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Assessing Groundwater Abstraction Scenarios with the Wairau Plain Surface Water – Groundwater Flow Model

Report [1053-08 R2]

Thomas Wöhling
Lincoln Agritech Ltd

30 June 2025

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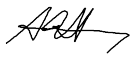
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DOCUMENT ACCEPTANCE

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1. EXECUTIVE SUMMARY

This report reviews the limit setting for the Wairau Aquifer groundwater resources as implemented in the Marlborough Environment Plan (MEP). The MEP specifies groundwater level and river flow thresholds for MDC groundwater monitoring sites and for Spring Creek. In addition, an annual allocation limit of 73 M m³ is implemented. The efficiency of these limits under different groundwater abstraction scenarios is investigated using the Wairau Plain surface water – groundwater model (WPM) which has been developed by Lincoln Agritech Ltd and TU Dresden. The simulation with 25 years of historic data shows a large inter-annual variability of groundwater storage (on average 16.5 M m³). Groundwater abstraction varies significantly between years; however, in 90% of the monitored years from 2000 to 2024, the actual abstraction is less than 30% of the annual allocation limit.

Model scenarios with 60% and 100% of the MEP limit showed a strong effect on storage during the summer months, with up to 8 M m³ additional storage variation compared to current conditions. Under the full MEP abstraction scenario, MEP threshold levels will be transgressed for up to two months each year. In contrast to MEP river allocation regimes to manage seasonal extremes of river flow, fixed thresholds are not an effective means of managing extremes of Wairau Aquifer groundwater storage. The modelling work conducted for this report indicates that the threshold levels in the MEP should be replaced and the annual allocation limit should be reduced.

The low-point of aquifer storage in a given year is dependent on several factors. The main drivers are antecedent storage during the previous winter, the number of days with river flow below 20 m³/s, land-surface recharge and groundwater abstraction demand. In the summer of 2024, compounding effects of low aquifer storage at the begin of the season combined with extended periods of low river flows, low land-surface recharge and high groundwater abstraction were identified as the main factors leading to record-low aquifer storage.

The groundwater system of the Wairau Plains is not in a state of equilibrium. In this sense, the scenario simulations conducted for this report represent “best-case” situations. Historic trends of declining groundwater levels and spring flows are likely to continue, further increasing the challenge to achieve environmental and cultural management goals, such as maintaining spring flows in the Blenheim region. Other factors such as changes in hydro-climatic extremes and long-term conditions (including climate change) as well as changes in land-use towards more water-demanding crops will add to the adverse effects, but were not considered in this report.

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2. OBJECTIVES

The objectives of the work are as follows (copied from MDCs modelling brief):

1. *To run simulations with the Wairau Plain Surface Water – Groundwater Flow Model (WPM) to test the sustainability of different levels of groundwater abstraction from the Wairau Aquifer up to the current MEP annual volumetric limit of 73 million m^3/year. Predicted effects on well levels at MEP monitoring wells and wells near the coast are described relative to current management thresholds.*

2. *Assuming sustainable aquifer storage is groundwater sitting above surface delineated by current MEP cut-off elevation thresholds, model simulations are evaluated with respect to whether the abstraction volume would meet demand of current land uses and municipal supply for a range of dry/wet years of the historic record. From this a "naturally available seasonal volume" representing the current state is derived.*

3. *The WPM is used to identify the minimum annual allocation/usage that is likely to generate intra-seasonal effects and exacerbates the current declining trend in Wairau Aquifer levels.*

4. *To assess the effects assuming a continuation of the trend in groundwater storage decline for ~30 years from now to when aquifer transmissivity/storage is less (under current abstraction conditions).*

5. *Run the WPM model to quantify level of usage under extremely dry conditions experienced in early 2024, and comment on how much of observed drawdown reflected low recharge versus high abstraction.*

The report is structured in five sections, each of which addresses one of the five objectives listed above.

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3. WPM MODFLOW MODEL SIMULATIONS

The purpose of the scenario simulations with the WPM model was to test the sustainability of different levels of groundwater abstraction from the Wairau Aquifer under the current Marlborough Environment Plan (MEP) with annual volumetric abstractions up to the current MEP limit of 73 million m³/year. In addition to the original tasks, a scenario was tested with no abstraction from the aquifer to assess the impact of current groundwater abstraction on groundwater levels in the aquifer. In preparation of the work, the WPM model underwent significant iterative conceptual development at Dresden University of Technology (TUD) (not contracted) to better capture the stream-groundwater interaction and groundwater contributions from the valleys of the Southern Hills (Taylor, Fairhall, Mills, Omaka Rivers). Although their contributions to the mass balance of the Wairau Aquifer are rather small, this development now provides more confidence and a closer fit to the large variability of observed groundwater levels in the Renwick and Athletic Park regions. The latest model version (Figure 1) and the scenario simulations were presented at the Hydrological Society Symposium in Blenheim on 26 November 2024. The WPM model simulations performed well in a benchmark study with five other model types, including Eigenmodels and Machine Learning models (Wöhling et al., 2025).

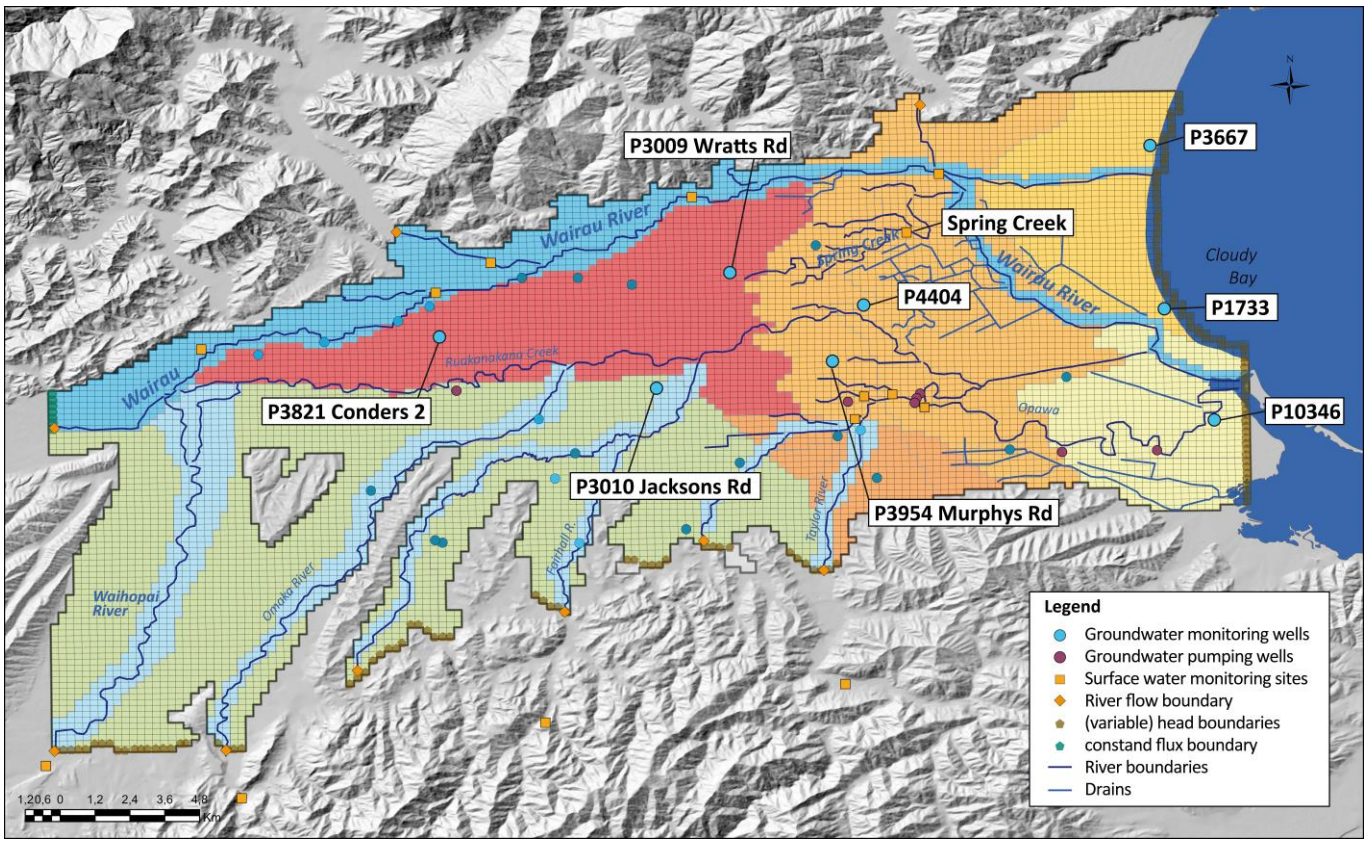


Figure 1: The Wairau Plain Aquifer MODFLOW model (WPM), reproduced from Wöhling et al. (2025, Supplemental Information).

The scenarios considered groundwater abstraction for irrigation, municipal abstraction, industrial abstraction and, additionally, a “basal use” that is associated with a year-round permitted water use. The irrigation abstraction under current conditions was computed by a spatially distributed daily soil water balance model that was calibrated in previous phases of the modelling work on metered data provided by MDC. Any data gaps were filled by regionalisation of daily abstraction values in space and time, conducted by TUD. Municipal and industrial abstraction are implemented as point abstractions in the model and incomplete meter records were filled and extended back in time by daily averages (thus maintaining seasonality).

The WPM model was calibrated for the time period 02/2014 - 02/2017 and extended for this work to the time period 01/2000 to 08/2024. Under current conditions, the total annual abstraction from the Wairau Aquifer for the years 2000 to 2024 is on average 18.1 M m³/year (Figure 2, top panel). Instead of using the average annual abstraction, the 90th

percentile of annual abstraction was used as a target for the model simulations. Under current conditions, this value is about 22.2 M m³/year (see base scenario, Figure 2 and Table 1) which accounts for approximately 30% of the annual MEP limit. This number represents an annual abstraction volume that is exceeded only once in ten years. In other words, if 22.2 M m³ would be the annual groundwater allocation limit, the reliability of meeting the abstraction demand in the past 23 hydrological years has been 90%. Conversely, in 10% of the years, that limit is transgressed (potentially requiring restrictions). Following this concept of reliability of supply, the annual variability of abstraction demand was maintained as observed under current conditions and factors are applied to scale-up the demand in the modelling scenarios.

As a result of conversations with MDC staff, four abstraction scenarios were considered. Scenario 1 is the base scenario that simulates current conditions (30% MEP limit). In scenario 2 and 3, current abstraction is scaled up to 60% and 100% of the MEP limit (73 M m³/year), respectively. In both scenarios, a constant rate of 0.2 m³/s (6.3 M m³/a) was added to all days of the year and evenly distributed across existing abstraction locations (Table 1). As for the base case scenario 1, the 60/100% MEP limits are reached or transgressed only in 10% of the years. The fourth scenario represents the natural state with no abstraction on the Wairau Plain.

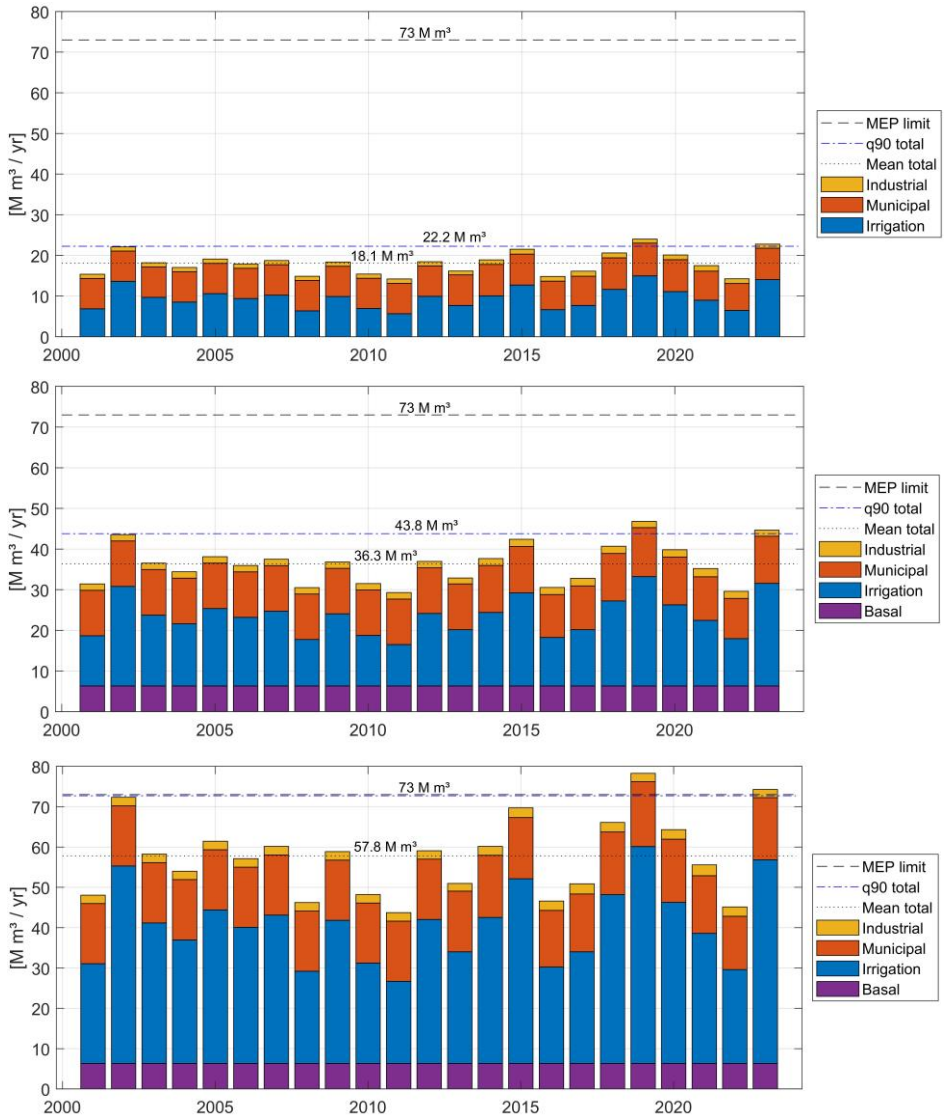


Figure 2: Annual sums of abstraction for the scenarios 1 (current conditions, 30% MEP), 2 (60% MEP) and 3 (100% MEP), respectively. The mean abstraction volumes and the 90% quantiles of annual abstraction are also shown. Note: abstractions are computed for hydrological yeas, not calendar years and the first year was omitted as warm-up period (initialization effects).

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Figure 2 shows the corresponding annual sums of groundwater abstraction for the simulation period (2000 – 2023) and the scenarios 1 – 3. To illustrate the seasonal and inter-annual variability of abstraction, the time-series of monthly aggregated abstraction is shown for the full-abstraction scenario in Figure 3 and monthly mean values in Figure 4.

Table 1: Abstraction volumes used for the WPM models scenarios

Groundwater abstraction	Scenario No.	Irrigation [M m³]	Municipal [M m³]	Industrial [M m³]	Basal use [M m³]	Total [M m³]	% of MEP
Base scenario	1	**13.7**	**7.5**	**1**	**0**	**22.2**	**30%**
60% allocation	2	24.7	11.2	1.5	6.3	43.8	60%
Full allocation	3	49.7	15	2	6.3	**73**	100%
No abstraction	4	0	0	0	0	0	0

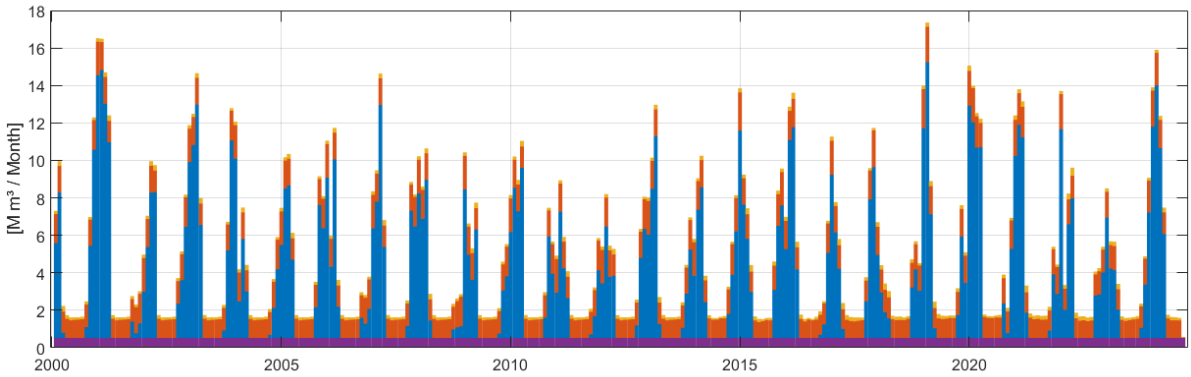


Figure 3: Variability of the monthly groundwater abstraction for the full allocation scenario 3.

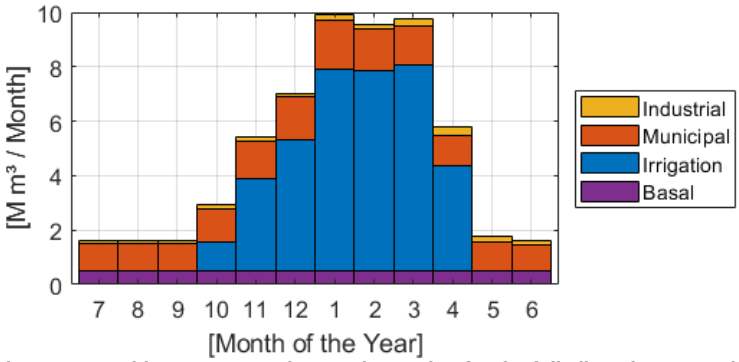


Figure 4: Monthly mean groundwater abstraction for the full allocation scenario 3.

Daily values of simulated groundwater levels in four predefined wells (P3821, P3009, P3954, P4404) and Spring Creek flows were evaluated for the scenarios 1 – 3. Resulting time-series of heads and flows are depicted in Figure 5. The wells and Spring Creek have fixed threshold levels defined in the MEP (except P3821), which are listed in Table 2 and depicted as dashed lines in the individual panels of Figure 5.

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The simulations clearly show the strong seasonality of groundwater levels with typical recessions in summer. It can also be seen that some MEP threshold levels are already transgressed for some years under current conditions (scenario 1). For the 60% and 100% abstraction scenarios, the MEP threshold levels are more frequently and more strongly transgressed. The strongest impact is observed for the spring-belt region, i.e. well P4404 and Spring Creek flows.

Table 2: **Cut-off levels as currently implemented in the Marlborough Environment Plan. [* unofficial value]**

Location	P3821	P3009	P4404	P3954	Spring Creek	P1733	P3667	P10346
Cut-off value	33.8 m*	11.8 m	6.1 m	6.5 m	2.6 m³/s	1.25 m	1.25 m	1.25 m

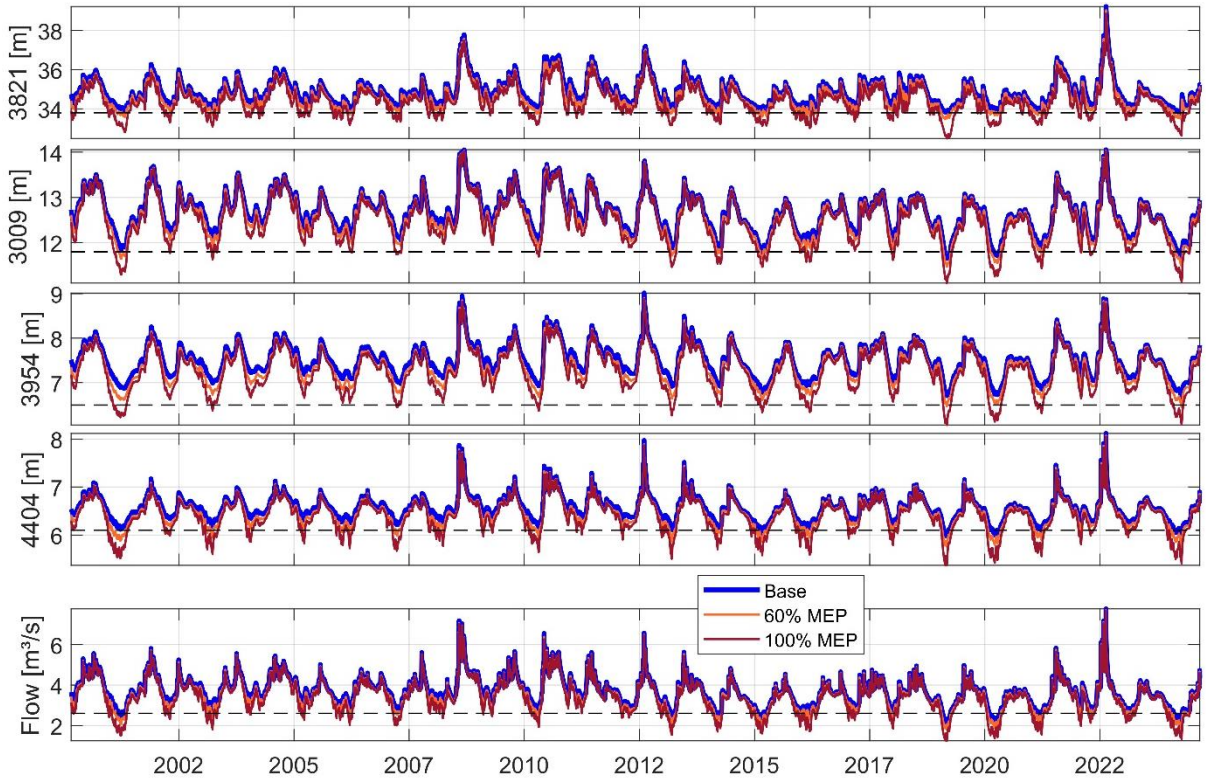


Figure 5: Simulated groundwater levels and Spring Creek flows for the model scenarios 1 - 3. Dashed lines depict the fixed threshold levels that are currently implemented in the MEP for these wells.

Figure 6 shows the differences of water levels compared to the base scenario for the observations in Table 2. The legend contains the maximum differences for the three scenarios: no abstraction, 60% MEP and 100% MEP. The full MEP abstraction scenario results in up to 1.5 m higher drawdown in the upper Wairau Plain region (well P3821) and has a lower effect at the coast (up to 0.23 m additional drawdown in well P10346). Spring Creek flows can be up to 1 m³/s less in this scenario.

Since the transgression of the threshold levels by the different scenarios is not easily seen in Figure 5, the data has been represented as exceedance probabilities in Figure 7. It shows for each scenario, the average number of days per year that a threshold has been transgressed. For example, the threshold of 6.1 m a.s.l. for well P4404 is transgressed under current conditions about six days in a year. Under the 60% MEP scenario, this would occur for 33 days, while under the 100% abstraction scenario, it would occur 73 days/year. Similar values were obtained for

Spring Creek flows. The least affected well is P3954 but this is only because the threshold has been set a bit higher compared to the average groundwater levels in well P4404.

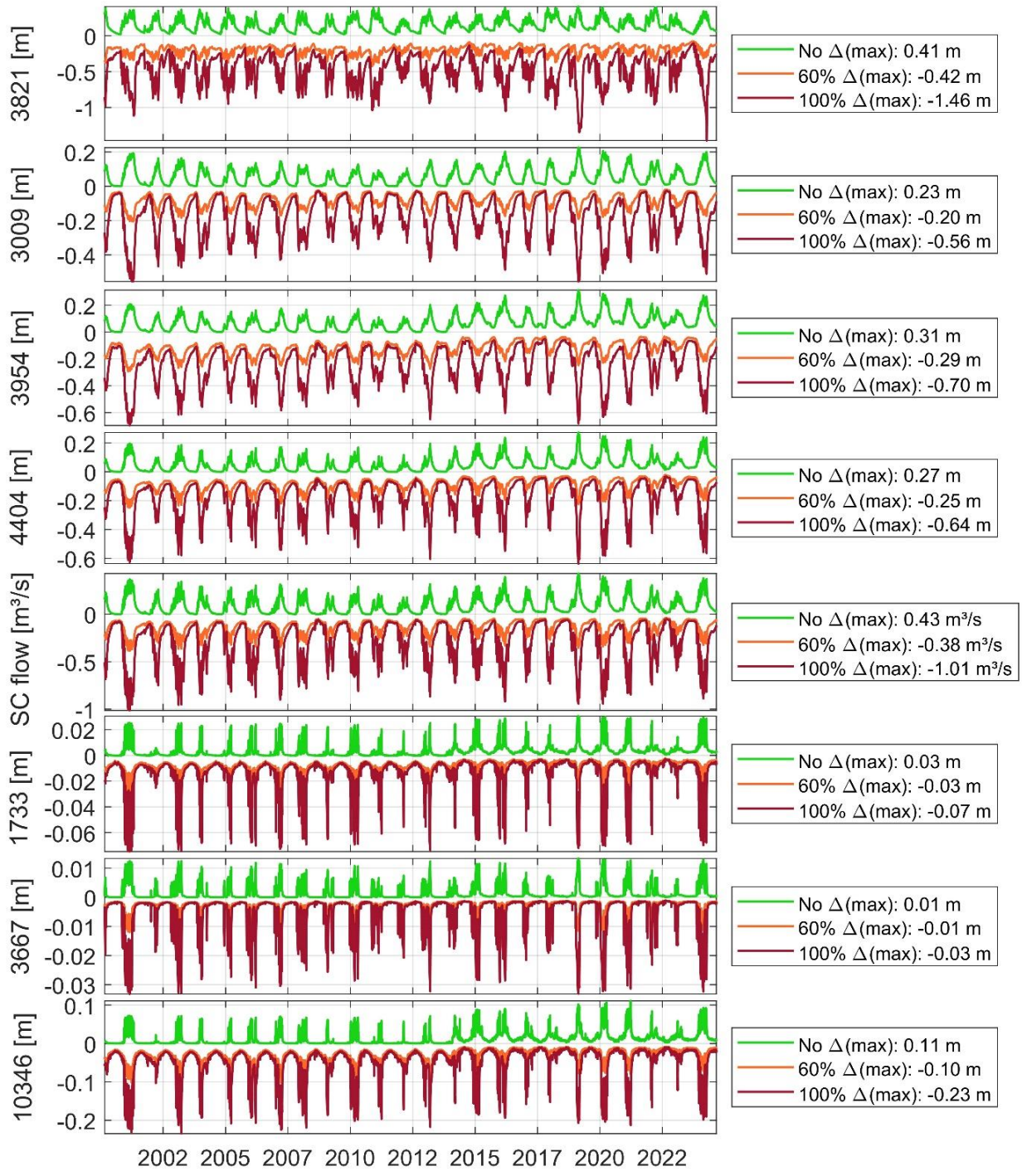


Figure 6: Differences of water levels and Spring Creek flows for the zero abstraction scenario (green), 60% MEP scenario (orange) and full MEP abstraction scenario (red) - compared to the base scenario (current conditions). The maximum differences in the time-series are recorded in the legend.

For comparison, the exceedance probabilities of the observed levels/flows are also shown in Figure 7 (black curve). If the black and the blue curves are matching, then the model simulates the observations well, including its extremes. This is the case for wells P4404, P3009 and Spring Creek flows. For wells P3821 and P3954 the low and high flow

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statistics also support this, which puts confidence in the estimated exceedance probabilities. Please note the shaded areas in the panels of Figure 7, which are the uncertainty bounds around the simulations under current conditions (blue) estimated by Null-Space Monte-Carlo simulation.

From this analysis it can be deducted that the fixed thresholds for the Wairau Aquifer in the MEP are not sustainable for future groundwater management. Even under current conditions, the thresholds are transgressed in years that are relatively dry. Additionally, groundwater levels have been declining for the past decades. If this trend continues, these thresholds will be exceeded more frequently. One could directly deduct this from Figure 7. For example, Wöhling et al. (2020) estimated the drop in well P3009 to be 3 cm/year. This would mean that under current abstraction conditions (i.e. no increase) the number of days with groundwater levels below the threshold would at least double in the next 10 years. A warming climate combined with more crop-water demand and increasing hydrological extremes, particularly extended summer-low flow conditions, would exacerbate the situation.

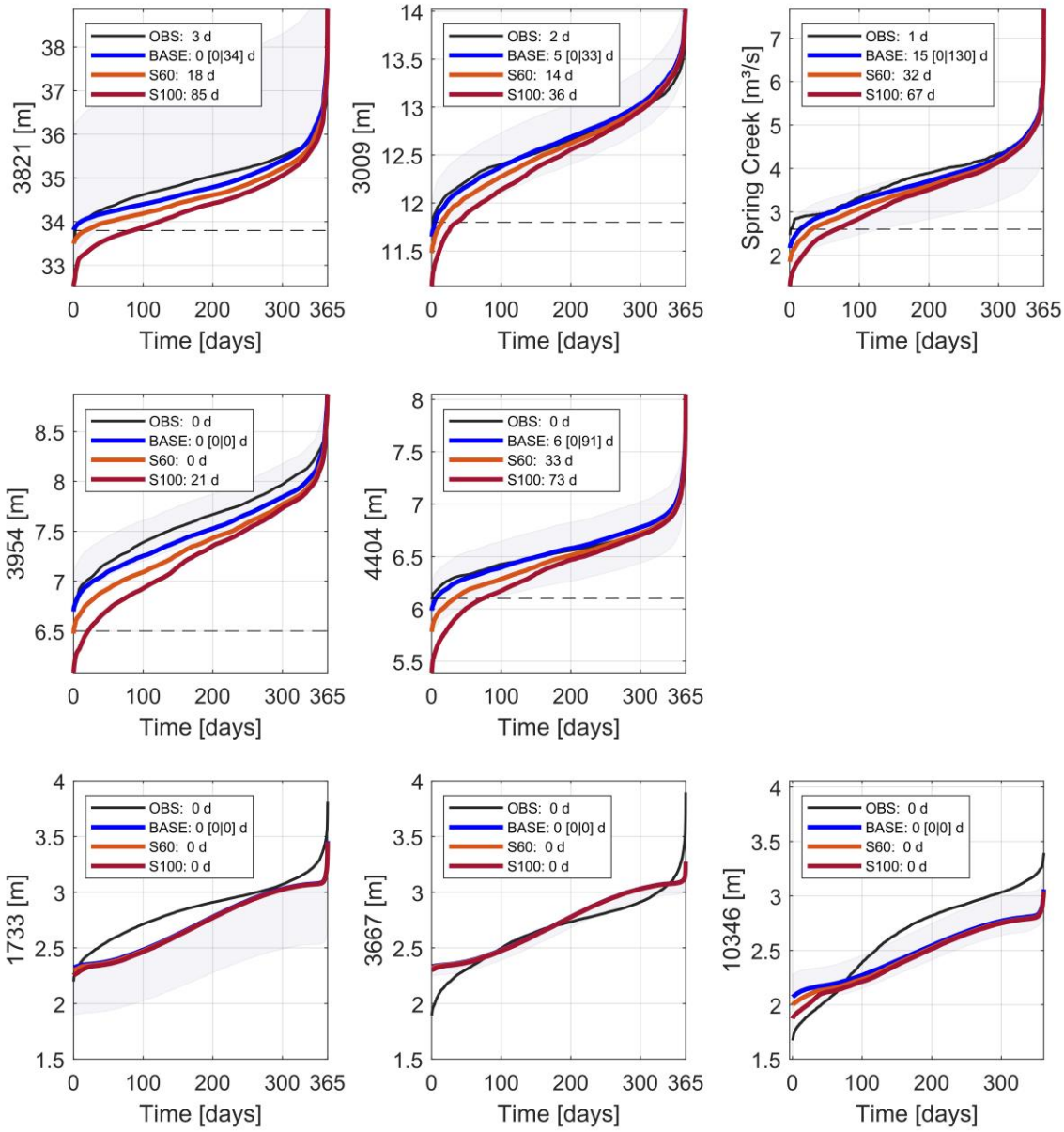


Figure 7: Exceedance probabilities for observed (black) and simulated groundwater levels and Spring Creek flows and the model scenarios 1 – 3 (blue, orange and red line, respectively). Dashed lines depict the fixed threshold levels that are currently implemented in the MEP for these wells. The numbers in the legend signify how often (on average) these thresholds are transgressed under the 3 abstraction scenarios. The uncertainty range is reported in brackets [.|.].

Coastal Region

The bottom row of Figure 7 shows the results for the wells P1733, P3667 and P10346 which are located in the coastal region (see locations in Figure 1). Here, the exceedance probabilities for the three scenarios exhibit little variation, which indicates that levels are largely unaffected by the abstraction from the Wairau Aquifer in the current model setup. This can be explained by the groundwater gradient in the confined aquifer in the coastal region, which has not changed much. The simulated groundwater levels are influenced by the seasonal head boundary condition that was imposed along the entire coastline which also explain the differences between the exceedance probabilities of the simulations and the observations. Please note that the groundwater level variation in those locations is much smaller than in the unconfined aquifer, and thus the model errors appear somewhat inflated. However, it is evident that the coastal groundwater levels in both the observed time-series and all the scenarios are not transgressing their thresholds of 1.25 m (Figure 7, bottom row).

The coastal region appears to be less influenced by the intensification of Wairau Aquifer abstraction, because the groundwater gradient across the Wairau Plains (West – East) in all cases remains large enough to push groundwater in the confined region of the aquifer and out offshore. At the Wairau Bar well P1733, the lowest observed groundwater levels are currently above 2 m a.s.l., i.e. about 0.8 m above the MEP threshold. The well P3667 levels are slightly lower, but the lowest levels are observed in P10346 (at 1.6 m a.s.l. closest to the 1.25 m threshold). Sea-level rise is expected to have an impact on these levels; however, it is outside of the scope of this report and has not been analysed here. While sea-level changes could be simulated with the WPM, the coastal aquifer and the low-land drains would need to be represented in slightly more detail than is currently implemented.

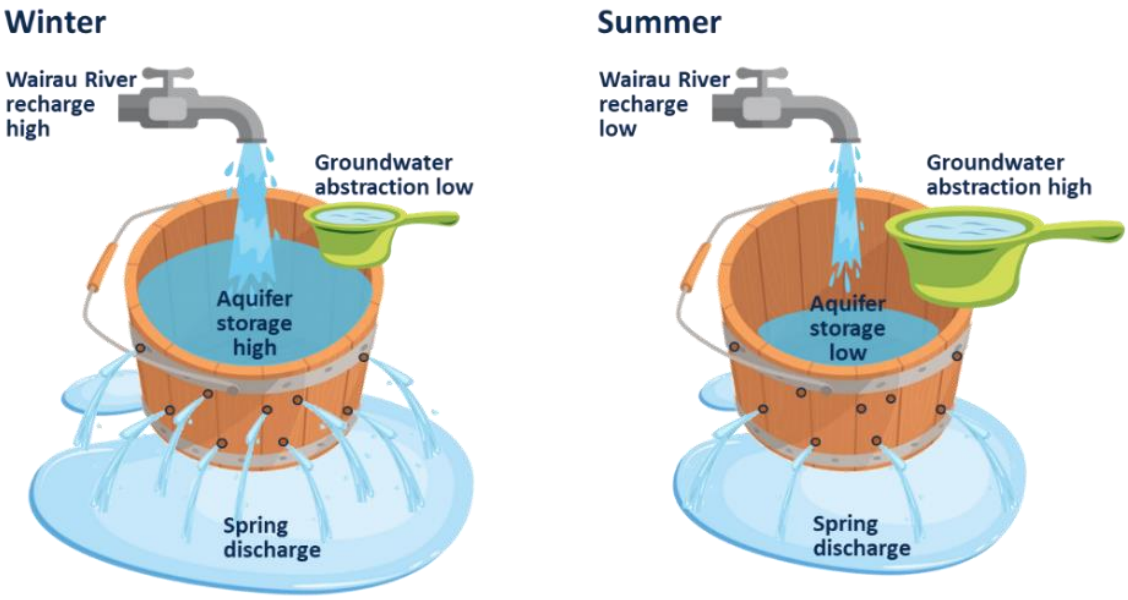


Figure 8: Conceptual representation of the Wairau Aquifer as a "leaky bucket".

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4. SUSTAINABLE AQUIFER STORAGE

The management of groundwater in the unconfined Wairau Aquifer is challenging because the residence times in the aquifer are relatively short, particularly for shallow groundwater, and only the top part of the aquifer is water available for use (see http://aquiferwatch.hydro.tu-dresden.de/methods.html). The Wairau Aquifer can be visualised as a **leaky bucket** (Figure 8): The water entering the aquifer by river recharge (on average 216 M m³/year) is similar to the volume of water leaving the aquifer via springs, drains and offshore flow (202 M m³/year). Despite this, inflows and outflows exhibit a strong natural seasonality. The 90%-quantile annual groundwater abstraction volume (~ 22 M m³) is just 10% of the annual recharge but peak demand (irrigation to meet crop water requirements) coincides with the timing of natural river flow recession in the summer months. The change in storage is small compared to the through-flow through the aquifer, as can be seen in the monthly water balance of the aquifer (Figure 9). The groundwater recharge (dark blue) is largely matched by discharge in springs and drains (light blue and purple). Only rainfall events (land-surface recharge) and wetter-than-average summers without prolonged dry periods can lead to a net recharge of aquifer storage (red, negative values). It has been discussed previously that long dry periods lead to Wairau River flow recessions, with a significant drop of river recharge and aquifer storage depletion that potentially extends to subsequent years (Wöhling et al., 2020).

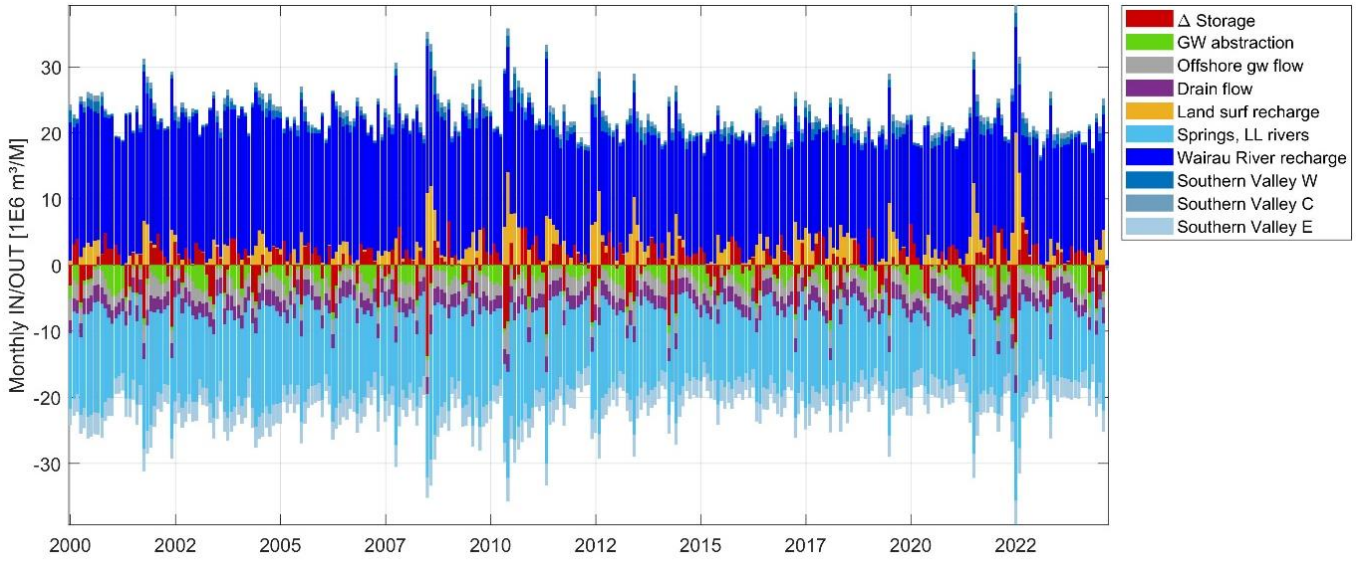


Figure 9: Monthly sums of water balance components for the Wairau Aquifer (base scenario), as simulated by the WPM V11b.

Figure 10 depicts the simulated Wairau Aquifer storage (a subdomain of the WPM model) for the simulation period 2000 – 2023 and the three abstraction scenarios. Again, the strong seasonality and inter-annual variability can be seen in the time-series. In the graph, the storage changes are plotted relative to the largest aquifer storage observed during this time, which occurred during the 2022 Wairau River flood event. The dashes in Figure 10 indicate the high-points (HP, blue) and low-points (LP, black) of storage for the individual years under current conditions (base case scenario 1). It is evident that the 60% and 100% MEP abstraction scenarios result in significantly more storage depletion in summer, with the low points being up to 8 M m³ lower than those of the base scenario. Interestingly, the model simulations do not indicate large differences in storage recovery (during winter) compared to the base scenario which indicates that the changes in carry-over effects are not very large.

To estimate a **base-level for storage under current conditions**, the high-points for the time period 05/2015 – 08/2024 were selected. The average of the high points for these years is the expected storage recovery under current conditions (depicted as dashed line in Figure 10) and used as the reference level in the considerations of sustainable storage described below. Note that the year 2022 was an extremely wet year and thus was excluded in the calculation of the mean.

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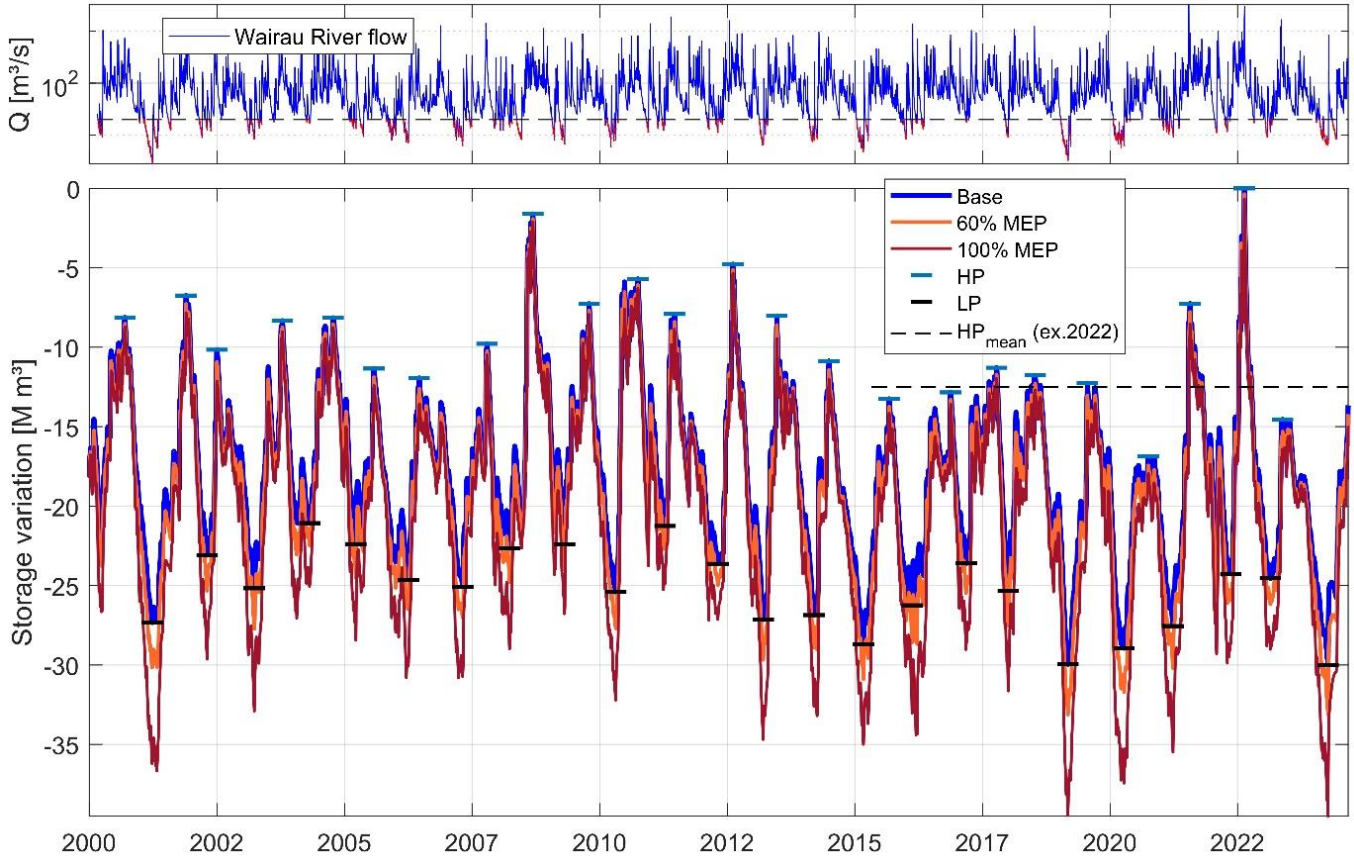


Figure 10: Wairau River flows (top panel) and Wairau Aquifer storage (bottom panel) as simulated by the WPM V11b for the three management scenarios. Annual high (HP) and low points (LP) of storage are depicted by blue and black dashes, respectively.

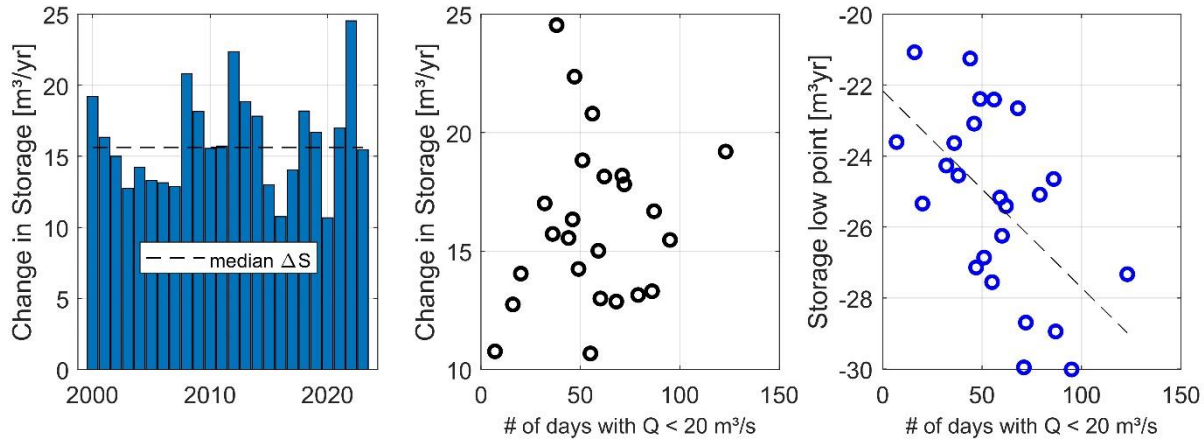


Figure 11: Simulated annual storage change in the Wairau Aquifer under current conditions (left panel), its relationship to the number of low flow days in a hydrological year (mid) and the annual storage low point as function of low-flow days (right).

The annual variation in aquifer storage under current conditions has a median value of about 16.5 M m³ but exhibits a large range of 11 – 24 M m³ (Figure 11, left panel). The annual storage variation is not directly related to the number of low flow days in a year (Figure 11, mid panel), but there are indications that the absolute low point of storage in a year is related to the number of days with low Wairau River flow (Figure 11, right panel). It has been shown by Wöhling et al. (2018, Figure 14) that Wairau River recharge covers a comparatively narrow range of 5 – 8 m³/s under most flow conditions. However, the river recharge rate drops faster for river flows below 20 m³/s. Since the discharge from the aquifer is not dropping simultaneously and lags behind the recharge, aquifer storage decreases rapidly for low-flow conditions in summer. Therefore, the number of low-flow days (i.e. Q < 20 m³/s) in summer are also a

predictor of how rapidly storage is depleting relative to the base level from the previous year. But aquifer storage recovery also depends on other factors such as the timing of the low-flow days, land-surface recharge (rainfall), but also on river braiding, flow-channel location and gravel erosion/aggradation in the recharge sector. Often, not a single factor but several compounding ones are leading to unusually low storage conditions.

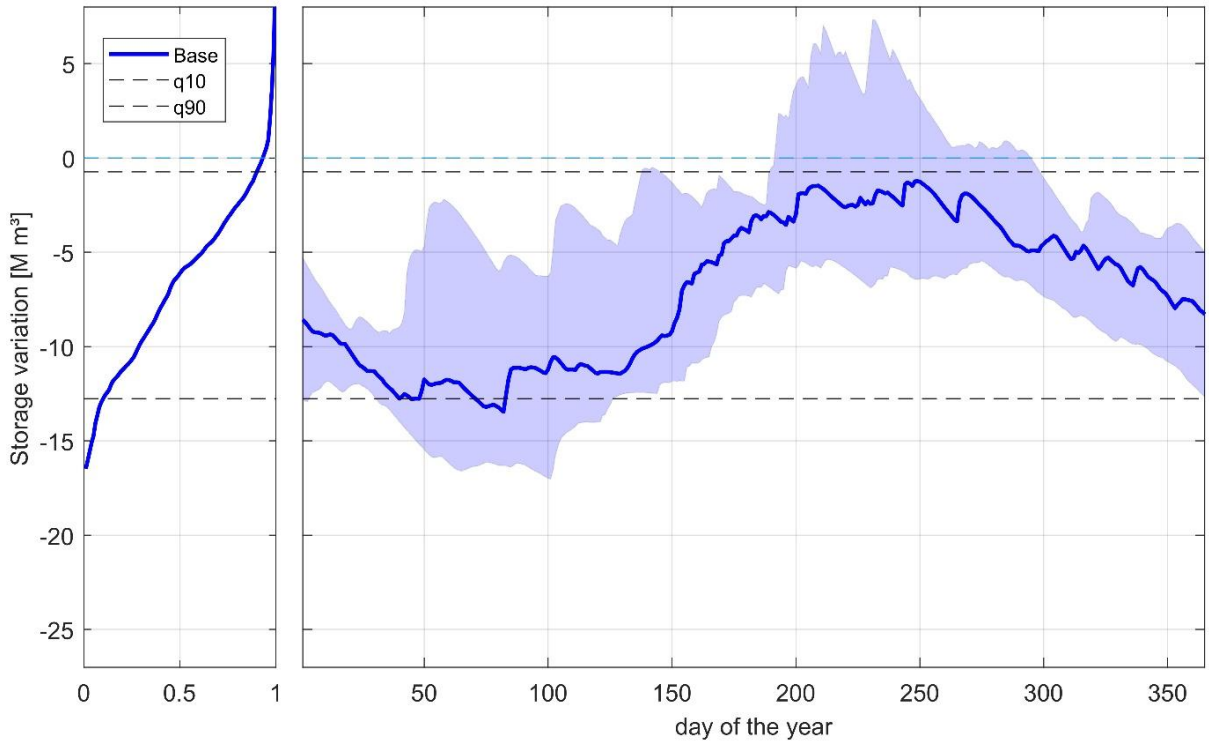


Figure 12: Exceedance probability of storage variation (left panel) and expected storage variation for an average year (right) under current conditions (base scenario). The dashed light blue line is the average aquifer high point shown in Fig 10.

Instead of plotting changes of aquifer storage over time (Figure 10), storage can also be aggregated and analysed statistically, as shown in Figure 12 for the base scenario. The left panel shows the exceedance probability of storage variation using the time-series 05/2015 – 08/2024 and the **base-level for storage under current conditions** as reference (storage = zero, blue dashed line). The 10- and 90-% quantiles of storage variation are shown as black dashed lines. The plot shows the probability (x-axis) of Wairau Aquifer **storage depletion** (y-axis). For example, in 10% of the time (p = 0.1), the storage is depleted by more than 12.7 M m³ (lower dashed line in the left panel of Figure 12) compared to the reference level. In half of the time (p = 0.5; i.e. median), the storage is depleted by more than 6 M m³. Further, in 1% of all cases the storage is depleted by 16.5 M m³ (i.e. y-axis intercept).

The right panel of Figure 12 has the same y-axis as the left panel, but storage variation is depicted for the calendar days of the year (starting 1 Jan). Values in the time-series are not sorted by magnitude (as in the left panel), but by the calendar day. The blue line indicates the expected (mean) value, the shaded area shows the 10- and 90-% quantiles of storage variation for the individual days. The graph represents the expected storage changes for an average year, relative to the actual storage in the Wairau Aquifer at the beginning of the calendar year (or any other reference date). In that it differs from Figure 10 which shows the “evolution” of Wairau Aquifer storage for consecutive years.

The Wairau Aquifer storage is seasonal: low storage occurs in summer when recharge is lower and abstraction is higher, conversely, recharge is high in winter. The variability around the mean is large for both summer-lows and winter-highs and moderate during shoulder seasons. Interestingly, the expected storage is at or below the 10-% quantile line from around day 40 to 80 (mid-February to end of March).

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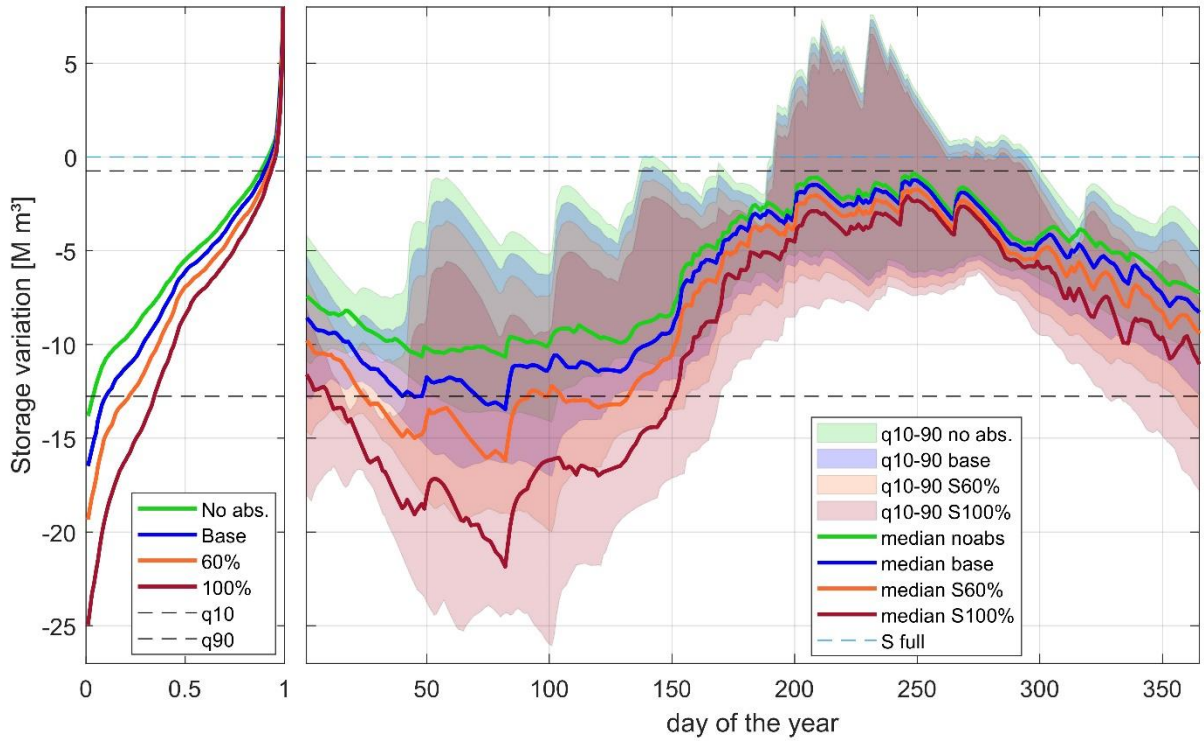


Figure 13: Exceedance probability of storage variation (left panel) and expected storage variation for an average year (right) and all abstraction scenarios, including a no-abstraction scenario (green).

To analyse changes in **expected** depletion of Wairau Aquifer storage caused by a change in abstraction, Figure 13 presents the same graphs as in Figure 12, but includes all abstraction scenarios. Note that "expected" again refers to the mean and that there is a large inter-annual variability around this mean as seen by the 10/90-% confidence intervals (shaded areas). The expected summer depletion increases drastically for the 60% and 100% MEP scenarios. It is an additional 8.5 M m³ for the full MEP scenario, equating to an approximate 50% increase. Also shown in Figure 13 is a scenario with no groundwater abstraction from the aquifer (green), which can be viewed as a base-line for the natural seasonality of groundwater variations in the Wairau Aquifer. The expected storage depletion without abstraction in an average year is 13.8 M m³ (Figure 13, green line on left panel, intercept with y-axis). The current-conditions groundwater abstraction of ~22 M m³ annually adds only 2.7 M m³ to the expected depletion of aquifer storage because of simultaneous recharge from the river and the land surface. Recharge rates are significantly lower in summer, particularly if the Wairau River is lower than 20 m³/s (Wöhling et al., 2018). The added depletion of aquifer storage compared to the scenario with no groundwater abstraction is 5.5 M m³ and 11.2 M m³ for the 60% and 100% MEP scenarios, respectively.

Figure 14 shows the annual average storage variation again for the three abstraction scenarios. In addition, times when current MEP thresholds (Table 2) are transgressed in the base scenario (i.e. current conditions) are plotted. As expected, this is happening in summer, but over extended periods of time. Interestingly, these violations of MEP thresholds are all below the 10% quantile line (solid black). Therefore, it could be concluded that current abstractions (30% MEP) are already higher than the naturally available seasonal volume in case that the MEP thresholds should not be transgressed. The currently available storage above MEP thresholds for these conditions would be 12.7 M m³/year as indicated by the blue shading in Figure 14. Note, that this volume would refer again to the average year and the natural variability could still lead to MEP threshold violations. Under the 60% and 100% MEP abstraction scenario conditions, this storage threshold would be transgressed in 22% and 35% of all days, respectively, as well as during extended periods of time. This is shown for the full MEP abstraction scenario in Figure 15.

The WPM scenario simulations demonstrate that even under current conditions, the thresholds in the MEP plan will be frequently transgressed. This is mainly caused by the declining trend in aquifer levels and storage. The trend is likely to continue (or even accelerate) without intervention through artificial recharge, gravel management or river corridor widening. Over the past decades, the Wairau River has changed from a braided river towards a wandering

river (i.e., a river with single channel reaches alternating between its banks) that incises deeper into the braidplain aquifer and thereby loses storage capacity and reduces river recharge (Wilson et al., 2023; Wöhling et al., 2024). Because the river – aquifer system (and the groundwater resource) is not at a state of equilibrium, fixed level and spring flow thresholds are not a sustainable method for future groundwater management.

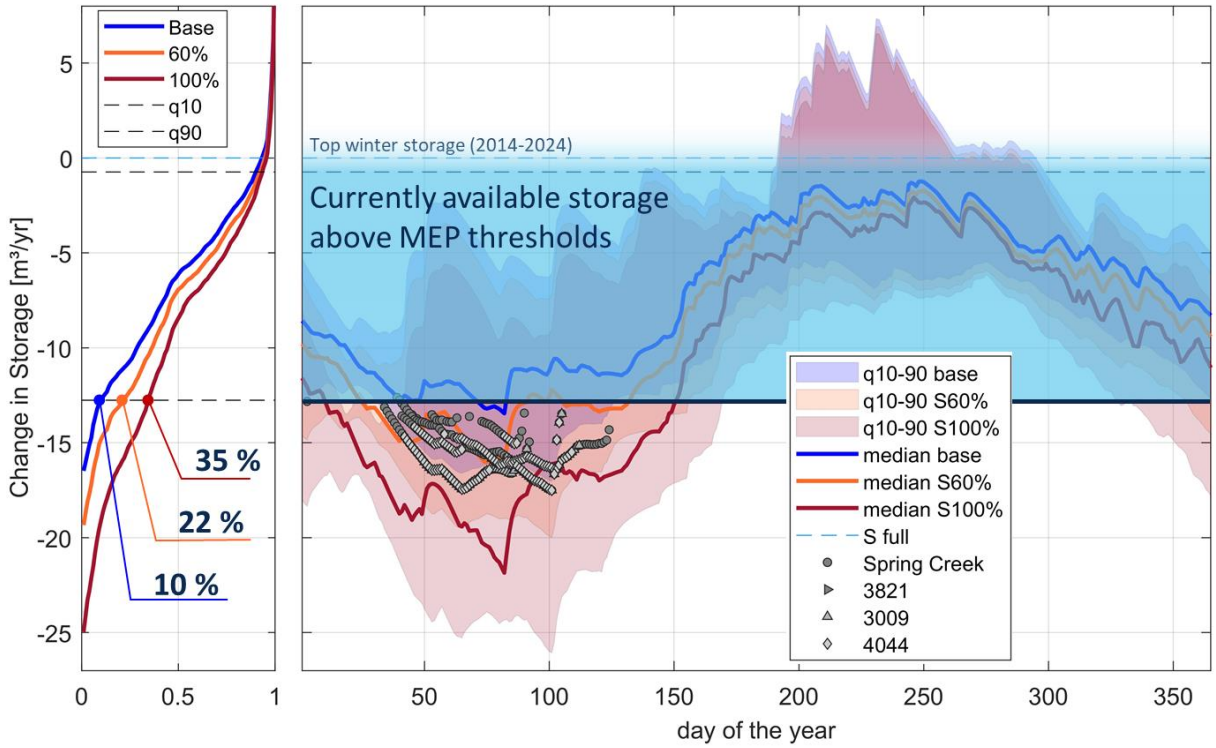


Figure 14: Exceedance probability of storage variation (left) and expected storage variation for an average year (right) and all abstraction scenarios, indicating times when MEP thresholds were transgressed under current conditions, as represented by the symbols.

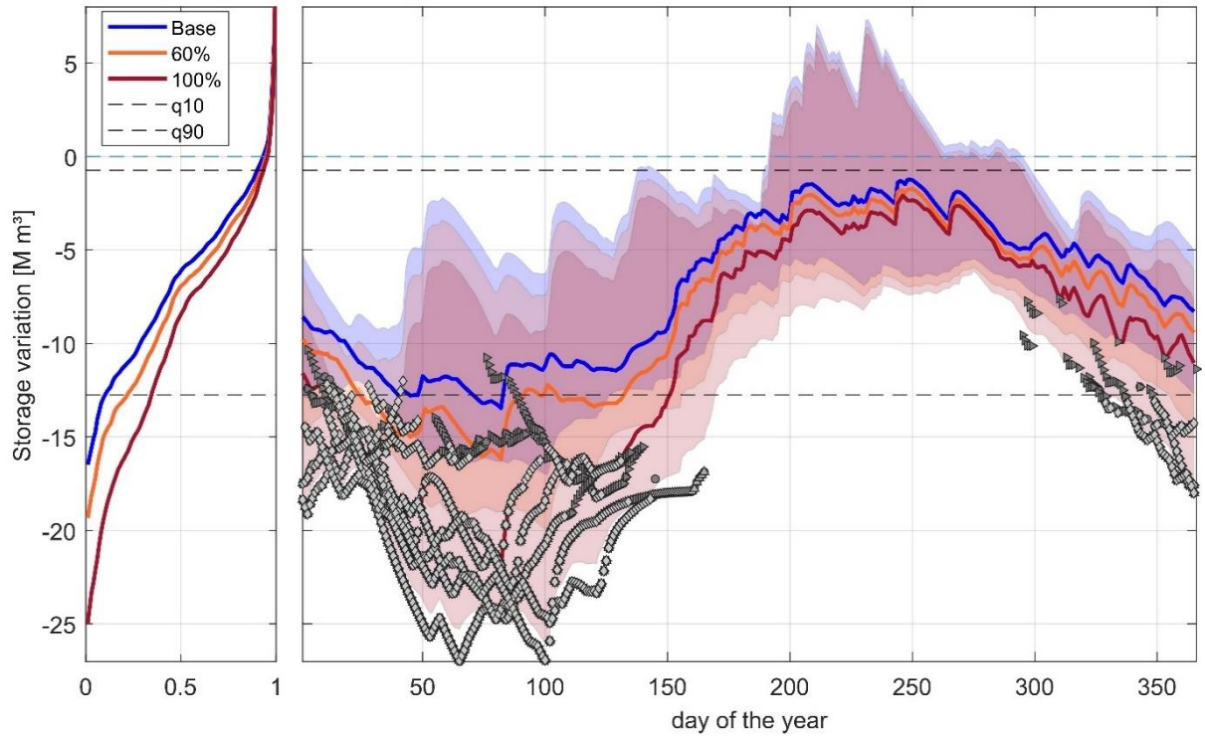


Figure 15: Exceedance probability of storage variation (left) and expected storage variation for an average year (right) and all abstraction scenarios, with times when MEP thresholds were transgressed in the full MEP abstraction scenario (symbols).

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5. ANNUAL ALLOCATION TO GENERATRE EXTRA-SEASONAL EFFECTS

The WPM modelling suggests only minor carry-over effects from additional aquifer depletion from one season to the next, as shown in Figures 10 and 13. Compared to current conditions (30% MEP volume), the 60% and 100% MEP abstraction scenarios show a drastic decline in storage during summer, but only small differences in the winter months, when the net flow to the aquifer becomes positive (i.e. net recharge). This is likely related to the higher recharge rates in winter that provide recharge surplus also in the 60% and 100% MEP abstraction scenarios. In contrast the increase in abstraction is much higher in summer for these scenarios, while the aquifer recharge remains small. Thus, the impact of the additional abstraction on storage is much higher in summer than in winter.

However, this does not indicate that there are generally no carry-over effects on aquifer storage. Consecutive dry years, especially years with prolonged low-flow in the Wairau River, can lead to a decrease of the subsequent “winter-high” aquifer storage. Two examples are the periods from 2005 – 2007 and 2013 – 2015 (Figure 10), where winter storage decreases for three and four subsequent years, respectively. These “carry-over” effects are largely caused by natural variability of hydro-meteorological drivers and only partly by anthropogenic factors and the variability in crop-water demand. Due to the high recharge through-flow in winter, the additional abstraction has no significant effect on the “winter-high” storage levels of the base case scenario, i.e. it does not significantly deplete aquifer storage beyond a single season. However, the increase in the basal (“year-round”) abstraction rates in scenarios 2 and 3 has a noticeable effect leading to lower expected storage values during the entire year, including in winter (Figure 13).

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6. FUTURE EFFECTS OF STORAGE LOSS

The declining trend in Wairau Aquifer groundwater levels is evidence for a decreasing storage capacity. The reasons for the trend are complex and have been analysed in previous work conducted by LAL (Wöhling et al., 2020; Wilson et al., 2023). It started some 150 years ago with river training and confinement works that continue until today. This led to significant changes in river morphology and sediment supply. Changes in hydro-meteorological conditions towards more pronounced summer-dry periods intensify the effects of these changes. These factors have led not only to lower aquifer levels, but also to a permanent loss of storage that cannot not easily be reversed. In particular, lower mean bed-levels in the upstream recharge regions from the Waihopai River to Wratts Road have led to a reduced thickness of the saturated braidplain aquifer associated with the Wairau River bed a diminished access of (lateral) recharge area. There is no clear understanding of the state, where gravel erosion and deposition processes in the Wairau River are in a state of equilibrium (or if such a state exists, for that matter) and how long it will take to reach it. Together, these factors present a complex picture of the processes at play. However, the trend currently seems to be continuing.

Presuming that the blue shaded area in Figure 14 is the currently available storage above MEP thresholds and black line is the bottom-line of it, the declining trend will push down (i.e., decrease) the volume from the top, because the "top winter storage" will be decreasing with decreasing aquifer levels. To allow current groundwater abstraction volumes to be taken in the future, this bottom-line has to be relaxed by reducing or disestablishing the fixed level/flow thresholds in the MEP (Table 1).

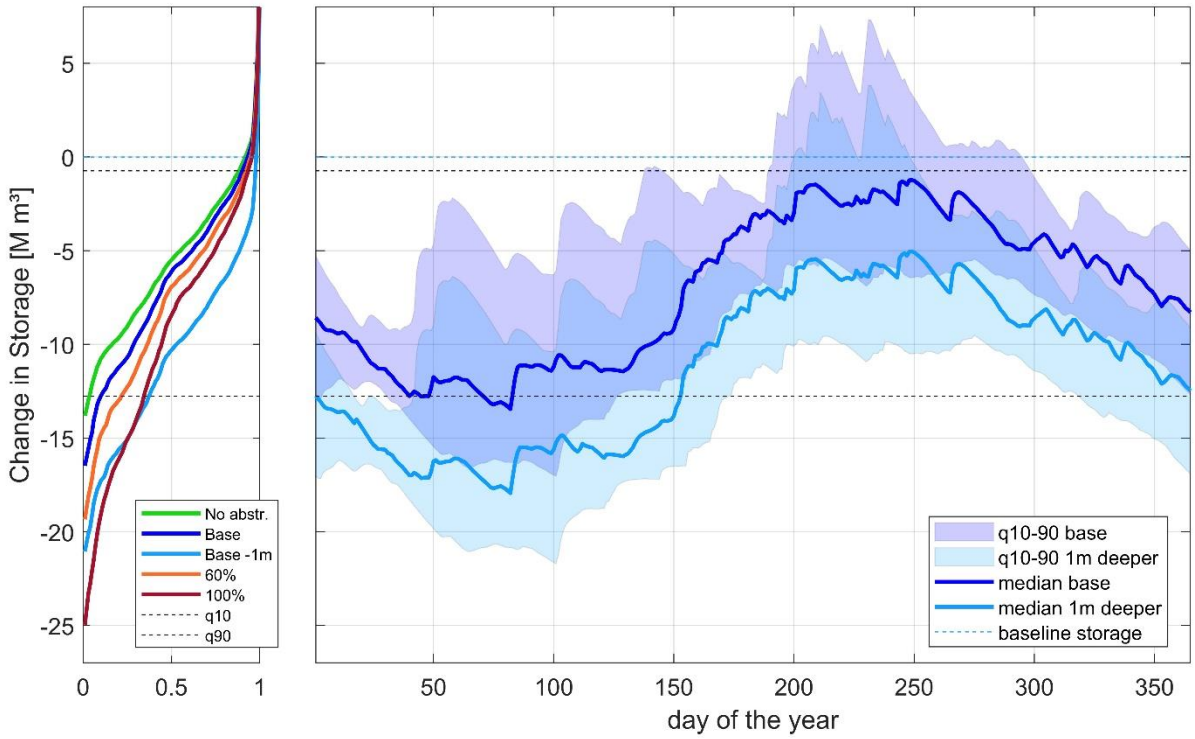


Figure 16: Exceedance probability of storage variation (left) and expected storage variation for an average year (right) and the base scenario as well as the scenario with 1 m lower Wairau River bed elevation upstream of Wratts Road, mimicking the situation in 2060

To analyse this further, the WPM model was used to create a scenario which mimics a drop in Wairau River bed elevation similar to what has been observed in the past decades. According to Gardner and Sharma (2016), the mean bed level dropped by approximately 1 m since the 1990s within the study reach of the Braided River Programme (a 2.2 km long study reach in the middle section of the Wairau Plain, between Jeffries and Giffords roads; see Wilson et al., 2024). Correspondingly, a scenario was created, where the Wairau River bed downstream of the Waihopai confluence drops to 1 m below current levels for the river reach down to Wratts Road and then linearly

increases again to current bed levels at SH1. This scenario would roughly mimic the situation in 2060 if the past trend continues at the same rate. The resulting effect on aquifer storage is depicted in Figure 16.

It is clearly visible that the effect on aquifer storage is profound. The 90% quantile of storage depletion under current condition (lower dashed line in the left panel) will be the 60% quantile in 2060, i.e. the safe “storage” is transgressed in 40% of all days instead of 10% today (Figure 16, left panel). The shift of the light blue line in the right panel of Figure 16 indicates that an additional volume of about 4 M m^3 Wairau aquifer storage will be lost by a continuing decline in groundwater levels. This effect will be superimposed on the effects of any changes in groundwater abstraction.

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7. ABSTRACTION UNDER EXTREMELY DRY CONDITIONS

The summer of 2023/2024 was extremely dry and record-low groundwater levels were observed in the Wairau Aquifer. The WPM model was used to assess this situation and the contributing factors for the record-low aquifer storage. For this purpose, the model simulation period was extended until 08/2024. The WPM was calibrated for a relatively short time period of three years (02/2014 – 02/2017) but it shows a good match to observed groundwater levels and Spring Creek flows for the 25-year time period from 01/2000 – 08/2024. This includes times with extreme conditions (floods of 2021 and 2022 and the extreme dry summer of 2024) which were outside the range of the calibration data (Figure 17 and Wöhling et al., 2025). This underlines that the WPM is physically plausible and that it is very well capable to provide realistic results for scenarios with environmental conditions that are outside of the historic observations.

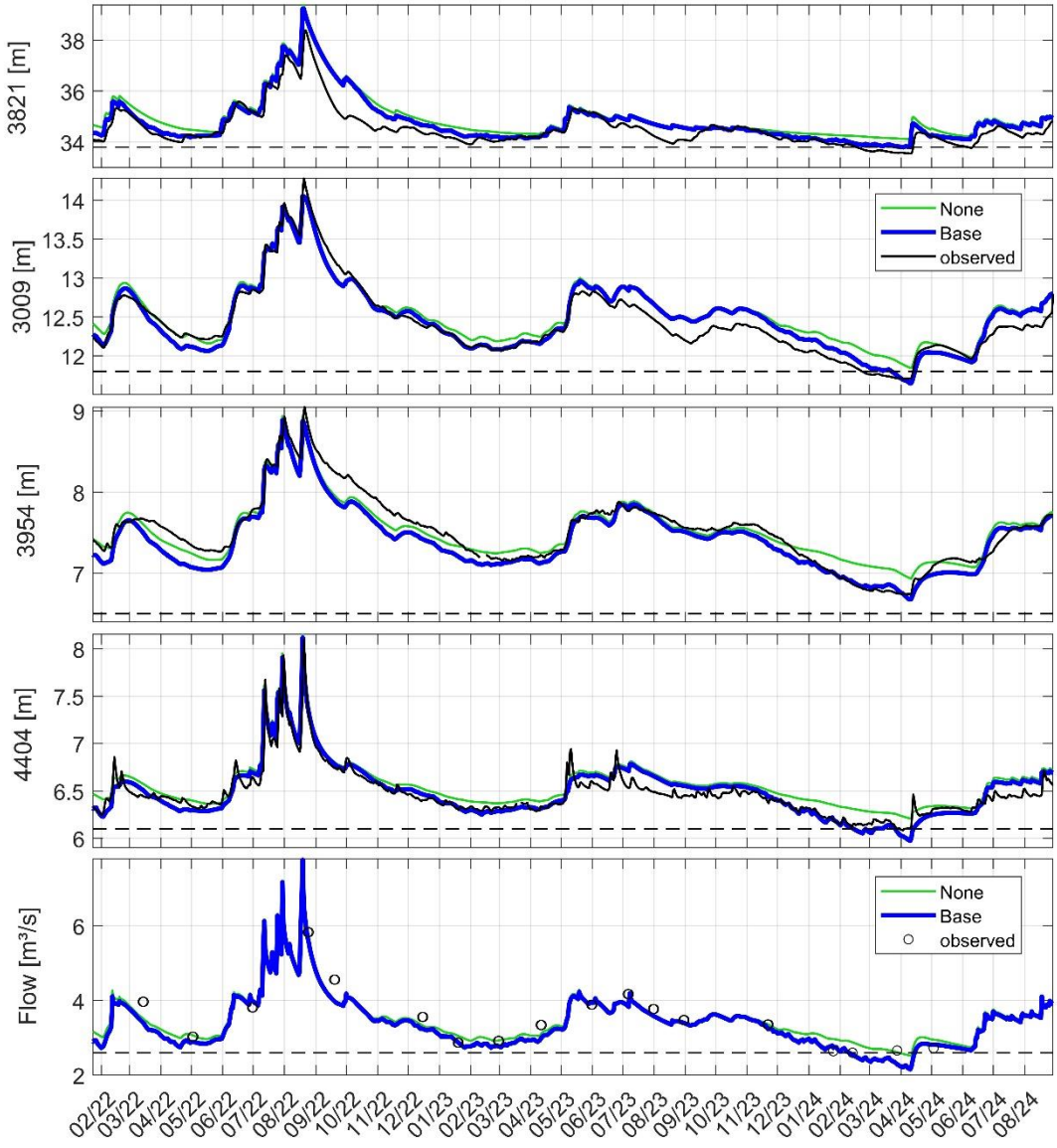


Figure 17: Observed (black) and WPM model simulated groundwater levels and Spring Creek flow (blue = current situation; green = scenario with no groundwater abstraction) for key MDC monitoring sites and the time period 01/2022 – 08/2024 which includes the record-low storage in April 2024. MEP threshold levels are indicated by horizontal black dashed lines.

Figure 17 shows the model simulations (blue) of key groundwater monitoring sites (panels 1 – 4) and Spring Creek flow (bottom panel) and the corresponding observations (black lines and circles) for the time period 01/2022 – 08/2024 which includes the record-low storage in April 2024. The simulated effect of groundwater abstraction on groundwater levels and Spring Creek flow is not excessive as can be seen by the green lines, which represent the scenario with no groundwater abstraction. In all monitoring wells analysed here, the effect of groundwater abstraction was less than 0.5 m (groundwater levels) and less than 0.5 m³/s (spring flow) and only noticeable in summer. The effect is much smaller near the coast as described in Section 3.1.

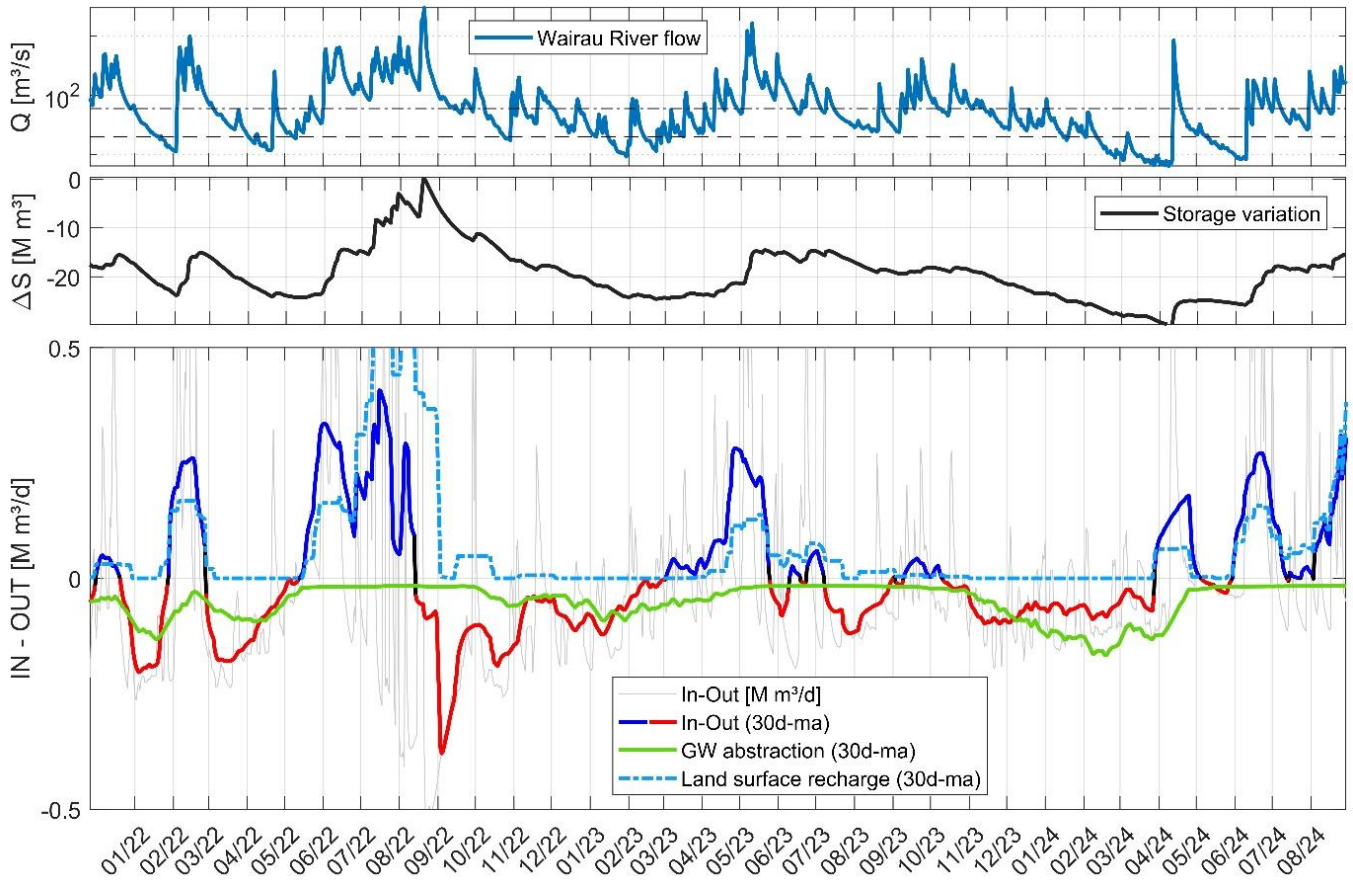


Figure 18: Wairau Aquifer storage for the time period 01/2022 – 08/2024 which includes the record-low storage in April 2024. Top panel: Wairau River flows (log scale), middle panel: WPM-simulated storage of the Wairau Aquifer, bottom panel: 30-day moving average of net-recharge (blue = recharge, red = discharge), groundwater abstraction (green) and land-surface recharge (light blue dashed line) to the aquifer.

To investigate this further, consider Figure 18, which shows the model simulated Wairau Aquifer storage for the dry summer 2024 and for comparison also for the previous summers of 2023 and 2022. The year 2022 was a year with wet conditions where the Wairau River received one of the largest floods on record. The top panel shows Wairau River flows (log scale) as the main driver of river recharge. The graph also shows the median river flow level (60 m³/s, dash-dotted horizontal line) and the 20 m³/s level (dashed line) which has been identified before as a level below which river recharge rates drop steeply (Wöhling et al., 2018). Comparing river flows in the summers 2022 and 2024, it is observed that flows were below the median for almost six months prior to the minimum storage in April 2024 and below the critical 20 m³/s threshold for almost two months. In contrast, this was the case only briefly (three weeks) in 2022. As a consequence, river recharge was much lower for a prolonged period of time in 2024.

In addition, land-surface recharge (driven by rainfall on the Plains) was low in the summer but, importantly, also in winter of 2023. Then it was virtually zero from July 2023 up to April 2024. This is depicted by the light blue dashed line in the lower panel of Figure 18. Also depicted is the *net aquifer storage change* which is an expression of the

water budget of the Wairau Aquifer. If the value is positive (blue) the inflows to the aquifer (e.g., river recharge, land surface recharge, groundwater inflow) are greater than the outflows from the aquifer (groundwater discharge to the Wairau River, spring flows, drains, offshore groundwater flow, groundwater abstraction). If the budget is negative (red line) the outflows are greater than the inflows and aquifer storage and thus groundwater levels decrease (middle panel).

After the flood in 2022, the water budget of the aquifer has been positive only over a brief period in the relatively dry winter of 2023 which means that aquifer storage continued to decline for most of the time. The low winter recharge and corresponding low aquifer storage at the beginning of the growing season of 2023/2024 is the main reason that the dry summer of 2024 had such severe consequences. At the beginning of the season (May) that led to the record-low aquifer storage, the Wairau Aquifer contained approximately 14 M m³ less storage than at the high point of 2022 and 2 M m³ less than the average high point for the period since 2015 (see Figures 10 and 18).

Another factor is groundwater abstraction. Due to low rainfall, the crop water demand was higher in 2024 than in 2023. Consequently, the groundwater abstraction from the Wairau Aquifer was also higher, as illustrated by the green line in Figure 18 (bottom panel). The 2024 drought ended when rain occured in the Wairau catchment at the end of April 2024. The resulting increase in river flow to above the median flow led to higher river recharge, and rain on the Plains led to land-surface recharge. The rain event coincided with the end of the growing season, where irrigation demand and thus groundwater abstraction decreased. All factors together led to a net positive water budget of the Wairau Aquifer, i.e. an increase in storage.

In summary, the record low groundwater storage in the 2023/2024 season resulted from hydrological extremes, particularly record-low rainfall in the catchment (Figure 19) and very low land surface recharge at the Wairau Plain in combination with a rather large demand for irrigation (Figure 20).

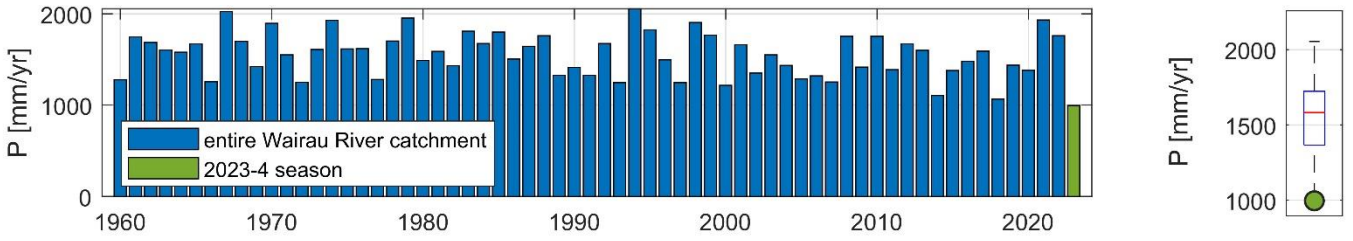


Figure 19: Annual rainfall in the Wairau catchment as computed using VCSN data (NIWA) for the hydrological years 1960-1 to 2023-4 (left panel). The right panel shows that the 2023-4 season (green dot) was the lowest on record.

These results show clearly that consecutive dry years can amplify the effect of a single dry year and also that a single flood event, even an extreme event, has no long-lasting effects on aquifer recharge. Important for a decent aquifer storage recovery is a longer time period in winter where flows are regularly at or above the median flow level. A possible future with more extreme flood flows and prolonged summer-low flow periods will lead to more frequent extremes of aquifer depletion in summer and an increase in groundwater demand during these periods. This will pose major challenges for future groundwater management in the region and beyond.

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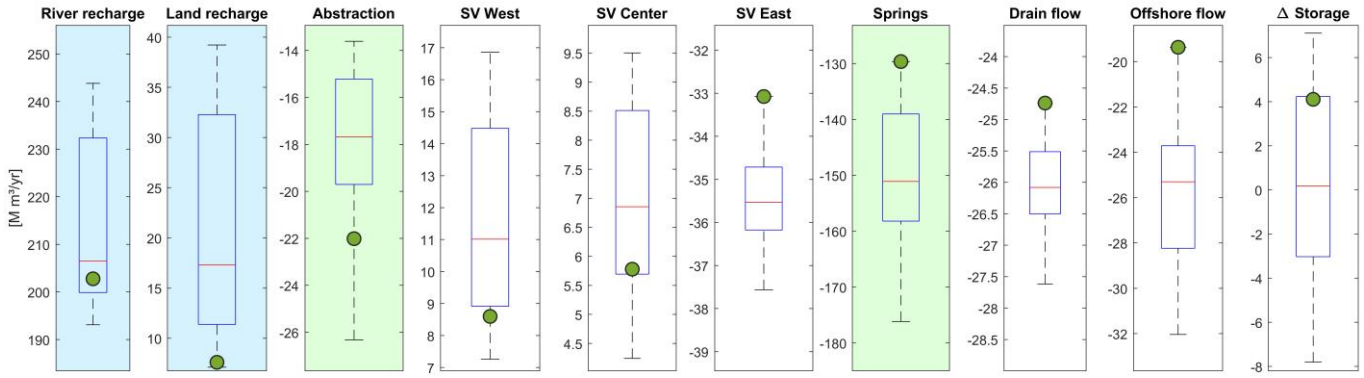


Figure 20: Annual Wairau Aquifer water balance components (WPM) for the hydrological years 2000/2001 to 2023/2024. The green dot indicates the values for the 2023/2024 season: low river and land surface recharge and high abstraction. Positive values indicate (net) flows recharging the Wairau Aquifer while negative values indicate (net) discharge flows. The blue shaded graphs represent river recharge and land surface recharge and the green shaded graphs represent groundwater abstraction volumes and spring discharge.

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8. CONCLUSIONS

The main conclusion from this work and other work on the Wairau Aquifer system suggests that that the fixed level and flow thresholds implemented in the Marlborough Environment Plan (MEP) are not sufficient for managing groundwater resources in the future because the system is not in a state of equilibrium. Due to the continuing decline of groundwater levels and spring flows, these thresholds will be transgressed frequently in the future, even in years with average hydro-climatic conditions and under the assumption that abstraction remains at current levels. An increase in groundwater abstraction and the likely intensification of hydro-climatic variability will further worsen the situation.

The Wairau Aquifer storage exhibits natural seasonality. Groundwater abstraction has a noticeable effect on storage during the summer period, when recharge is low and coincides with the largest abstraction demand. The summer low points of aquifer storage will be further exacerbated with increasing groundwater abstraction. This could lead to up to 8 M m^3 less storage annually compared to current conditions. This is a significant amount, considering that the sustainable annual storage variation is in the order of 20 – 25 M m^3. Concurrent with the lower storage, summer flow of the low-land springs will also decrease. If this is to be prevented, the abstraction volume of 73 M m^3 in the current MEP could be reduced.

But a fixed annual volume does not account for the state of the aquifer at the beginning of the growing season (April). There is clear evidence of inter-annual variability of storage and of the storage base-level in winter: subsequent years with below average recharge (particularly in winter) leads to a continuing decrease of storage in subsequent seasons. Single flood events typically don't have a lasting mitigating effect. However, it should be noted that hydro-meteorological variability between seasons, rather than abstraction is responsible for these carry-over effects. Higher abstraction causes larger depletion of storage in summer but has no significant effect on winter recovery levels.

The analysis conducted here supports earlier findings that aquifer storage is particularly sensitive to Wairau River flows below ~20 m^3/s. Extensive periods of time with river flow below this threshold lead to a lasting decline of aquifer storage that only gets offset by above-average wet winters. Raising the lower limit for surface water takes to 20 m^3/s would potentially increase Wairau Aquifer recharge but the interdependency with other factors are complex and a trade-off exists to meet the demands of Wairau Valley water users and the SVIS diversion.

A main challenge for the management of the Wairau Aquifer are compounding effects of antecedent storage, the duration of river flow below the threshold, (lack of) land-surface recharge, and abstraction demand. One example is the summer of 2024, where a low level of aquifer storage at the beginning of the season combined with extended periods of low river flows and the absence of land-surface recharge were identified as the main factors leading to record-low aquifer storage. Superimposed on these factors is the declining trend in groundwater levels (likely caused by changes in river morphology), long-term changes in the hydro-climatic conditions (including climate change), seawater rise, potential changes in land-use towards crops with higher water demand, as well as consented abstraction for crop irrigation in the Wairau Valley and its follow-on effects (e.g., lower summer Wairau River flows). These will further intensify the pressure on the Wairau Aquifer groundwater resources.

An alternative to fixed threshold levels for managing the Wairau Aquifer groundwater resources could be a more adaptive, volume-based management, potentially accompanied by instantaneous abstraction limits. Any modification to the current management approach should account for the challenge that the groundwater system of the Wairau Plains is not in equilibrium and will likely continue to change in the decades to come. In addition, a more integrative management approach that encompasses surface water takes and groundwater takes at both the Wairau Plains and the Wairau Valley could potentially be more effective in trading-off different demands and to mitigate the effects of hydro-meteorological extremes.

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9. MODEL LIMITATIONS

As with every modelling study, there are some limitations that arise from the limited knowledge about the natural system under consideration and from the approximations and assumptions when building models. Models are always simplifications of reality and the 3D Wairau Plain surface water – groundwater flow model (WPM) is no exception. Uncertainty in modelling results stem from uncertainties in the hydrogeological conceptualization, uncertain properties of the aquifer such as hydraulic conductivity, scaling effects, uncertainty of hydro-meteorological drivers, among others. However, the WPM conceptual model has been developed iteratively with available hydrogeological data, expert knowledge from MDC groundwater and hydrology staff, a review of aquifer stratigraphy by LAL staff (Wilson 2016) and additional data explicitly made available for the purpose of refining the model and reducing its uncertainties. The WPM was calibrated with several data types and state-of-the-art modelling practices and tools, has been regularly updated and extended as new information became available, and has been rigorously tested with data that has not been seen in the calibration period (Wöhling et al. 2018, 2020, 2025).

Nevertheless, there are inherent uncertainties pertaining in the WPM which can be quantified, perhaps reduced, but not entirely be eliminated. Parametric uncertainty has been assessed by Null-Space Monte-Carlo simulation (Wöhling et al. 2025) but is not considered in the simulations reported here. Since differences between observed and model-simulated quantities remain, the model results have been reported here as relative changes between scenarios.

The choice of the future groundwater abstraction scenarios is not based on projections of future demand (this was outside the scope of this work). Current groundwater abstraction was simply scaled-up by factors. This means the relative spatial distribution of abstraction also remains the same in all scenarios. The scaling, particularly for the full MEP scenario could overestimate the variability of the demand of individual years. Current abstraction was also not directly measured, but estimated by a spatially and temporally distributed soil water balance model which was calibrated with selected records of metered data (actual use). While the locations of wells for municipal and industrial water supply are explicitly considered in the model, abstraction for irrigation is implemented as irrigation demand for each cell of the model grid. The modelling approach taken here is also conservative by not considering higher soil moisture and leaching in the scenarios with higher irrigation rates, potentially overestimating aquifer depletion.

Other limitations encompass inherent assumptions of system stationarity (fix river geometry, fix land-use, no climate trends, no sea level change): some of which are more sensitive to the model results than others. The most sensitive ones (higher abstraction demand by either land use change and/or temperature rise; and a continuing loss of aquifer storage) were separately addressed by scenario simulations but not simultaneously, as this was outside the scope of this work.

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