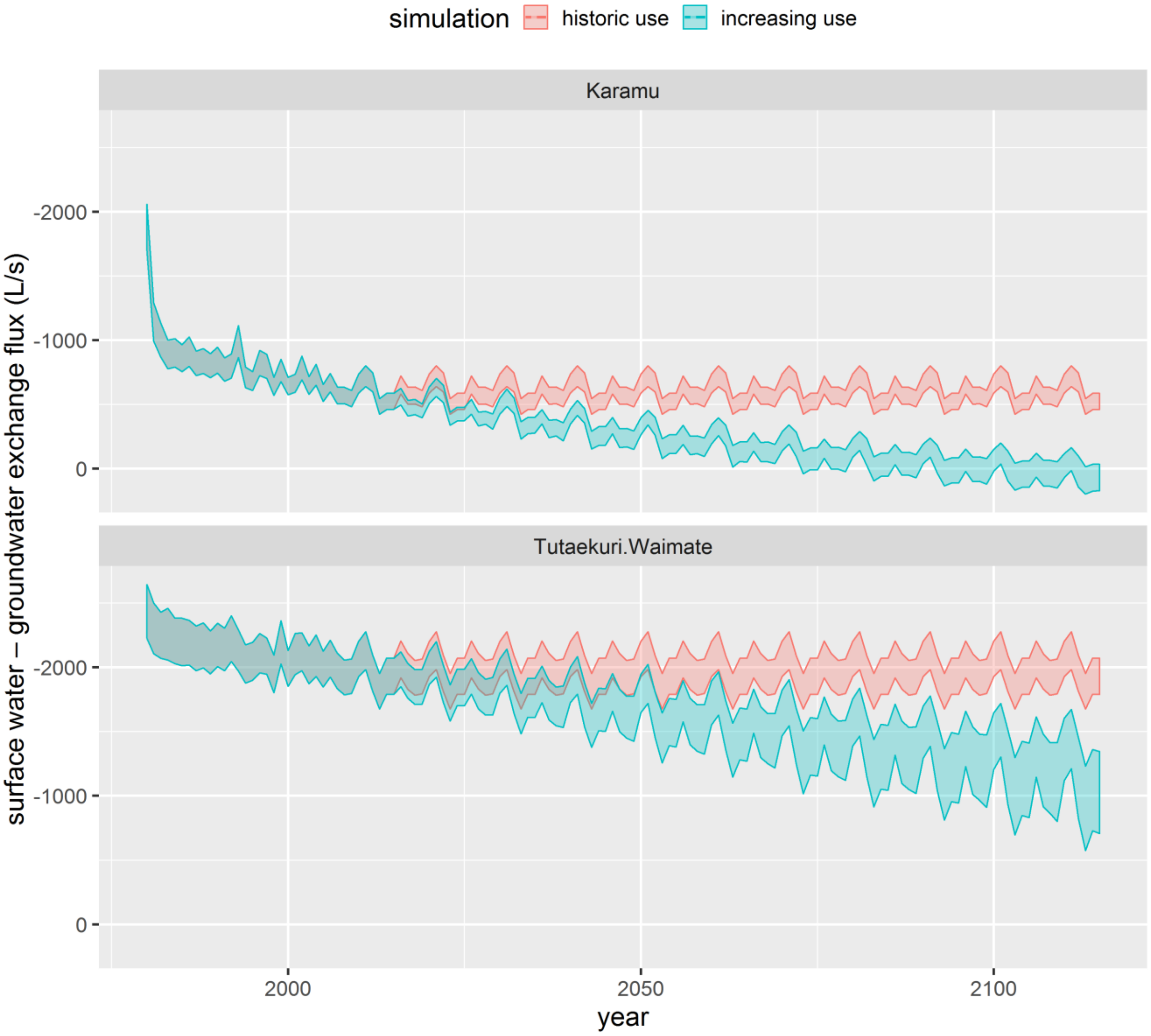

Figure 6-15: Surface water - groundwater exchange flux for all realisations for 100 years simulation for large springs. Showing "historical use" and "increasing use" simulations. Dashed line represents original prediction. Shading represents 5th and 95th percentile of predictions.

Figure 6-16: Surface water - groundwater exchange flux for all realisation for 100 years simulation for small springs. Showing "historical use" and "increasing use" simulations. Dashed line represents original prediction. Shading represents 5th and 95th percentile of predictions.

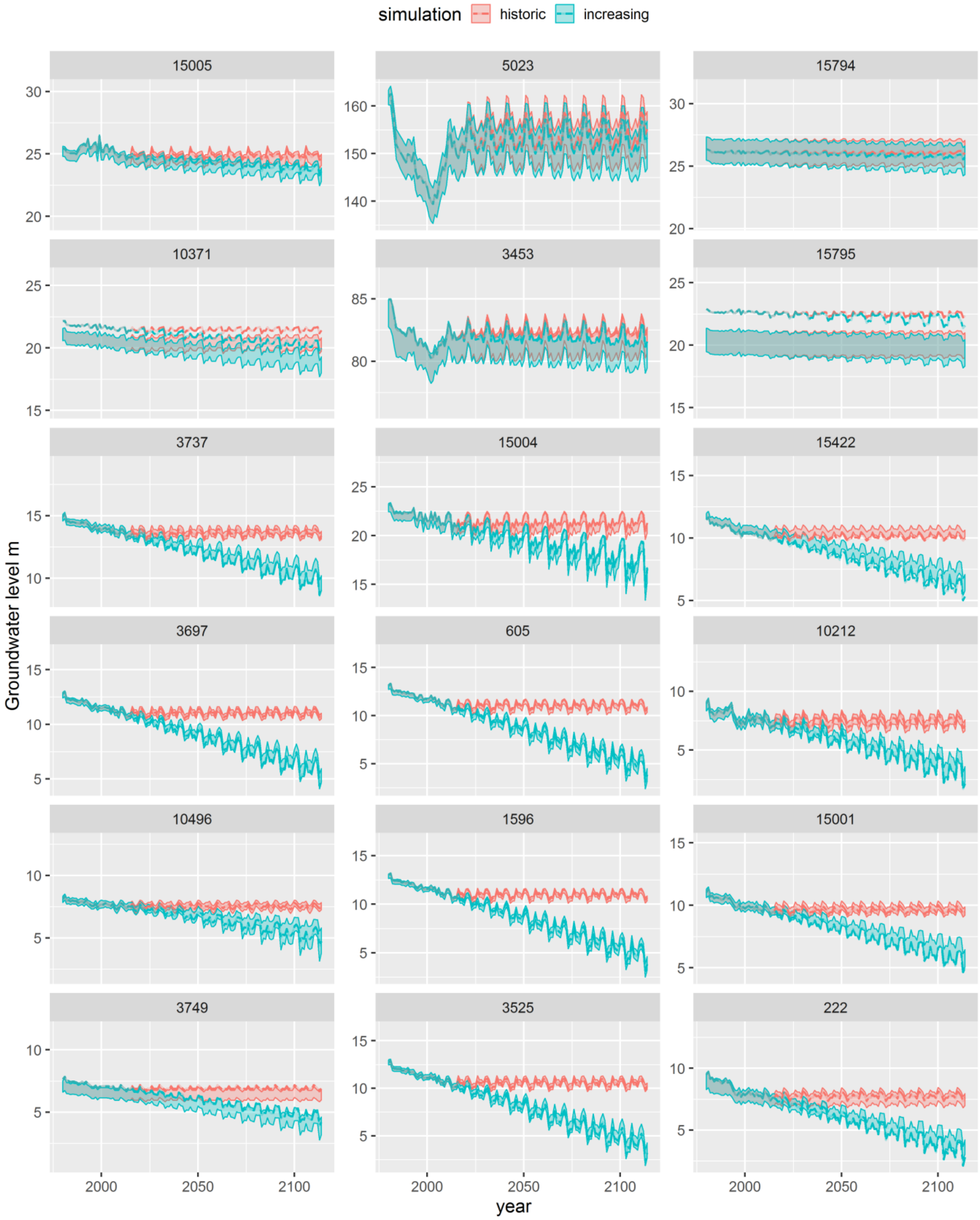

Figure 6-17: Groundwater levels for future scenarios for all realisations part. Dashed line represents original prediction. Only minimum value shown in each year. Shading represents levels between 5th and 95th intervals.

7 Acknowledgements

Many people and organisation have contributed to this study. All published publications relied on in this report are referenced, but there are also a number of people who contributed to the study, but are not mentioned in the list of authors.

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Thanks to HBRC scientists Simon Harper, Rob Waldron, Thomas Wilding for their valuable input in data preparation and advice on Heretaunga Plains hydrology with special thanks to Jeff Smith for management and technical overview of the project.

8 Glossary of abbreviations and terms

term or abbreviation	description
abstraction	Pumping of groundwater from the aquifer.
artesian aquifer	A confined aquifer containing groundwater under positive pressure. This causes the water level in a well to rise to a point where hydrostatic equilibrium has been reached. A well drilled into such an aquifer is called an artesian well. If water reaches the ground surface under the natural pressure of the aquifer, the well is called a flowing artesian well.
confined aquifer	see artesian aquifer
drawdown	The reduction in hydraulic head observed at a well in an aquifer, typically due to pumping.
GW	groundwater
HBRC	Hawke's Bay Regional Council
IRRICALC	Irrigation demand and recharge model.
LSR	Land Surface Recharge
MAR	Managed Aquifer Recharge - an intentional and controlled recharge (e.g. through injection pumping or recharge pit) of water into the aquifer
MODFLOW	Groundwater modelling software

Monte Carlo method	a type of computational algorithm that rely on repeated random sampling to obtain numerical results.
PEST	Parameter Estimation software
Pumping Ban	are a method that is used s a mitigation measure to maintain river flow during low flow periods, by banning pumping of water (e.g from the aquifer or river) when river flow drpots below prescribed threshold
recharge	Recharge is precipitation, river bed seepage, flooding and other natural forms of water that enter the groundwater system.
SOURCE	Surface water modelling software
Spring	A location where water flows naturally from an aquifer to the Earth's surface.
Stream Augmentation	a strategy that involves pumping groundwater from the aquifer and discharging it to the stream to supplement streamflow
TANK	Tutaekuri, Ahuriri, Ngaruroro and Karamu Rivers' catchment.
Unconfined aquifer	An aquifer whose upper water surface (water table) is at atmospheric pressure, and thus is able to rise and fall.
Well	An structure created in the ground by digging, driving, boring, or drilling to access groundwater in underground aquifers.

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