





Climate change resilience of groundwater pumping wells for drinking water production

Klimaatrobuustheid van grondwaterwinningen voor drinkwaterproductie in
Vlaanderen



Colofon

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1 Nederlandse samenvatting

Klimaatveranderingsprojecties geven aan dat België nattere winters en drogere zomers kan verwachten in de toekomst, met hogere evapotranspiratie door de verhoogde temperaturen (Tabari et al., 2015; Vlaamse Overheid, 2022; Sumaqua, 2022). Hierdoor voorspellen klimaatveranderingsprojecties uiteenlopende impacts op de jaarlijkse grondwatervoeding, afhankelijk van het gebruikte klimaatscenario en hydrologische model, maar met een gemiddelde negatieve impact op de grondwatervoeding (Reinecke et al., 2021; Atawneh et al., 2021; Dams et al., 2012; Sumaqua, 2022).

Analyse van 14 globale klimaat-impact modellen toont dat voor Vlaanderen de spreiding op de berekende effecten van klimaatverandering op grondwatervoeding zeer groot is. Bijna alle modellen voorspellen een daling van de grondwatervoeding in de zomer. De gemiddelde afname van de grondwatervoeding in de zomer van deze modellen bedraagt 20% maar de meest extreme klimaat-impact modellen voorspellen een daling van 60%. Op jaarbasis wordt tegen 2050 een gemiddelde daling van 5% in de grondwatervoeding verwacht, omdat de wintertoename de zomerdaling niet volledig compenseert, maar de spreiding op deze voorspelling is opnieuw erg groot. Deze analyse bevestigt dat Vlaanderen zich moet voorbereiden op een mogelijke daling in grondwatervoeding, met name in de zomer. Deze verwachte daling in grondwatervoeding doet zich in heel Vlaanderen voor.

Analyse van de grondwaterbalans in intrekgebieden van grondwaterwinningen voor drinkwaterwinningen toont dat klimaatverandering gemiddeld een negatieve impact zal hebben op de ratio grondwatervoeding/onttrekking in heel Vlaanderen. We zien dat de verhouding onttrekking over grondwatervoeding vooral hoog is in enkele grondwaterwinningen in de Kempen en ten zuiden van Leuven. Hierbij moet opgemerkt worden dat dit vooral diepere winningen zijn waarvoor het bepalen van het intrekgebied complexer is. We zien ook zeer duidelijk dat de infiltratie in de winningen van Aquaduin een zeer positieve invloed heeft op de ratio grondwatervoeding/onttrekking.

Met behulp van tijdreeksanalyse werd de impact van klimaatverandering op grondwaterstanden in de omgeving van drinkwaterwinningen bepaald. Deze analyse toont dat, hoewel we overal in Vlaanderen een daling van de grondwatervoeding verwachten, de effecten van deze daling op de grondwaterstanden niet overal dezelfde zijn. Klimaatverandering zal vooral in het noorden van Vlaanderen tot dalingen van de gemiddelde grondwaterstanden leiden omwille van de hydrogeologische eigenschappen van de ondergrond. Kunstmatige infiltratie zoals in de winningen van Aquaduin heeft een positief effect op de gesimuleerde grondwaterstanden. Deze analyse heeft ook enkele winningen geïdentificeerd waar de daling van grondwaterstanden meer dan 10 cm zou bedragen. Interpretatie van de absolute waarden van deze analyse dient met de nodige voorzichtigheid te gebeuren aangezien data-gedreven methoden sterk afhangen van de hoeveelheid en kwaliteit van de inputdata, de fit van de modellen niet voor alle locaties zeer goed was en er andere lokale factoren een rol kunnen spelen dat diegenen die in de modellen zijn meegenomen. Bij de interpretatie van alle modelresultaten in dit rapport moeten deze onzekerheden en veronderstellingen in rekening genomen worden.

We raden aan om voor de winningen met een mogelijke hoge klimaatimpact lokale transiënte MODFLOW-modellen worden opgesteld om toekomstscenario's door te rekenen. Hiermee kan de impact van klimaatverandering op grondwaterstanden in meer detail worden doorgerekend en kunnen ook mogelijke oplossingen doorgerekend worden. De daling van grondwaterstanden kan gecompenseerd worden door een reductie van het onttrekkingsgebied maar kan ook opgevangen

worden door een reductie van andere winningen, minder draineren of meer infiltreren in het intrekgebied. Deze studie bevestigt het belang van duurzaam grondwaterbeheer door in te zetten op meer infiltratie, slimmer draineren en slimmer grondwater onttrekken in een veranderend klimaat. Omwille van de additionele druk die klimaatverandering op het grondwater zal betekenen, bevestigt deze ook opnieuw het belang van bescherming van de kwantiteit en de kwaliteit van het grondwater in de intrekgebieden.

2 Introduction

Climate change projections indicate that Belgium can expect wetter winters and drier summers in the future, with higher evapotranspiration due to increased temperatures (Tabari et al., 2015; Flemish Government, 2022; Sumaqua, 2022). As a result, climate change projections predict varying impacts on annual groundwater recharge depending on the climate scenario and hydrological model used, but with an average negative impact on groundwater recharge (Reinecke et al., 2021; Atawneh et al., 2021; Dams et al., 2012; Sumaqua, 2022).

Climate models predict an increase in annual groundwater recharge in Northern Europe and a decrease in Southern Europe. The expected effect in Western Europe is less clear and characterised by high uncertainty, with an expected decrease in annual groundwater recharge in general (Reinecke et al., 2021; Atawneh et al., 2021). For Belgium and Flanders specifically, Dams et al. (2012) predict a change in annual groundwater recharge between –20% and +7% by 2070–2101, with an average decrease of 7% in the Kleine-Nete basin. As a consequence of the different climate projections for winter and summer precipitation, this also leads to a different effect on groundwater recharge. Dams et al. (2012) conclude that groundwater recharge increases in winter and decreases in summer in most scenarios. A study conducted by Sumaqua (2022) based on SWAP models (with Neumann boundary condition) shows a median decrease in Flemish groundwater supply of 20% by 2100. Furthermore, the study indicates an average decrease in groundwater levels in summer, with a median decrease of 37 cm in 2100, but with strong differences between the analyzed wells. A less pronounced increase in groundwater levels is expected in winter, with a median increase of up to 9 cm in 2100. As a result, a net decrease in groundwater is expected on an annual basis (Sumaqua, 2022).

Because climate change can have a significant impact on groundwater supply and groundwater levels, capacity of aquifers may change. This can have consequences for groundwater extraction for drinking water production. For some extractions, there is a risk that the pumped volumes will exceed the capacity of the aquifer and that the combined impact of climate change and drinking water extraction will lower groundwater levels to an extent that it may increase the risk of subsidence and/or damage to nature.

3 Objectives

This study aims to determine the climate robustness of groundwater pumping wells for drinking water production in Flanders. More specifically, this research aims to

- 1) Analyze climate change impact on groundwater recharge in Flanders
- 2) Analyze groundwater budgets in drinking water well zones under climate change
- 3) Analyze climate change impact on groundwater levels in drinking water well zones

In this study, data-driven methods are used to determine which groundwater extractions may not be climate-robust. The effect of future climate scenarios for groundwater supply on the groundwater balance of catchment areas of drinking water extractions and on the levels in the vicinity of extractions is calculated in a data-driven manner. A GIS-based groundwater balance method is used to calculate the groundwater balance per catchment area based on the methodology of Speijer et al. (2024) and time series analysis based on Pastas models (Collenteur et al., 2019) is used to analyze climate change impact on groundwater levels in drinking water well zones.

4 Climate change impact on groundwater recharge in Flanders

4.1 Data and methods

To assess future groundwater recharge scenarios for Flanders, groundwater recharge projections of 17 global climate-impact models were used. This data was obtained from the inter-sectoral impact model intercomparison project's (ISIMIP) most recent simulation round, ISIMIP3b (ISIMIP, n.d.). This is the same dataset as used in Reinecke et al. (2021), however from a more recent simulation round (ISIMIP3b instead of ISIMIP2b). Reinecke et al. (2021) assessed global trends of climate change on groundwater recharge (Figure 1), while here a zoom-in approach is taken for Flanders. 17 climate-impact model outputs for groundwater recharge, available during this analysis (based on 4 impact models, namely CWatM, H08, MIROC-INTEG-LAND and WaterGAP2-2e, in combination with 5 climate forcing models, namely GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0 and UKESM1-0-LL) were analyzed (Table 1). Each climate-impact model consists of three climate change scenarios (SSP1-2.6, SSP3-7.0, SSP5-8.5).

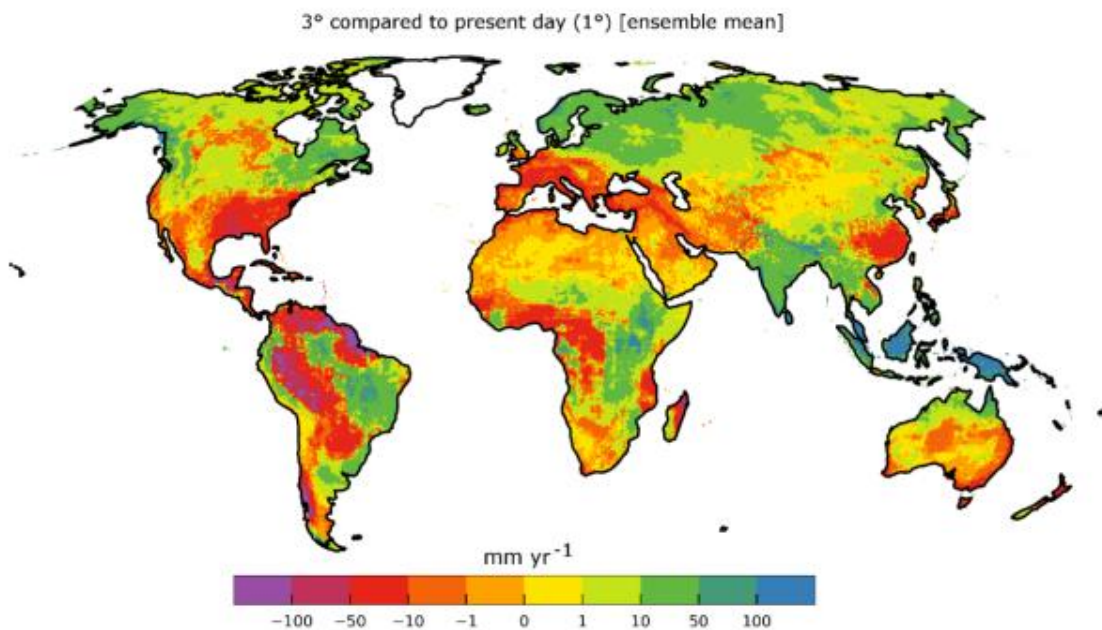


Figure 1: Global analysis of climate change impact on groundwater recharge. Ensemble mean change in groundwater recharge (mm/year) between present-day warming of 1°C global warming compared to 3°C global warming, averaged over the groundwater recharge changes of all model combinations (Reinecke et al., 2021).

Table 1: Analyzed climate-impact models from ISIMIP3b

Impact model	Climate forcing
CWatM	GFDL-ESM4
CWatM	IPSL-CM6A-LR
CWatM	MPI-ESM1-2-HR
CWatM	MRI-ESM2-0
CWatM	UKESM1-0-LL
H08	GFDL-ESM4
H08	IPSL-CM6A-LR
H08	MPI-ESM1-2-HR
H08	MRI-ESM2-0
H08	UKESM1-0-LL
MIROC-INTEG-LAND	GFDL-ESM4
MIROC-INTEG-LAND	IPSL-CM6A-LR
MIROC-INTEG-LAND	MPI-ESM1-2-HR
MIROC-INTEG-LAND	MRI-ESM2-0
MIROC-INTEG-LAND	UKESM1-0-LL
WaterGAP2-2e	GFDL-ESM4
WaterGAP2-2e	IPSL-CM6A-LR

These global climate-impact models simulate groundwater recharge on 0.5° grid cells, of which the 14 grid cells overlaying Flanders were assessed. An example for the grid cells on Flanders is provided in Figure 2 for one climate-impact model (GFDL ESM W5E5), for one climate change scenario (SSP5-8.5). As there are high uncertainties on using simulated values for one grid cell, an average of the 14 grid cells was taken to get an average projection for Flanders. The models project monthly recharge values, so that an analysis was carried out for a yearly, summer (April - September) and winter (October - March) scale. Furthermore, average groundwater recharge values were taken over 30-year time periods, to remove any short-term climatic variations. For each climate-impact model, historical simulated groundwater recharge values over the period 1985-2015 were compared for the horizon 2050 (2035-2065) and 2085 (2070-2099).

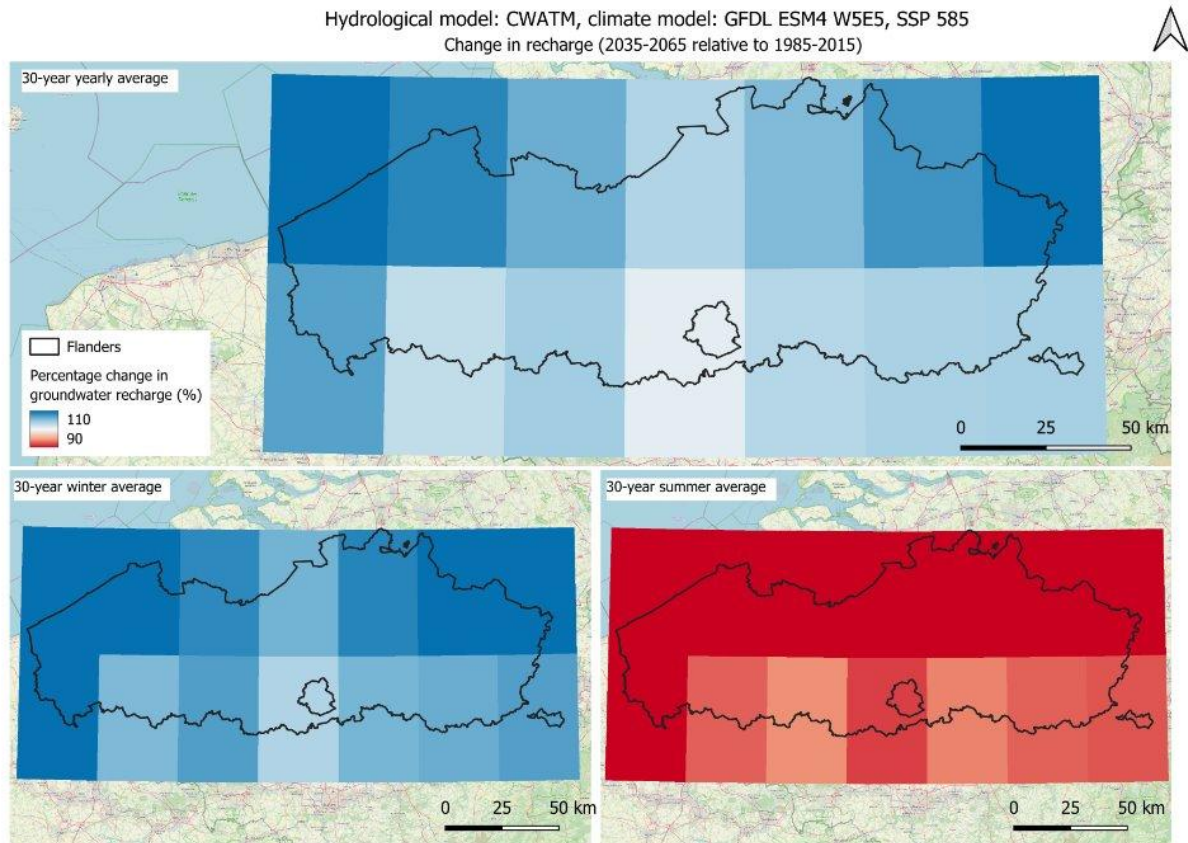


Figure 2: Example of the global climate-impact model outputs for 0.5° grid cells on Flanders for model GFDL ESM4 W5E5, climate change scenario 5-8.5.

4.2 Results

Figure 3 shows the projected percentage change in average groundwater recharge in Flanders under three climate change scenarios, i.e. SSP1-2.6, SSP3-7.0, SSP5-8.5, for the 17 climate-impact models by 2050 and 2085, while Table 2 shows the summary statistics of these results. The results show a wide spread of potential future impacts due to climate change, which increases the further the projections go into the future (i.e., wider spread for 2085 compared to 2050). As Reinecke et al. (2021) describe, this can be attributed to the high uncertainties in the global hydrological models to estimate groundwater recharge. Since it is difficult to measure groundwater recharge, this makes it also hard to verify the modelled results (Reinecke et al., 2021).

Furthermore, it is important to highlight that these results stem from global climate-impact models, with a grid size of 0.5° . This is a coarse grid size for regional to local analysis of climate change impacts. Therefore, only an average projection of Flanders was possible. To further explore differences on a smaller scale, (dynamical or statistical) downscaling of the global data is recommended, similar to efforts on statistical downscaling of precipitation and evapotranspiration for Belgium (Ntegeka et al., 2014; Tabari et al., 2015; Paz & Willems, 2023).

It is visible that the summer projections show the highest decreases in recharge, with the most extreme projections for 2050 indicating a change in groundwater recharge to only 40% remaining of current groundwater recharge. However, a few models project slight increases, especially for the horizon 2085 for the lowest SSP scenario (SSP1.2-6), which shows the high uncertainties in these simulations. The winter shows fewer extreme changes in recharge, and it is less clear from

the model ensemble if an increase or decrease in recharge can be expected, as the 5th and 95th percentile range of projected recharge changes for 2050 range between 88 (decrease in recharge) and 106 % (increase in recharge). Finally, the yearly average ensemble is a combination of both winter and summer projections, in which the relatively wetter winter projections do not completely compensate for the dryer projected summers. Therefore, the ensemble mean shows a change in yearly recharge by 2050 of 95%, indicating a 5% decrease in overall groundwater recharge in future. These trends in expected groundwater recharge under climate change correspond with previous studies in Flanders, such as Dams et al. (2012) and Sumaqua (2022).

In general, the projections for 2050 and 2085 show similar patterns, with wider ranges of projected changes (indicating higher uncertainties) for the 2085 horizon. It is noticeable in the summary statistics (Table 2) that the ensemble mean of change in average yearly groundwater recharge is slightly higher (97.05%) for the 2085 projection compared to 2050 (95.11%). This can be attributed to higher uncertainties of climate models the further projections run into the future. Additionally, more climate models predict wetter winters for 2085, which potentially compensates the general trend of dryer summer periods. This means that the results (although with high uncertainties) indicate that climate change impacts are less severe on a yearly scale, but with an uneven distribution of this recharge on a smaller timescale. This suggests that climate change projections of precipitation and evapotranspiration, indicating wetter winters and dryer summers for Flanders (Tabari et al., 2015), are also propagating into wetter winters and dryer summers in terms of groundwater recharge, suggesting more potential extreme events on a seasonal scale.

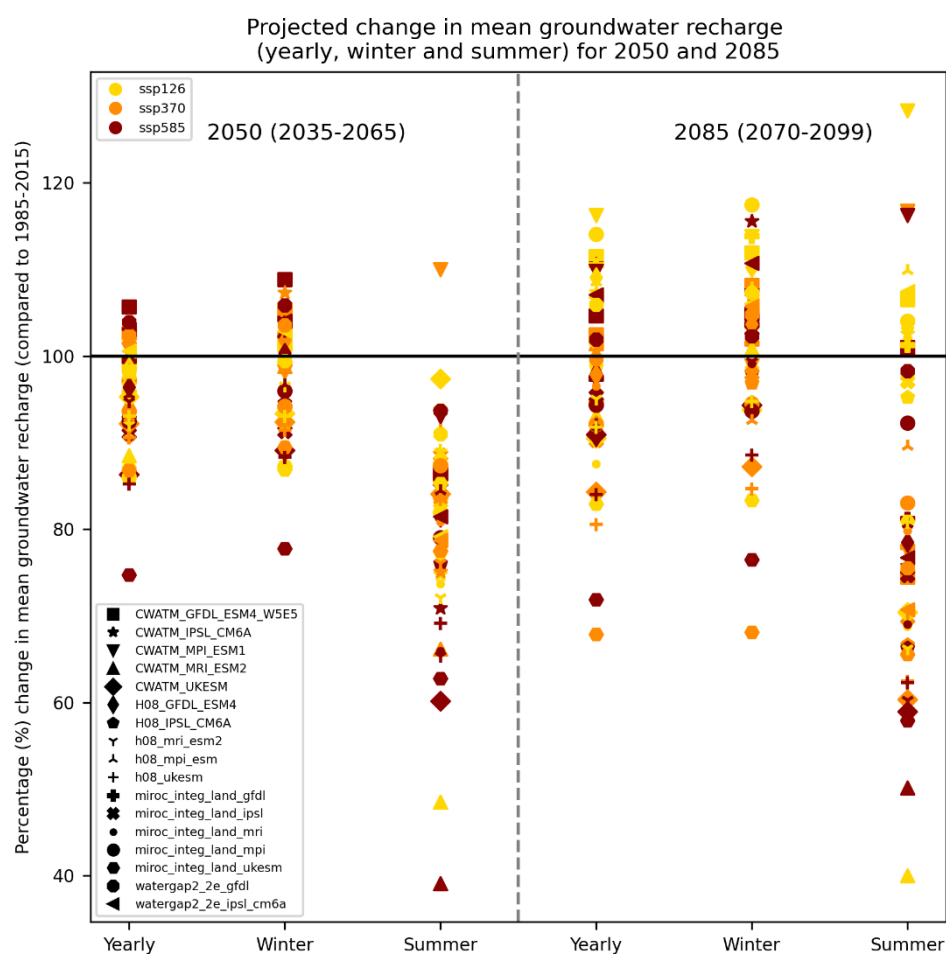


Figure 3: Climate change projections of change in groundwater recharge for 2050 and 2085, based on 17 global climate-impact models (for 3 climate change scenarios, i.e. SSP1-2.6, SSP3-7.0, SSP5-8.5) for Flanders (Belgium).

Table 2: Summary statistics of ensemble of climate change projections for groundwater recharge in Flanders.

% change in groundwater recharge	Ensemble mean	Ensemble 5th quantile	Ensemble 95th quantile
2050 (2035-2065)			
Yearly	95.11	85.88	103.44
Winter	97.79	87.86	105.60
Summer	80.22	61.61	93.70
2085 (2070-2099)			
Yearly	97.05	81.88	110.99
Winter	100.44	84.09	113.82
Summer	80.80	58.29	112.41

5 Water budget in well zones under climate change

5.1 Data and methods

Based on the selected climate projections (section 4), the impact of climate change on the groundwater supply in the groundwater abstraction zones was calculated based on a GIS analysis, following a similar approach as Speijer et al. (2023) by comparing the current and future groundwater supply with groundwater abstraction in the recharge areas of the extraction wells, in order to gain insight into the water budgets in the areas and how they change due to climate change. In this way, it can be estimated whether the pumped volumes would take a substantially larger share of the groundwater supply in future. This analysis is only carried out on a yearly scale, as this budget analysis has to be seen as a long-term average idea of the balance between recharge and abstraction.

The recharge zones of each extraction site are defined as the 100 year travel time of groundwater particles to the well (Figure 4). These zones are partly available on DOV (extraction areas) (DOV, 2022) based on particle tracking performed by VMM, but not for every well zone. Therefore, recharge zones of De Watergroep were used from DOV, whereas recharge zones from Aquaduin were received from Aquaduin, and recharge zones from Pidpa were obtained based on model particle tracking results from VMM. As there was no well zone defined on DOV for the De Watergroep site in Lommel, this abstraction zone is excluded from this analysis. Furthermore, as no data was provided from drinking water company AGSO Knokke-Heist, this abstraction site is not incorporated in the analysis.

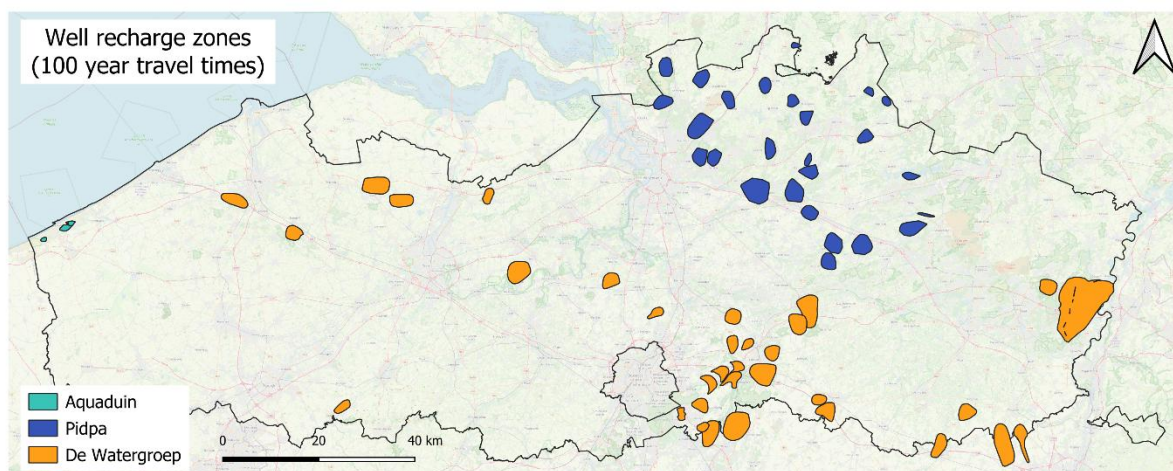


Figure 4: recharge zones (100 year travel times) around groundwater pumping wells for drinking water production in Flanders.

Important to note that this 100 year delineation is most suitable for phreatic, shallow aquifers, of which most of the abstracted water is less than 100 years old. However, for deeper wells (for example in semi- or confined aquifers) these travel times can be much longer, so that this delineation of 100 year travel times excludes a larger portion of the total recharge zone. Especially for the deeper semi-confined wells in the Campine area (mostly in possession of Pidpa), considerable parts of the actual well zone are excluded because of this 100-year zone delineation (Figure 5).

Additionally, an important consideration here is that we assume same recharge zones for current and future climate, since the recharge zones are delineated based on current groundwater

systems. In reality these zones will most likely also change with climate change and human driven land development. However, it is out of the scope of this research to incorporate this aspect, as extensive groundwater flow modelling would be needed for every well site.

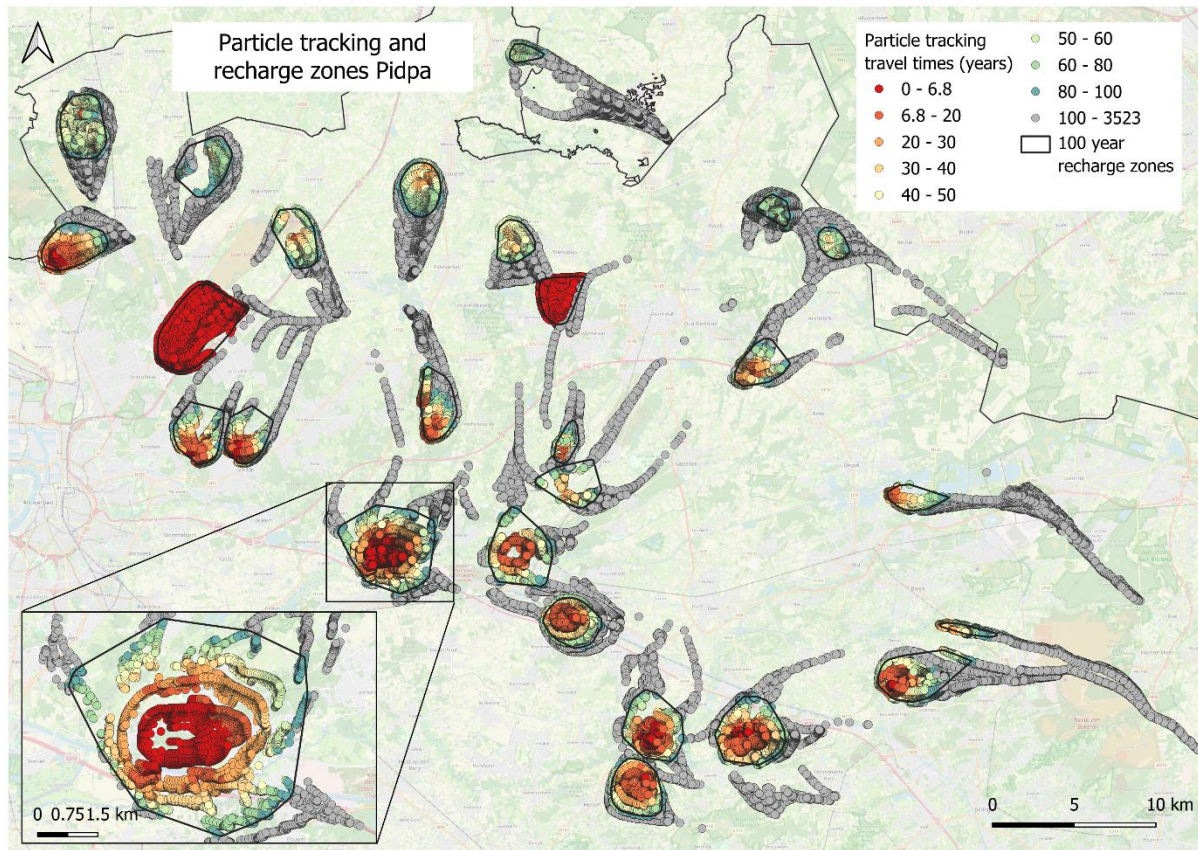


Figure 5: Delineation of the 100-year recharge zones around abstraction wells based on particle tracking from groundwater modelling. For certain deeper abstraction wells, the fraction of recharge zone with travel times larger than 100 years is visible.

For the abstraction part of the budget, an average yearly abstraction volume is taken over the period 2000-2023 for all wells of De Watergroep and Pidpa. For Aquaduin, abstraction data for the period 2015-2024 was used. Wells in one well zone are combined as they are part of the same recharge zone. Additionally, confined wells of De Watergroep were excluded, as this relationship between recharge zones and abstraction is more difficult to interpret for confined wells. However, deeper, semi-confined wells are still taken into account. Figure 6 shows the location and depth of all analyzed abstraction wells, while Figure 7 shows the type of aquifer of De Watergroep wells (confined, semi/unconfined), of which the confined wells are excluded from this water balance analysis. Some well fields consist of both confined and unconfined abstraction wells, in this case only confined well abstraction volumes are excluded. Importantly to note is that there are no analyses incorporated of future pumping rate scenarios, and so the pumping rate in current climate conditions are kept constant for future climate projections on the water balance.

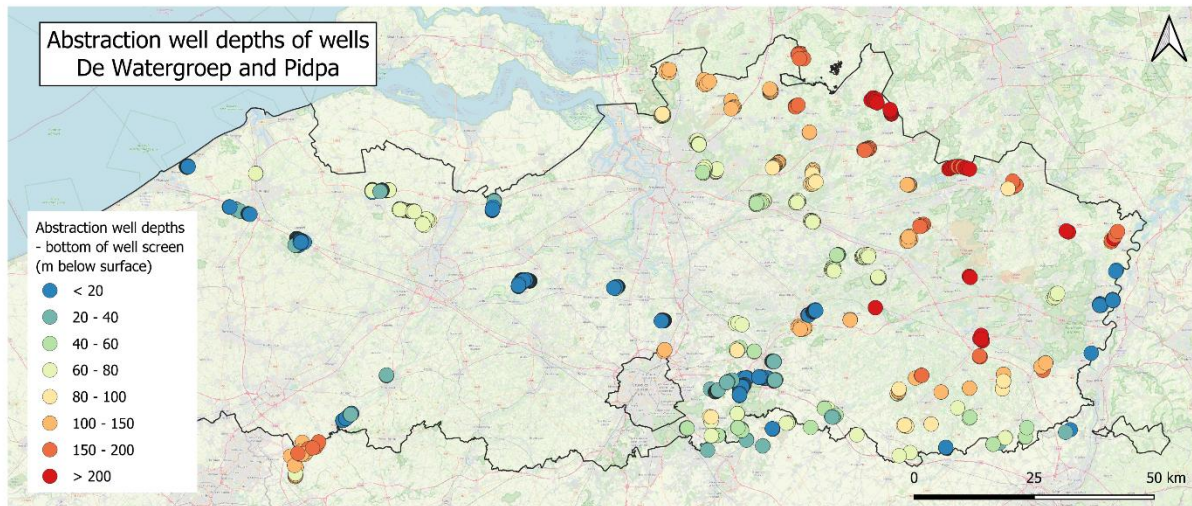


Figure 6: Depth of bottom of well screen (relative to surface) for wells of De Watergroep and Pidpa.

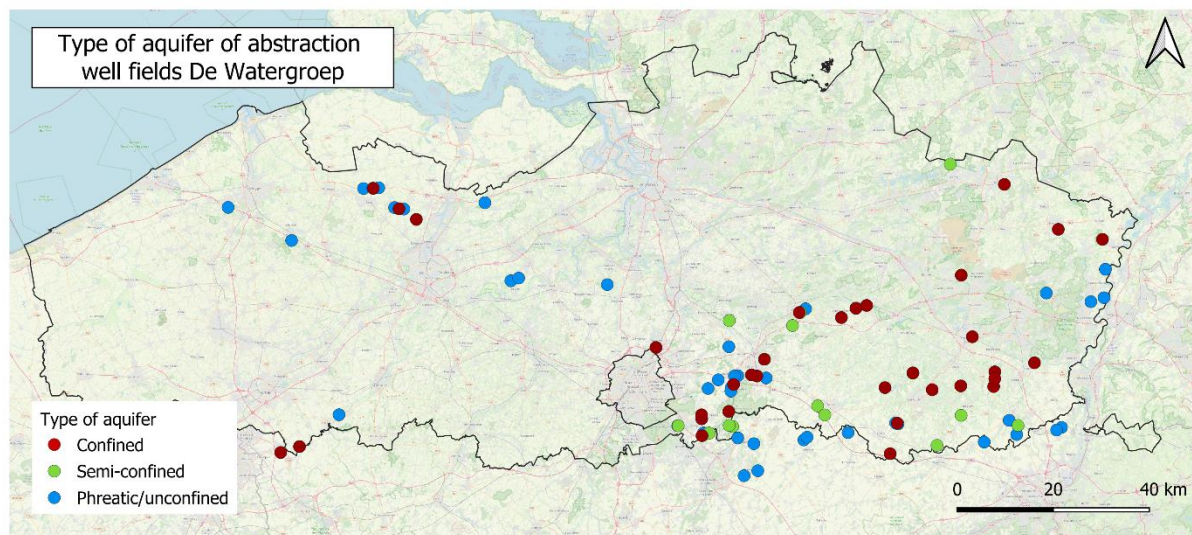


Figure 7: Type of aquifers of abstraction well fields De Watergroep. Confined abstraction wells are excluded from this water balance analysis. Certain well fields consist of both unconfined and confined wells, only the confined abstraction volumes are excluded.

For the recharge part of the water balance, the current annual recharge map simulated with WETSPASS is used (Figure 8) (Zomlot et al., 2015). Since groundwater recharge is difficult to measure, there are various methods to calculate groundwater recharge. In Flanders, the groundwater recharge maps developed by the VUB based on the WETSPASS model (Batelaan & De Smedt, 2007; Zomlot et al., 2015) are often used. Groundwater recharge maps are available on an annual and seasonal (winter and summer) scale. However, only the annual map is used in this analysis to look at long-term annual trends in water balances.

Additionally, for the Aquaduin Sint André site, extra recharge is added based on the infiltration rates of the installed Managed Aquifer Recharge system (Aquaduin, n.d.). For parts of the recharge zones located in the Netherlands or Wallonia, no simulated recharge values are available from WETSPASS (Zomlot et al., 2015). Here, an average recharge was given to the no-data cells based on the average recharge in the rest of the recharge zone.

For future groundwater recharge volumes, the current recharge volumes are multiplied with a projected change in groundwater recharge calculated in section 4 based on global climate-

impact model projections. As there is a high uncertainty in potential future impacts on groundwater recharge, the mean, 5th and 95th quantile of the expected change in groundwater recharge from the model ensemble (Table 2) are taken to incorporate both average and extreme worst-case scenarios in future groundwater recharge projections. Here it is important to notice that section 4 only provided average changes in groundwater recharge for Flanders combined, as uncertainties become too high to look at smaller scales of these global climate-impact outputs. Therefore, an important assumption in this analysis is that groundwater recharge changes in the whole region of Flanders equally as percentage of the current groundwater recharge. However, in reality, groundwater recharge might react differently to climate change throughout the region, given varying characteristics such as soil type, depth to groundwater, and slope. For this, more local, unsaturated zone modelling is needed to capture the impact of climate change on infiltration and groundwater recharge.

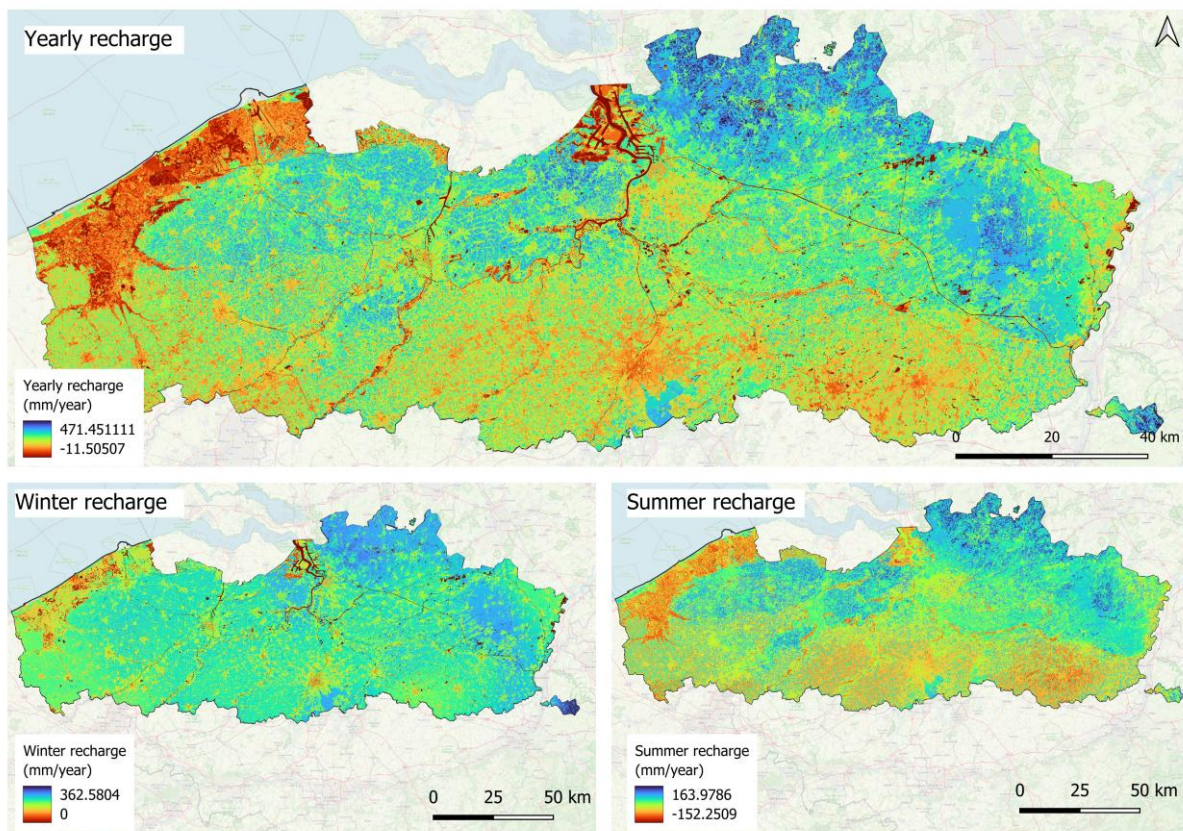


Figure 8: Simulated long-term average yearly, winter and summer groundwater recharge (mm/year) in Flanders (Zomlot et al., 2015)

5.2 Results

Figure 9 shows the calculated water balances in each groundwater well zone under the current climate. This shows a wide range of percentages of abstraction volume relative to current groundwater recharge. A percentage higher than 100% means that abstraction volumes are exceeding recharge volumes in this area. There are several well-fields showing high percentages, indicating potential stresses on the water budget in these areas with future climate change. These areas are specifically noticeable in several wells in the Campine region, as well as in a few well fields south of Leuven.

An important sidenote to make with these results is that abstraction volumes from semi-confined aquifers were included in this analysis. As shown in Figure 6, especially Pidpa (in the Campine area in the North of Flanders) has some deeper wells in semi-confined aquifers. Therefore, this water balance analysis of directly comparing the surrounding recharge zone with abstraction becomes less straightforward. Additionally, bigger portions of the complete recharge zone have travel times larger than 100 years, which were excluded in the 100-year recharge delineation (Figure 5) which means that the recharge in the well zones is underestimated for these well zones. Therefore, it is important to note that, although there are several well fields identified as having high percentages of abstraction versus recharge in the Campine area, that these results are more uncertain than water balance analyses of more shallow wells. Additionally, it is very logical that in regions with thick and permeable aquifers such as in the Campine area, larger volumes of groundwater can be extracted.

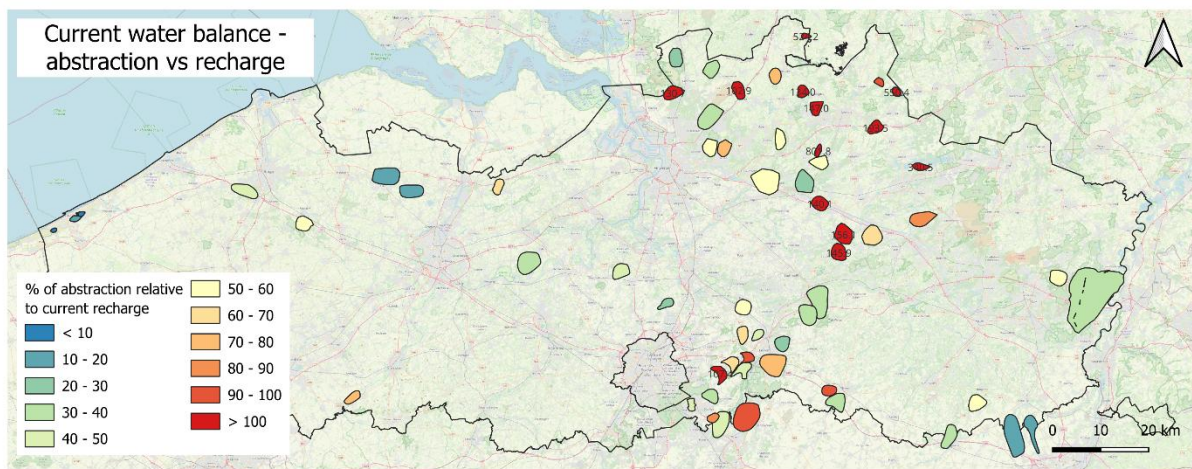


Figure 9: Calculated water balance of annual recharge versus abstraction in well zones for current climate conditions. Values show the percentage of yearly abstraction relative to recharge in each zone, with a percentage lower than 100% meaning recharge volume exceeds abstraction volume, while a percentage higher than 100% indicates the opposite.

Additionally, as Aquaduin possesses a Managed Aquifer Recharge system of infiltration ponds to enhance groundwater recharge (Aquaduin, n.d.) in the Sint André site, it was calculated how much this infiltration contributes to the water balance in the well sites (Table 3). Important sidenote is that infiltration in Sint André ZP1 site started in 2019, which skews average infiltration rates over the period 2015-2024 for this area. Results show that the infiltration volumes in both sites compensate a large share of the abstracted water. Additionally, especially for location ZP2 the infiltration significantly enhances natural groundwater recharge in the well zone. The analysis of the water balance of well sites of Aquaduin shows that all well sites are within the lower range of percentages (max. 18%) (Figure 9, Table 4), indicating that abstraction only takes up a small part of the recharge, of which the MAR system contributes to. However, as Aquaduin is located at the coast, these well sites face the threat of saltwater intrusion due to sea level rise given climate change, which was however out of the scope of this analysis.

Important sidenote is that other initiatives towards drought adaptation, focussing on increasing groundwater recharge are deployed in some well sites. However, as the data for these measures were not provided, these were excluded from this budget analysis. These existing and potential future initiatives (will) make the water balance of abstraction versus recharge less vulnerable to climate change, as more water is supplied to the groundwater system. Important examples are an infiltration basin in Grobbendonk supplied with 1 Mm³ treated canal water per year, infiltration

basins of rinse water at all water production centers of Pidpa adding to approximately 3% of the abstracted water and irrigation measures in well sites such as Balen-Kanaal, Oostmalle and Arendonk to dampen the effects of the abstraction wells.

Table 3: Contribution of Aquaduin's MAR system on the water balance

Site	Average yearly infiltration volume relative to abstraction volume (%)	Average yearly infiltration volume relative to natural recharge (WETSPASS) (%)
Sint-André (STA) ZP1	28.82	2.42
Sint-André (STA) ZP2	67.34	13.38

Figure 10 shows the future climate change projections of these water balances, based on the calculated changes in groundwater recharge in section 4, including scenarios for the ensemble mean (expected slightly dryer conditions of a decrease in recharge of 5%), ensemble 5th quantile (representing worst-case dry projections) and ensemble 95th quantile (representing worst-case wet projections). Here, we see that the water balance in each of the well zones slightly deteriorates for the ensemble mean scenario (Figure 5, top), while the 5th quantile scenario shows even higher percentages of abstraction versus recharge due to the expected decrease in recharge of 14%. Oppositely, the 95th quantile scenario represents a worst-case wet annual climate change projection, in which the recharge increases by 3%, which indicates that the groundwater system will experience less pressure from abstraction for drinking water production.

However, an important sidenote must be made regarding the future projections of climate change on recharge in this budget analysis. As only a regional average of change in recharge could be obtained for Flanders from global climate-impact models, no regional patterns of effects of climate change on recharge could be taken into account. Therefore, the effect of different subsurface characteristics on recharge in a changing climate in Flanders is not considered. Also, as a percentage change in recharge is taken, this change will be bigger in absolute terms in areas with higher recharge compared to areas with lower recharge values (see Figure 8). Future research, including downscaling of global climate change projections of recharge, as well as unsaturated zone modelling incorporating properties such as the soil, slope and land use are important to assess the impact of climate change on groundwater recharge in different locations in Flanders. Additionally, the pumping rates in future scenarios are kept equal to abstraction rates in current climate. These results should therefore be combined with the parallel report on water demand projections. Table 4 gives an overview of the calculated percentages of the water balance (abstraction versus recharge) for each of the well zones, in order from highest to lowest percentages per drinking water company, for the current and future scenarios. From this analysis, we can conclude that, as climate change is projected to result in an decrease in groundwater recharge, the ratio of pumping versus recharge is expected to increase everywhere in Flanders. High ratios of abstraction versus recharge do not necessarily translate into large effects on groundwater levels. The effects on groundwater levels are calculated in chapter 6.

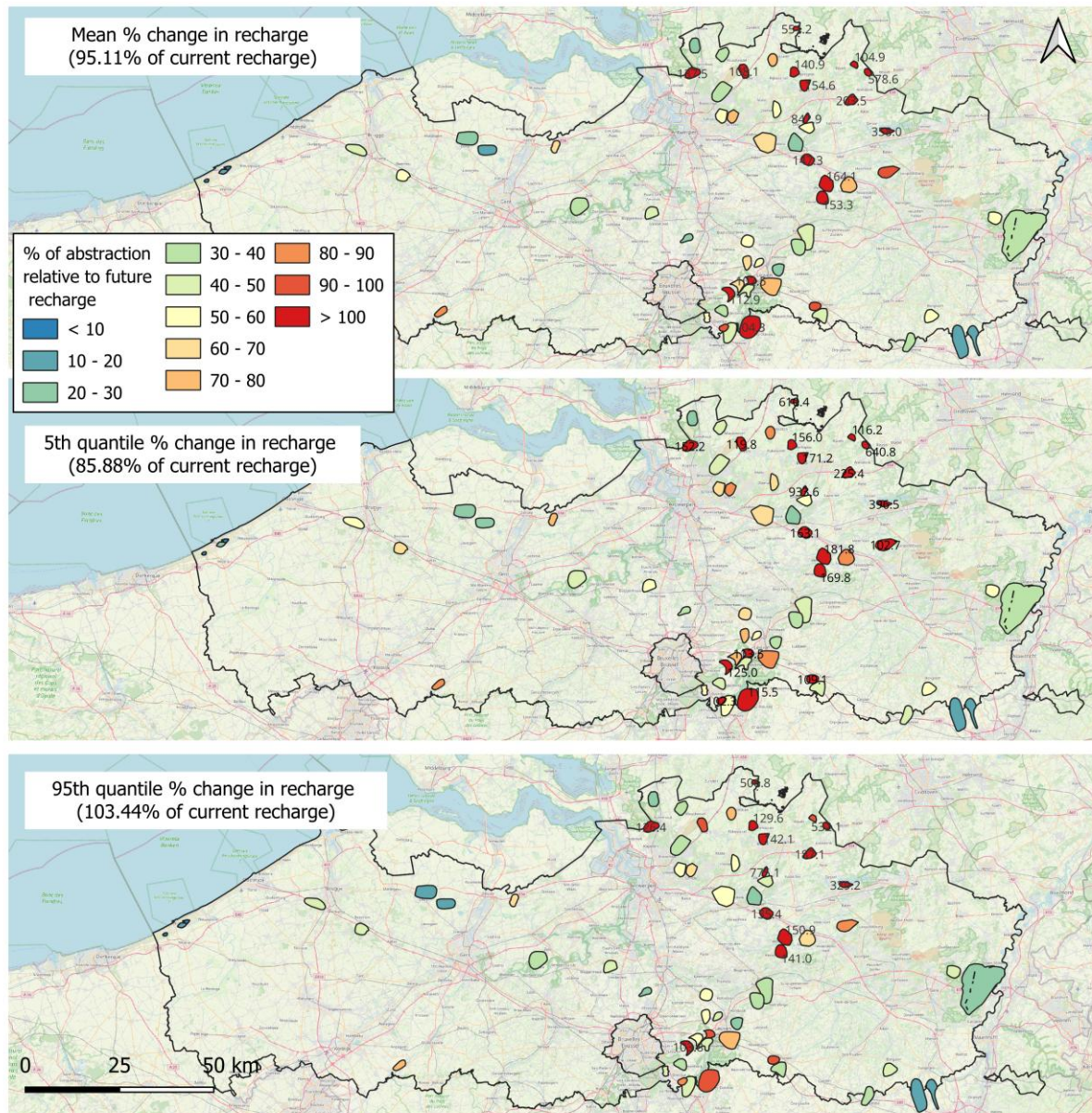


Figure 10: Calculated water balance of annual recharge versus abstraction in well zones for projected changes (for 2050 horizon) in groundwater recharge due to climate change. Top: ensemble mean of estimated change in yearly recharge. Middle: 5th quantile of ensemble, representing worst-case scenarios of very dry conditions. Bottom: 95th quantile of ensemble, representing worst-case scenarios for very wet conditions.

Table 4: Summary statistics of ensemble of climate change projections for groundwater balance in drinking water well fields in Flanders.

% yearly abstraction versus recharge volume	Current water balance	2050 water balance, mean	2050 water balance, 5th quantile	2050 water balance, 95th quantile
Change in groundwater recharge	/	95.11% of current recharge	85.88% of current recharge	103.44% of current recharge

De Watergroep

Leefdaal-Puttebos-Keiberg	107.35	112.86	125.00	103.79
St-Agatha-Rode-Veeweyde-Grez-Doiceau	99.22	104.31	115.53	95.92
Egenhoven-Oost-en-West	97.50	102.51	113.53	94.26
Kumtich-Menebeek	93.69	98.50	109.09	90.58
Overijse-Venusberg	87.90	92.41	102.35	84.98
Avelgem-Waarmaarde-Kerkhove	76.98	80.94	89.64	74.43
Huiskens-Abdij-Cadol	73.90	77.70	86.05	71.45
Moerbeke-Wachtebeke	65.58	68.95	76.36	63.40
Leefdaal-St-Veronica-en-Dispatching	61.40	64.55	71.49	59.36
Winksele-Kastanjebos	60.17	63.26	70.07	58.17
Haacht-den-Dijk	56.39	59.29	65.66	54.52
Beernem	51.54	54.19	60.02	49.83
As	50.93	53.54	59.30	49.24
Voort	50.81	53.42	59.17	49.13
Hoeilaart	49.79	52.35	57.98	48.14
Herent-Bijlok	49.42	51.96	57.55	47.78
Overijse-Sana-Rosieres	47.49	49.92	55.29	45.91
Londerzeel-Koevoet	45.32	47.65	52.77	43.81
Snellegem	43.01	45.22	50.08	41.58
Korbeek-Dijle	41.42	43.54	48.23	40.04
Tienen-Groot-Overlaar	39.68	41.72	46.21	38.37
Schoonhoven-Weerderlaak	38.20	40.16	44.47	36.93
Bovelingen	37.29	39.21	43.43	36.06
Overijse-Kouterstraat-Nellebeek	36.46	38.33	42.45	35.25

Berlare-Zele	34.59	36.36	40.27	33.44
Nieuwrode-het-Rot	32.17	33.82	37.46	31.10
Eisden-Meeswijk	30.71	32.29	35.76	29.69
Kessel-lo-Vlierbeek	28.05	29.49	32.66	27.11
Zemst-Spelt	27.90	29.33	32.49	26.97
Eeklo	19.20	20.19	22.36	18.56
Lembeke-Oost-Eeklo	18.67	19.62	21.73	18.05
Diets-Heur	15.99	16.81	18.62	15.46

Pidpa

Gierle	801.76	842.91	933.57	775.13
Arendonk	550.36	578.60	640.83	532.08
Meerle	524.25	551.15	610.43	506.83
Mol	340.54	358.02	396.53	329.23
Oud-Turnhout	193.55	203.48	225.37	187.12
Westerlo	156.12	164.13	181.78	150.93
Beerse	147.00	154.55	171.17	142.12
Herselt	145.85	153.34	169.83	141.01
Olen	140.08	147.27	163.11	135.43
Merksplas	134.00	140.88	156.03	129.55
Kapellen	130.75	137.46	152.24	126.40
Brecht	102.86	108.14	119.77	99.44
Ravels	99.79	104.91	116.19	96.48
Balen-Kanaal	88.18	92.71	102.68	85.26
Hoogstraten	74.05	77.85	86.23	71.59
Schilde	71.55	75.22	83.31	69.17
Vorst	68.81	72.34	80.12	66.53

Grobbendonk	58.94	61.97	68.63	56.98
Oostmalle	53.20	55.94	61.95	51.44
Schoten	52.05	54.72	60.61	50.32
Poederlee	50.76	53.36	59.10	49.07
Brasschaat	36.94	38.84	43.02	35.72
Wuustwezel	36.35	38.21	42.32	35.14
Herentals	25.66	26.97	29.87	24.80
Essen	24.35	25.60	28.35	23.54

Aquaduin

ZP2 Sint-André (STA)	17.52	18.31	20.02	17.01
ZP1 Sint-André (STA)	8.18	8.59	9.49	7.92
Westhoek (WH)	5.87	6.17	6.83	5.67

6 Climate change impact on groundwater levels in well zones

6.1 Data

The climate data used as stresses in the Pastas models are two series of precipitation and potential evapotranspiration for 30-years series for current climate and future climate conditions following a reduced set of 30 climate model runs for 2050 and 2100 as shown in Figure 11.

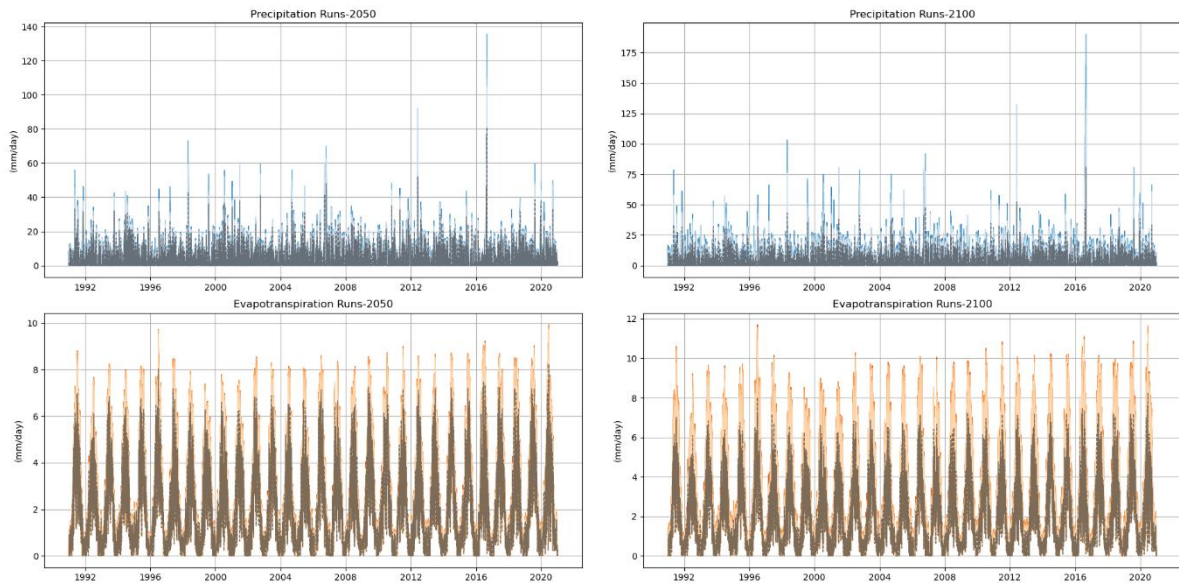


Figure 11: Precipitation and evapotranspiration perturbed scenarios.

Observed groundwater levels and abstraction data was provided by Pidpa, De Watergroep and Aquaduin. As no data was provided from drinking water company AGSO Knokke-Heist, this abstraction site is not incorporated in the analysis. The analysis was carried out for each well with data but filtered in the results by the accuracy of the simulation (further detailed in the next sections).

6.2 Methods

Historical data was used to perform timeseries analysis. These data-driven models were used to predict future groundwater levels. They rely on historical data and statistical or machine learning techniques to understand and forecast groundwater behaviour (Collenteur et al., 2019; Wu et al., 2023; Ahmadi et al., 2022; Feng et al., 2024). The models can identify patterns and relationships in historical data, which can be used to predict future groundwater. For this analysis, Pastas (Collenteur et al., 2019) was applied to the areas of interest to assess their reliability and robustness under future scenarios.

Pastas is an open-source Python package designed for the analysis and modelling of groundwater time series. It provides tools for processing, analysing, and interpreting groundwater data to understand and predict groundwater behaviour. It uses numerical optimization to fit the model to observed data, adjusting parameters of the response functions

and stress models to minimize the difference between observed and simulated groundwater levels.

Pastas uses linear and non-linear transfer function noise (TFN) models to estimate groundwater recharge. These TFN models are then used here to translate recharge into groundwater levels. They can be applied to the wells of interest and apply stressors such as recharge, as mentioned before, but also observed river levels and pumping wells. As precipitation and evaporation can only explain some of the fluctuations observed in the groundwater levels, adding these stressors to the model would provide more accurate simulated groundwater levels. This can provide a more comprehensive understanding of how different hydrological components interact and influence groundwater levels.

A comparison of recharge and groundwater levels estimates using different models is possible, as well as model performance, and shown in the example in figure 12. Other stressors, such as pumping data, can also be added to the model

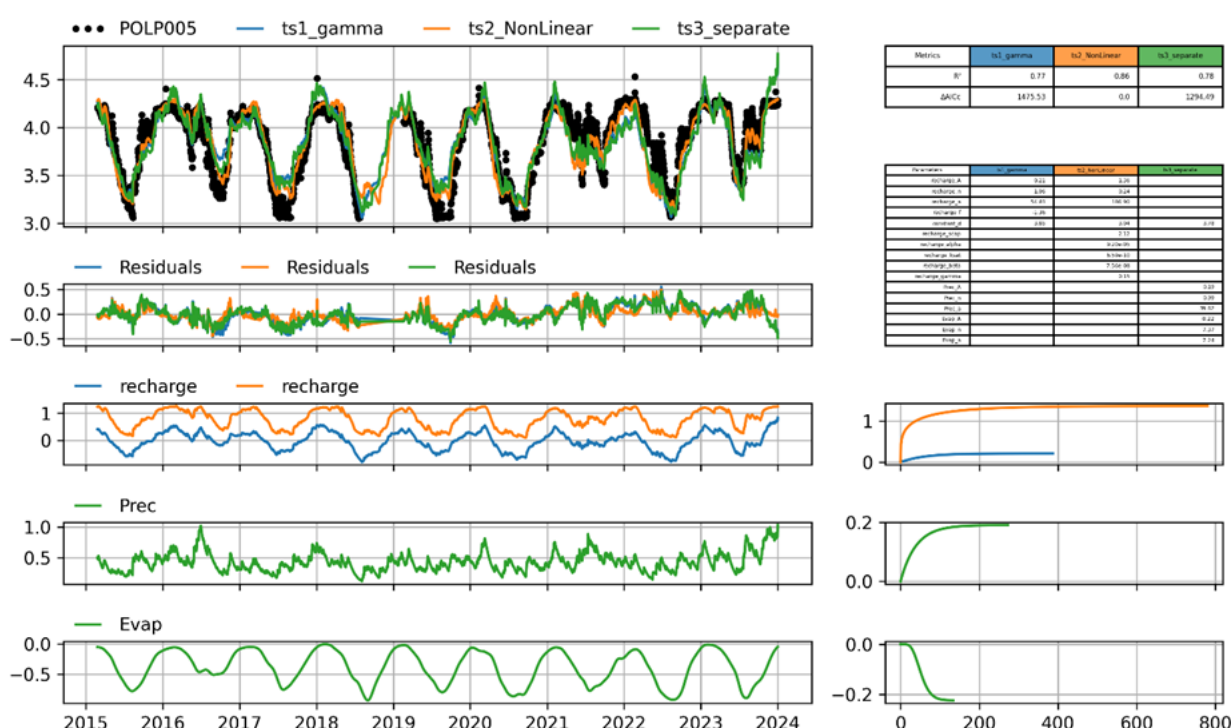


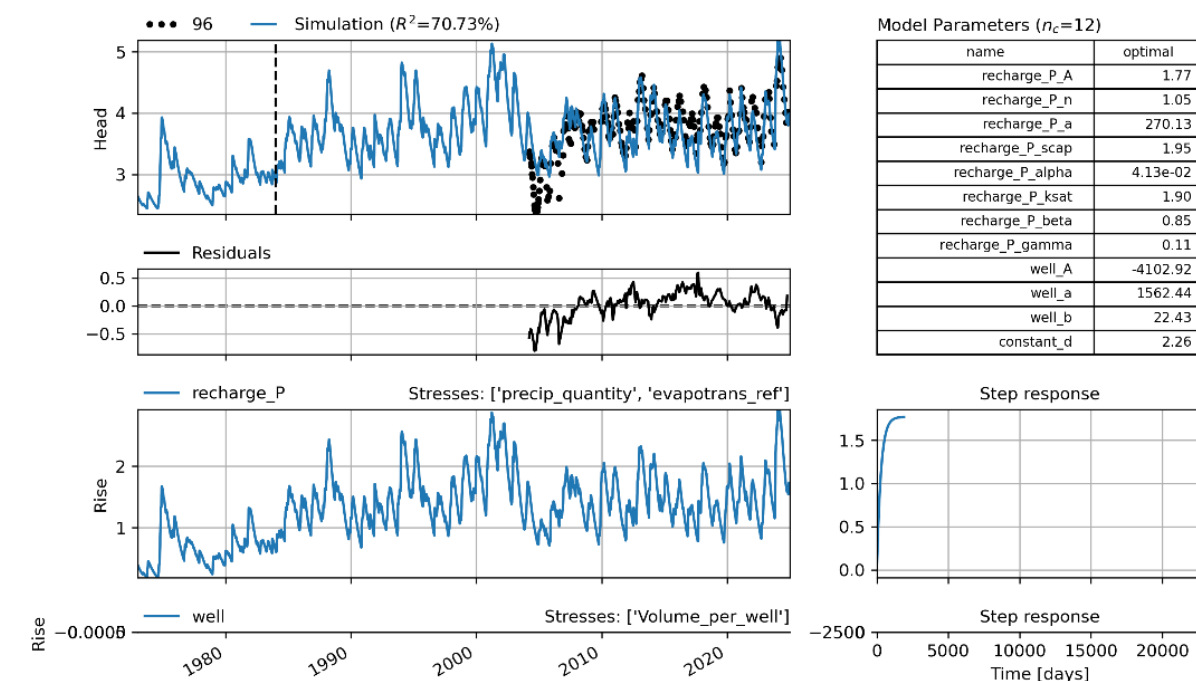
Figure 12: Example of different simulations with different methodologies calculating recharge.

A scenario analysis for future climate conditions was then carried out with the most appropriate methodology depending on quality and quantity of data needed, and model performance. The simulated groundwater levels provided by pastas are the basis for predicting groundwater levels under climate change scenarios.

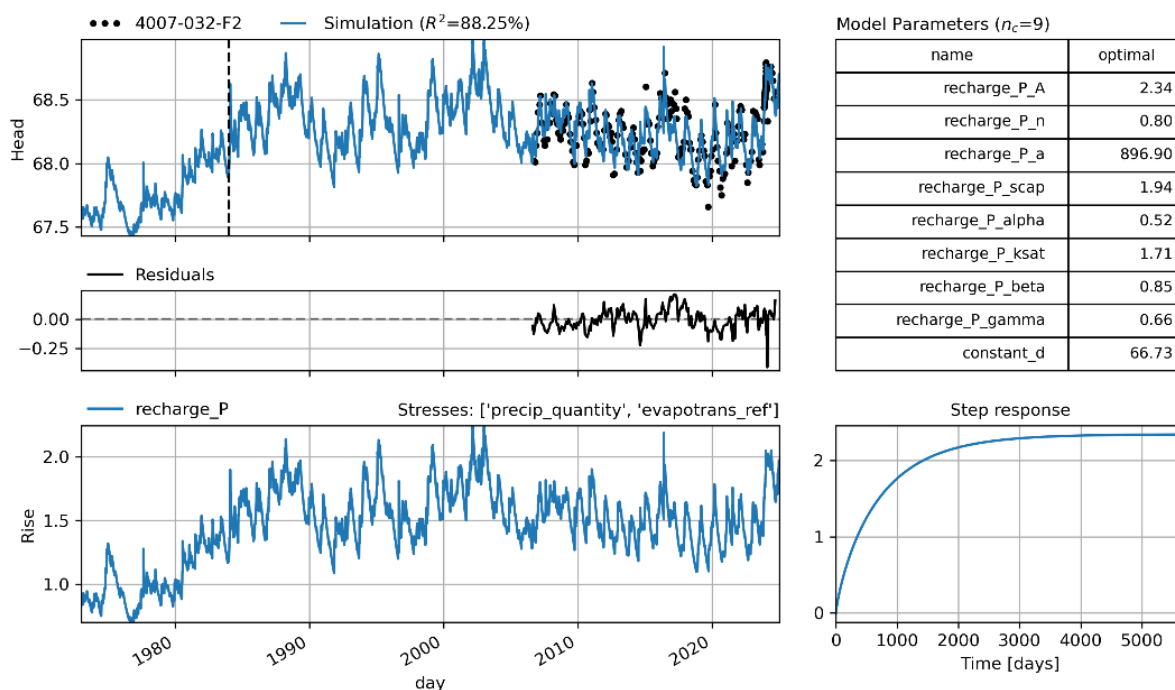
6.3 Results

Pastas timeseries analysis was used for all group of wells for Pidpa, De Watergroep and Aquaduin. Observed groundwater levels, precipitation and evapotranspiration corresponding to well location were used. Pastas uses linear and non-linear transfer function noise (TFN) models to estimate groundwater recharge. Simulations have been made for several methodologies, and overall it was found that non-linear methods perform better. After simulations were carried out for

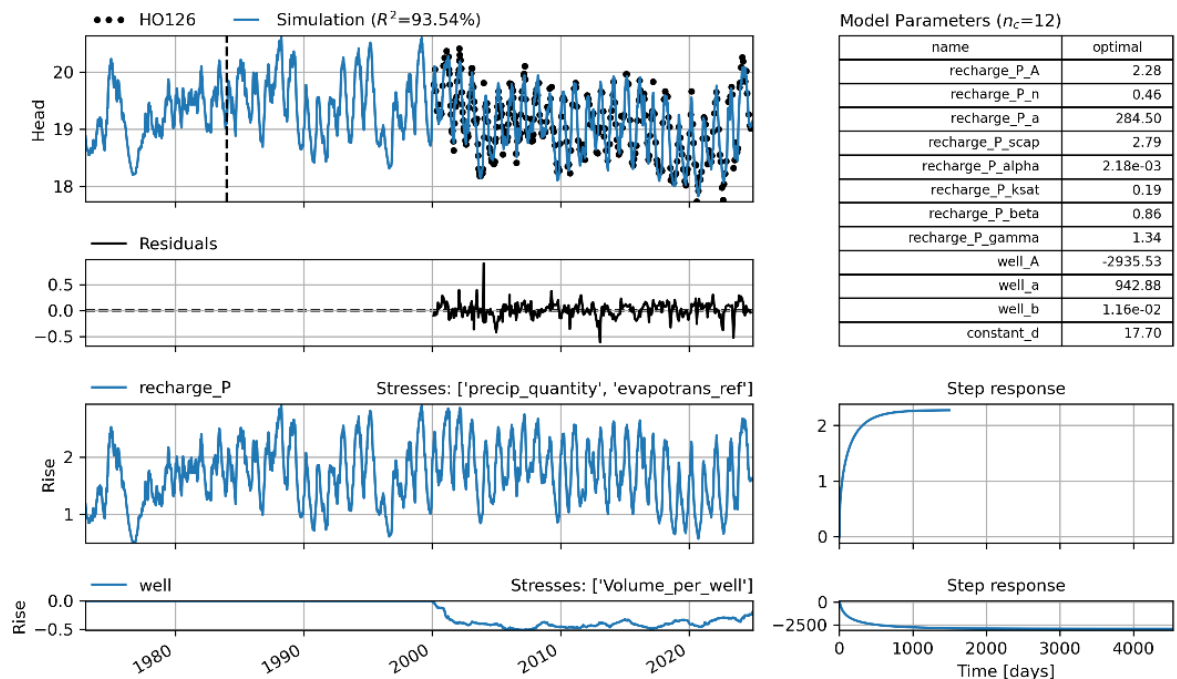
all wells, the results were filtered for the ones that produced simulations with at least 50% accuracy for Aquaduin and 70-80% accuracy for Pidpa and De Watergroep. The lower cutoff percentage for Aquaduin was chosen because of a lower performance of Pastas for Aquaduin data. An example of each of the water companies' results for historical simulations to illustrate the method is shown in Figure 13.



a)



b)



c)

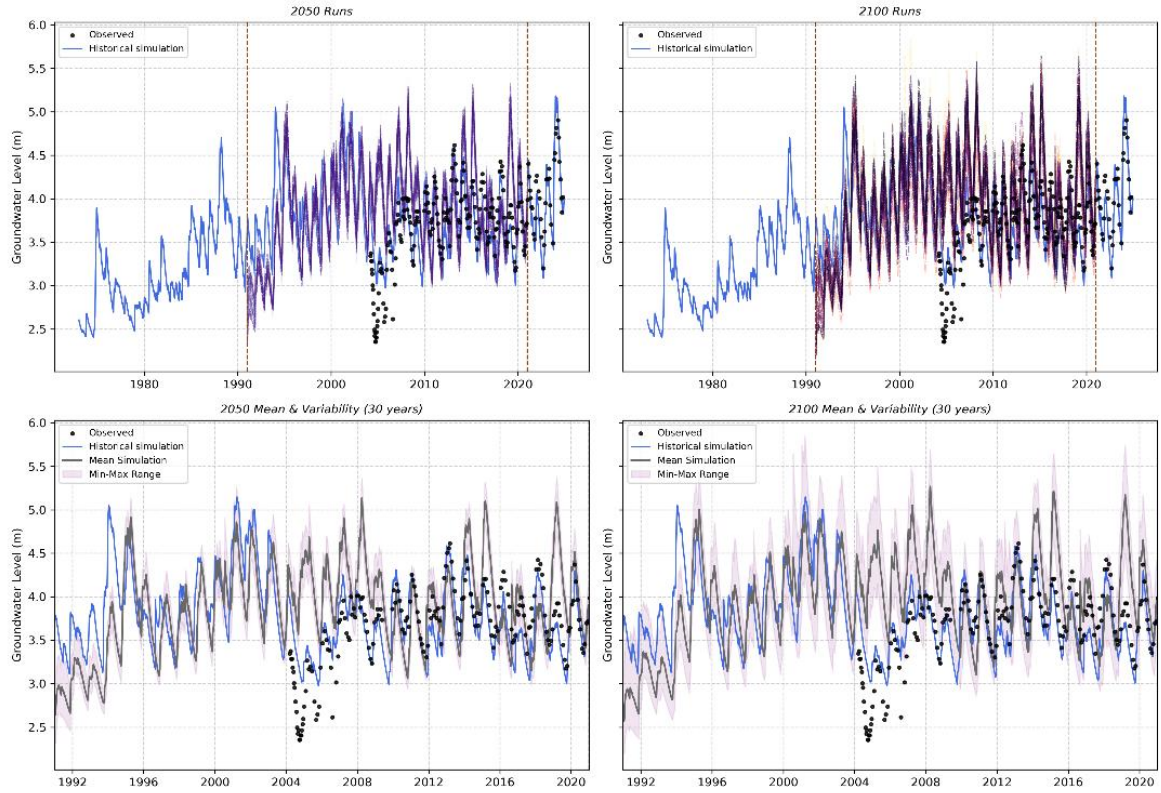
Figure 13: Examples of historical pandas simulations for a) Aquaduin; b) De Watergroep; and c) Pidpa

Following the historical simulations of wells, climate impact on groundwater levels was analysed for each of these wells. These simulations were carried out by:

1. Calibrating the model on historical data
2. Recreating the recharge model with the new rain and evapotranspiration data for each run of the 2050 and 2100 perturbed scenarios
3. Recreating the well abstraction stress model (when applicable)
4. Creating a new model with the same structure as the calibrated model
5. Setting the parameters of the new model to the calibrated values
6. Simulating using the already-calibrated parameters

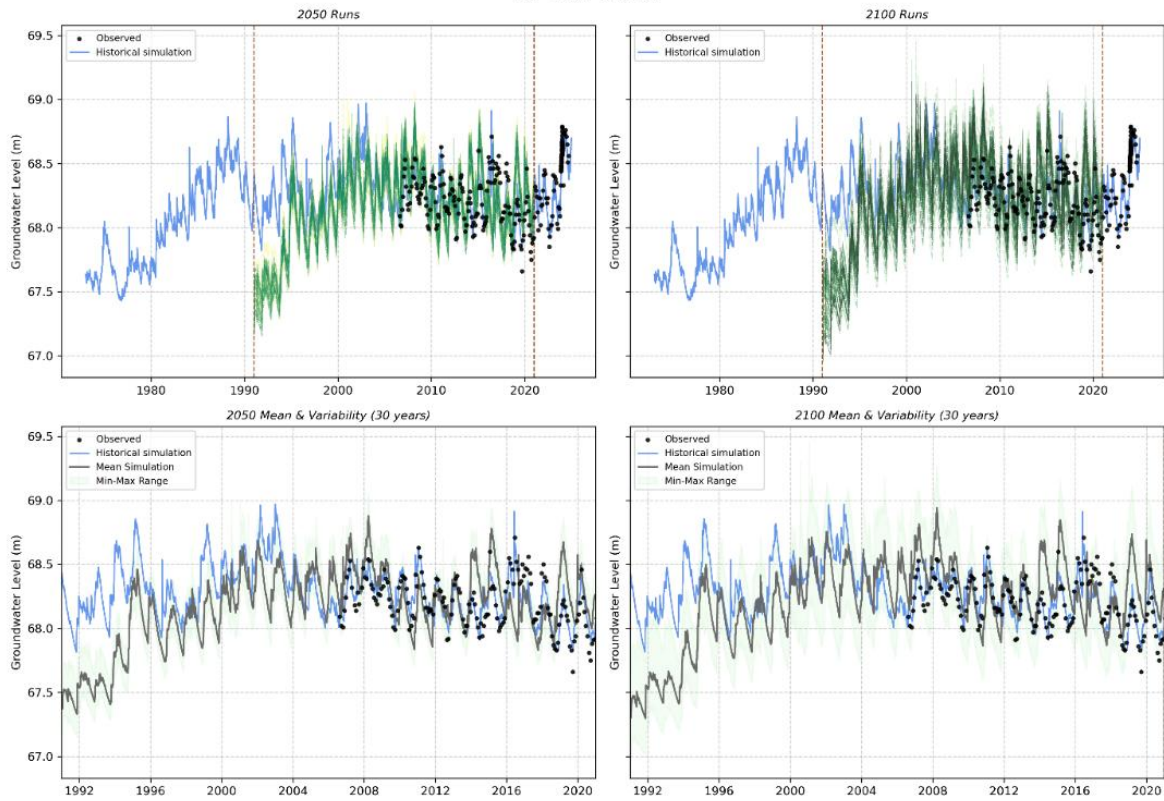
Results seen in Figure 14 show examples of historical simulations, observed levels, and each of the simulated runs for 2050 and 2100 runs (top figures), and mean timeseries for 2050 and 2100 scenarios with the minimum and maximum range (bottom figures). To be able to compare the future perturbed simulations, they are plotted on the same graphs but obviously do not correspond to the horizontal time axis.

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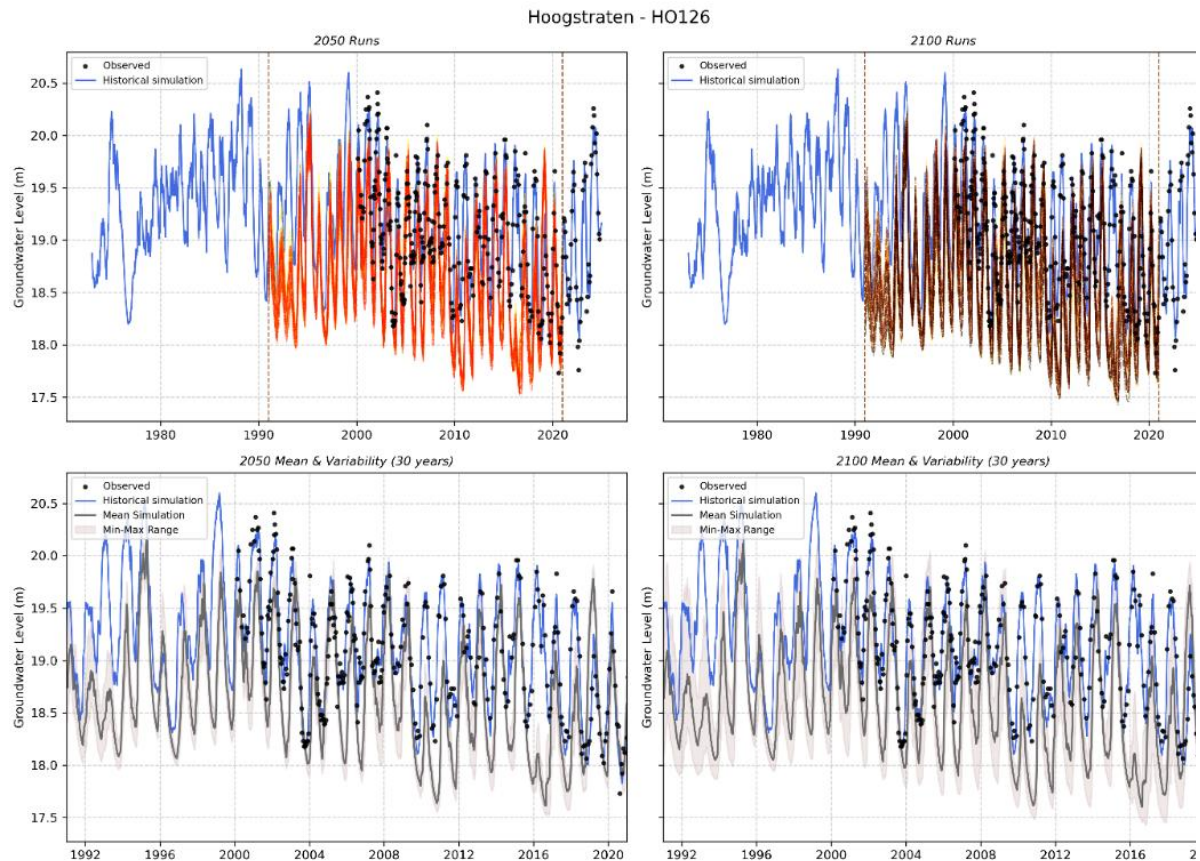


a)

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b)



c)

Figure 14: Examples of 2050 and 2100 perturbed scenarios for a) Aquaduin; b) De Watergroep; and c) Pidpa.

Figure 15 summarizes the calculated effect of climate change on groundwater levels around drinking water wells. Decreases in projected average groundwater levels occur mainly in the north of Flanders while stable or increasing groundwater levels are mainly projected for southern Flanders. This seems to indicate that especially regions with permeable soils and aquifers and shallow groundwater levels are prone to groundwater level decline under climate change. As in regions with shallow groundwater levels and permeable soils and aquifers, groundwater levels decline more rapidly in periods of drought and as climate change will result in more frequent and longer periods of drought, it is logical that in such regions groundwater levels will on average be lower in a changing climate, even if groundwater levels recover after drought.

This effect and spatial patterns were also observed in an earlier study from Sumatra. This study used a spatial interpolation model with information from 217 point locations to create a spatial map with potential GLG (mean lowest groundwater level) changes in 2050 based on SWAP models. The spatial interpolation model is a machine learning model that takes into account, among other things, the thickness of the phreatic aquifer, the topographic position index, the distance to the drainage base, soil texture, average rainfall surplus, and land use (Franken and Wolfs, 2022). This study suggested that overall, locations with a thin aquifer layer and shallow groundwater levels, are more sensitive to drying out due to climate change with an increase in the number of dry days and the frequency of extremely low groundwater levels (**Figure 16**).

Although the current study and the Sumaqua studied used completely different methodologies and although Sumaqua calculated GLG (mean lowest groundwater level) while the current study calculated average groundwater level changes, similar patterns can be observed with decreasing levels in the north and west of Flanders and stable or increasing levels in the south of the provinces of Limburg and Vlaams-Brabant.

Interpretations of these maps and subsequent tables and maps in the next section should be done carefully. As purely data-driven models are used, not all models had a very good fit and not all local factors are taken into account in the models, readers should be aware that these models results exhibit some uncertainty.

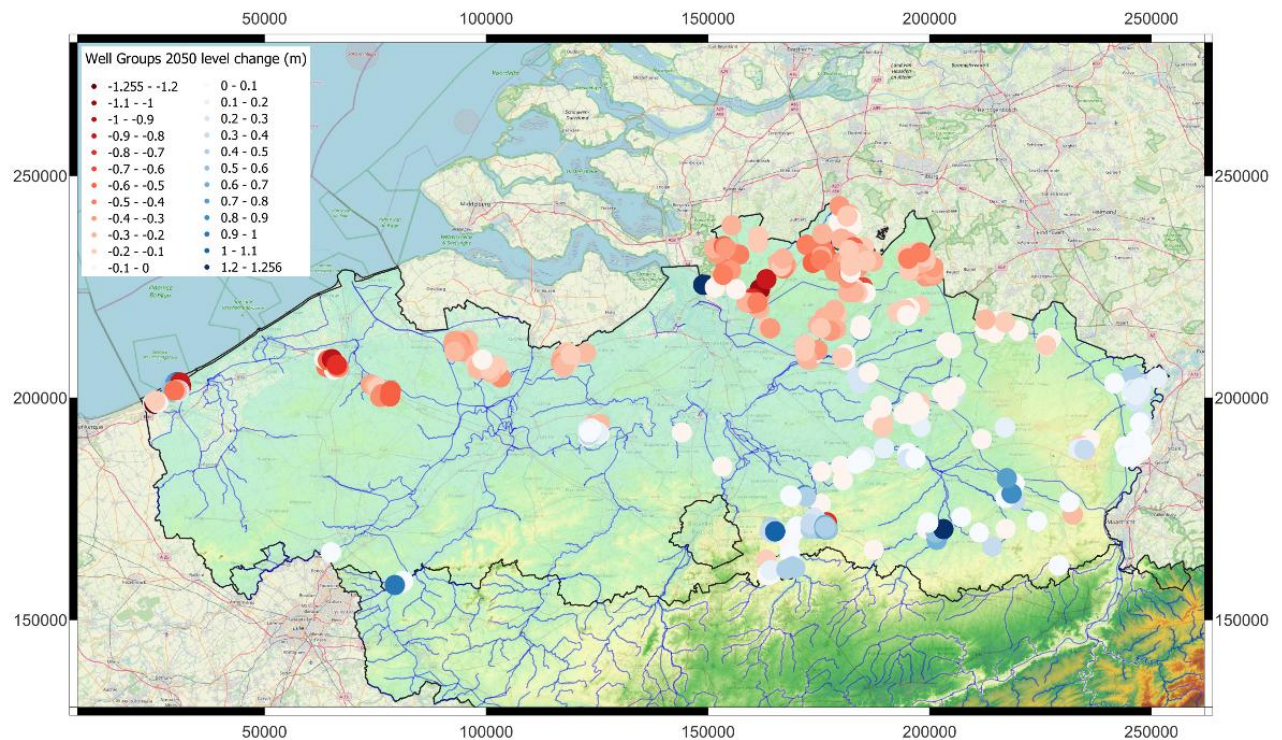


Figure 15: Distribution of simulated groundwater level change in Flanders in 2050.

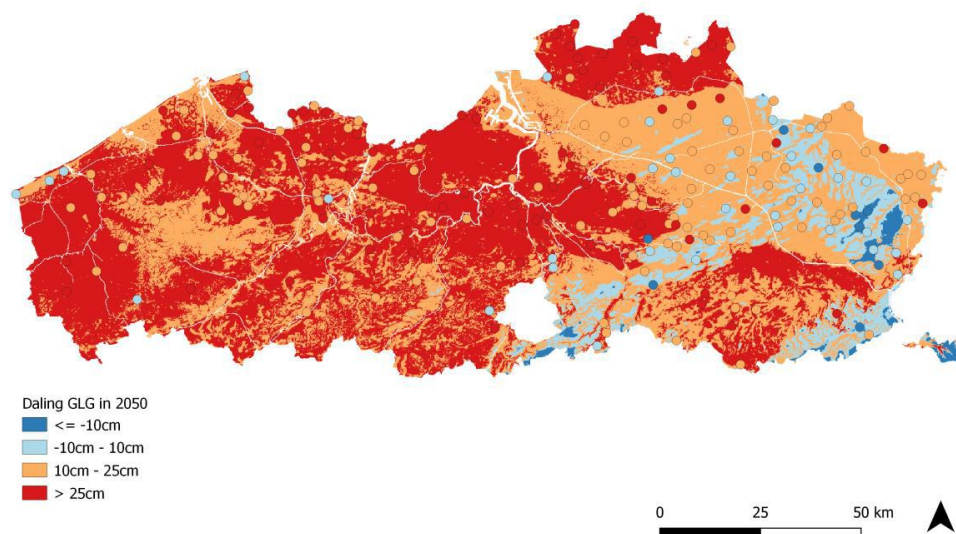
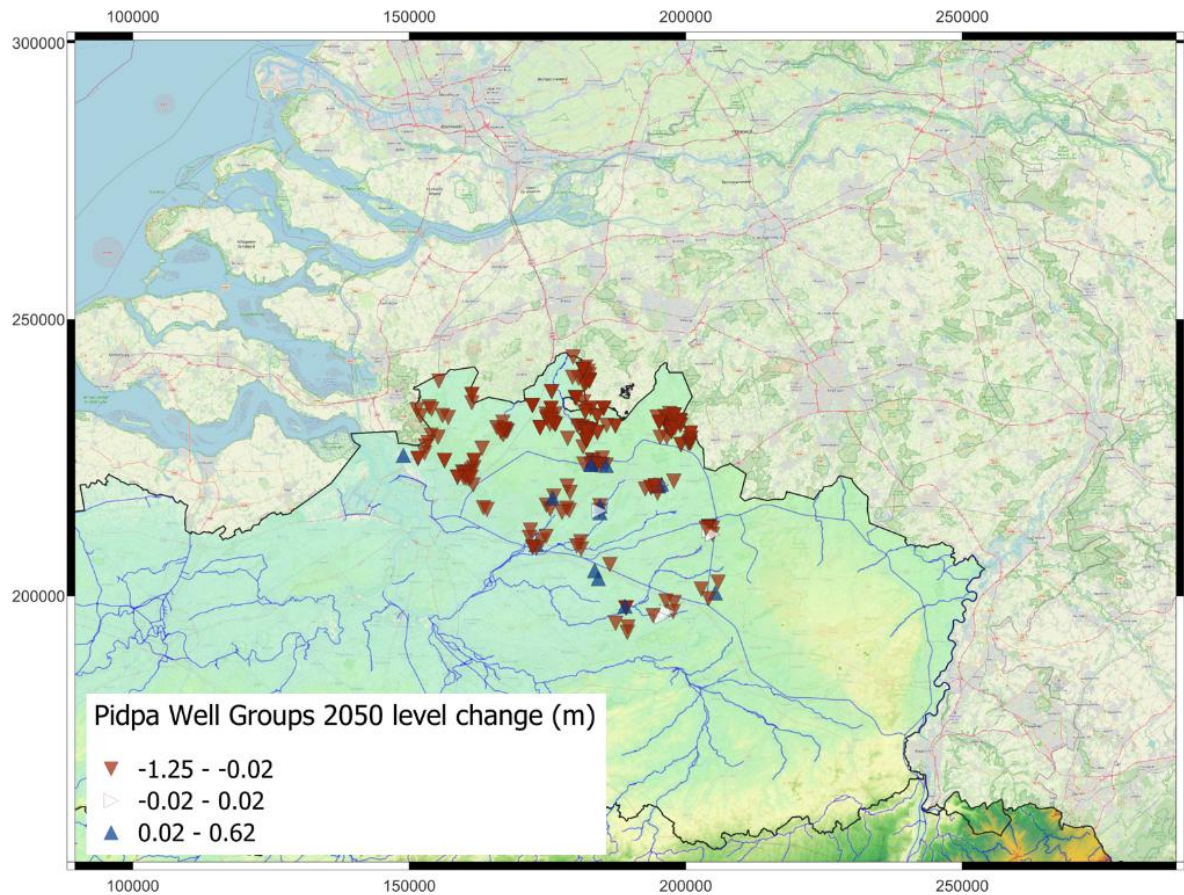


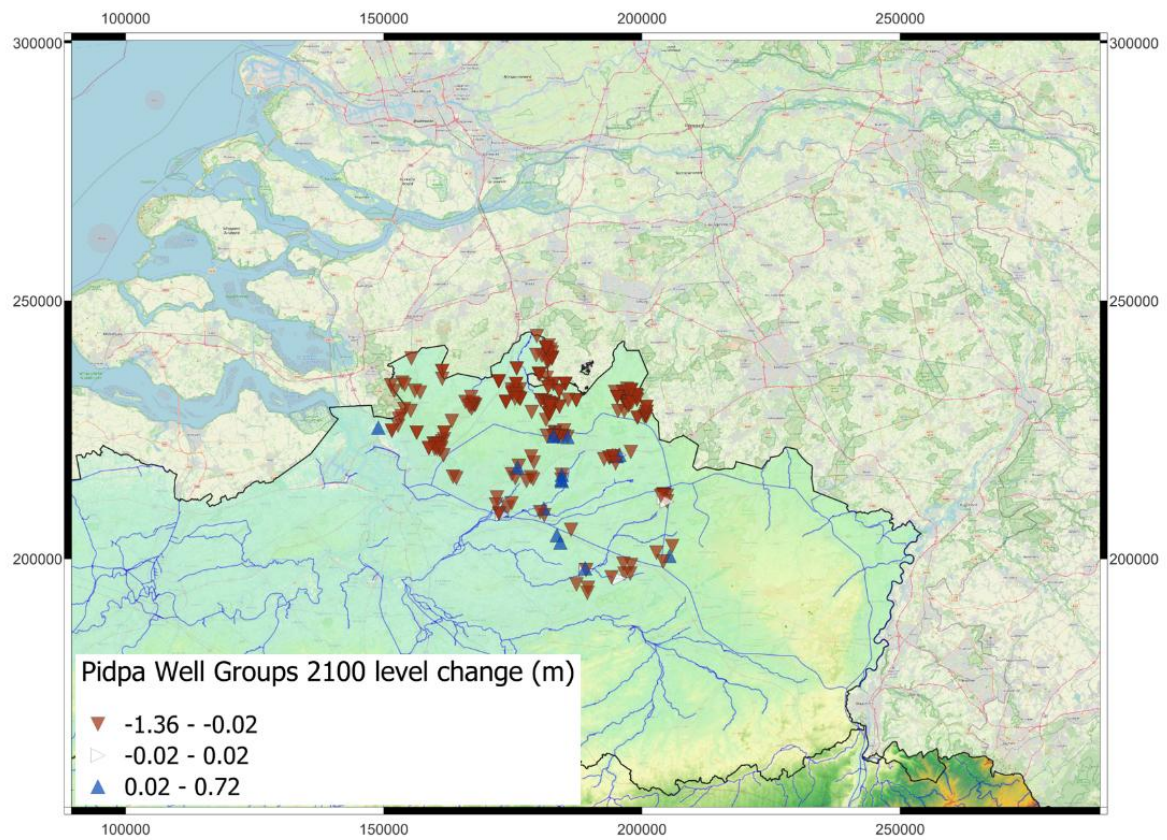
Figure 16: Decline of the Groundwater Levels in 2050. Points represent the results based on the SWAP models (translated from Sumaqua, 2022).

6.3.1 Pidpa analysis

The Pidpa group of wells are located in the North-Eastern part of Flanders. The analysis of potential climate disturbed scenarios provided an overview of the change in level between 30 years during the historical period (1991-2020) and the 2050 (Figure 17a) and 2100 (Figure 17b) perturbed scenarios. Figure 17a shows the spatial distribution of a number of selected wells with levels mostly decreasing, with some wells showing increases or some potential stability (this was calculated with a change between -2cm and 2cm). A selection of wells was made based on simulation accuracy using a R-square calculation of more than 80%. Wells with a lower simulation accuracy are not included in the map and table.



a)



b)

Figure 17: a) 2050 level change from historical values; and b) 2100 level change from historical values.

Well Group	2050 median difference	2100 median difference
Brasschaat	-0.6282	-0.699
Hoogstraten	-0.4825	-0.5324
Merksplas	-0.3382	-0.3848
Essen	-0.3335	-0.3378
Brecht	-0.2985	-0.2969
Schoten	-0.2742	-0.2274
Ravels	-0.2669	-0.3185
Oostmalle	-0.259	-0.2691
Kapellen	-0.246	-0.2604
Meerle	-0.2418	-0.2867
Herselt	-0.2383	-0.2925
Grobbendonk	-0.2364	-0.1389
Beerse	-0.2253	-0.2539
Arendonk	-0.1947	-0.2328
Wuustwezel	-0.1931	-0.2226
Herentals	-0.1412	-0.1089
Oud Turnhout	-0.1371	-0.1533
Gierle	-0.0995	-0.0755
Balen Kanaal	-0.0938	-0.0605
Mol	-0.0303	-0.0353
Westerlo	-0.028	-0.0137
Vorst	0.0049	0.0034
Olen	0.1689	0.1636

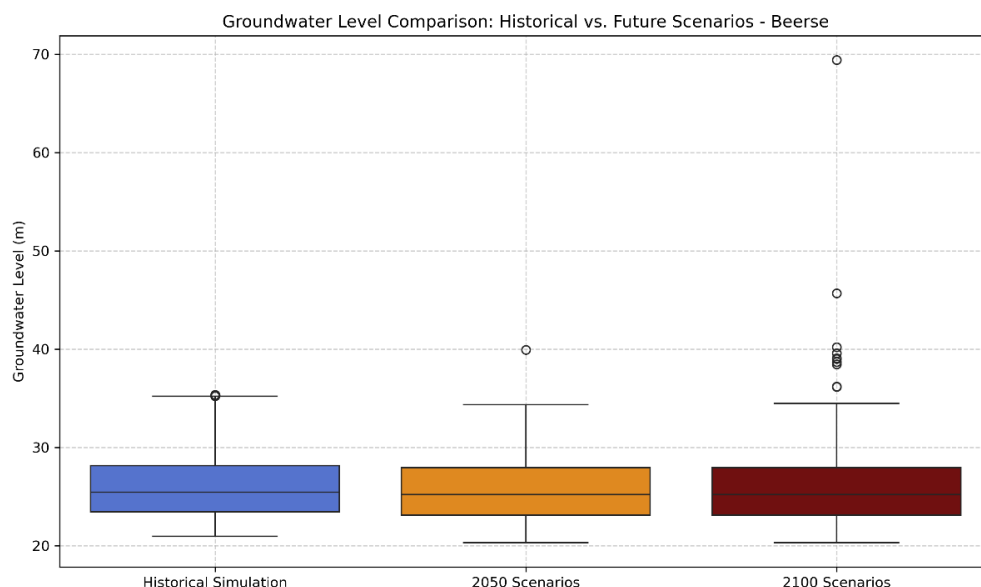
Table 5: Median level difference (m) from historical simulations for the different well groups, classified by highest decrease in levels for the 2050 perturbed scenarios.

Well Group	2050 median difference	2100 median difference
Brasschaat	-0.6282	-0.699
Hoogstraten	-0.4825	-0.5324
Merksplas	-0.3382	-0.3848
Essen	-0.3335	-0.3378
Ravels	-0.2669	-0.3185
Brecht	-0.2985	-0.2969
Herselt	-0.2383	-0.2925
Meerle	-0.2418	-0.2867
Oostmalle	-0.259	-0.2691
Kapellen	-0.246	-0.2604
Beerse	-0.2253	-0.2539
Arendonk	-0.1947	-0.2328
Schoten	-0.2742	-0.2274
Wuustwezel	-0.1931	-0.2226
Oud Turnhout	-0.1371	-0.1533
Grobbendonk	-0.2364	-0.1389
Herentals	-0.1412	-0.1089
Gierle	-0.0995	-0.0755
Balen Kanaal	-0.0938	-0.0605
Mol	-0.0303	-0.0353
Westerlo	-0.028	-0.0137
Vorst	0.0049	0.0034
Olen	0.1689	0.1636

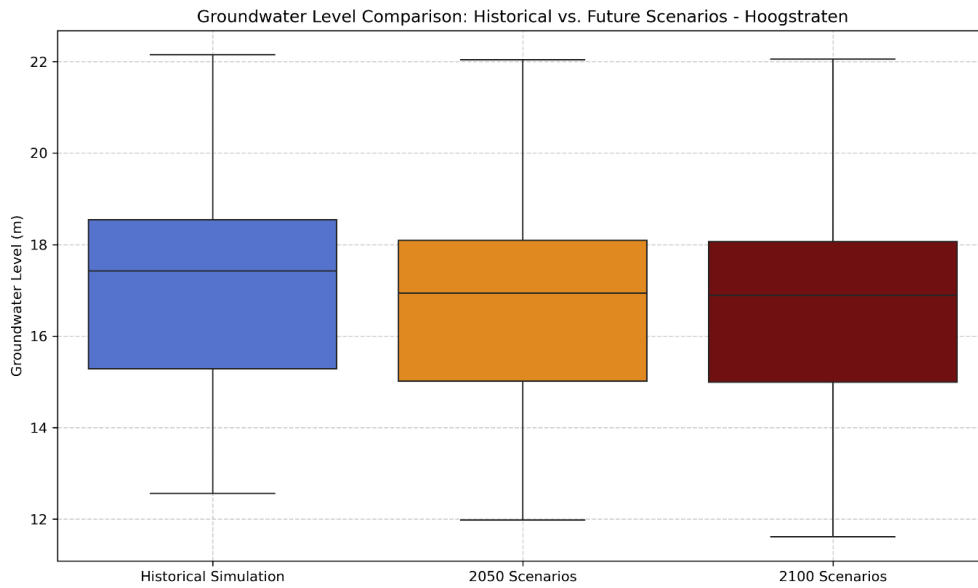
Table 6: Median level difference (m) from historical simulations for the different well groups, classified by highest decrease in levels for the 2100 perturbed scenarios.

Tables 5 and 6 show the median difference between historical and scenarios values for each group of wells arranged by highest decrease in levels for 2050 runs (Table 5) and 2100 runs (Table 6). Interpretations of the absolute values of these results should be done carefully. As purely data-driven models are used, not all models had a very good fit and not all local factors are taken into account in the models, readers should be aware that these models results exhibit some uncertainty.

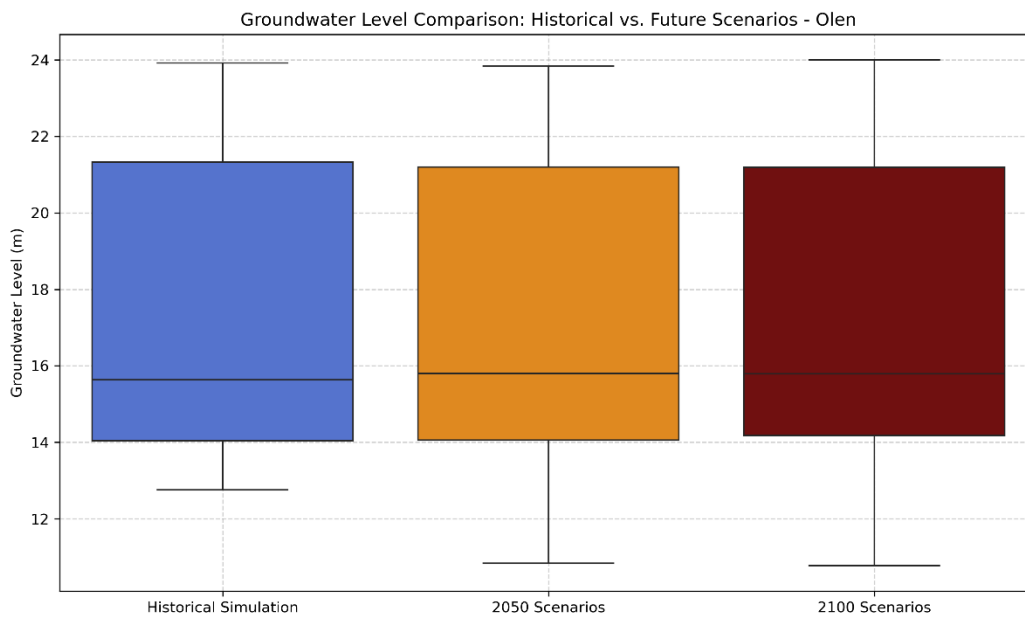
Figure 18 show some examples of boxplots with the distribution of groundwater levels under three simulation periods: Historical Simulation (1991–2020), 2050 perturbed climate scenarios and 2100 perturbed climate scenarios. Each box shows the median, interquartile range, and potential outliers. These are three examples showing a degree of variability. The Beerse group of wells do not show much difference between future scenarios for 2050 and 2100. Some unrealistic outliers for 2100 seem to indicate that the sensitivity of the model for this particular group of wells to very wet conditions is too high. Hoogstraten shows a declining trend, and Olen is showing a slightly increasing trend. Appendix A shows these comparisons for all groups of wells.



a)



b)



c)

Figure 18: Comparison of simulated groundwater levels under historical and future climate scenarios for three examples of group of wells a) Beerse; b) Hoogstraten; and c) Olen

Figure 19 represents the distribution of extreme groundwater level events under future scenarios. The left figures displays *low extreme events* (values below the 5th percentile), while the right figures shows *high extreme events* (values above the 95th percentile). The two boxplots of each figure represent the number of extreme groundwater level events for 2050 and 2100 scenario runs. As a reference, the dashed blue line indicates the number of extreme events under the historical simulation. As an example, group Hoogstraten shows a potential increase in the number and variability of low extreme events under future climate conditions, particularly in the 2100 runs. These results suggest that groundwater extremes may become more frequent and intense over time. The number of high extreme events will potentially decrease during these perturbed scenarios. The analysis of the other groups of wells is shown in Appendix A.

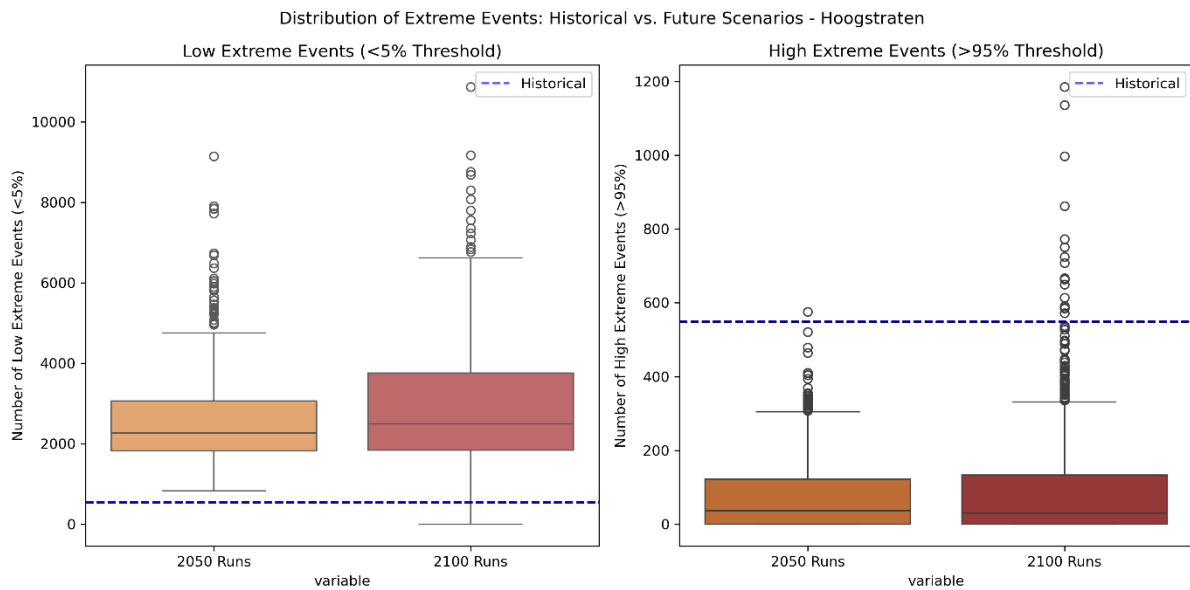
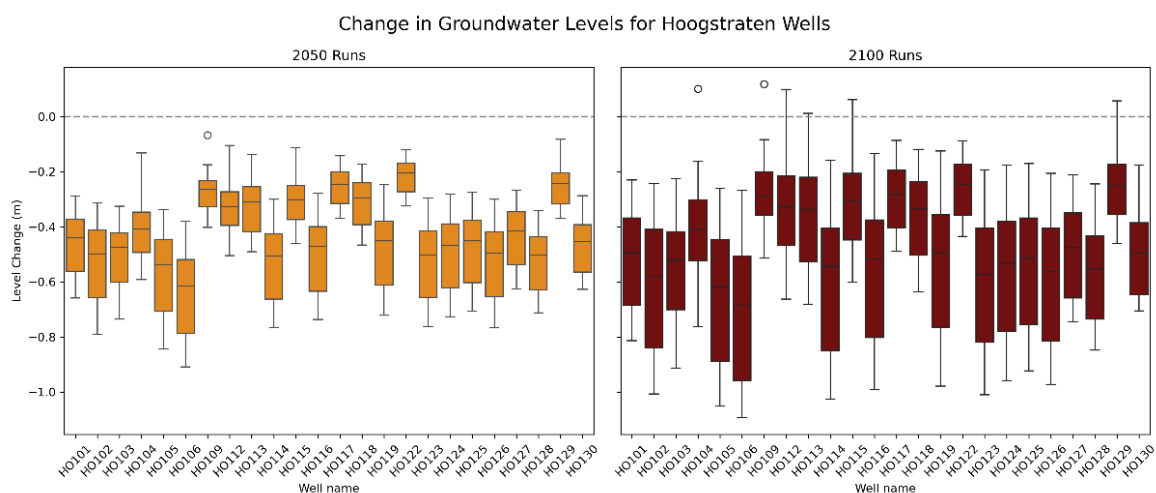


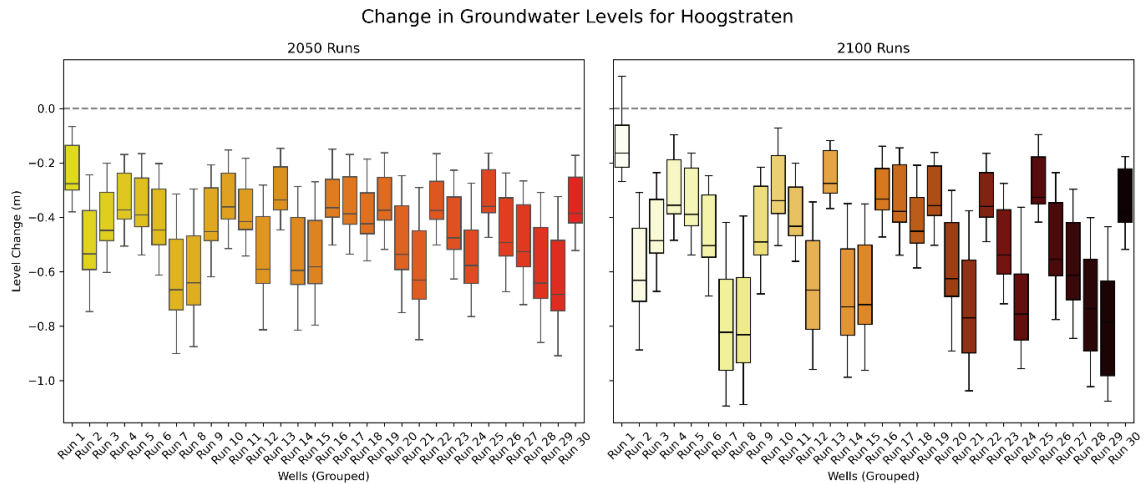
Figure 19: Distribution of extreme groundwater level events under future scenarios for the Hoogstraten group of wells.

The next set of figures present projected changes in groundwater levels for the Hoogstraten group of wells under two climate scenarios. Most wells show a decline in groundwater levels under both scenarios, more pronounced in 2100 than in 2050 for many wells. Some wells show less variability (e.g., HO114), while others show wider spreads (e.g., HO105, HO124), indicating different sensitivities to the scenarios. Some outliers could reflect occasional runs where groundwater levels remained closer to historical values (Figure 20).

Figure 20b shows groundwater level changes grouped by simulation run, with each box summarizing changes across all wells for that run. The variability and potential decline in levels is very similar to the previous figure in both 2050 and 2100 runs. The progression from lighter to darker red-brown shades reflects the sequence of simulation runs.



a)



b)

Figure 20: Projected change in groundwater levels across a) individual wells for aggregated simulation runs (2050 and 2100); and b) simulation runs for group of wells Hoogstraten.

An initial estimation of the percentage of change in pumping values was calculated for each of the individual runs based on of the difference in groundwater levels from the historical simulation. For this estimation, a random forest model which is a common machine-learning algorithm, combining multiple decision trees to reach a single result (Ho, 1998).

Table 7 shows the group of wells with a potential need of decreasing pumping to maintain groundwater levels abstraction averaged across all wells in each group and all runs in scenario (2050 and 2100)m and averaged through the 30 years of perturbed climate data. However, variability exist across runs, with some showing the need for decrease in pumping to maintain historical simulated groundwater levels (shown in tables in Appendix A). Wells with a high percentage of change such as Ravels should be interpreted as well were historic groundwater levels are sensitive to pumping and where groundwater levels respond strongly to drought. Given the uncertainties and assumptions inherent to the method, these are estimates that would need to be further investigated using local transient MODFLOW models.

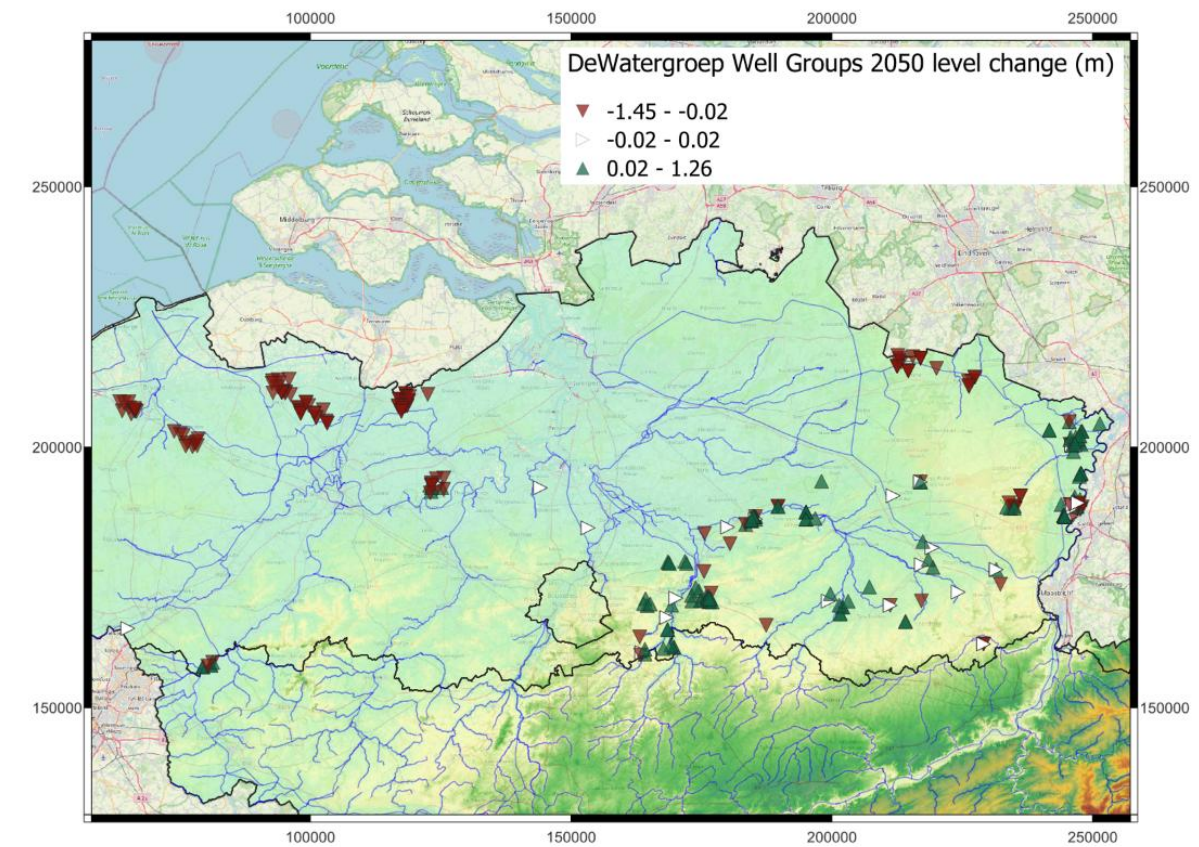
Well Group	% percentage of change 2050 scenarios	% percentage of change 2100 scenarios
Arendonk	-2.4	-2.9
BalenKanaal	-0.1	-0.1
Beerse	-7.2	-7.8
Brasschaat	-12.3	-13.2
Brecht	-5.3	-5.3
Essen	-10.4	-9.1
Gierle	-0.4	-0.4
Grobbendonk	-2.9	-2.9
Herentals	-0.3	-0.1

Herselt	-0.2	-0.3
Hoogstraten	-13.1	-15.2
Kapellen	-0.6	-0.7
Meerle	-3.7	-5.1
Merksplas	-9.7	-11.0
Mol	-0.5	-0.7
Oostmalle	-6.0	-7.8
OudTurnhout	-0.7	-0.9
Ravels	-33.0	-39.8
Schoten	-1.7	-1.2
Vorst	-0.2	-0.4
Wuustwezel	-6.2	-7.2

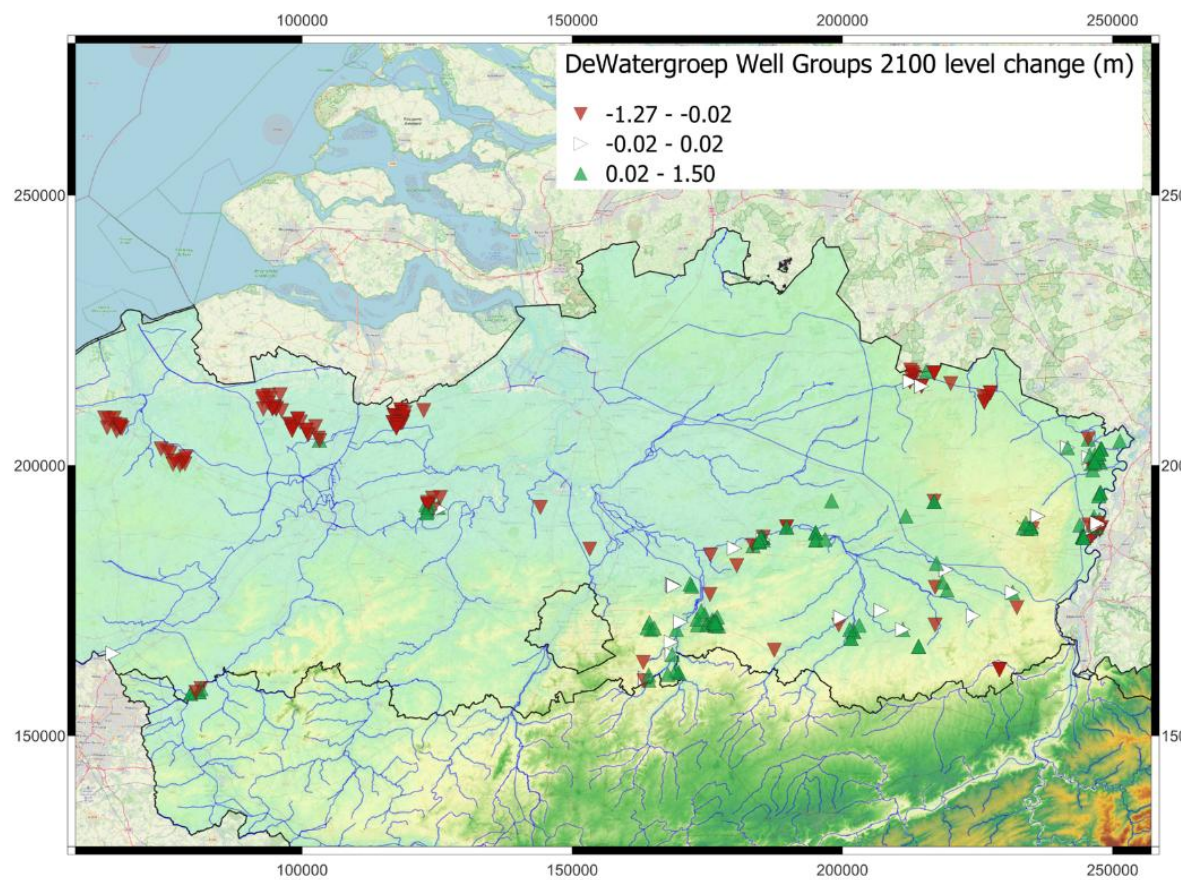
Table 7: *Percentage of change in abstraction values to maintain historical simulated groundwater levels. Group of wells with a potential need to decrease abstraction.*

6.3.2 De Watergroep analysis

The De Watergroep group of wells are located in a large part of Flanders, and northern parts of Wallonia. The analysis of potential climate disturbed scenarios provided an overview of the change in level between 30 years during the historical period (1991-2020) and the 2050 (Figure 21a) and 2100 (Figure 21b) perturbed scenarios. Figure 21 shows the spatial distribution of a number of selected wells with levels increasing in the eastern part of Flanders; decreasing in the western and north-eastern areas and showing some stability in certain parts of the South-east of Flanders (this was calculated with a change between -2cm and 2cm). The selection of wells was made based on simulation accuracy using a R-square calculation of more than 80%.



a)



b)

Figure 21: a) 2050 level change from historical values; and b) 2100 level change from historical values

The tables below shows the median difference between historical and scenarios values for each group of wells arranged by highest decrease in levels for 2050 runs (Table 8) and 2100 runs (Table 9Table).

Table 8: Median level difference from historical simulations for the different well groups, classified by highest decreased in levels for the **2050** perturbed scenarios.

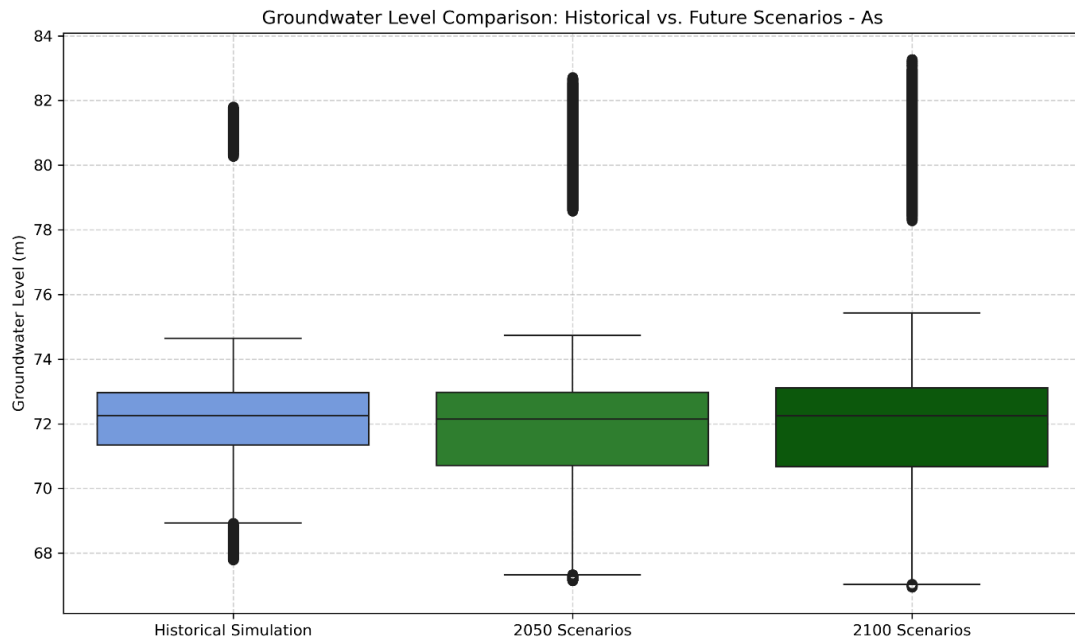
Well Group	2050 median difference	2100 median difference
Waltwilder	-0.0049	-0.0028
Zoutleeuw	0.0043	-0.0518
Wintershoven	0.0087	0.0089
Zichem Vinkenberg	0.0087	-0.0147
Overijse Venusberg	0.0104	-0.0076
Nieuwerkerken	0.0142	-0.024
Meerheuvcl	0.0231	0.0456
Weerderlaak	0.0554	0.0942
Eisden Mijnsite	0.0628	0.0839
Sint-Agatha-Rode Geuzenhoek	0.0666	0.0545
Tessenderlo	0.0667	-0.007
Overijse Sana	0.0755	0.0786
Maaseik Vlakenhof	0.0817	0.0895
Sint-Agatha-Rode Veeweyde	0.128	0.599
Trekschuren	0.2469	0.3093
Heverlee Cadol	0.2605	0.3544
Tgv	0.3341	0.549
GreZ-Doiceau Pecrot	0.3514	0.5747
Zepperen	0.3869	0.7371
Osseweg	0.5085	0.6524
Leefdaal Puttebos	0.5199	0.7431
Heverlee Abdij	0.5717	0.974
Herent Bijlok	0.6305	0.7351
Willekensmolen	0.7482	0.7999

Well Group	2050 median difference	2100 median difference
Snellegem	-0.3134	-0.3937
Eeklo	-0.2527	-0.306
Wellen	-0.1555	-0.2905
Lembeke-Oosteeklo	-0.249	-0.2697
Moerbeke-Wachtebeke	-0.2341	-0.2495
Lommel	-0.2071	-0.2256
Kumtich Menebeek	-0.1419	-0.2176
Overijse Kouterstraat Nellebeek	-0.1418	-0.1934
Korbeek-Dijle Het Broek	-0.0592	-0.152
Overhaem	-0.0636	-0.1271
Neerpelt	-0.1178	-0.1186
Beernem	-0.126	-0.1091
Hoepertingen	-0.0986	-0.099
Winksele Kastanjebos	-0.0377	-0.0922
Kessel-Lo Vlierbeek	-0.0295	-0.0618
Zemst Spelt	-0.0202	-0.0615
Meeswijk	-0.0492	-0.0563
Zoutleeuw	0.0043	-0.0518
Berlare-Zele	-0.0771	-0.0494
Londerzeel Koevoet	-0.0231	-0.0355
Kluizen	-0.032	-0.0332
Nieuwrode Het Rot	-0.0166	-0.0326
Nieuwerkerken	0.0142	-0.024
Zichem Vinkenberg	0.0087	-0.0147
As	-0.1111	-0.012

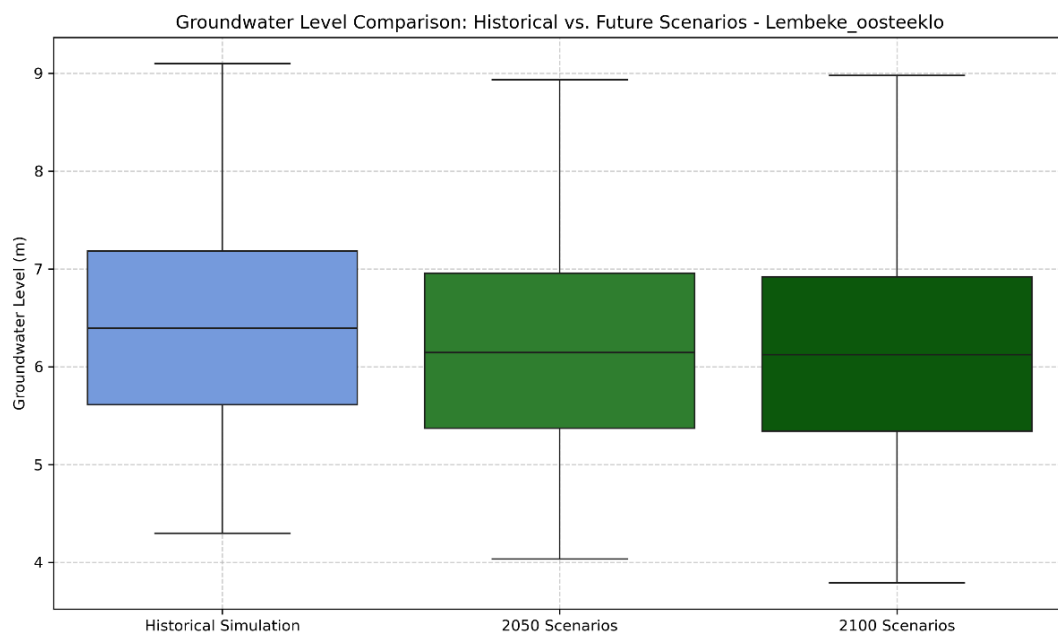
Table 9: Median level difference from historical simulations for the different well groups, classified by highest decreased in levels for the **2100** perturbed scenarios.

Well Group	2050 median difference	2100 median difference
Overijse Venusberg	0.0104	-0.0076
Tessenderlo	0.0667	-0.007
Waltwilder	-0.0049	-0.0028
Heusden-Zolder	-0.034	0.0005
Spiere-Helkijn	-0.0369	0.0039
Wintershoven	0.0087	0.0089
Schoonhoven	-0.012	0.0212
Meerheuvel	0.0231	0.0456
Sint-Agatha-Rode Geuzenhoek	0.0666	0.0545
Overijse Sana	0.0755	0.0786
Eisden Mijnsite	0.0628	0.0839
Maaseik Vlakenhof	0.0817	0.0895
Weerderlaak	0.0554	0.0942
Trekschuren	0.2469	0.3093
Heverlee Cadol	0.2605	0.3544
Tgv	0.3341	0.549
Grez-Doiceau Pecrot	0.3514	0.5747
Sint-Agatha-Rode Veeweyde	0.128	0.599
Osseweg	0.5085	0.6524
Herent Bijlok	0.6305	0.7351
Zepperen	0.3869	0.7371
Leefdaal Puttebos	0.5199	0.7431
Willekensmolen	0.7482	0.7999
Heverlee Abdij	0.5717	0.974

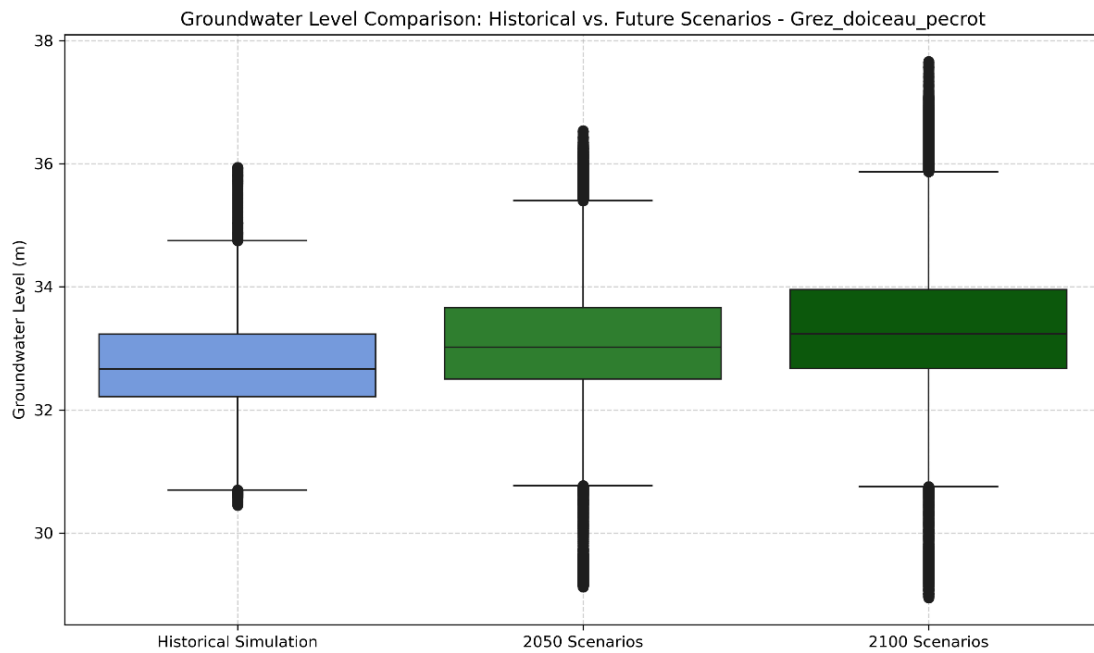
Figure 22 show examples of boxplots with the distribution of groundwater levels under three simulation periods: Historical Simulation (1991–2020), 2050 perturbed climate scenarios and 2100 perturbed climate scenarios. Each box shows the median, interquartile range, and potential outliers. These are three examples showing a degree of variability. As group of wells shows similar median groundwater levels for historical and scenarios, but showing a certain level of decrease overall. *Lembeke-Oosteeklo* group of wells show a decrease in future scenarios for both 2050 and 2100. *Greze-Doiceau Pecrot* shows a increasing trend for both scenarios of 2050 and 2100 runs. Appendix B shows these comparisons for all groups of wells.



a)



b)



c)

Figure 22: Comparison of simulated groundwater levels under historical and future climate scenarios for three examples of group of wells a) As; b) Lembeke-Oosteeklo; and c) Grez-Doiceau Pecrot.

Figure 23 represents the distribution of extreme groundwater level events under future scenarios. The left figures displays *low extreme events* (values below the 5th percentile), while the right figures shows *high extreme events* (values above the 95th percentile). The two boxplots of each figure represent the number of extreme groundwater level events for 2050 and 2100 scenario runs. As a reference, the dashed blue line indicates the number of extreme events under the historical simulation. As an example, group As shows a potential increase in the number and variability of low extreme events under future climate conditions, very similar in both 2050 and 2100 runs. In this case, the number of high extreme events will potentially increase for 2100 runs and staying stable during 2050 perturbed scenarios. The analysis of the other groups of wells is shown in Appendix B.

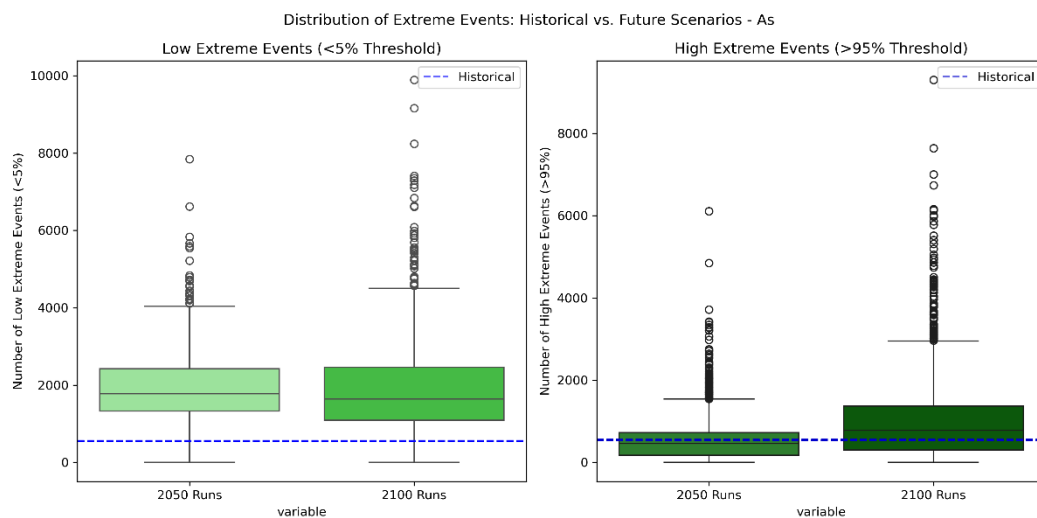
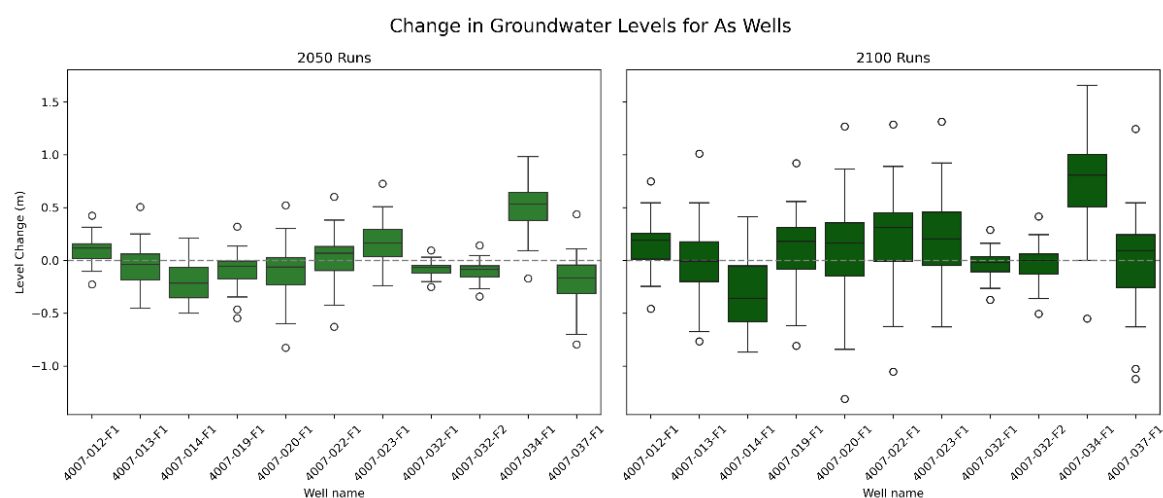


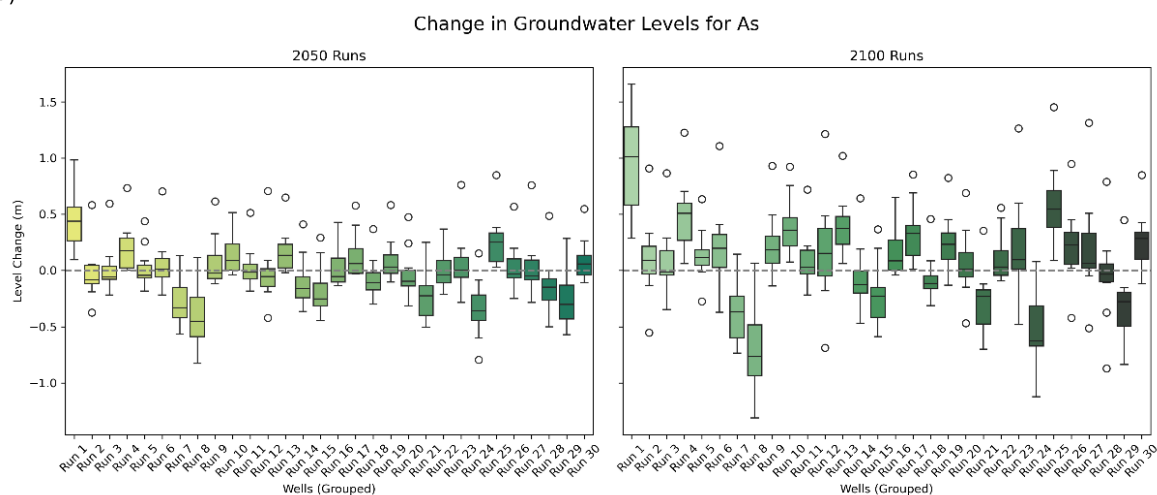
Figure 23: Distribution of extreme groundwater level events under future scenarios for the As group of wells.

The next set of figures presents projected changes in groundwater levels for the As group of wells under two climate scenarios: the left panel (2050 Runs): Most wells show modest declines, with a few showing increases. Increased variability for 2100 runs, showing potential increases for several wells and a greater spread in potential outcomes under longer-term climate projections (Figure 24a).

Figure 24b shows groundwater level changes grouped by simulation run, with each box summarizing changes across all wells for that run. 2050 Runs (left figure) shows great variability across all runs; however, 2100 runs shows a potential positive increase in level changes across most wells, with some exceptions showing a greater decrease. The progression from lighter to darker green shades reflects the sequence of simulation runs.



a)

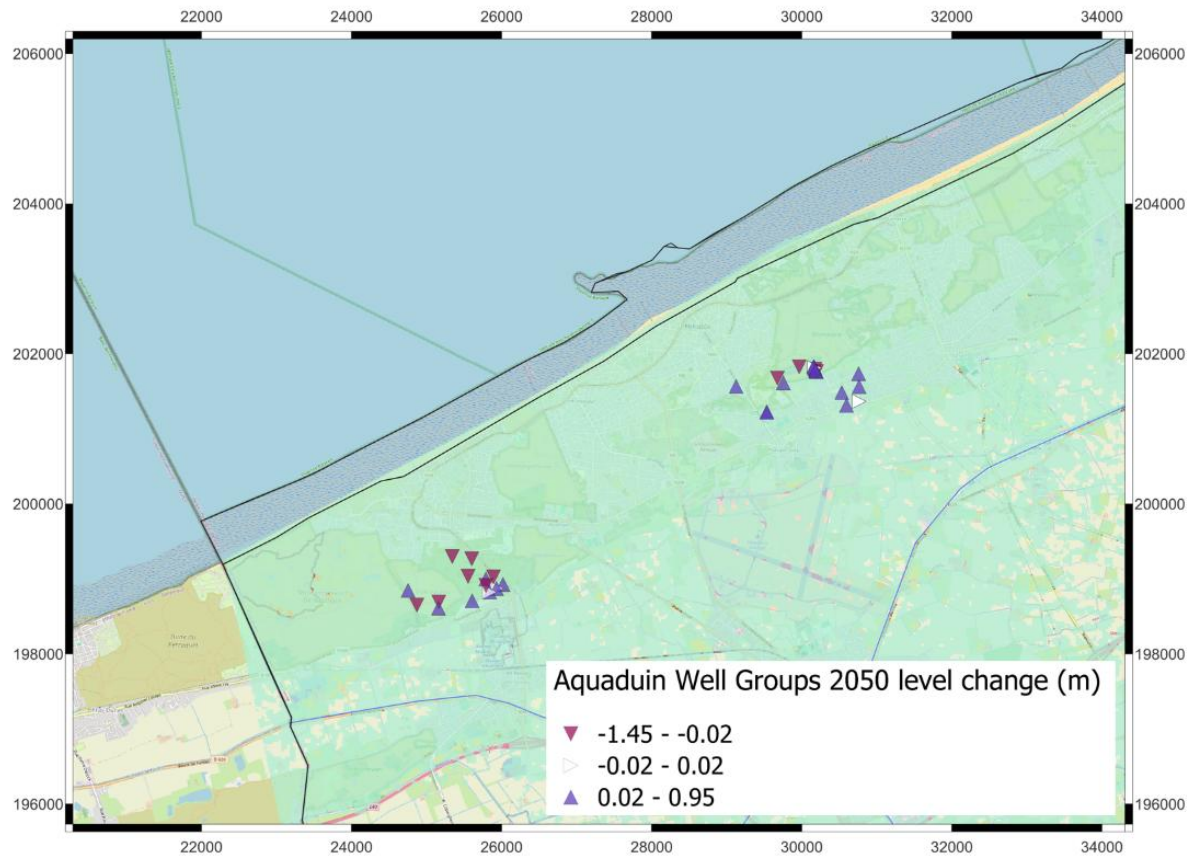


b)

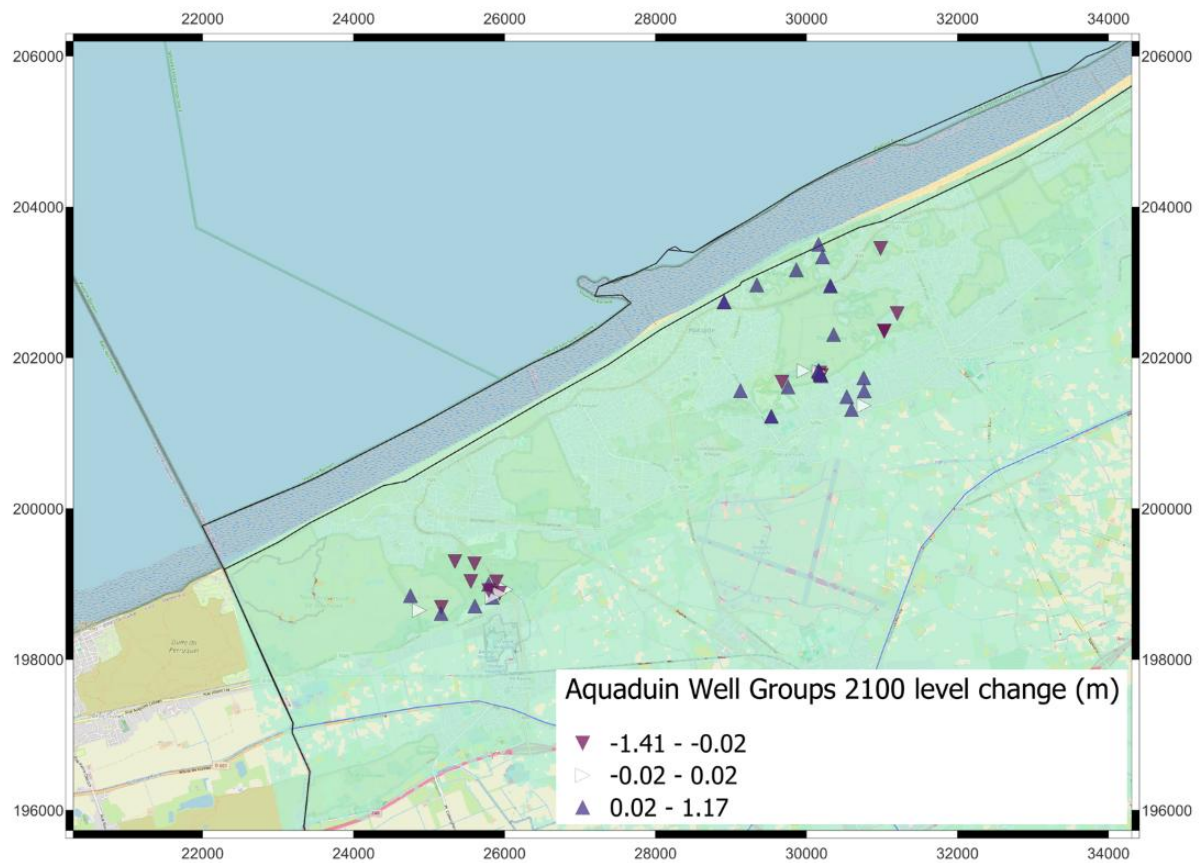
Figure 24: Projected change in groundwater levels across a) individual wells for aggregated simulation runs (2050 and 2100); and b) simulation runs for group As.

6.3.3 Aquaduin analysis

The Aquaduin group of wells are located in the coast of Western Belgium. The analysis of potential climate disturbed scenarios provided an overview of the change in level between 30 years during the historical period (1991-2020) and the 2050 (Figure 25a) and 2100 (Figure 25b) perturbed scenarios. This figure shows the spatial distribution a number of selected wells with levels increasing, decreasing or staying stable (this was calculated with a change between -2cm and 2cm). Interpretation of these results should be done carefully as the time-series models for the Aquaduin data performed less than for the other well fields.



a)



b)

Figure 25: a) 2050 level change from historical values; and b) 2100 level change from historical values.

The tables below shows the median difference between historical and scenarios values for each group of wells arranged by highest decrease in levels for 2050 runs (Table 10) and 2100 runs (Table 11Table).

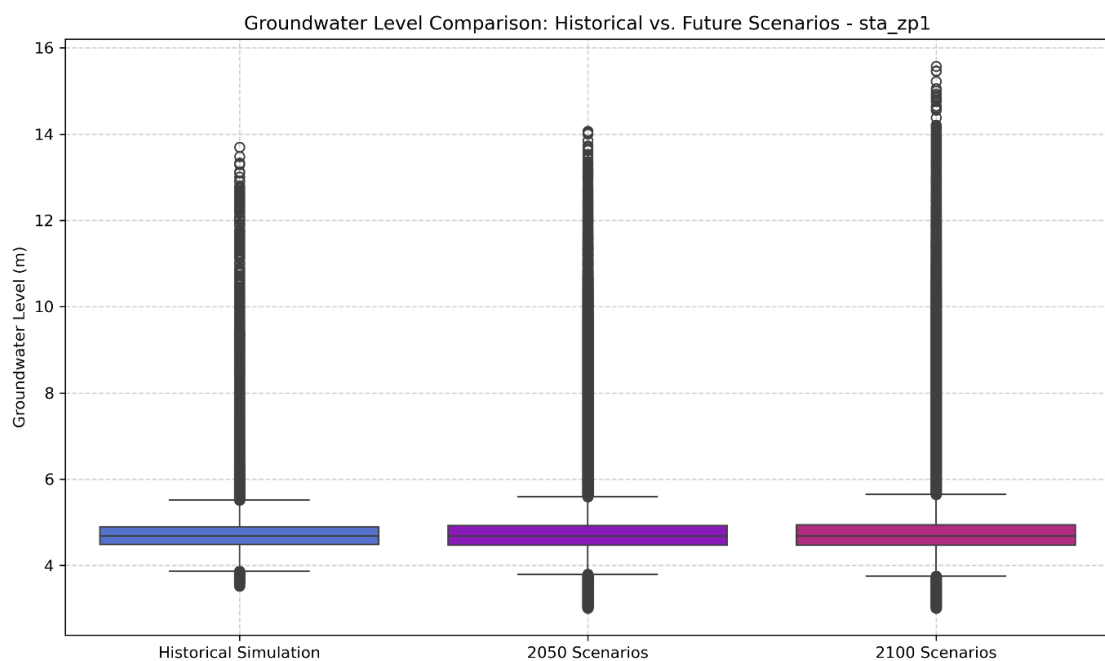
Well Group	2050 median difference	2100 median difference
WH	-0.0302	-0.024
STA ZP1	-0.0034	0.0025
STA ZP2	0.0078	0.0618

Table 10: Median level difference from historical simulations for the different well groups, classified by highest decreased in levels for the 2050 perturbed scenarios.

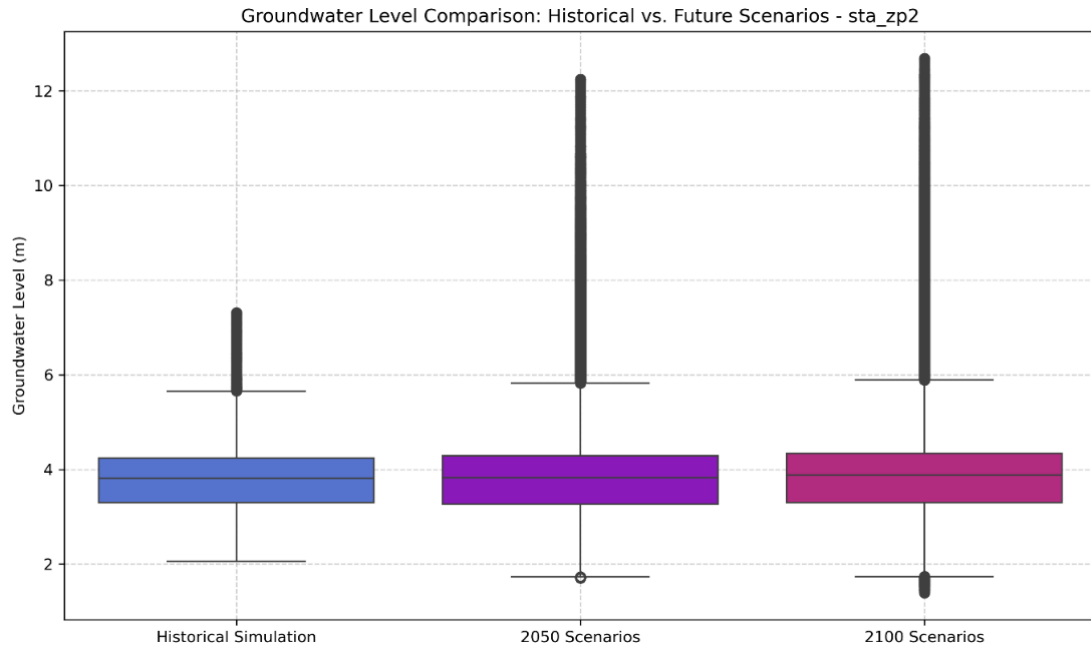
Well Group	2050 median difference	2100 median difference
WH	-0.0302	-0.024
STA ZP1	-0.0034	0.0025
STA ZP2	0.0078	0.0618

Table 11: Median level difference from historical simulations for the different well groups, classified by highest decreased in levels for the 2100 perturbed scenarios.

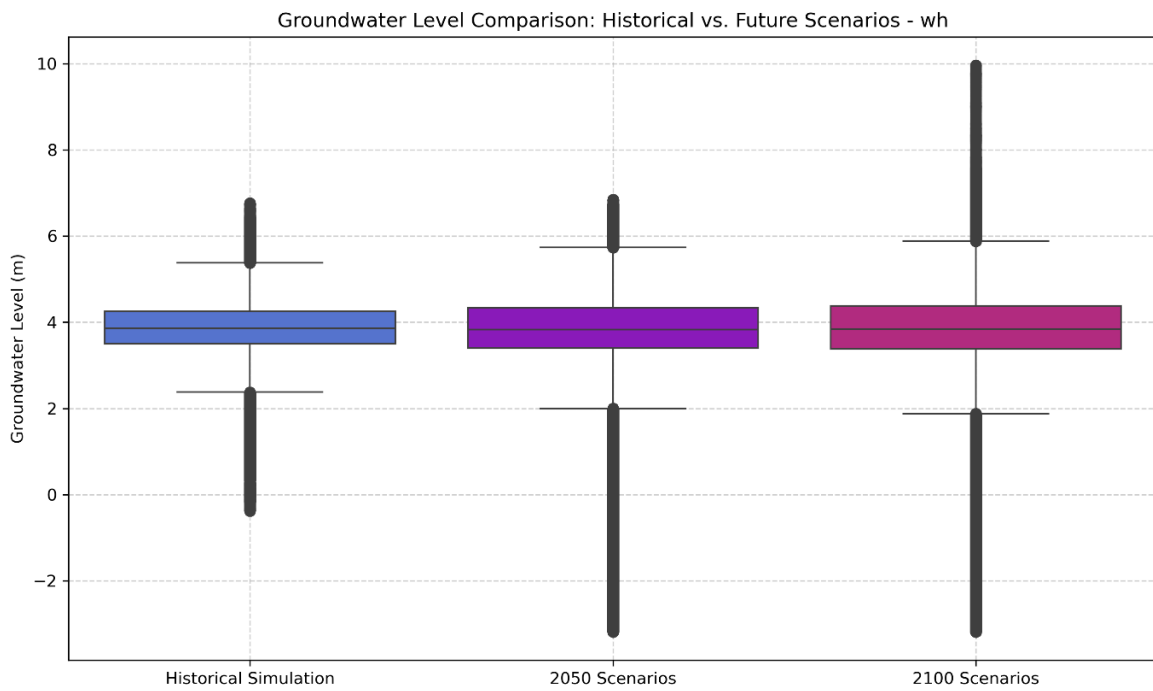
Figure 26 show examples of boxplots with the distribution of groundwater levels under three simulation periods: Historical Simulation (1991–2020), 2050 perturbed climate scenarios and 2100 perturbed climate scenarios. Each box shows the median, interquartile range, and potential outliers. For group ZP1, all historical and scenarios shows a great spread of outliers for high values, suggesting high variability. The results for group ZP2 indicate a consistent shift toward slightly higher groundwater levels in future scenarios (2050 and 2100), as evidenced by an slight upward shift in the median and upper whiskers compared to the historical simulation, and also confirmed by the previous table. The future scenarios also exhibit a greater spread and a larger number of both high-value and low- value outliers, reflecting increased variability and potential for extreme groundwater level events under changing climate conditions. For group WH, this potential for extremes is further explored in the next set of figures. Some unrealistic outliers for 2050 and 2100 seem to indicate that the sensitivity of the model for this particular group of wells to wet conditions is too high.



a)



b)



c)

Figure 26: Comparison of simulated groundwater levels under historical and future climate scenarios for a) STA ZP1; b) STA ZP2; and c) WH.

Figure 27 represents the distribution of extreme groundwater level events under future scenarios. The left figures displays *low extreme events* (values below the 5th percentile), while the right figures shows *high extreme events* (values above the 95th percentile). The two boxplots of each figure represent the number of extreme groundwater level events for 2050 and 2100 scenario runs. As a reference, the dashed blue line indicates the number of extreme events under the historical simulation. As an example, group WH shows a potential increase in the number and variability of low extreme events under future climate conditions, particularly in the 2100 runs. These results

suggest that groundwater extremes may become more frequent and intense over time. The analysis of the other two groups of well is shown in Appendix C.

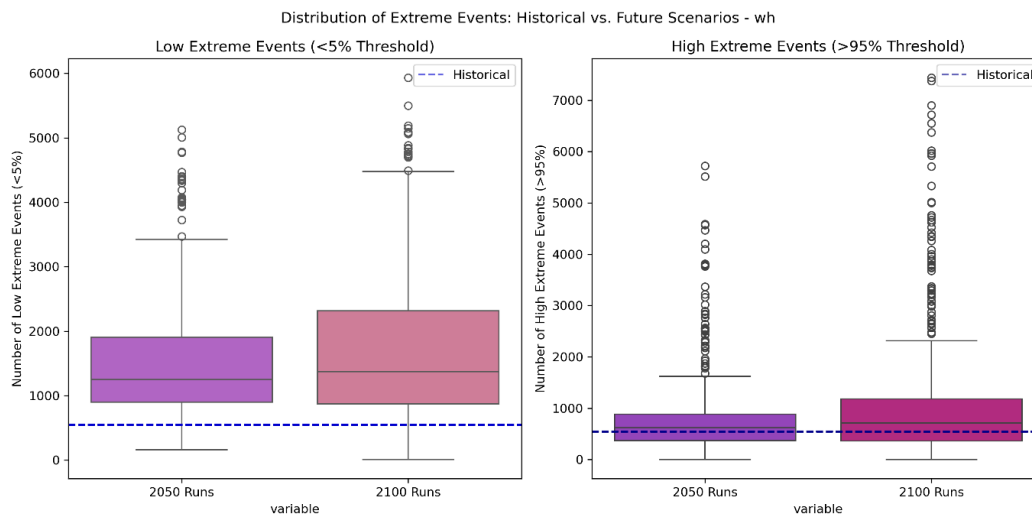
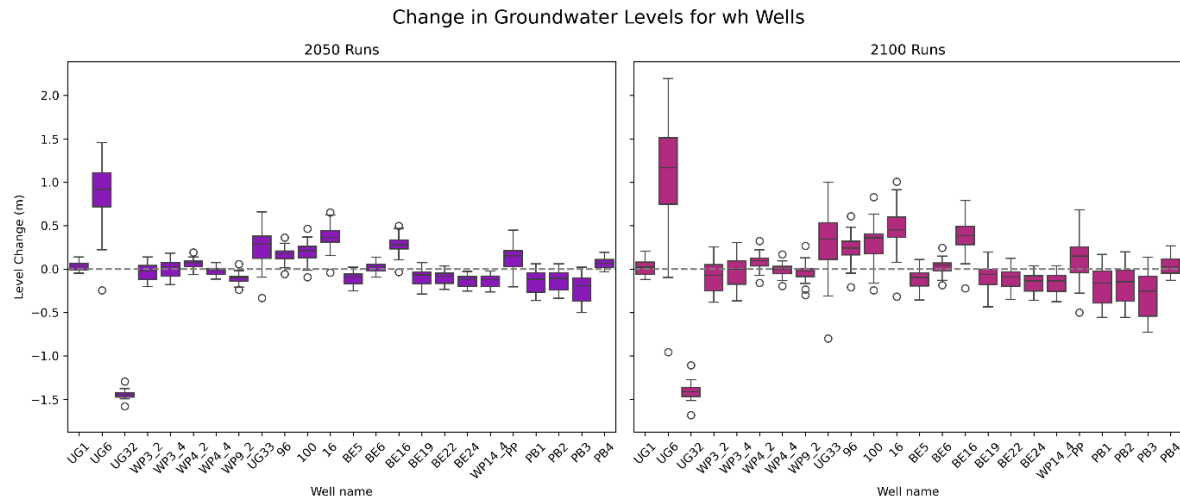
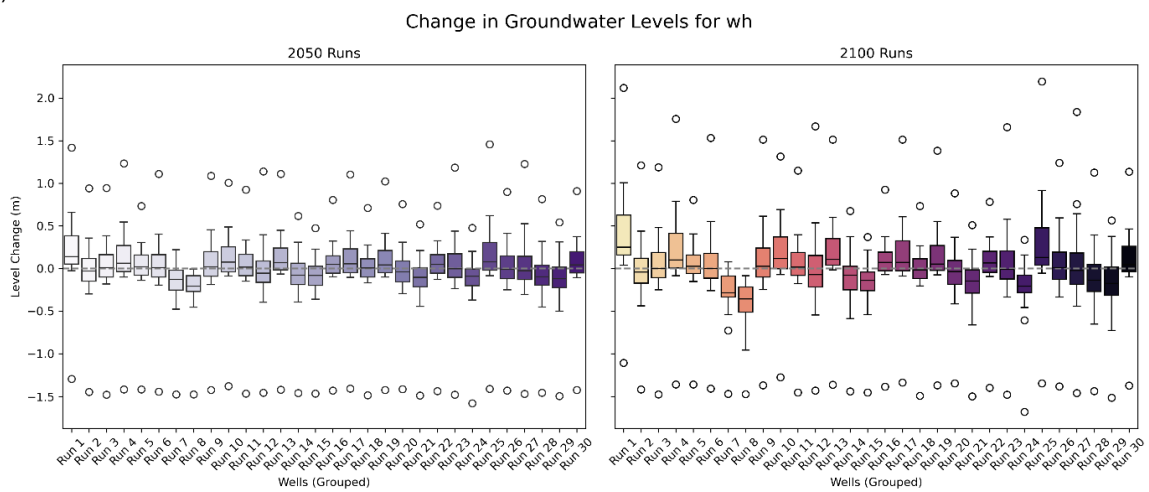


Figure 27: Distribution of extreme groundwater level events under future scenarios for a) group STA ZP1; b) group STA ZP2; and c) group WH.

The distribution of groundwater level changes for the aggregated 2050 (left figure) and 2100 runs (right figure) for all wells in the group WH are shown in Figure 28a. For the 2050 runs, most wells show some declines, with a few outliers experiencing greater variability and larger magnitudes of change (both positive and negative). For the 2100 runs, the variability increases, suggesting a greater impact for those runs for this particular group of wells (see Appendix B for all De Watergroep group of wells). Figure 28 represents the distribution of level changes per simulation run, aggregated across wells. The progression from lighter to darker colours represents the sequence of simulation runs. It compares groundwater level changes across the 30 scenario runs under the 2050 (left figure) and 2100 (right figure) climate perturbed scenarios. Each box represents the distribution of level changes per simulation run, aggregated across wells. A general shift toward positive level changes is observed in some 2050 runs, but many runs also show declines or minimal change. For 2100, results are more variable, with certain runs showing stronger declines, indicating greater uncertainty and spatial variability in groundwater response under more distant future conditions.



a)



b)

Figure 28: Projected change in groundwater levels across a) individual wells for aggregated simulation runs (2050 and 2100); and b) simulation runs for group WH.

An initial estimation of the percentage of change in pumping values was calculated for each of the individual runs based on of the difference in groundwater levels from the historical simulation. For this estimation, a random forest model which is a common machine-learning algorithm, combining multiple decision trees to reach a single result (Ho, 1998).

Table 12 shows the group of wells with an the potential change in abstraction averaged across all wells in each group and all runs in scenario (2050 and 2100)m and averaged through the 30 years of perturbed climate data. However, variability exist across runs, with some showing the need for decrease in pumping historical simulated groundwater levels (shown in tables in Appendix C). Given the uncertainties and assumptions inherent to the method, these are estimates that would need to be further investigated using local transient MODFLOW models.

Well Group	% percentage of change 2050 scenarios	% percentage of change 2100 scenarios
STA ZP1 Station	- 4.8	- 6.9
STA ZP2 Station	- 1.8	- 2.4
WH Station	- 12.3	- 10.3

Table 12: Percentage of change in abstraction values to maintain historical simulated groundwater levels. Group of wells with a potential need to decrease abstraction.

6.4 Discussion of results

An analysis of groundwater levels and abstraction timeseries was done to determine risk of groundwater decrease in the Flanders area. Moreover, an initial analysis of potential decrease in abstraction to maintain historical simulated groundwater levels was also carried out. The next table summarises the group of wells more impacted by potential climate risks, with decreases in groundwater levels higher than 10cm for both 2050 and 2100 scenarios (Table 13), and Figure 29 **Figure** shows the spatial distribution of these wells.

Well Group	Water company	Median decrease in groundwater levels	
		2050	2100
Brasschaat	<i>Pidpa</i>	-0.63	-0.70
Hoogstraten	<i>Pidpa</i>	-0.48	-0.53
Merksplas	<i>Pidpa</i>	-0.34	-0.38
Essen	<i>Pidpa</i>	-0.33	-0.34
Ravels	<i>Pidpa</i>	-0.27	-0.32
Brecht	<i>Pidpa</i>	-0.30	-0.30
Herselt	<i>Pidpa</i>	-0.24	-0.29
Meerle	<i>Pidpa</i>	-0.24	-0.29
Oostmalle	<i>Pidpa</i>	-0.26	-0.27
Kapellen	<i>Pidpa</i>	-0.25	-0.26
Beerse	<i>Pidpa</i>	-0.23	-0.25
Arendonk	<i>Pidpa</i>	-0.19	-0.23
Schoten	<i>Pidpa</i>	-0.27	-0.23
Wuustwezel	<i>Pidpa</i>	-0.19	-0.22
OudTurnhout	<i>Pidpa</i>	-0.14	-0.15
Grobbendonk	<i>Pidpa</i>	-0.24	-0.14
Herentals	<i>Pidpa</i>	-0.14	-0.11
Snellegem	<i>De Watergroep</i>	-0.31	-0.39
Eeklo	<i>De Watergroep</i>	-0.25	-0.31

Lembeke-Oosteeklo	<i>De Watergroep</i>	-0.25	-0.27
Moerbeke-Wachtebeke	<i>De Watergroep</i>	-0.23	-0.25
Lommel	<i>De Watergroep</i>	-0.21	-0.23
Wellen	<i>De Watergroep</i>	-0.16	-0.29
Kumtich Menebeek	<i>De Watergroep</i>	-0.14	-0.22
Overijse Kouterstraat Nellebeek	<i>De Watergroep</i>	-0.14	-0.19
Beernem	<i>De Watergroep</i>	-0.13	-0.11
Neerpelt	<i>De Watergroep</i>	-0.12	-0.12

Table 13: Group of wells at risk of potential decrease in groundwater levels from simulated 2050 and 2100 scenarios.

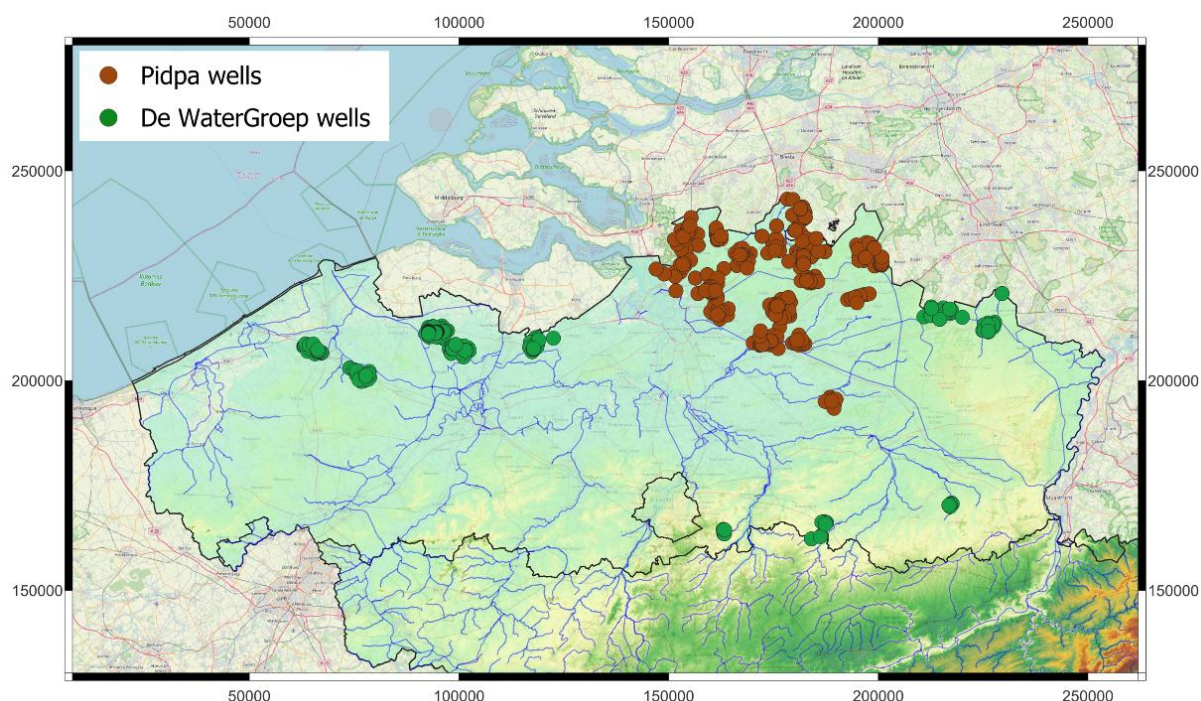


Figure 29: Location of the group of wells at risk of potential decrease in groundwater levels from simulated 2050 and 2100 scenarios

7 Conclusions

This analysis has estimated for each groundwater extraction for drinking water production what effect climate change has on the groundwater balance in the catchment area and the hydraulic heights in the vicinity of the extractions.

Analysis of 14 global climate impact models shows that, for Flanders, the range of projected effects of climate change on groundwater recharge is very large. Almost all models predict a decrease in summer groundwater recharge. On average, these models project a 20% decrease in summer recharge, but the most extreme climate impact models predict a drop of up to 60%. On an annual basis, an average 5% decrease in groundwater recharge is expected by 2050, as

increased winter recharge does not fully compensate for summer losses. However, the uncertainty in this projection is again very high. This analysis confirms that Flanders must prepare for a possible decline in groundwater recharge, especially during summer.

An analysis of the groundwater balance in abstraction zones for drinking water production shows that climate change will generally have a negative impact on the recharge/abstraction ratio everywhere in Flanders. The abstraction-to-recharge ratio is particularly high at several wells in the Kempen region and south of Leuven. It should be noted that these are mainly deeper abstractions, for which delineating the recharge area is more complex. The analysis also clearly shows that artificial infiltration at the Aquaduin abstraction sites has a very positive effect on the recharge/abstraction ratio.

Using time series analysis, the impact of climate change on groundwater levels near drinking water abstraction sites was assessed. This analysis shows that, although groundwater recharge is expected to decrease everywhere in Flanders, the effect of decreased groundwater recharge on groundwater levels vary in space. This analysis confirms the positive effects of managed aquifer recharge on groundwater levels. This analysis shows that climate change may lead to lower average groundwater levels, particularly in northern Flanders, because of the hydrogeological properties of the subsurface. Some abstraction sites were identified where the projected decline in groundwater level could exceed 10 cm. Interpretation of all model results should take into account the assumptions and uncertainties inherent to the models used.

In light of the portfolio of future investments requirement in Flemish drinking water infrastructure, these results indicate in which locations increasing or maintaining groundwater discharge in the future might be challenged by climate change impacts. Declining groundwater levels can be compensated by reducing the abstraction discharges, lowering other abstractions, limiting drainage, or increasing infiltration in the recharge area. This study confirms the importance of sustainable groundwater management in a changing climate by increasing infiltration, smarter drainage and smarter groundwater extraction . Given the additional pressure climate change will place on groundwater resources, this analysis also again confirms the importance of protecting both the quantity and quality of groundwater in recharge zones of drinking water wells.

8 Recommendations for further research

The data-driven approach applied in this study has allowed a screening of climate change impacts of all drinking water wells in Flanders. This analysis has identified some locations where the impact of climate change on groundwater levels might be important. Results of data-driven models should be interpreted with care as their reliability depends on data quality, model performance and relevant local factors taken into account in the models. For those abstraction sites with potentially high climate impact based on data-driven methods, we recommend developing local transient MODFLOW in order to calculate future scenarios. These models can simulate the impact of climate change on groundwater levels in greater detail, assess the impact on nature and/or subsidence and allow for the evaluation of potential mitigation measures such as reducing abstractions, reducing drainage or increasing infiltration.

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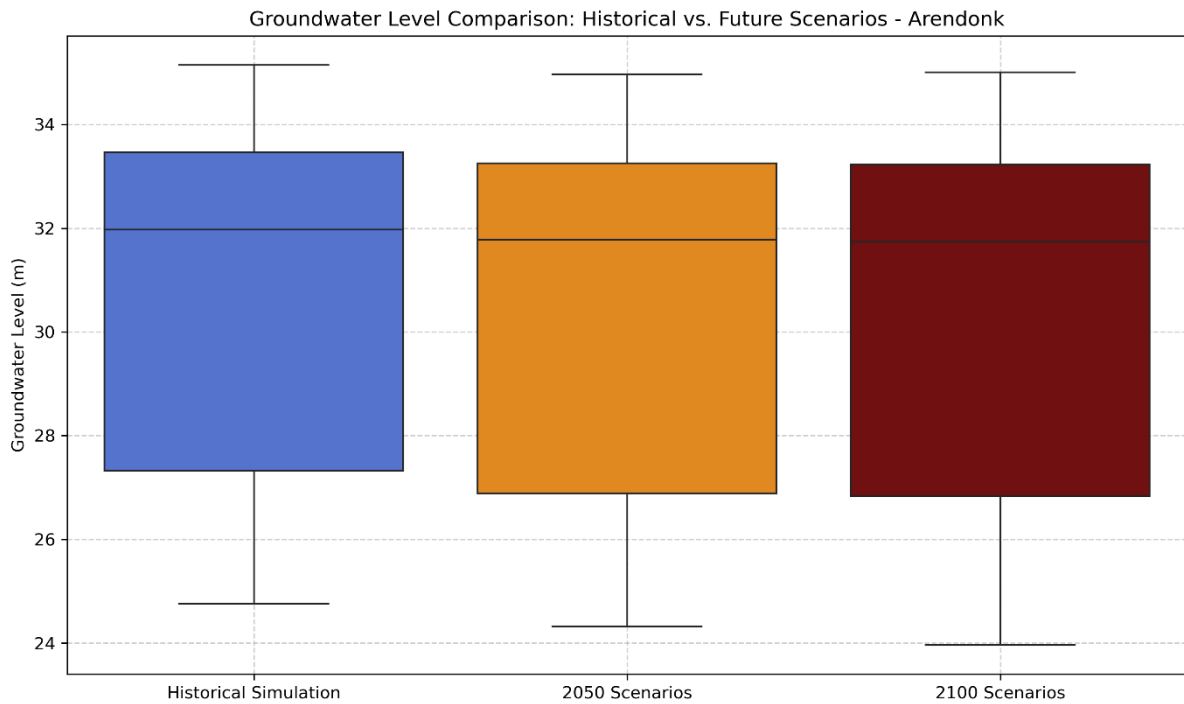
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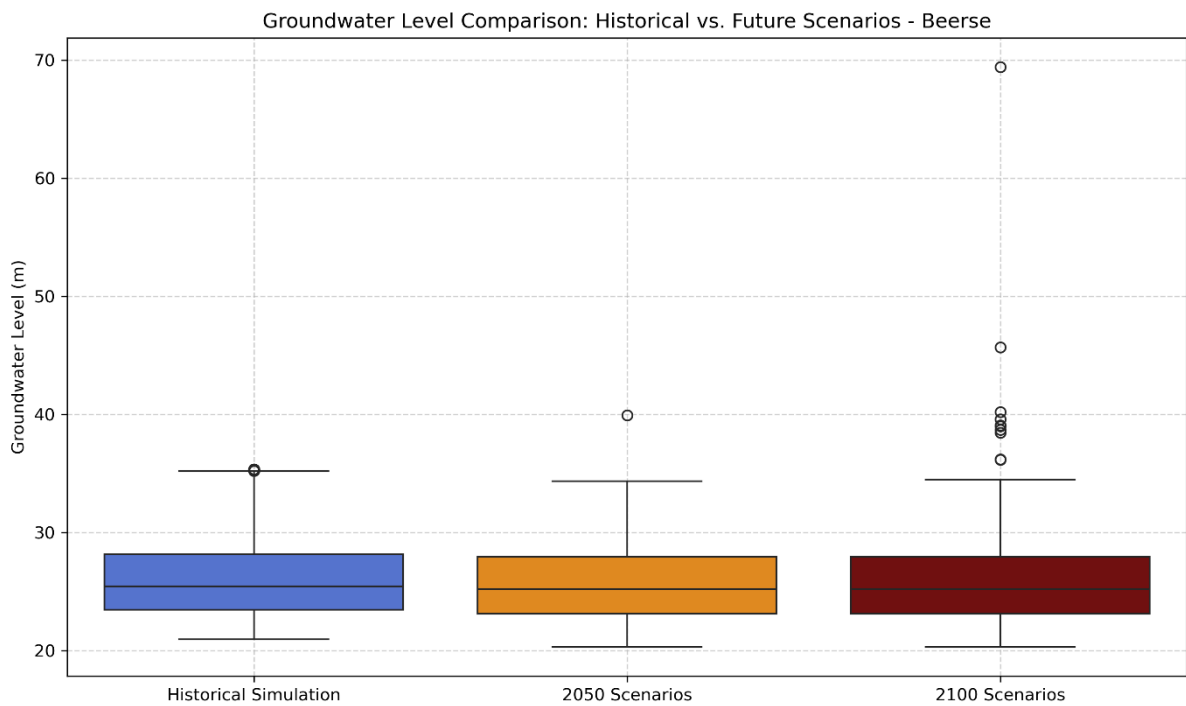
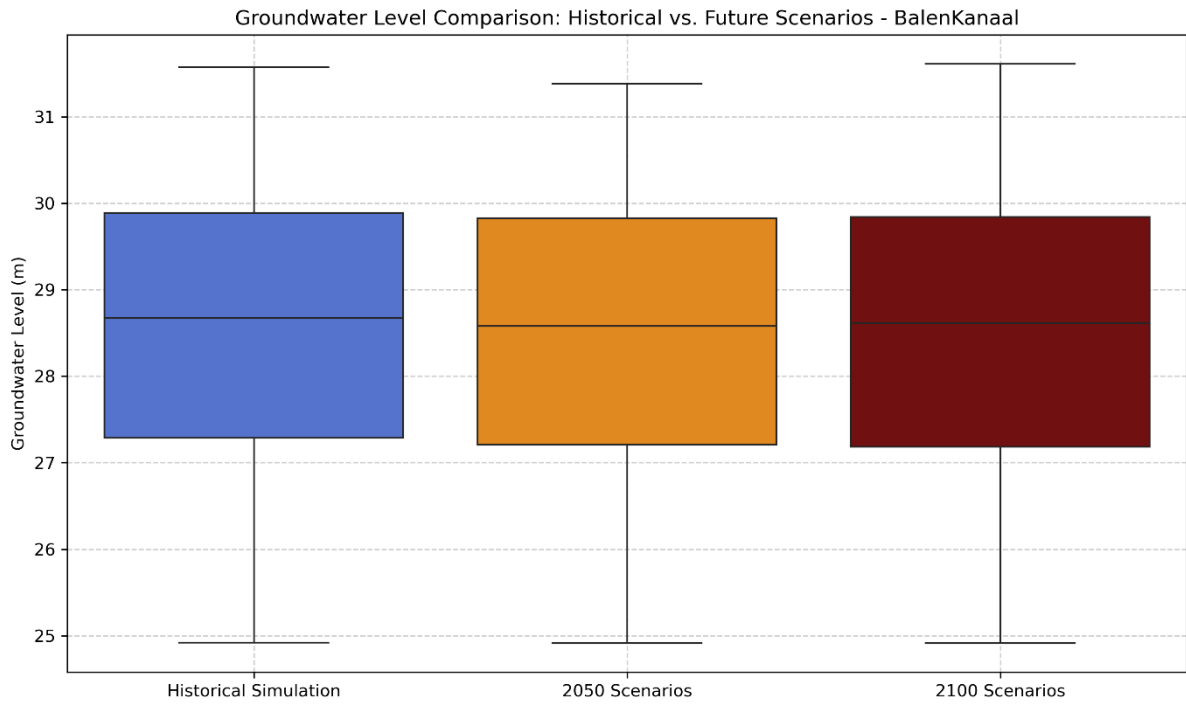
10 Appendices

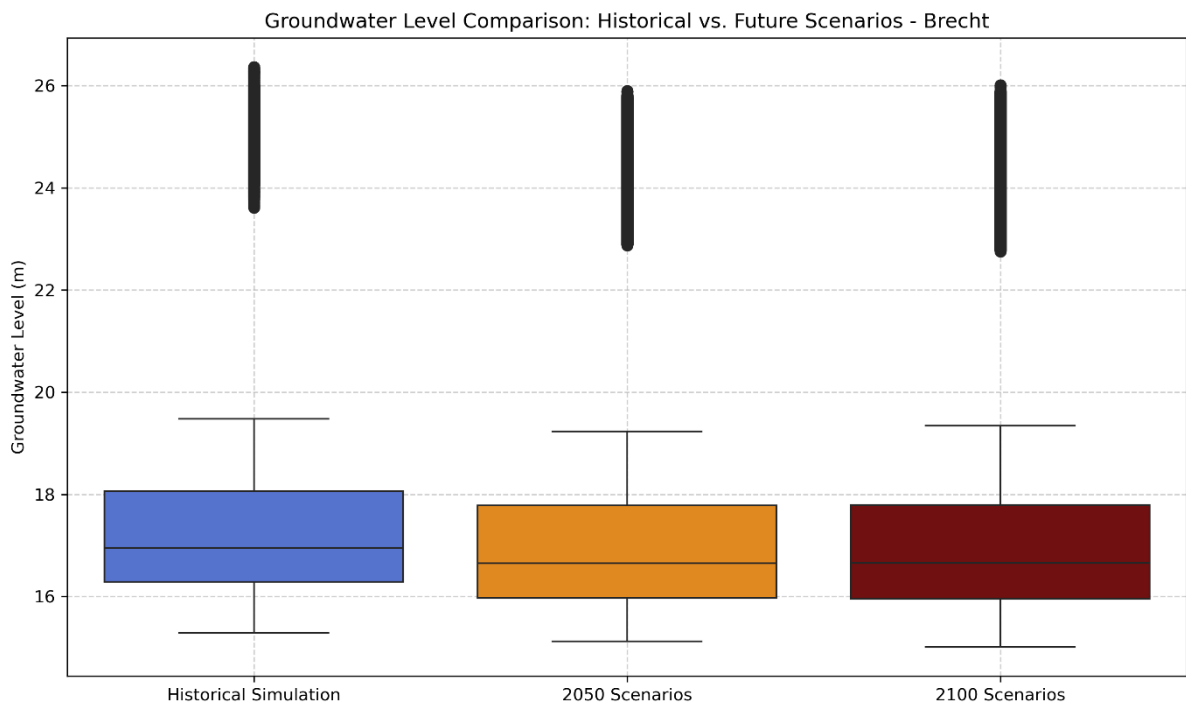
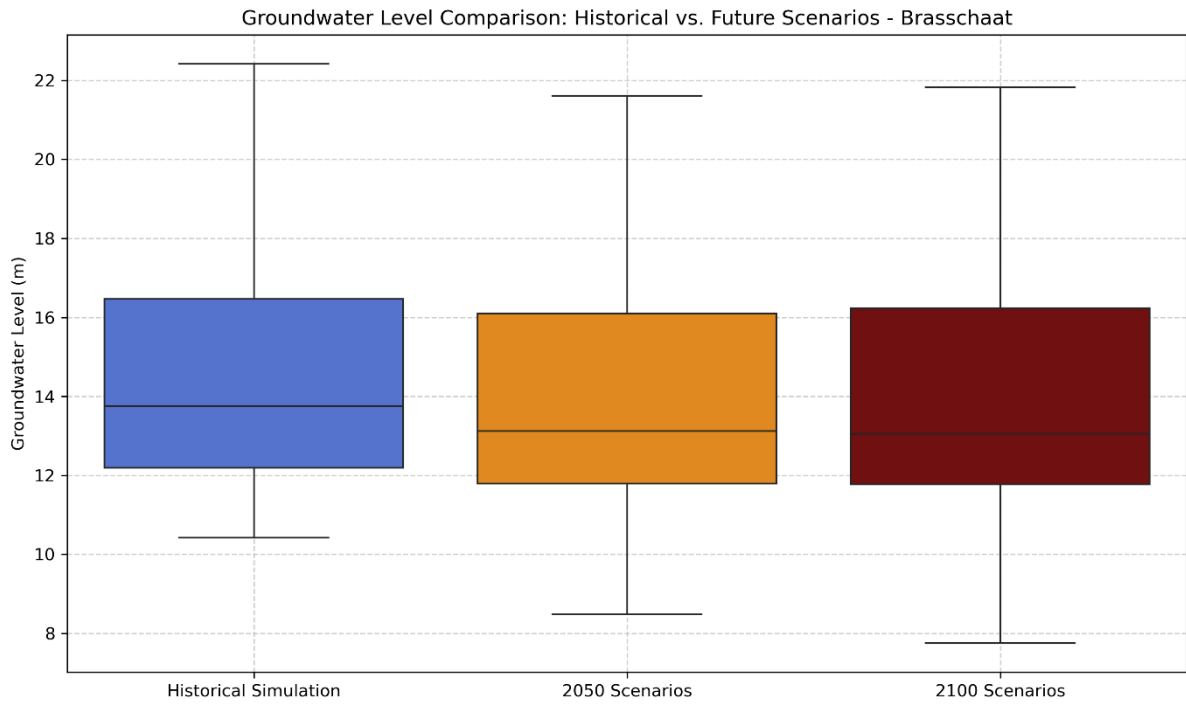
10.1 Appendix A: Pidpa results

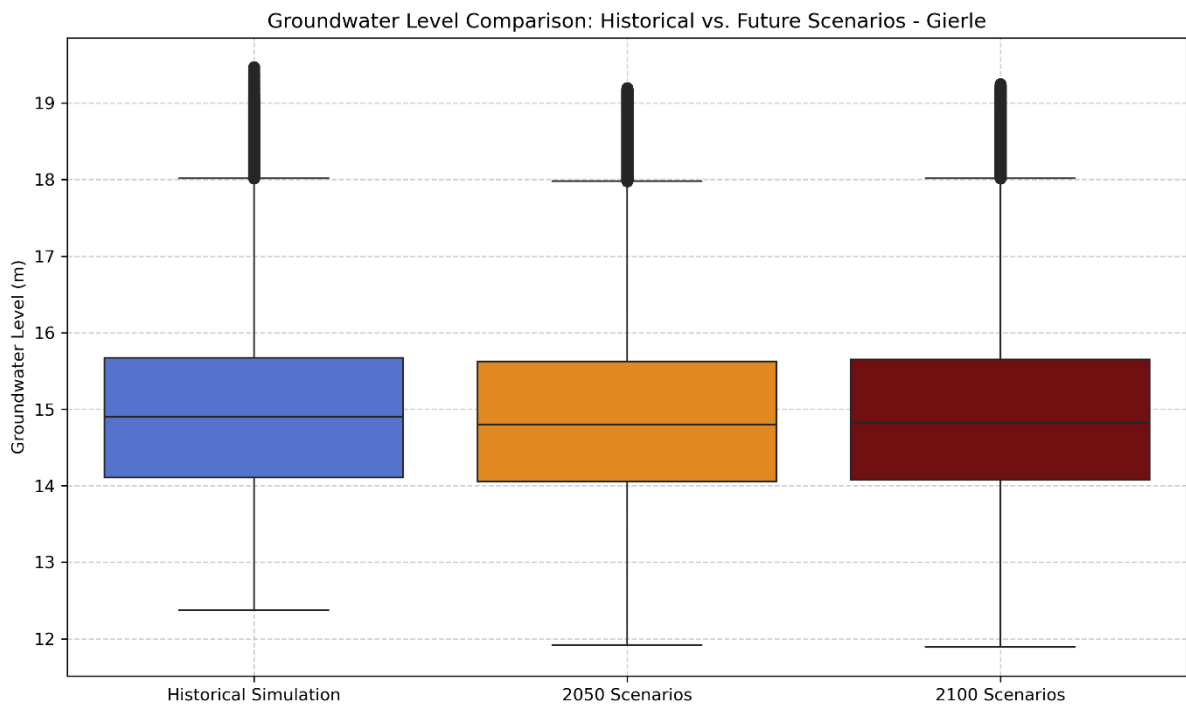
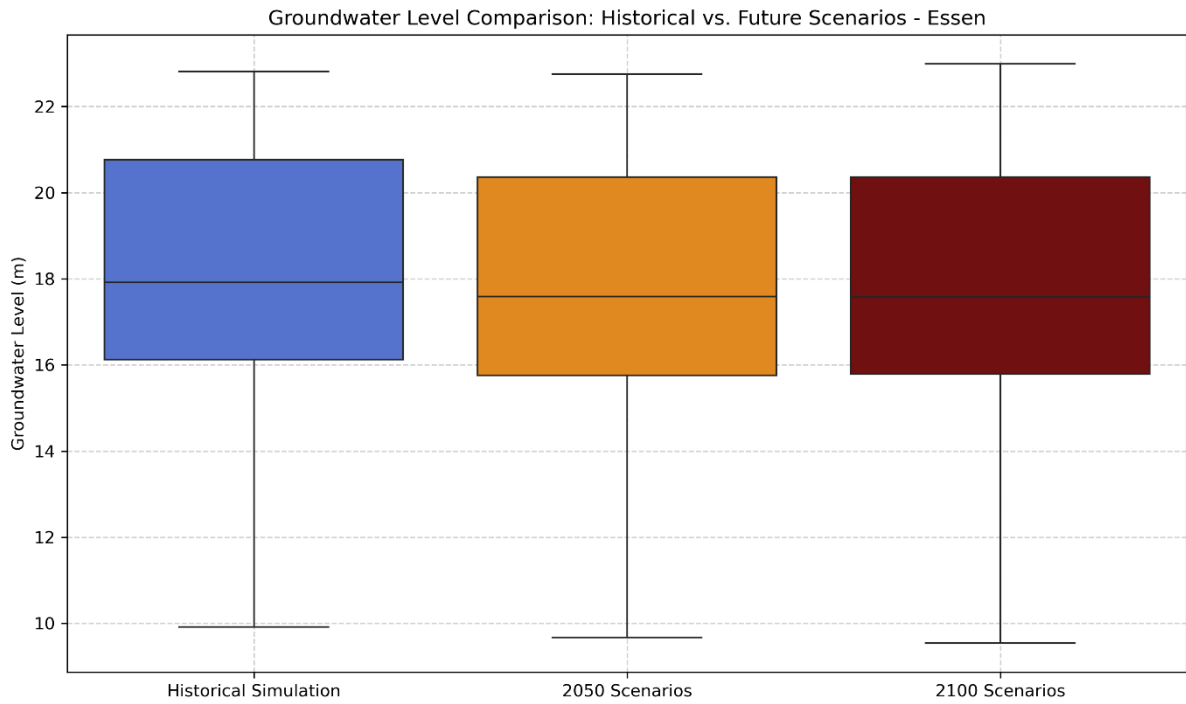
10.1.1 A.1 Pidpa Groundwater Level comparison

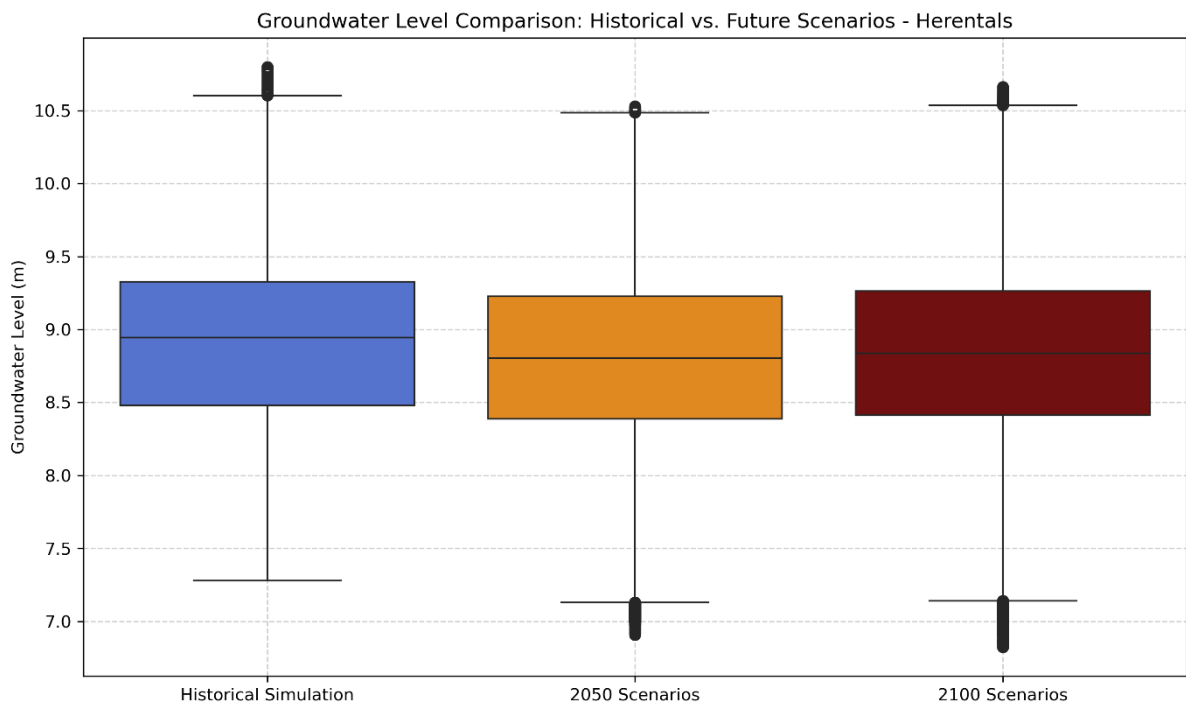
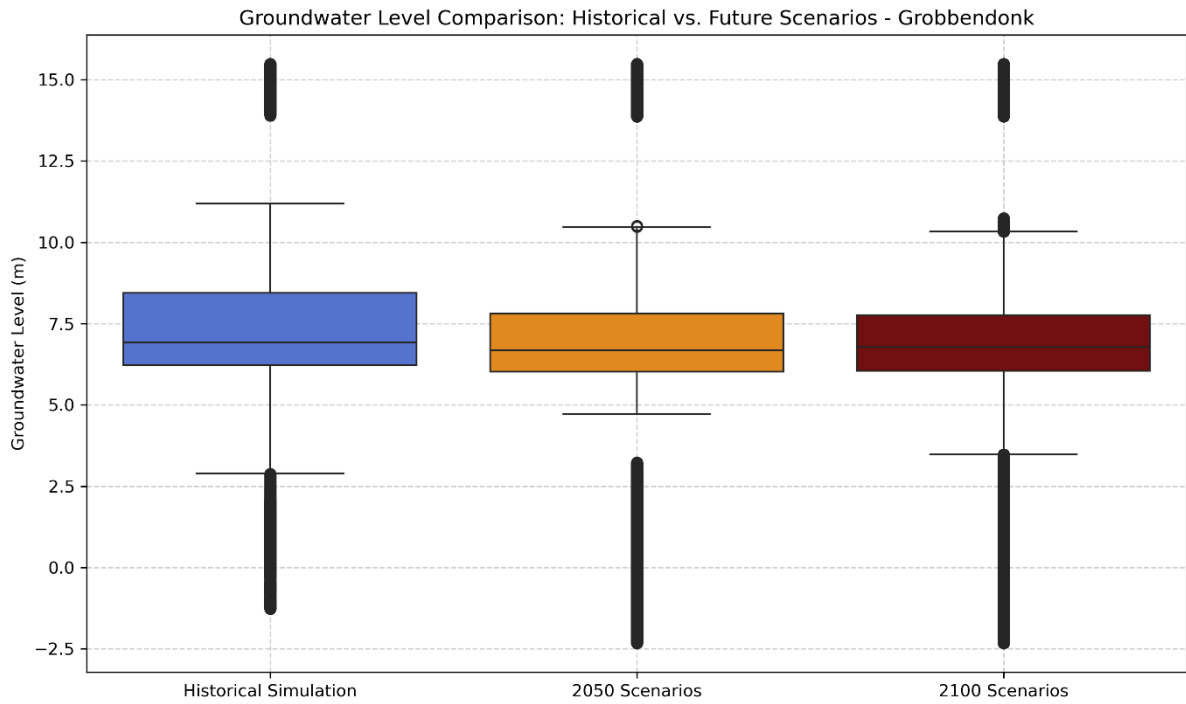
Comparison of simulated groundwater levels under historical and future climate scenarios for three examples of group of wells.

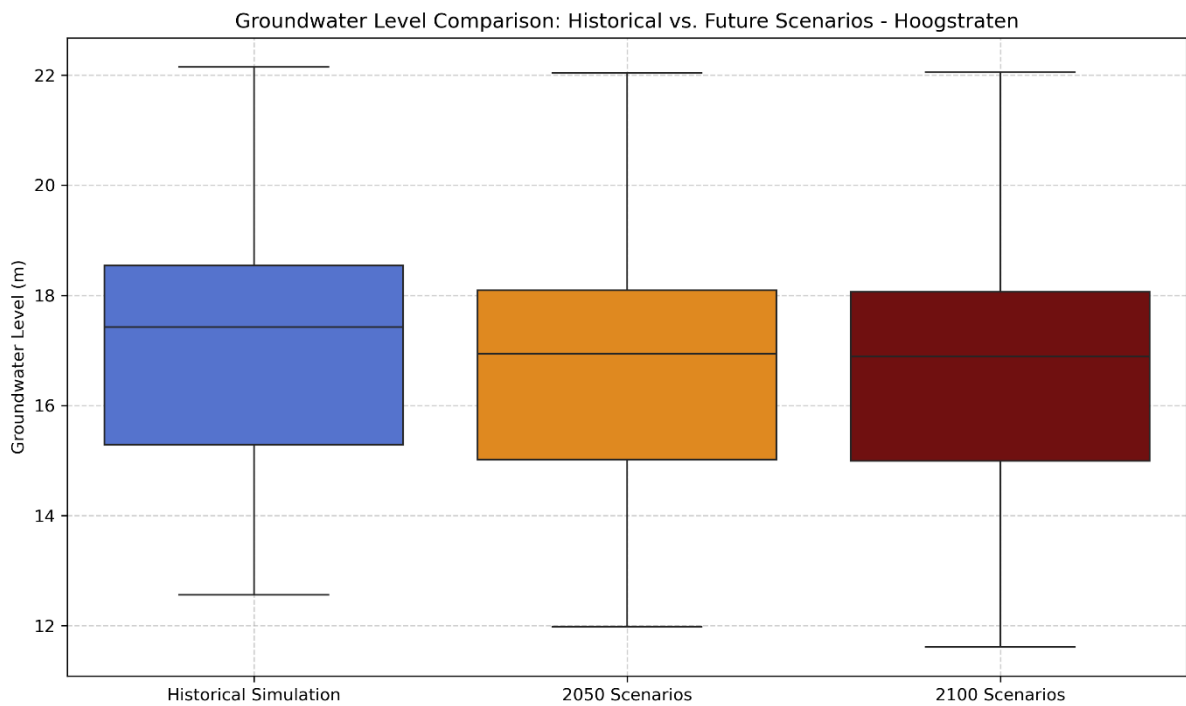
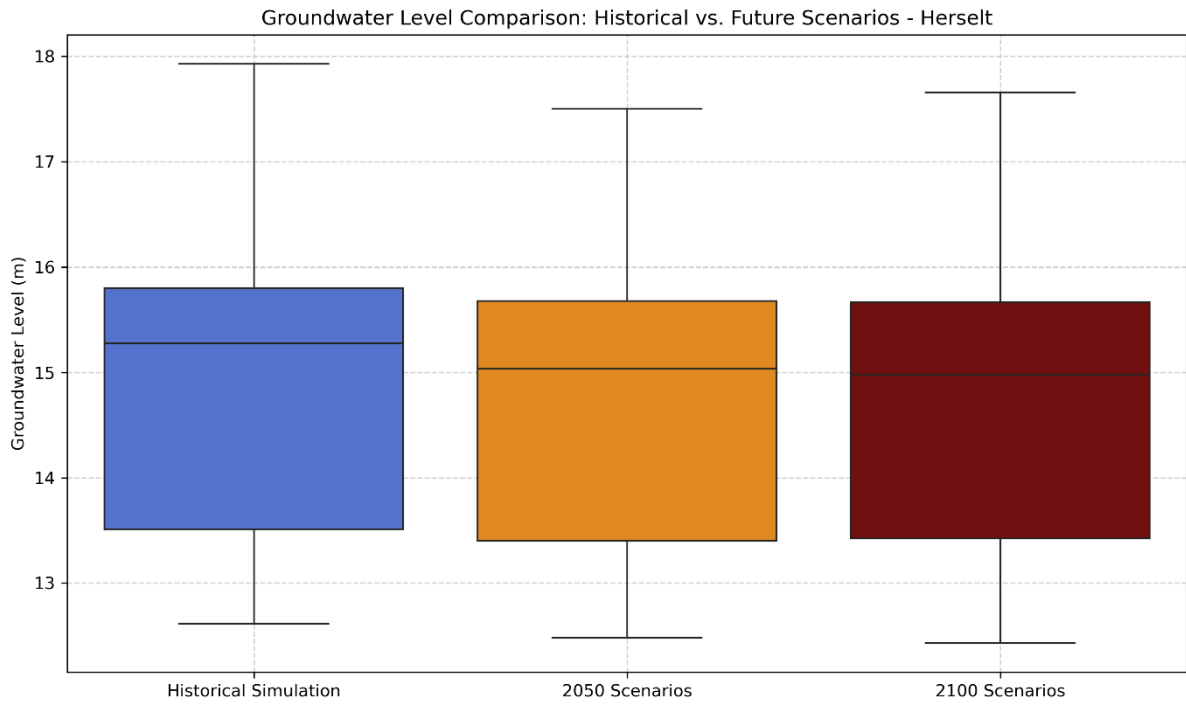


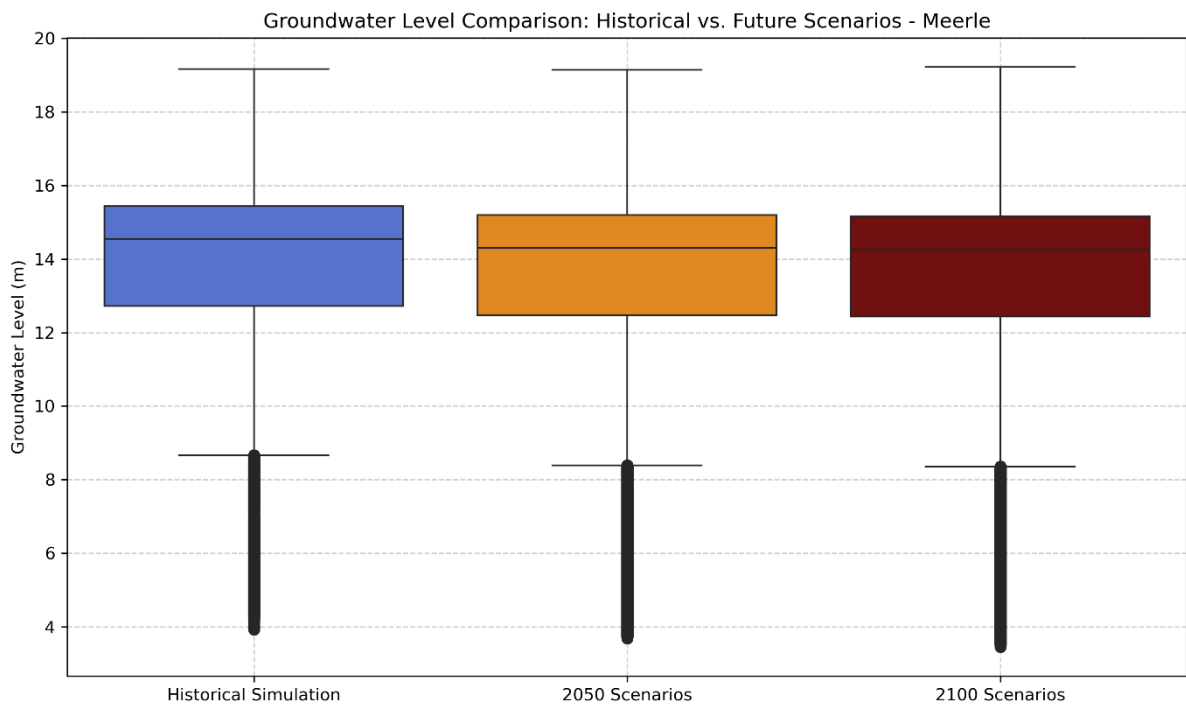
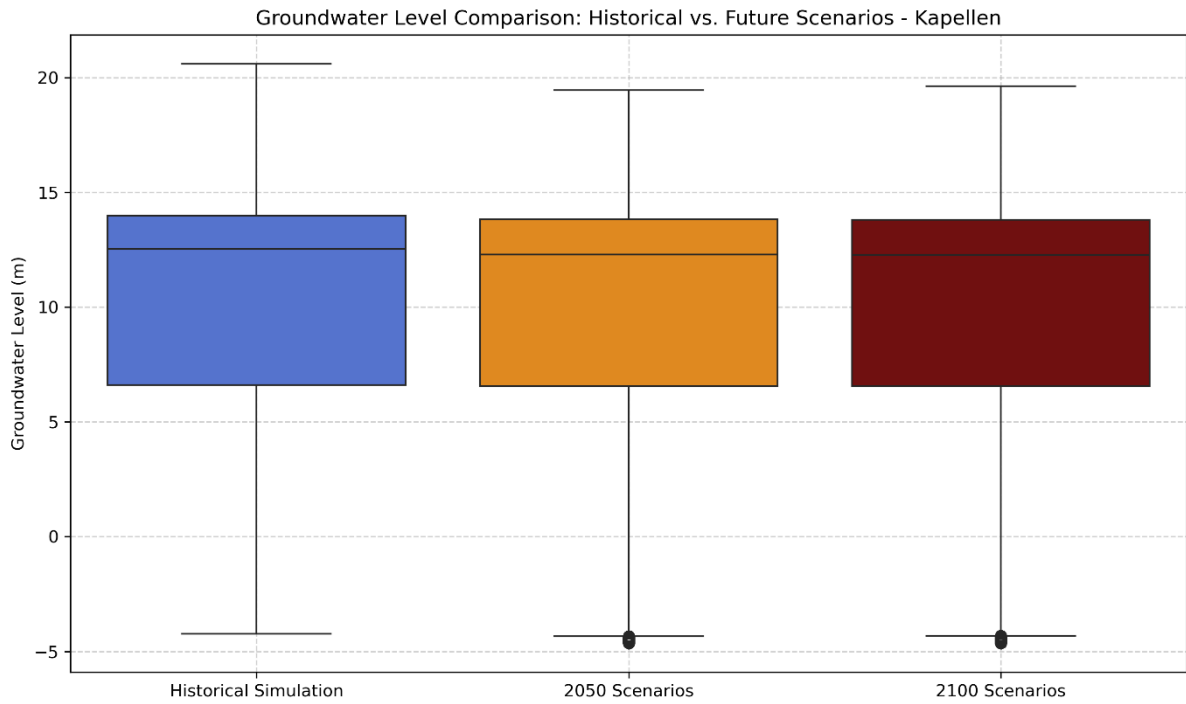


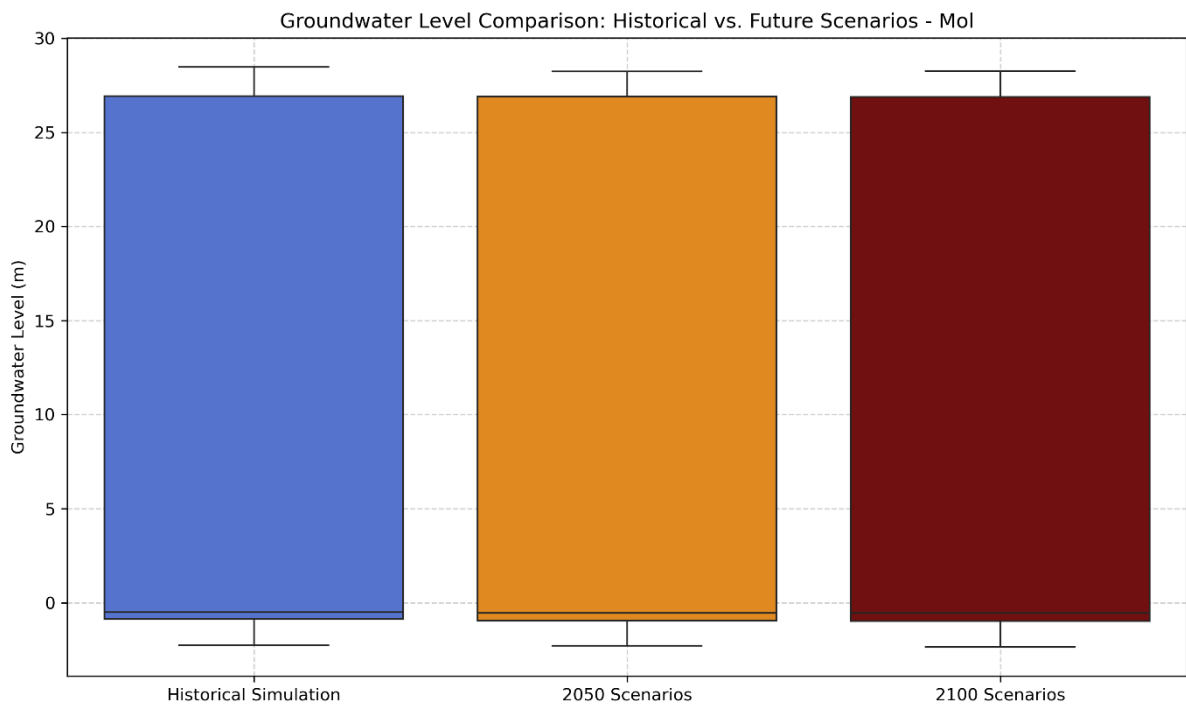
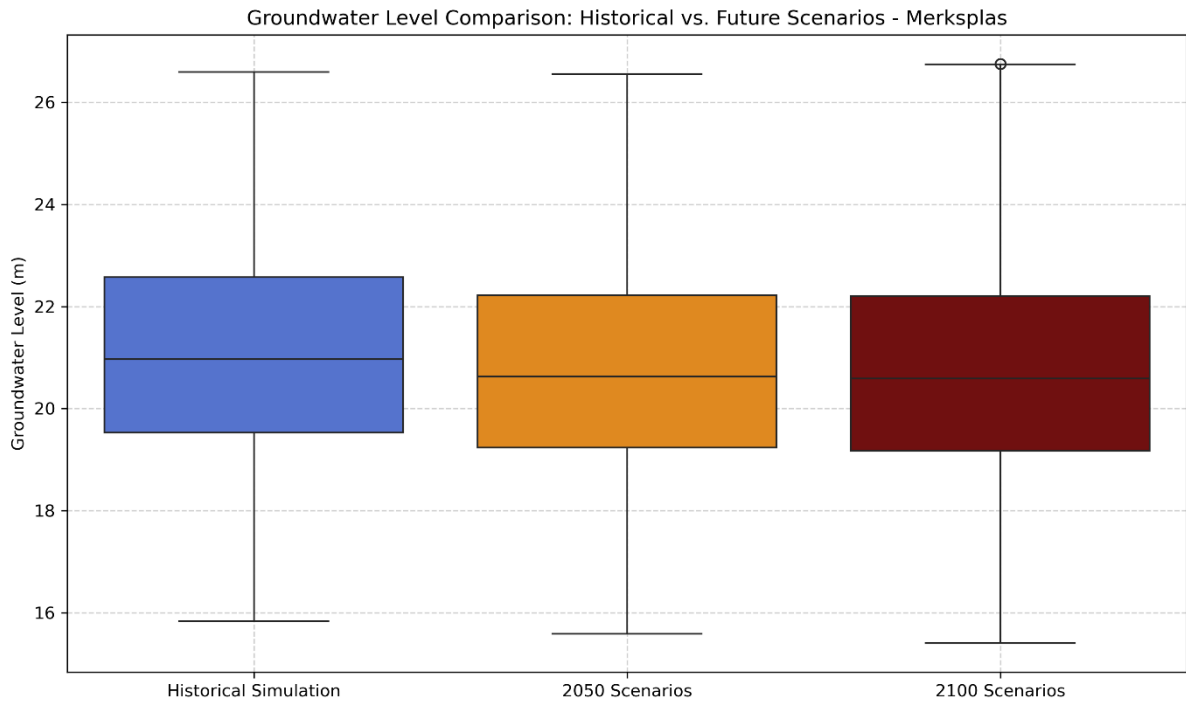


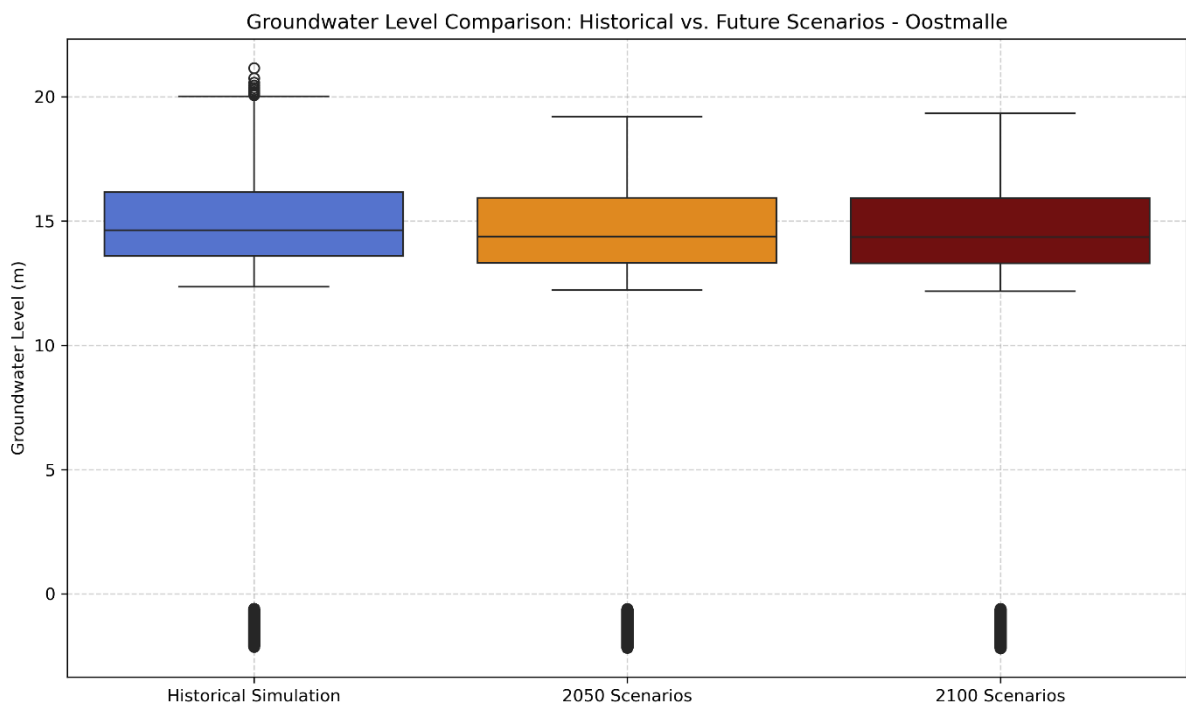
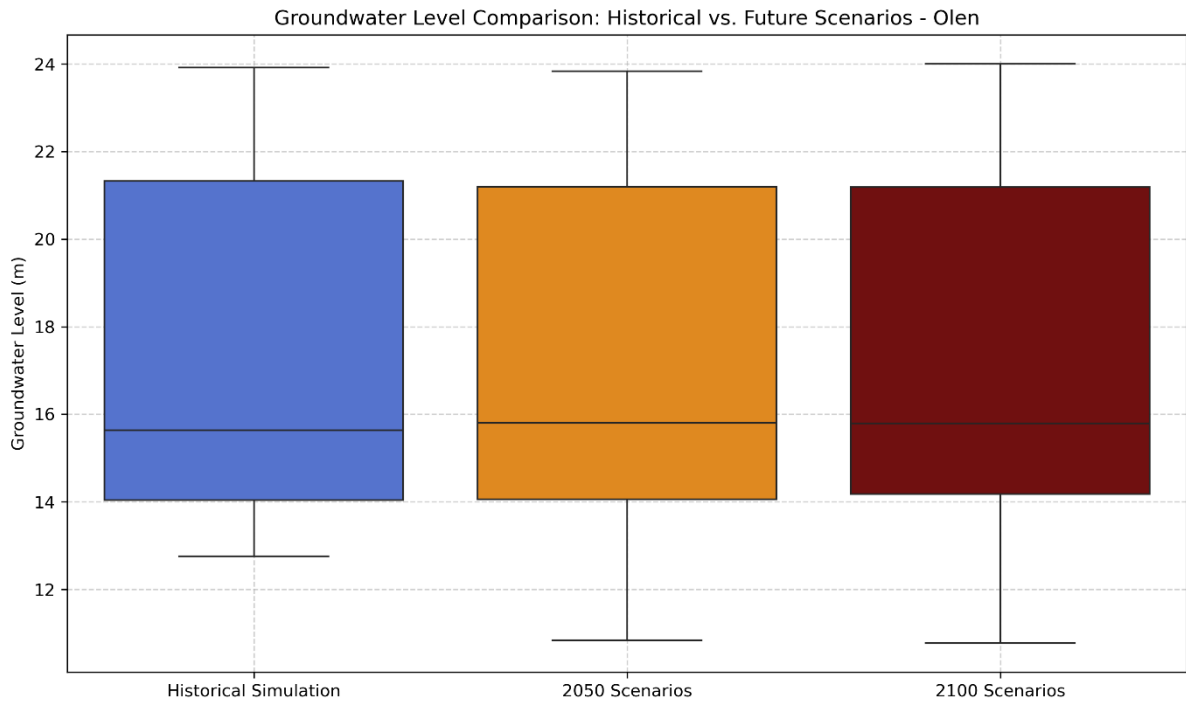


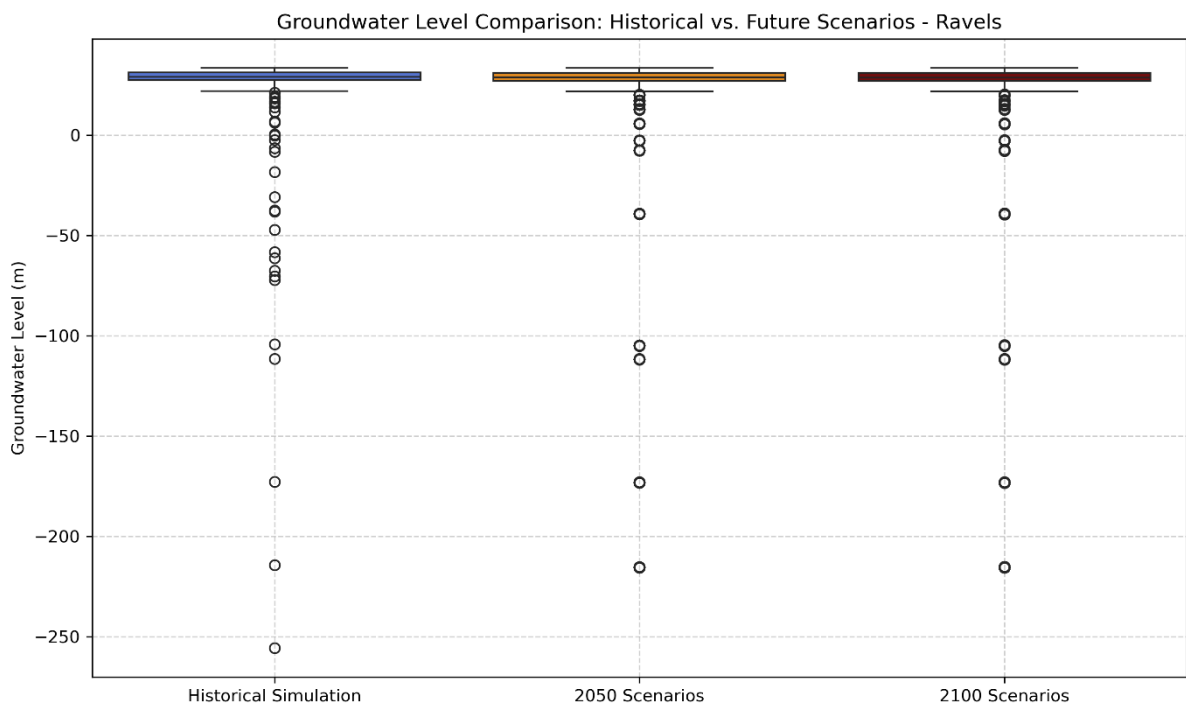
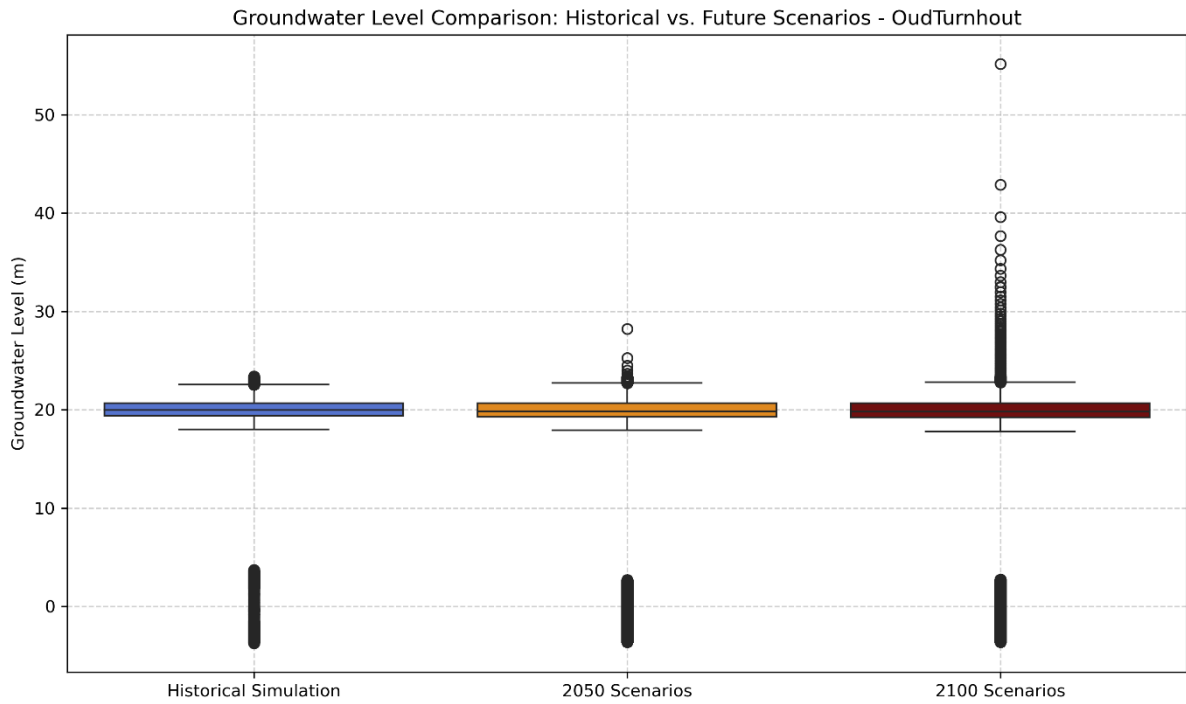


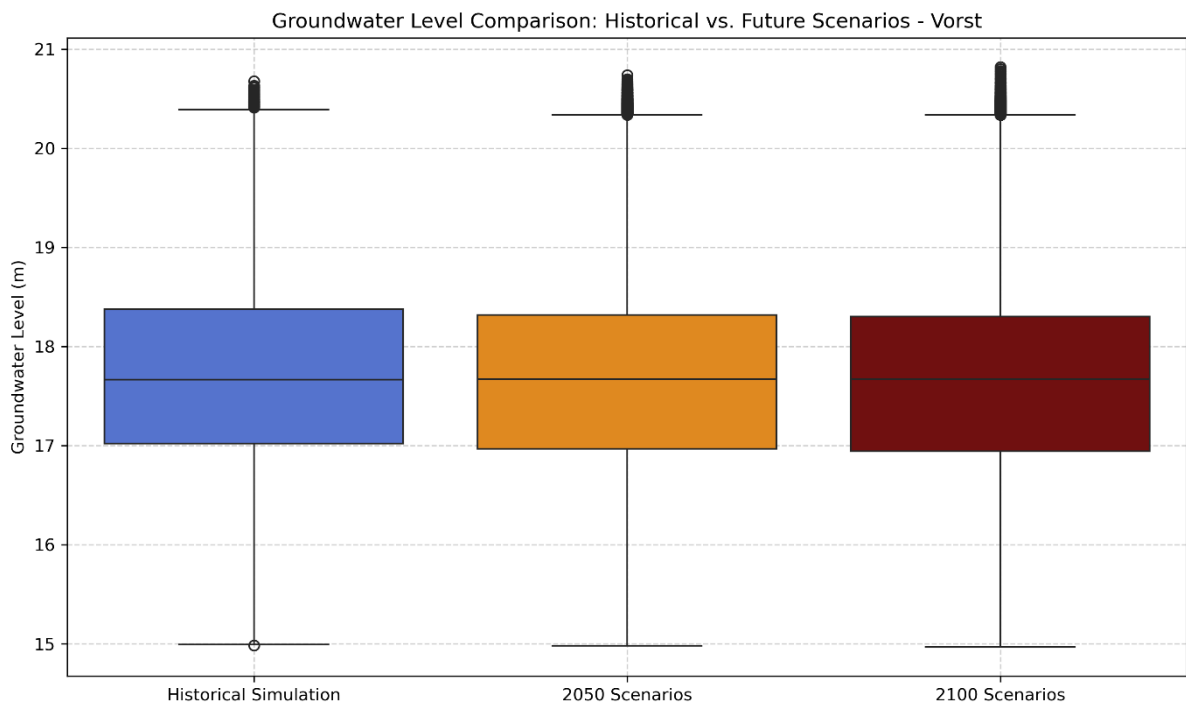
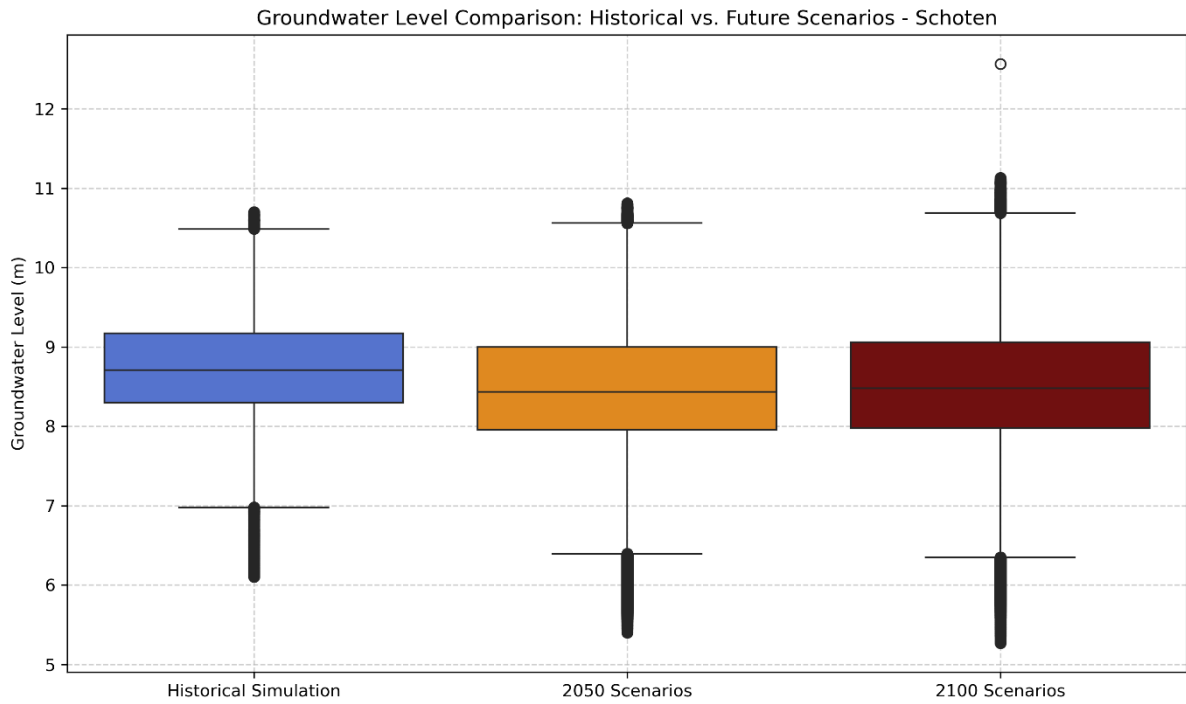


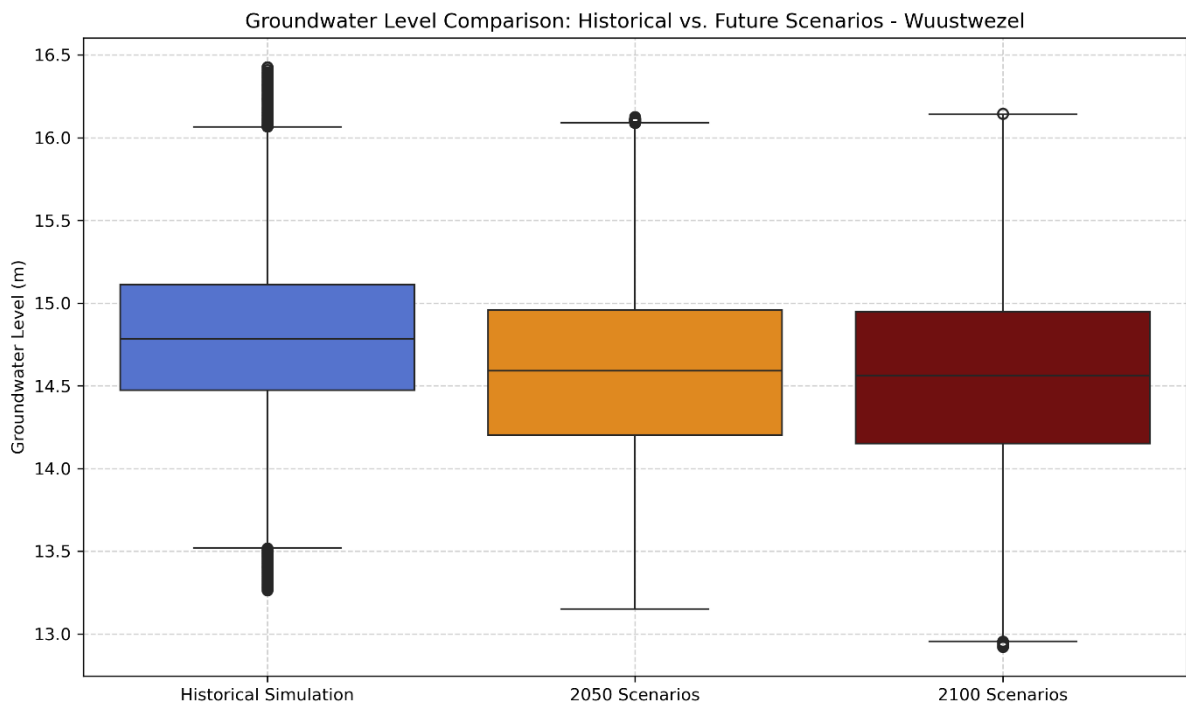
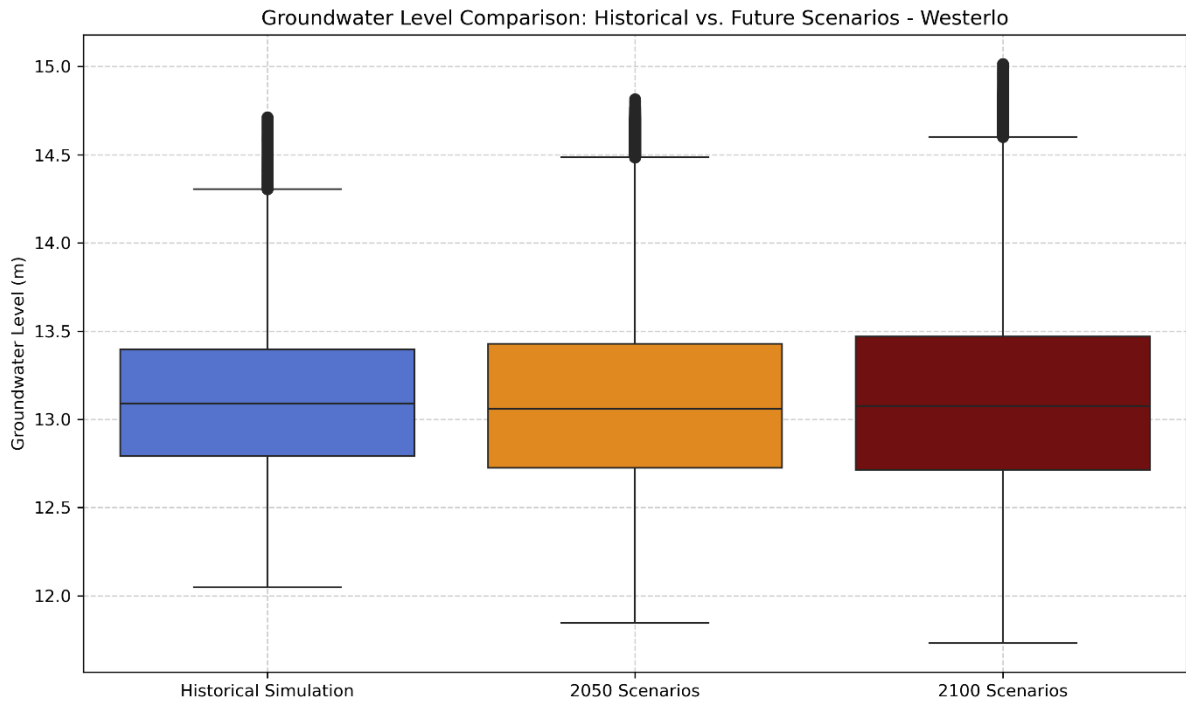






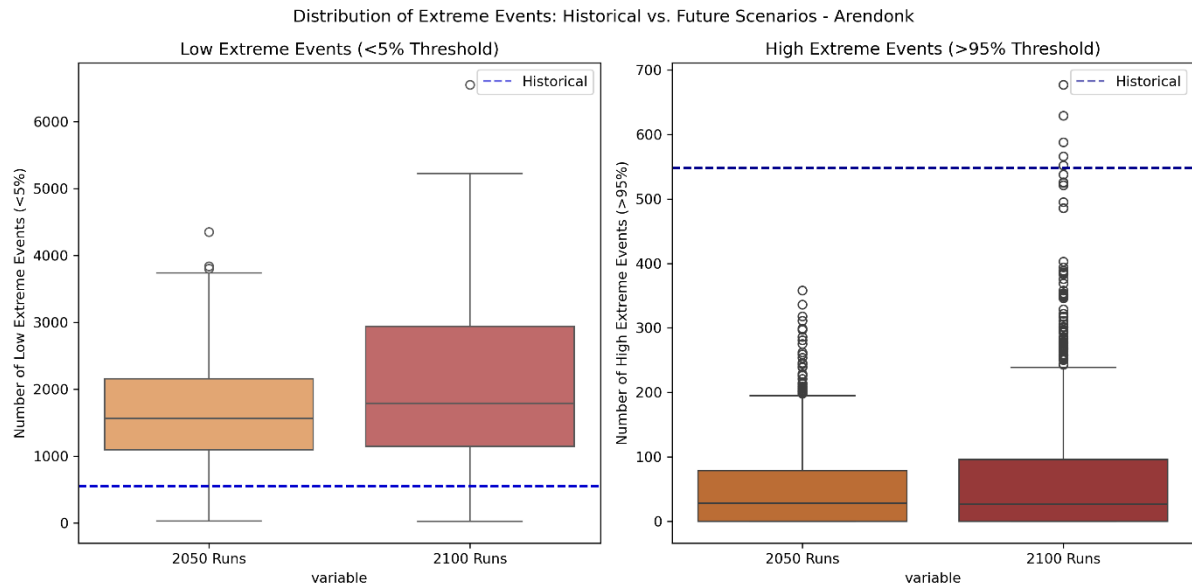




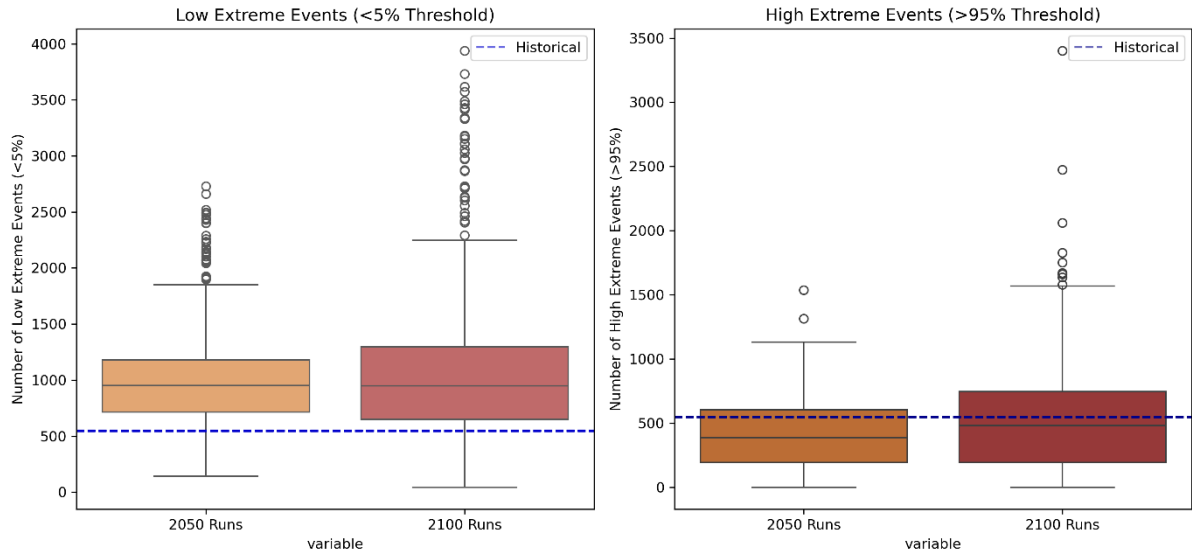


10.1.2 A.2 Pidpa Distribution of Extreme Events

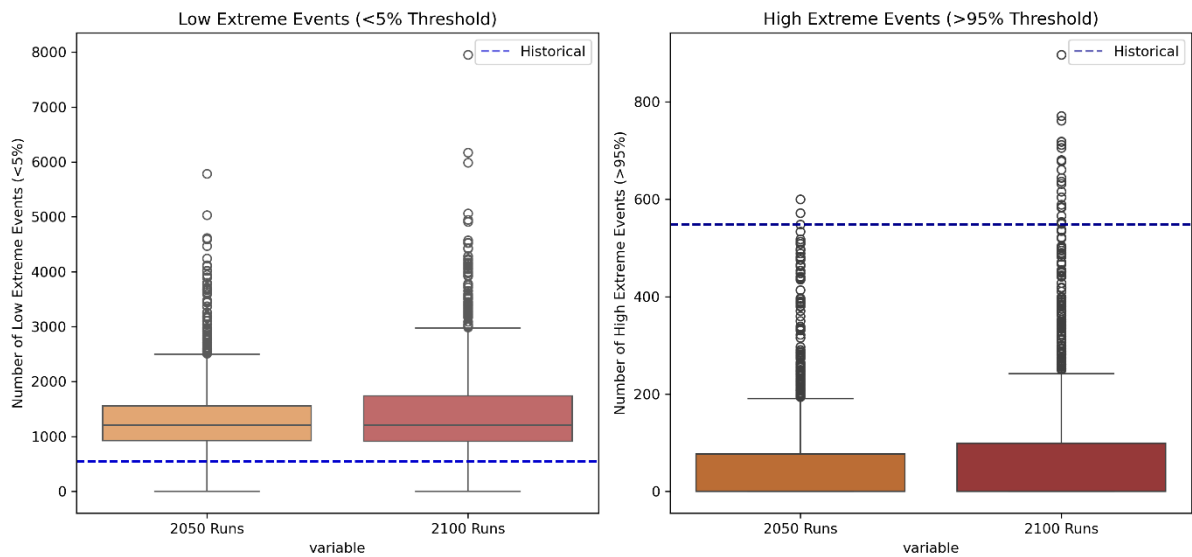
Distribution of extreme groundwater level events under future scenarios for the Hoogstraten group of wells.



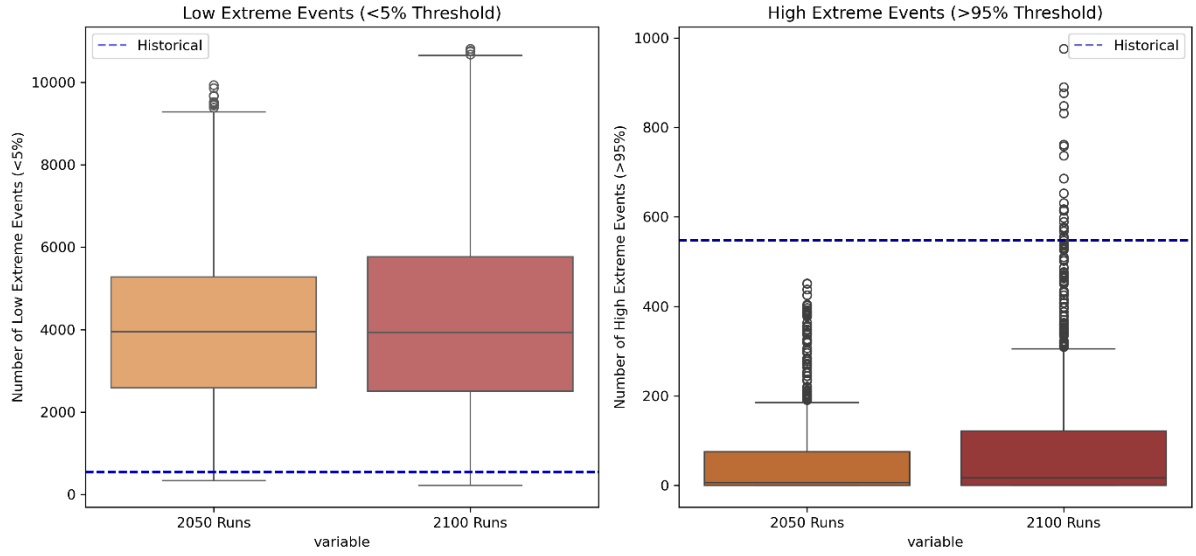
Distribution of Extreme Events: Historical vs. Future Scenarios - BalenKanaal



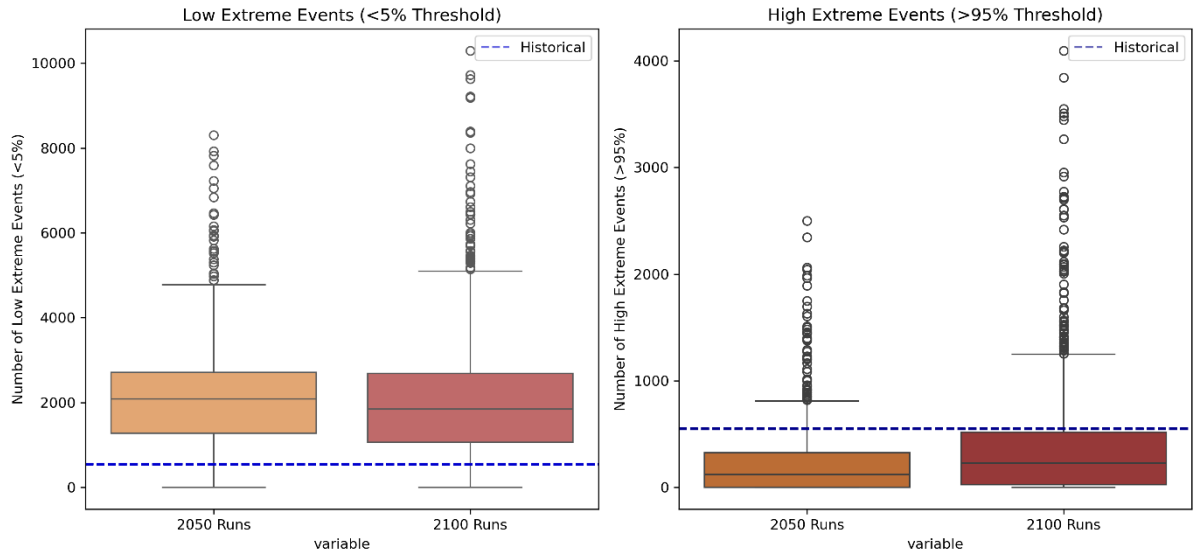
Distribution of Extreme Events: Historical vs. Future Scenarios - Beerse



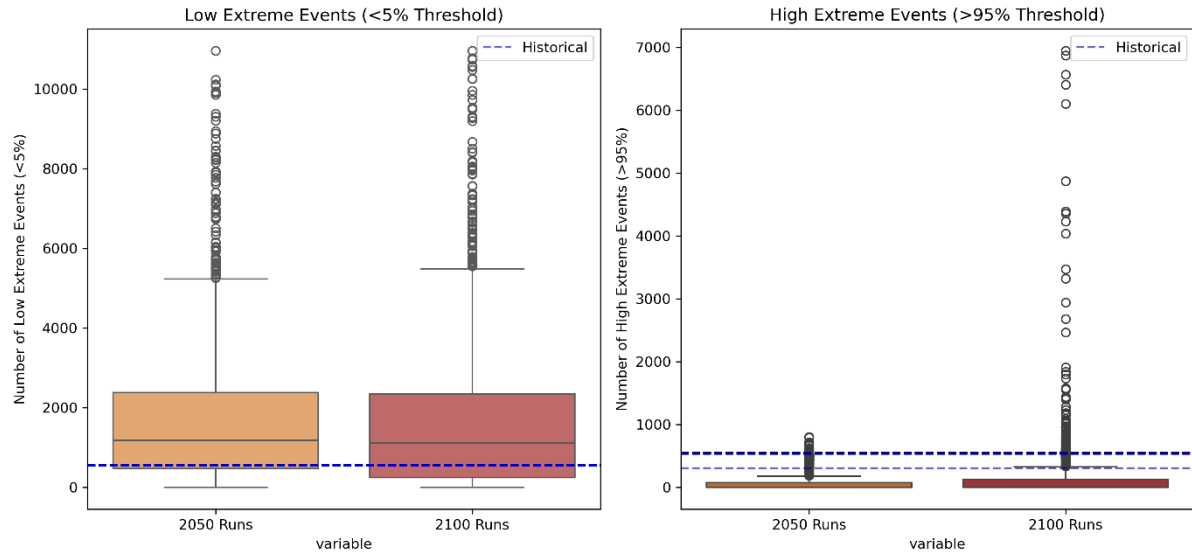
Distribution of Extreme Events: Historical vs. Future Scenarios - Brasschaat



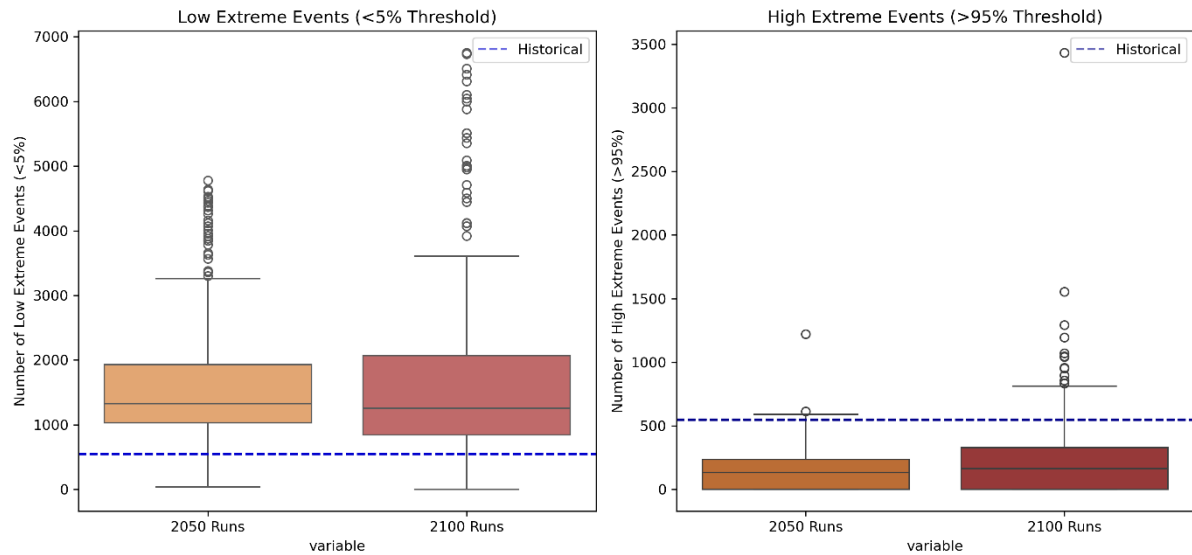
Distribution of Extreme Events: Historical vs. Future Scenarios - Essen



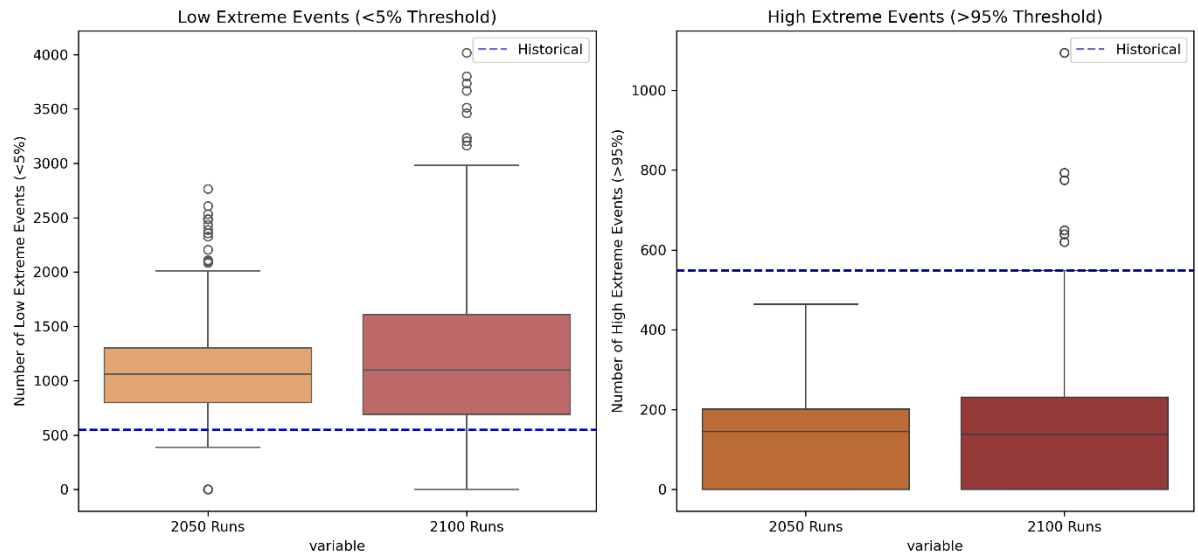
Distribution of Extreme Events: Historical vs. Future Scenarios - Grobbendonk



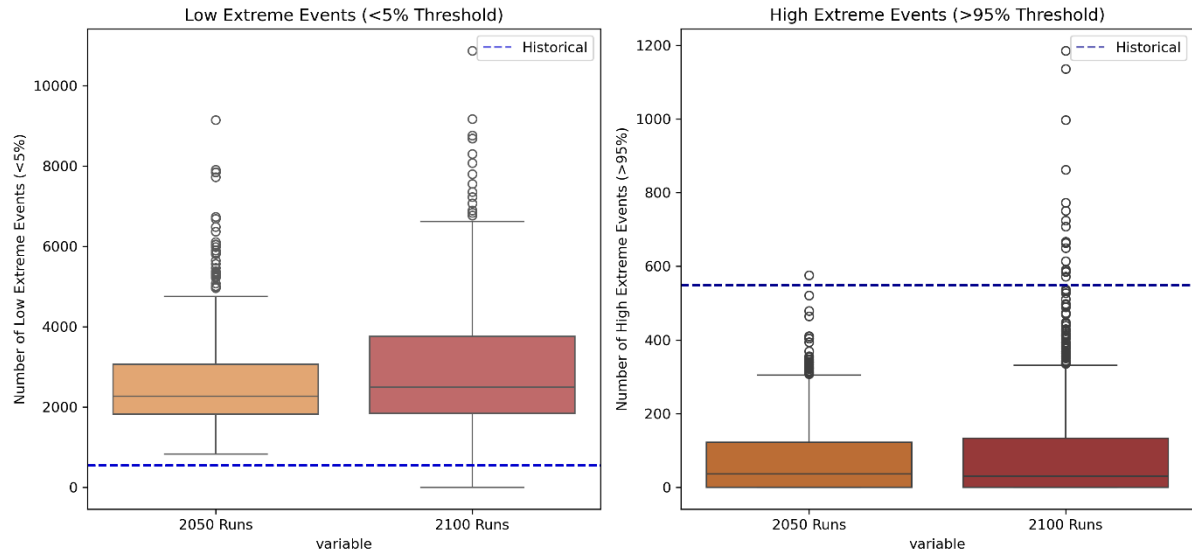
Distribution of Extreme Events: Historical vs. Future Scenarios - Herentals



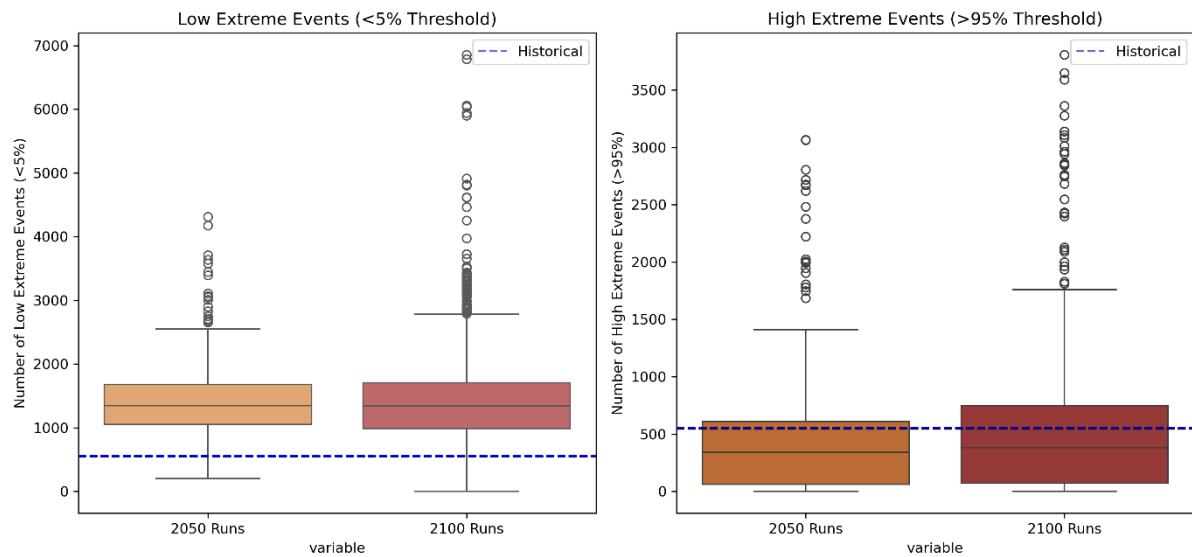
Distribution of Extreme Events: Historical vs. Future Scenarios - Herselt



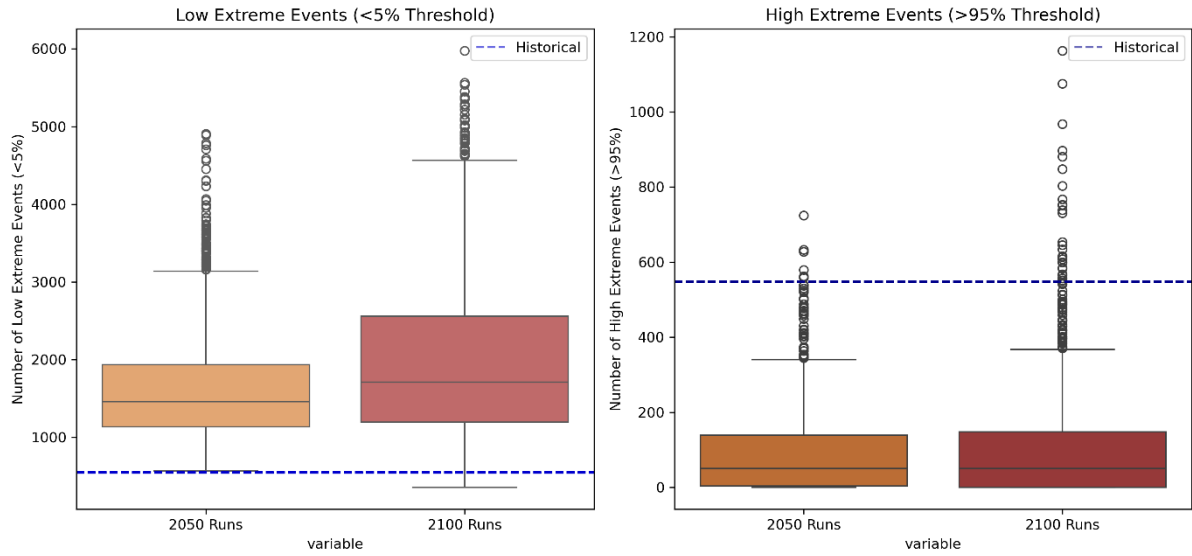
Distribution of Extreme Events: Historical vs. Future Scenarios - Hoogstraten



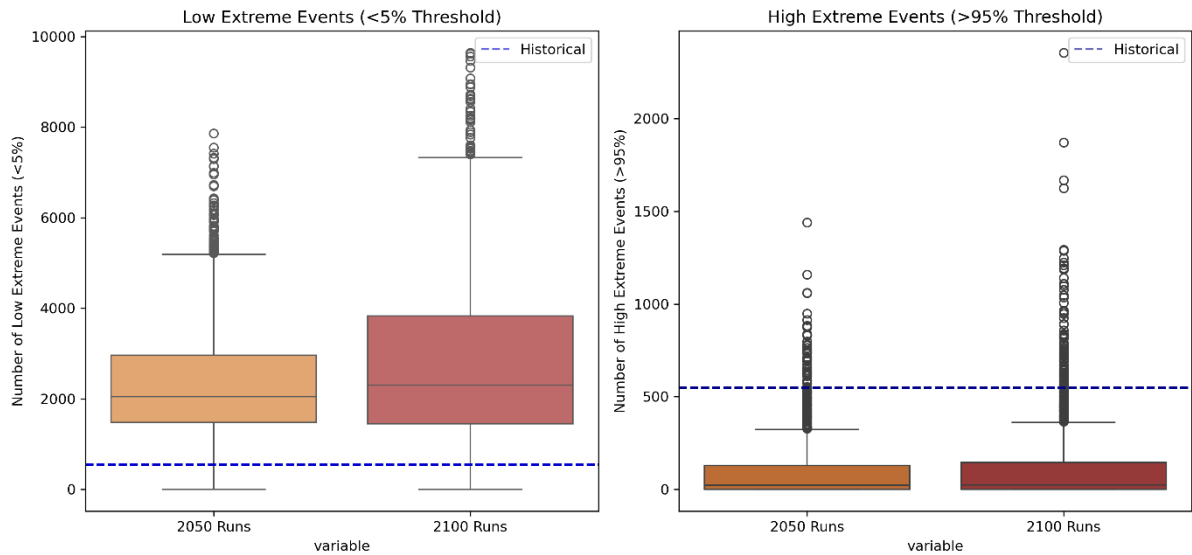
Distribution of Extreme Events: Historical vs. Future Scenarios - Kapellen



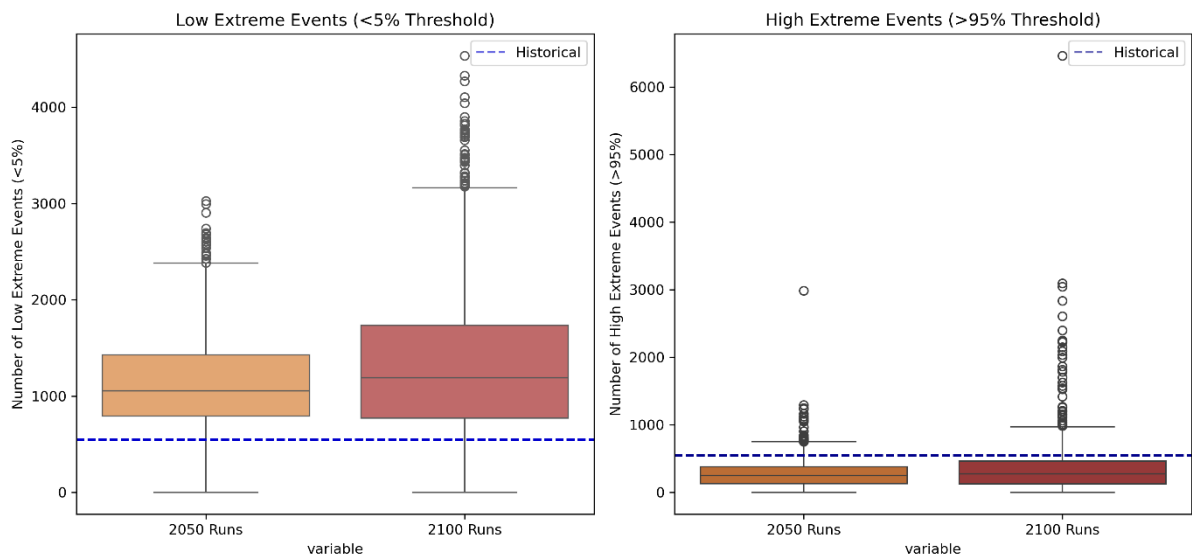
Distribution of Extreme Events: Historical vs. Future Scenarios - Meerle



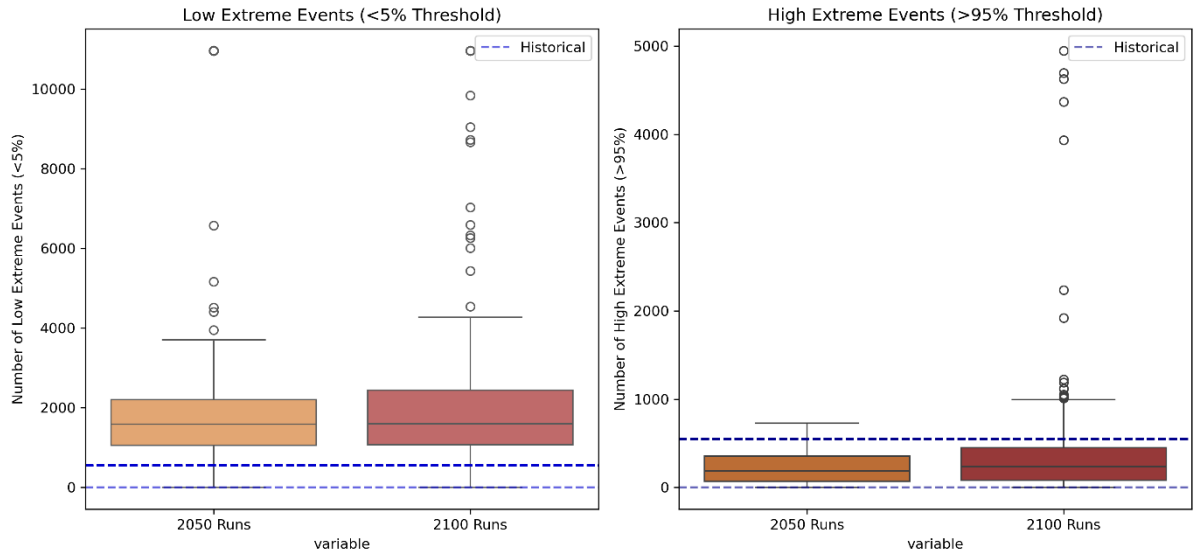
Distribution of Extreme Events: Historical vs. Future Scenarios - Merksplas



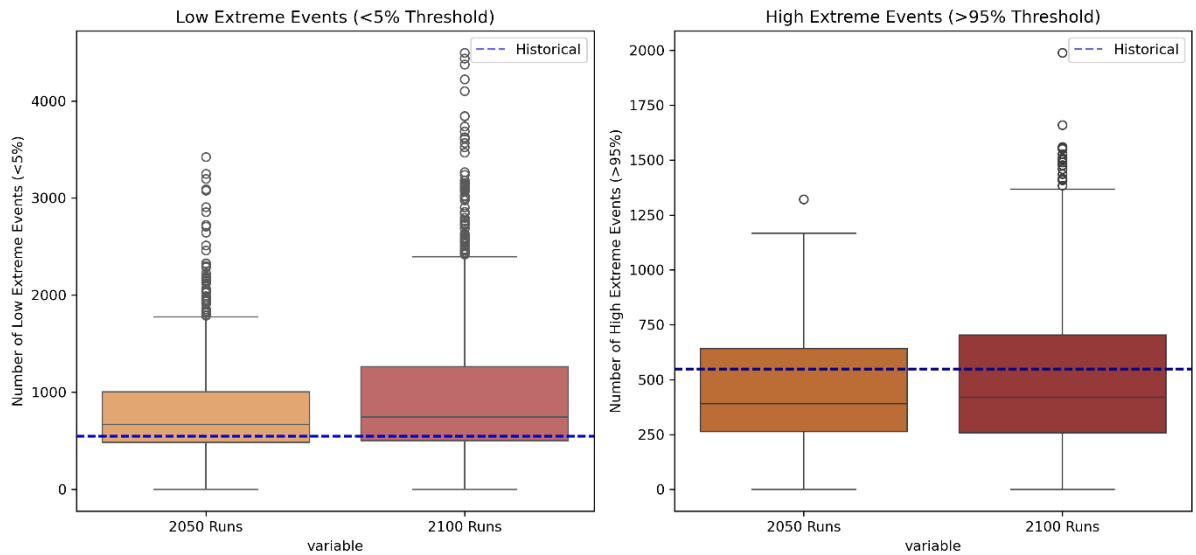
Distribution of Extreme Events: Historical vs. Future Scenarios - Mol



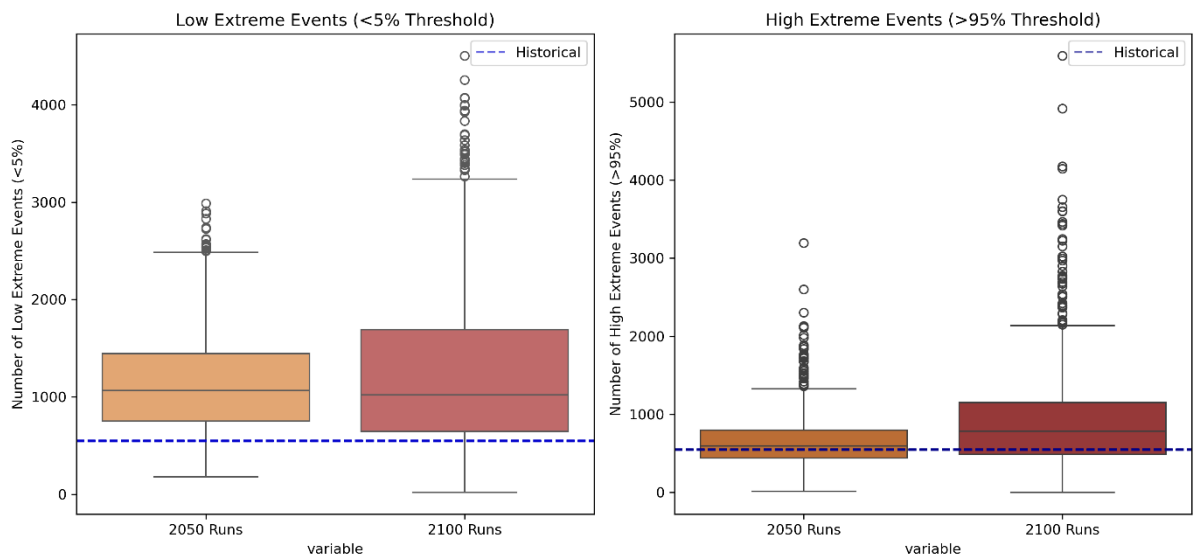
Distribution of Extreme Events: Historical vs. Future Scenarios - Oostmalle



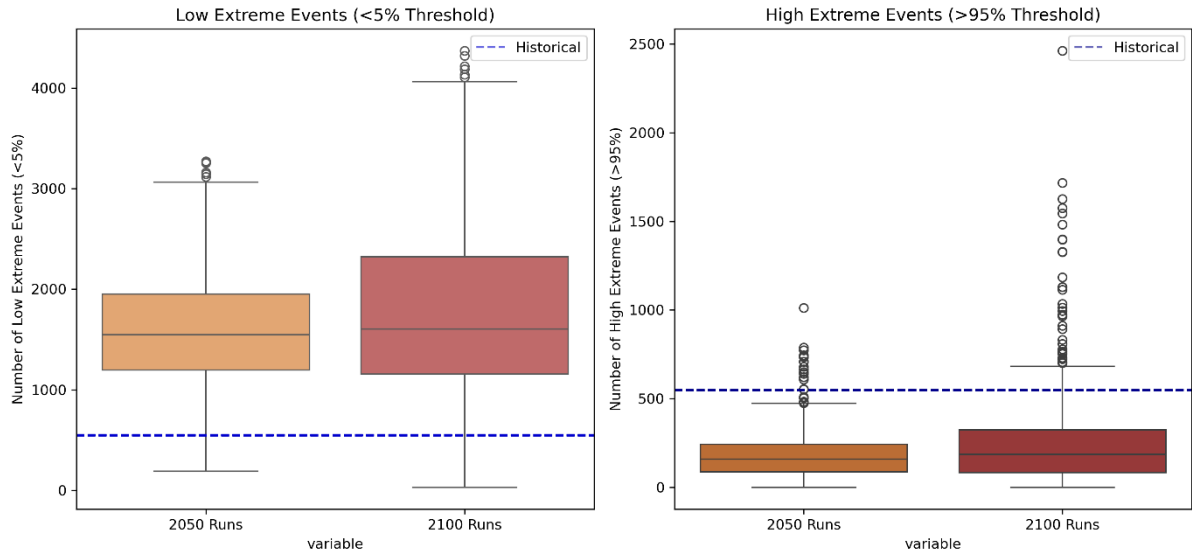
Distribution of Extreme Events: Historical vs. Future Scenarios - Vorst



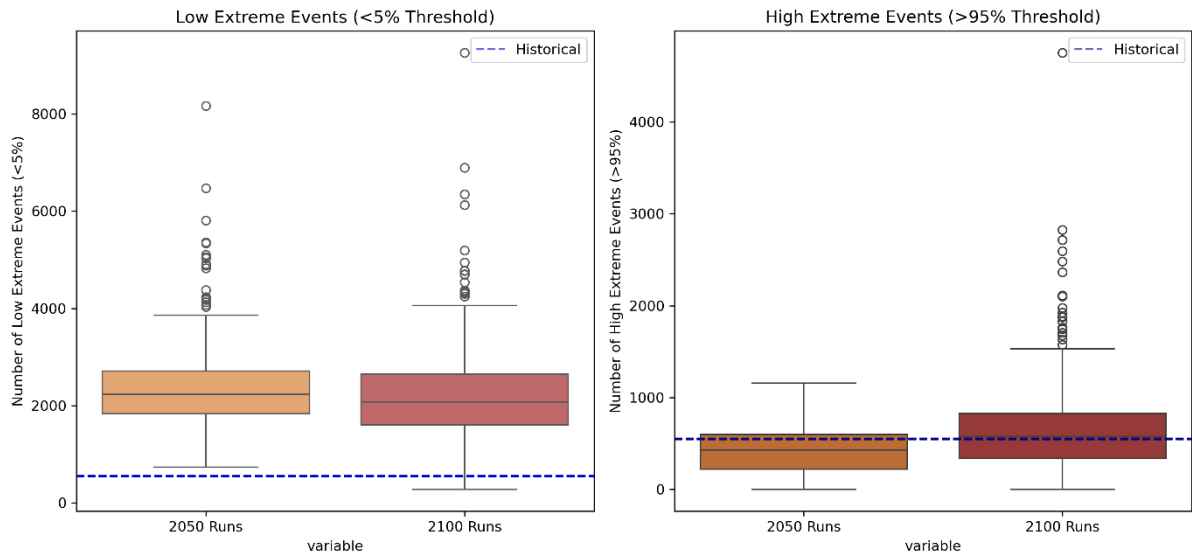
Distribution of Extreme Events: Historical vs. Future Scenarios - Westerlo



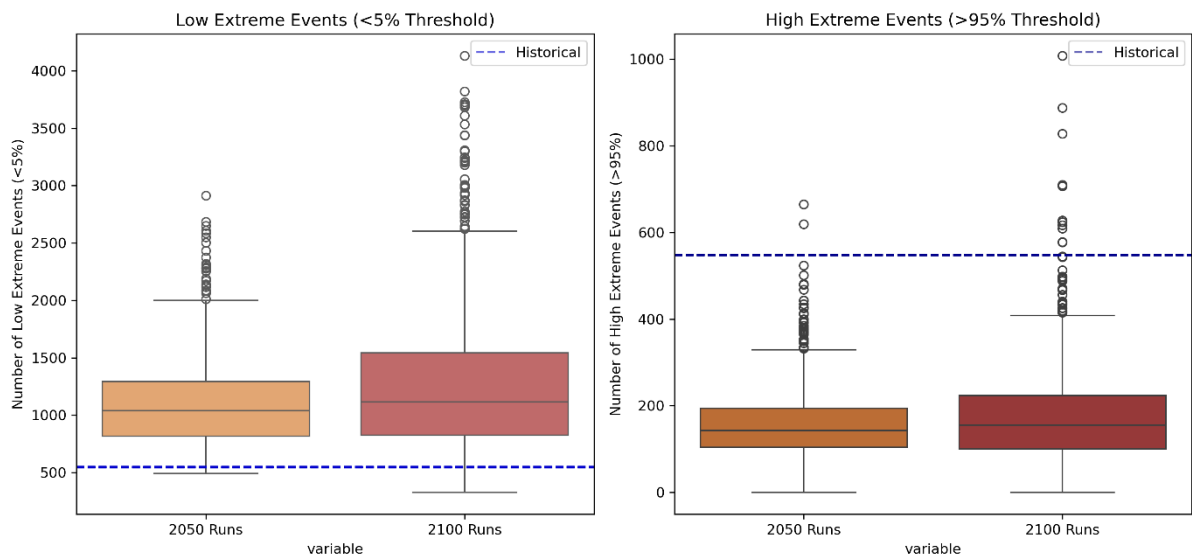
Distribution of Extreme Events: Historical vs. Future Scenarios - Wuustwezel



Distribution of Extreme Events: Historical vs. Future Scenarios - Schoten

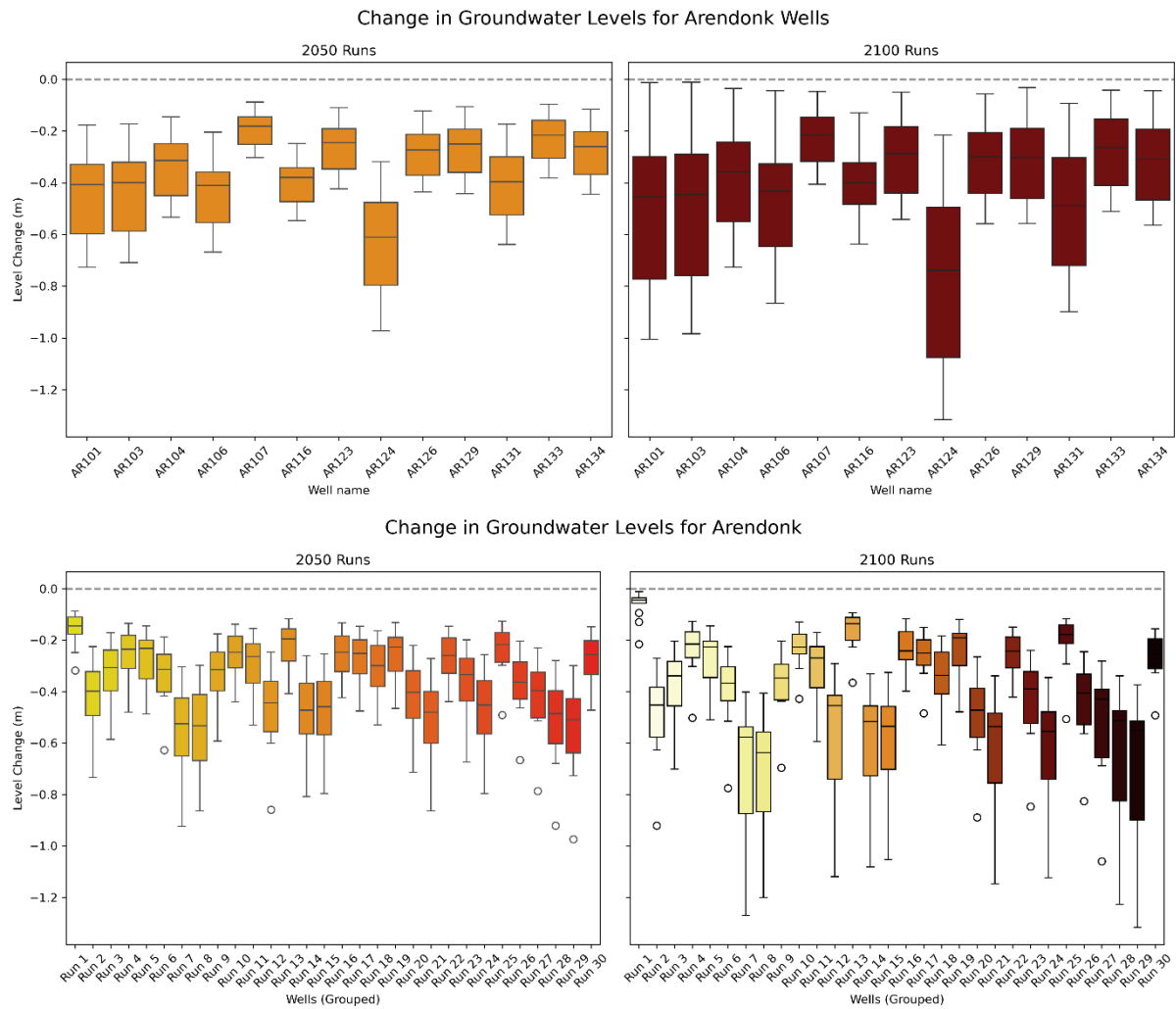


Distribution of Extreme Events: Historical vs. Future Scenarios - OudTurnhout

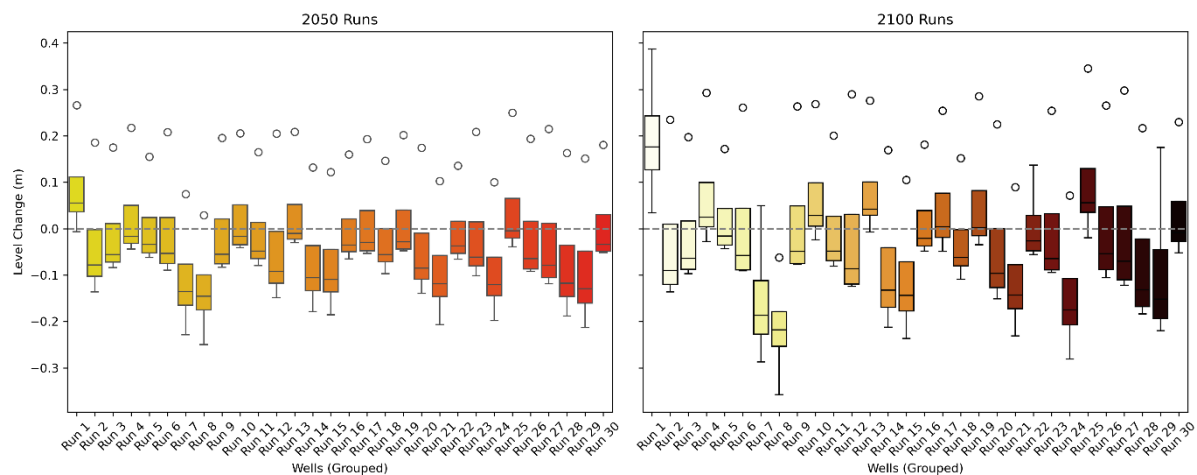


10.1.3 A.3 Pidpa Projected change in groundwater levels

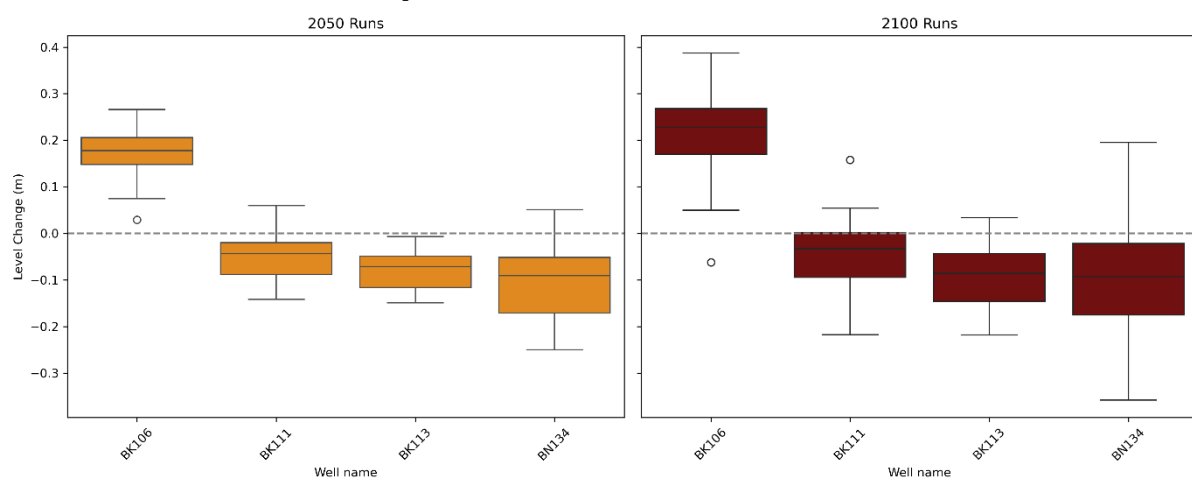
Projected change in groundwater levels across a) individual wells for aggregated simulation runs (2050 and 2100).



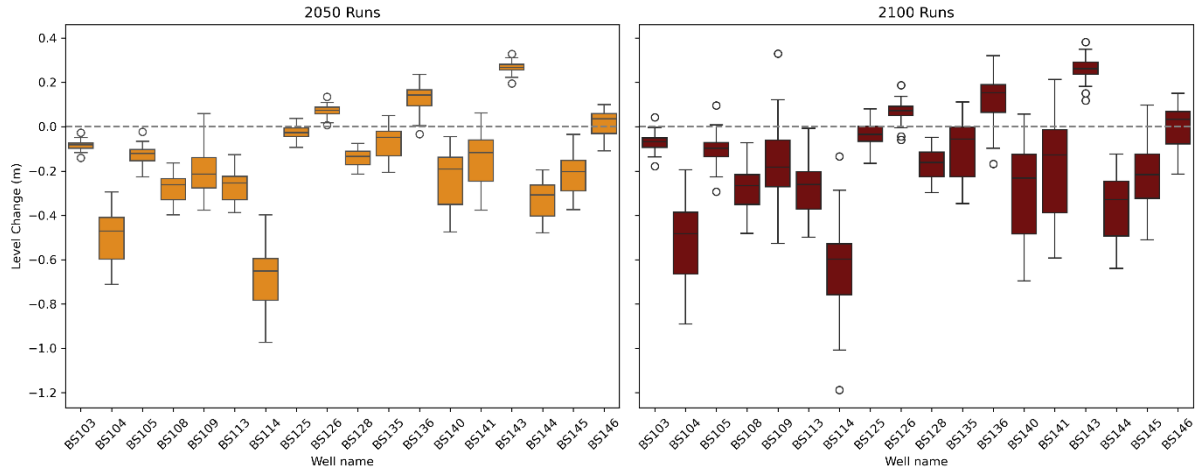
Change in Groundwater Levels for BalenKanaal



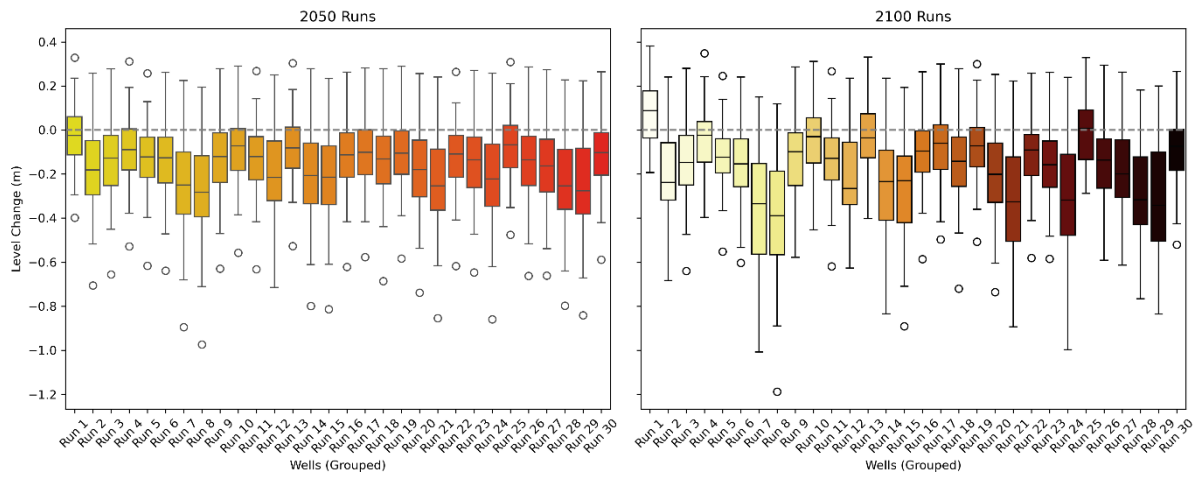
Change in Groundwater Levels for BalenKanaal Wells



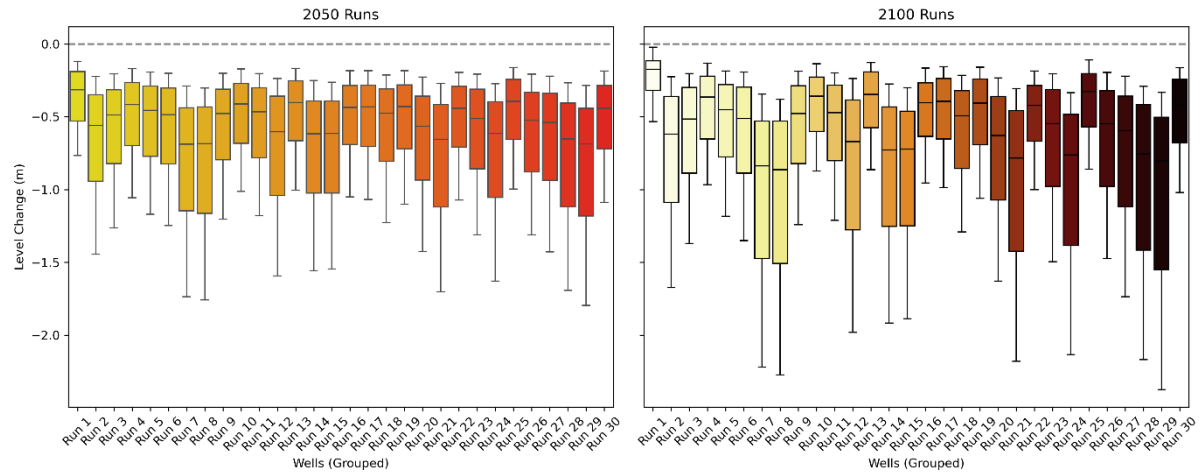
Change in Groundwater Levels for Beerse Wells



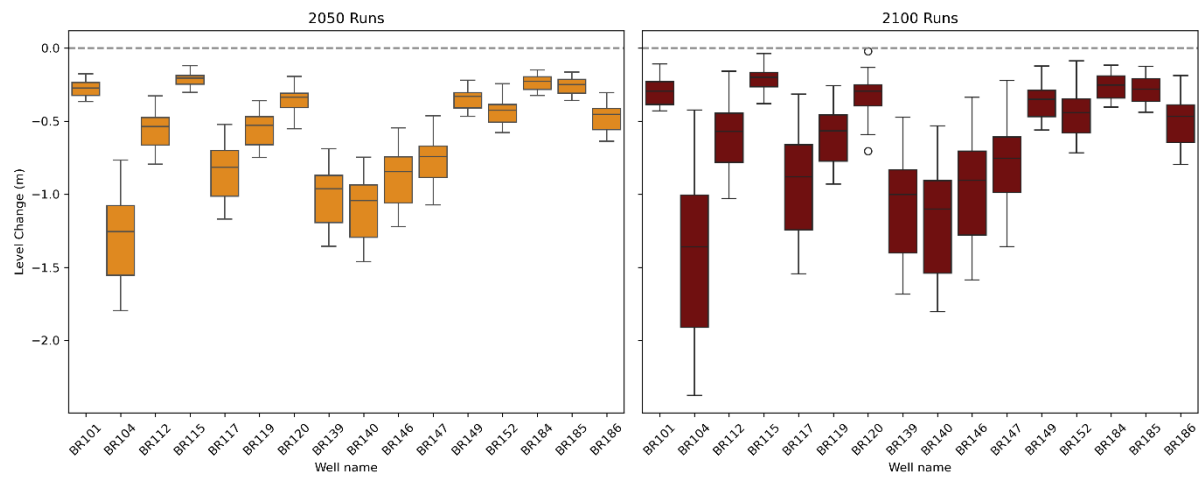
Change in Groundwater Levels for Beerse



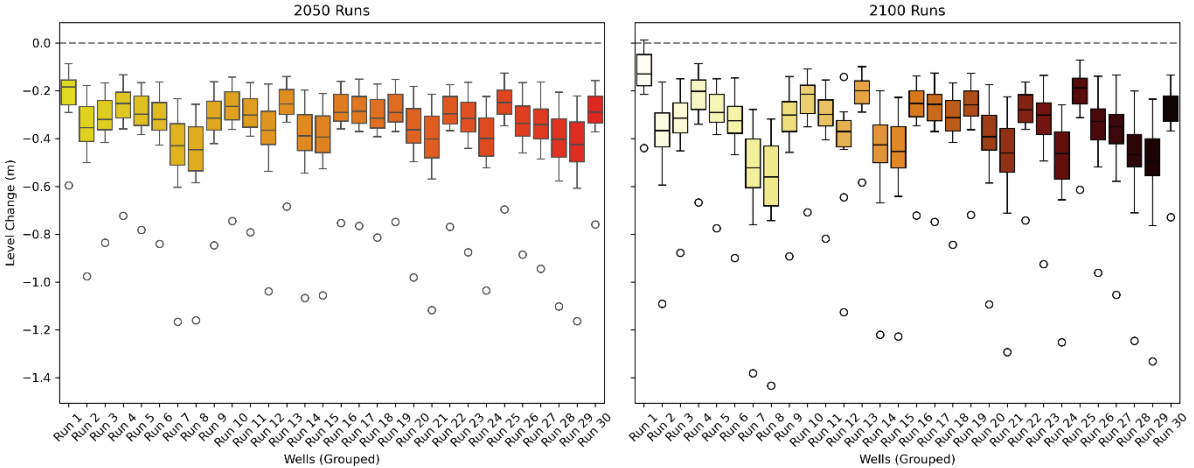
Change in Groundwater Levels for Brasschaat



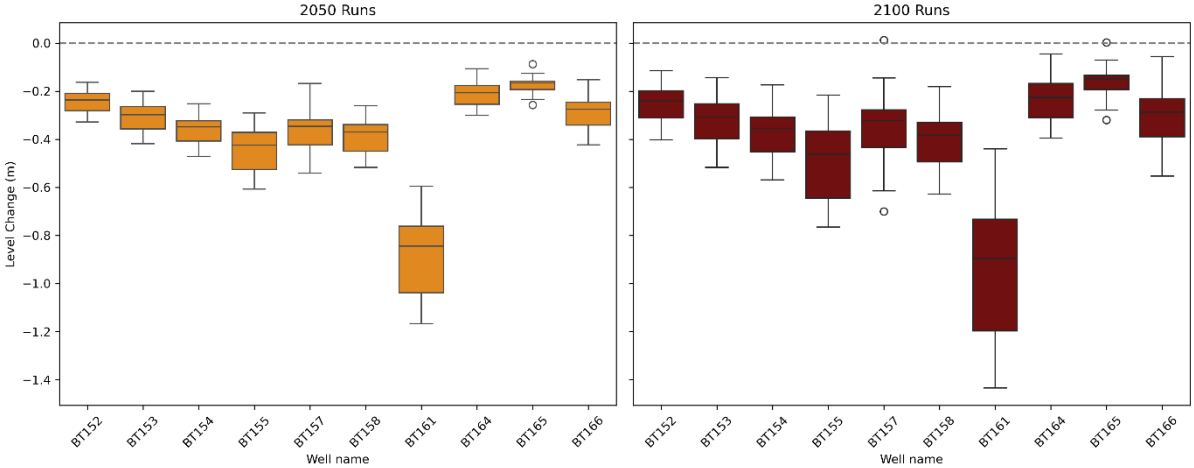
Change in Groundwater Levels for Brasschaat Wells



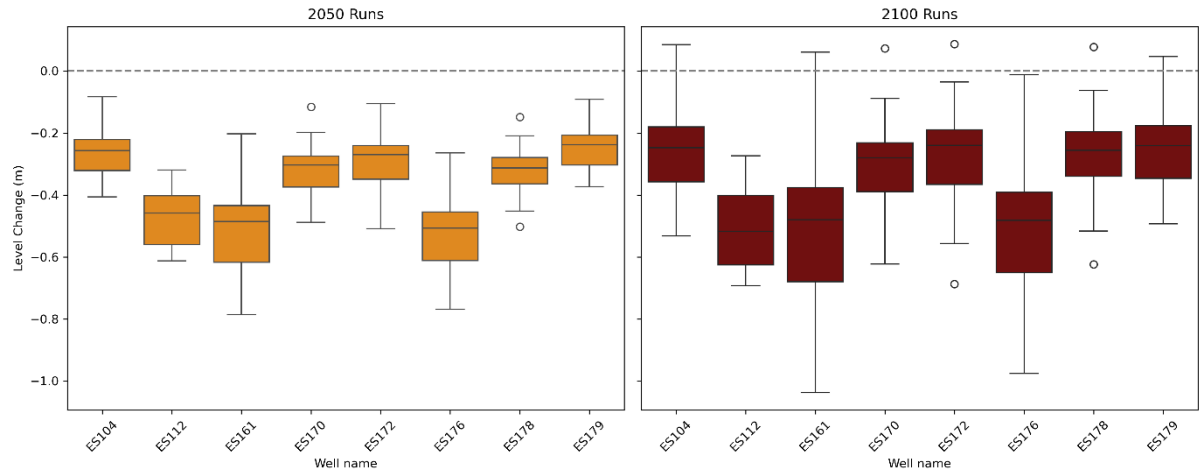
Change in Groundwater Levels for Brecht



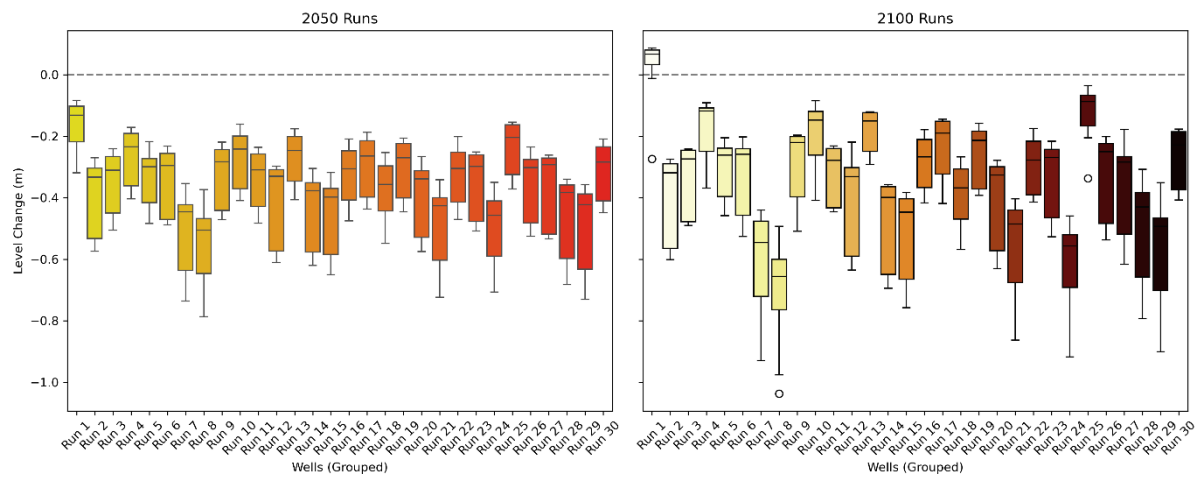
Change in Groundwater Levels for Brecht Wells



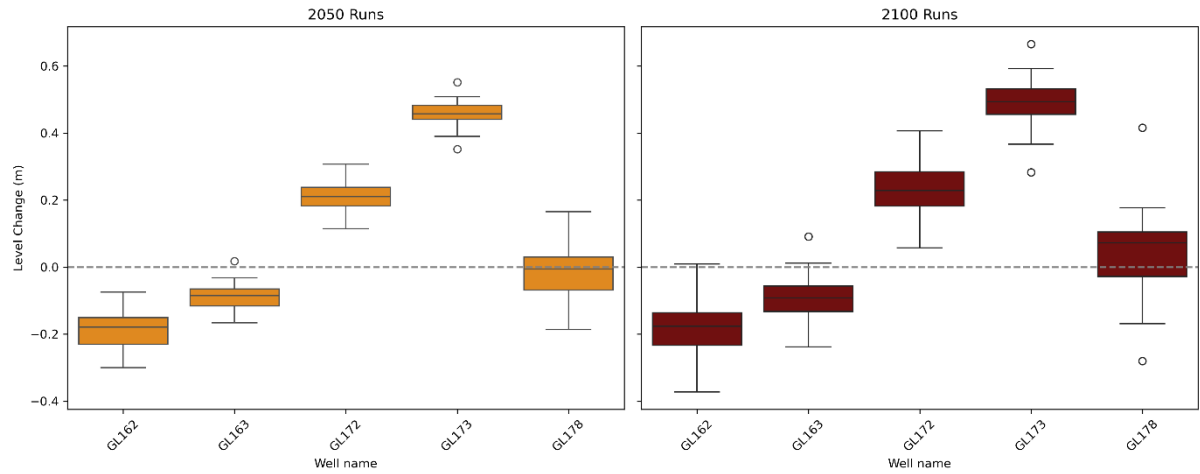
Change in Groundwater Levels for Essen Wells



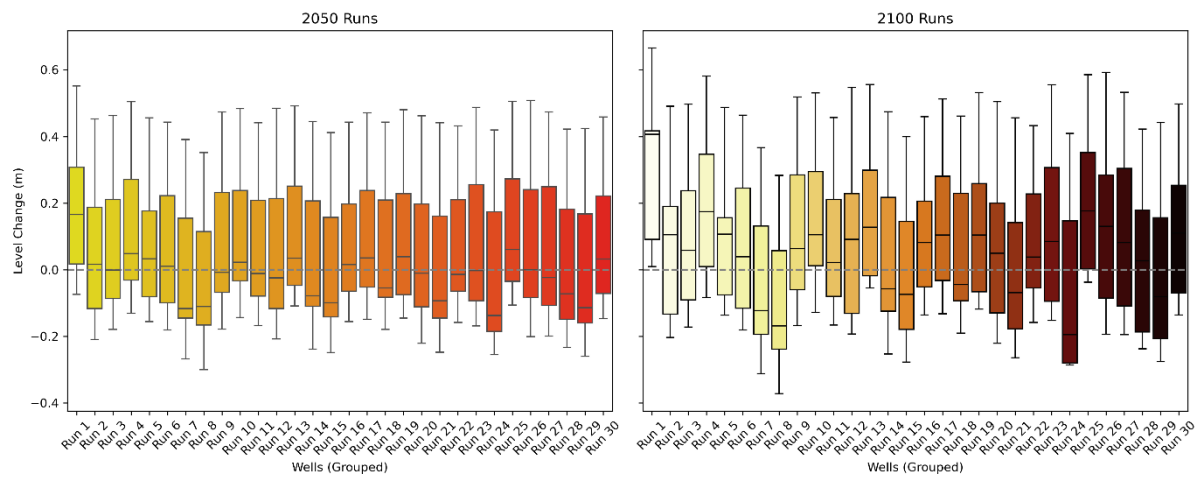
Change in Groundwater Levels for Essen



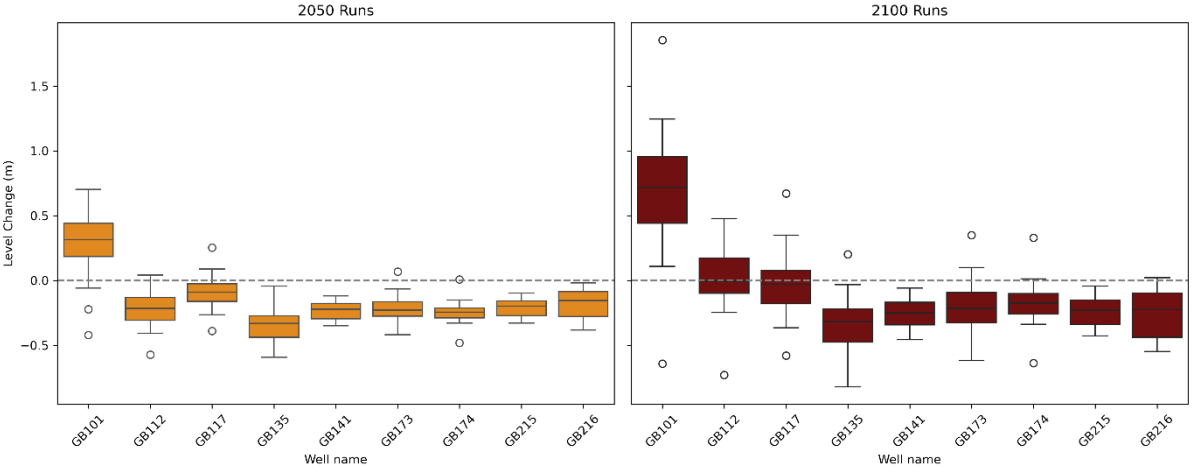
Change in Groundwater Levels for Gierle Wells



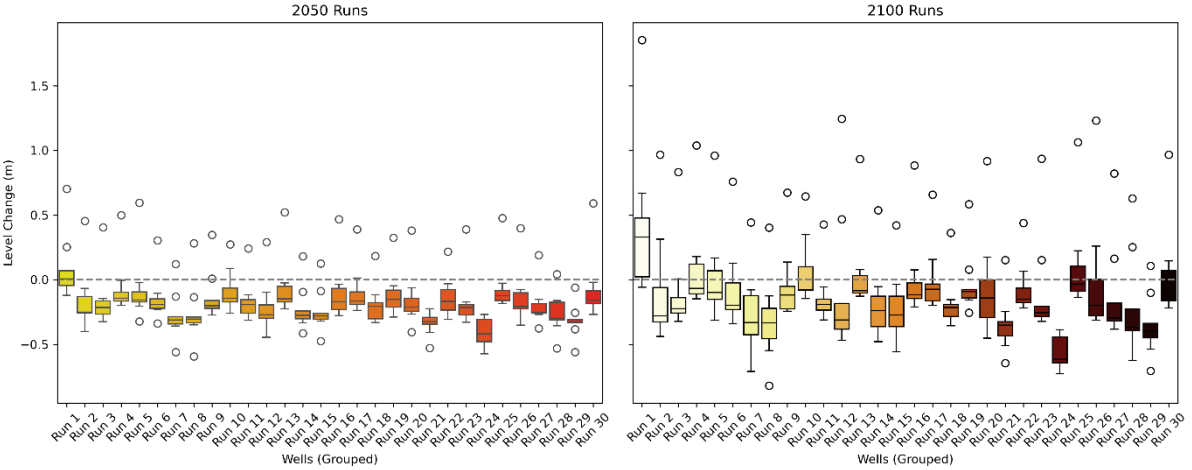
Change in Groundwater Levels for Gierle



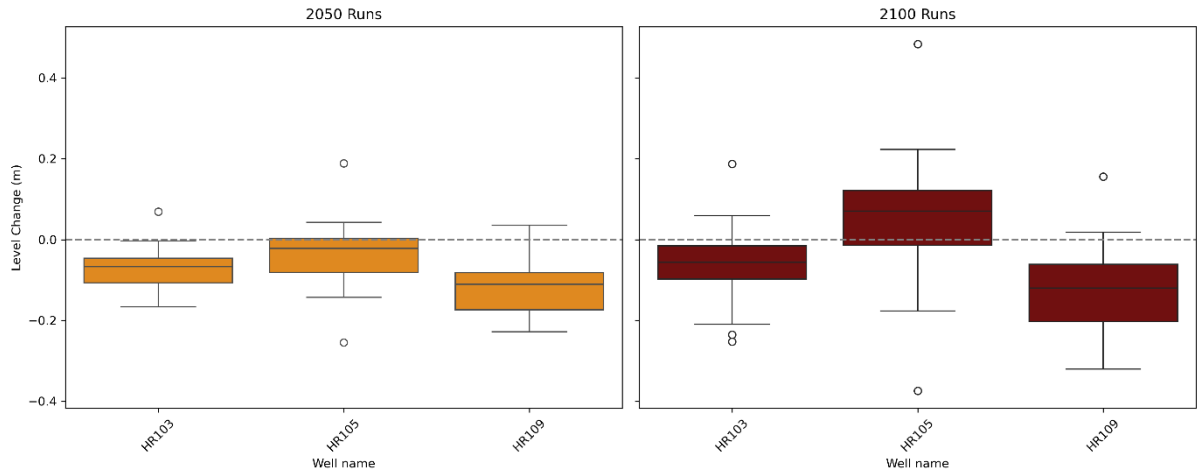
Change in Groundwater Levels for Grobbendonk Wells



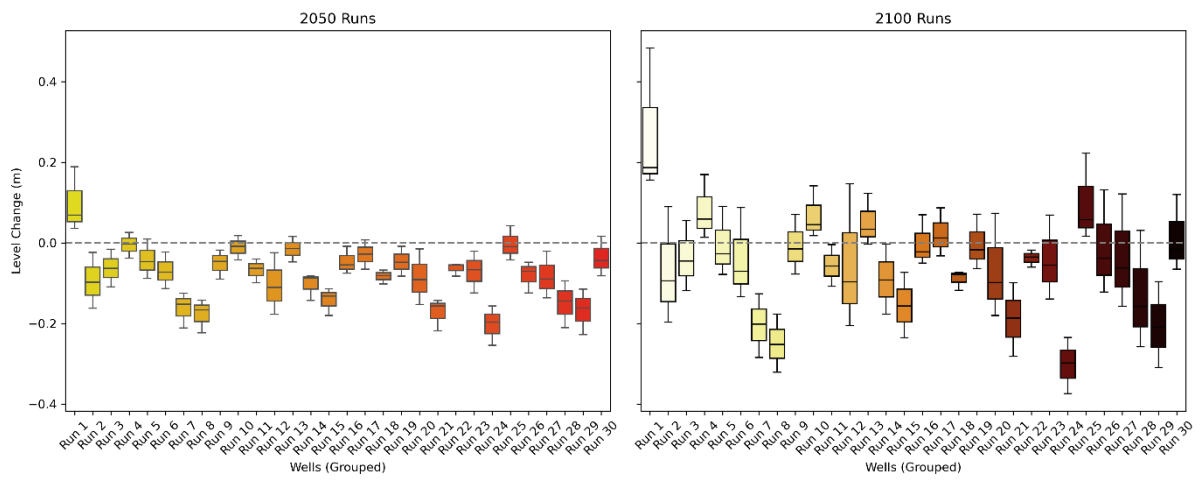
Change in Groundwater Levels for Grobbendonk



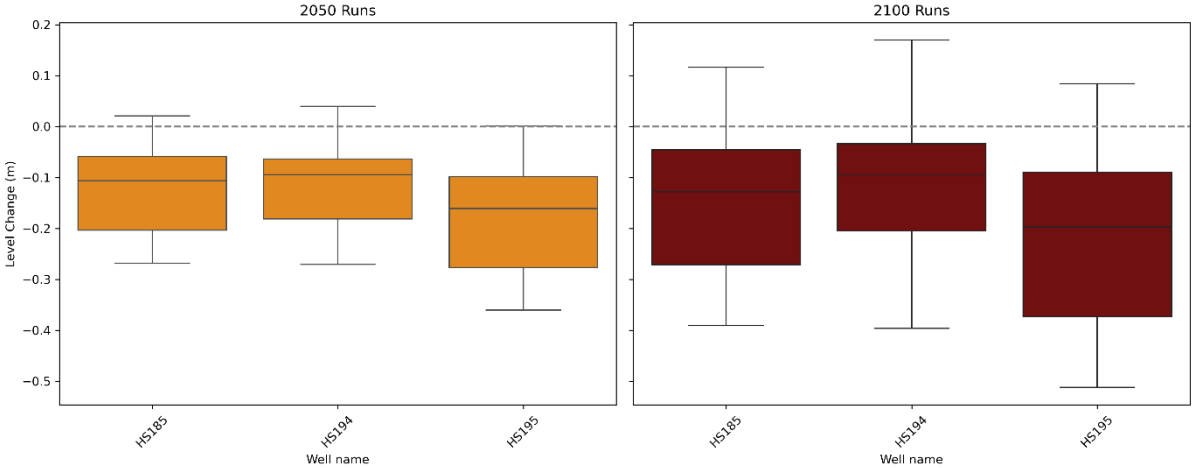
Change in Groundwater Levels for Herentals Wells



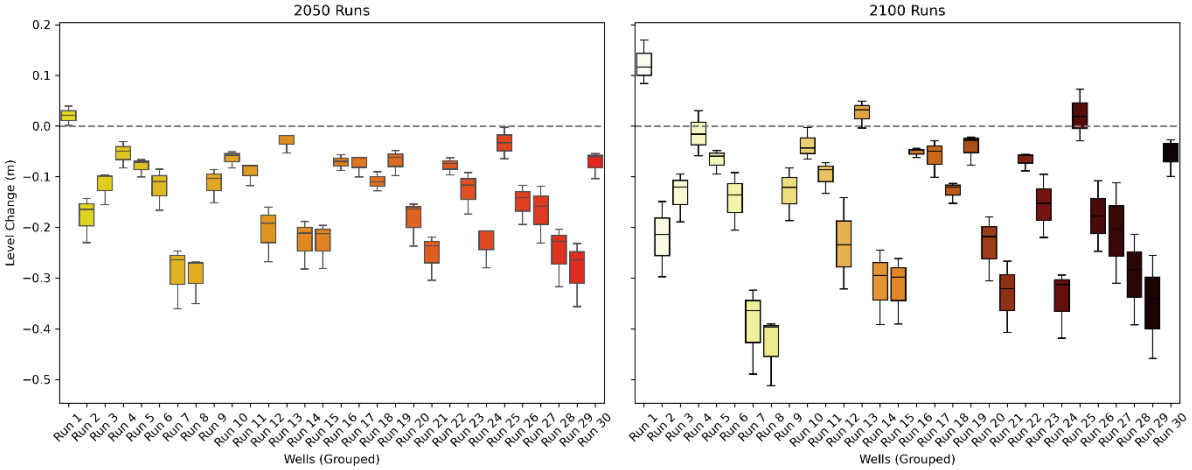
Change in Groundwater Levels for Herentals



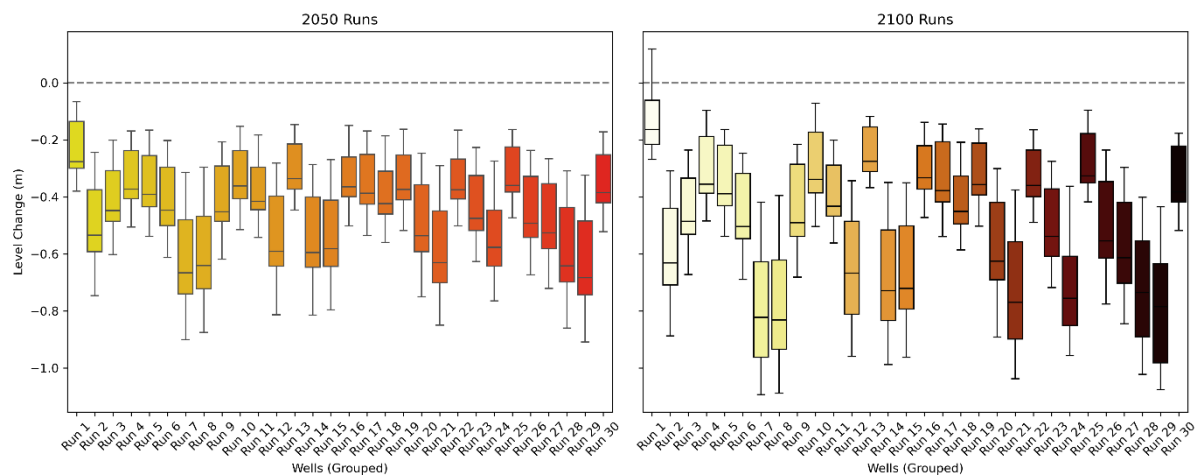
Change in Groundwater Levels for Herselt Wells



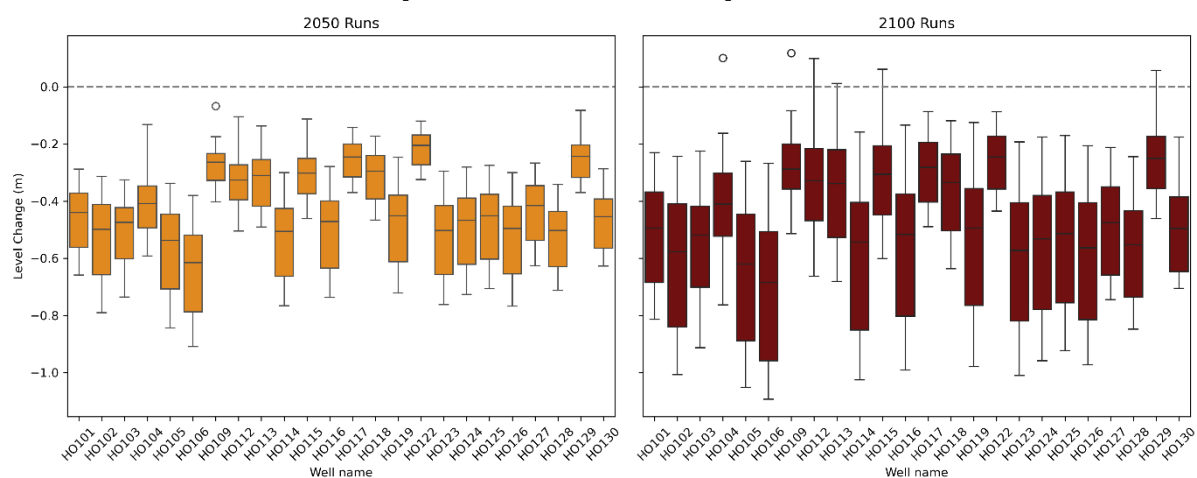
Change in Groundwater Levels for Herselt



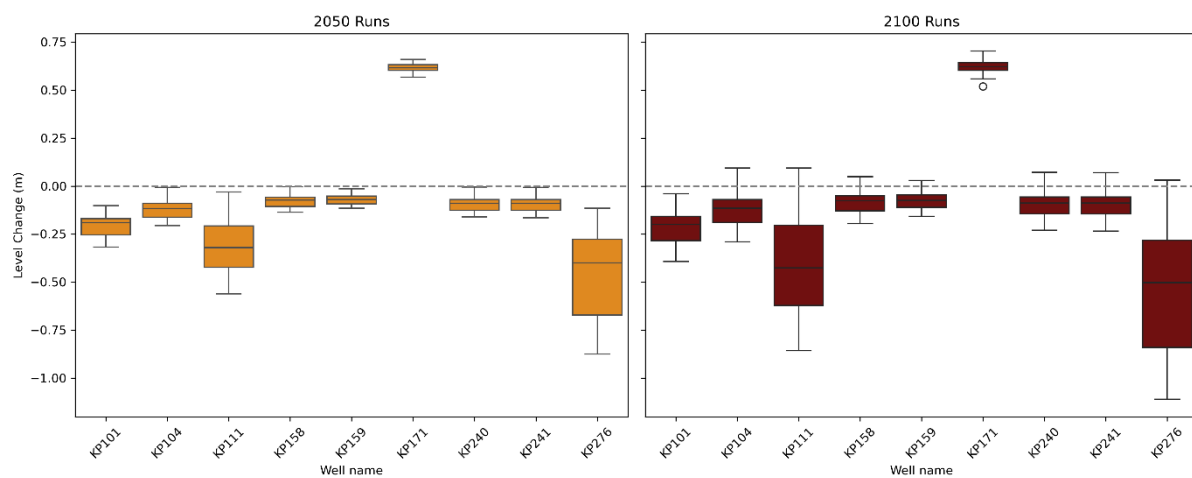
Change in Groundwater Levels for Hoogstraten



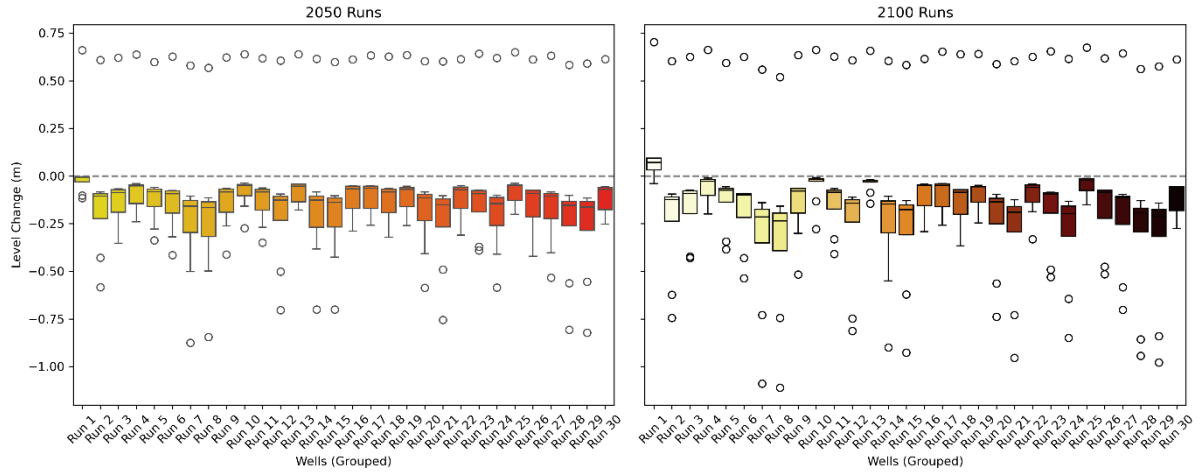
Change in Groundwater Levels for Hoogstraten Wells



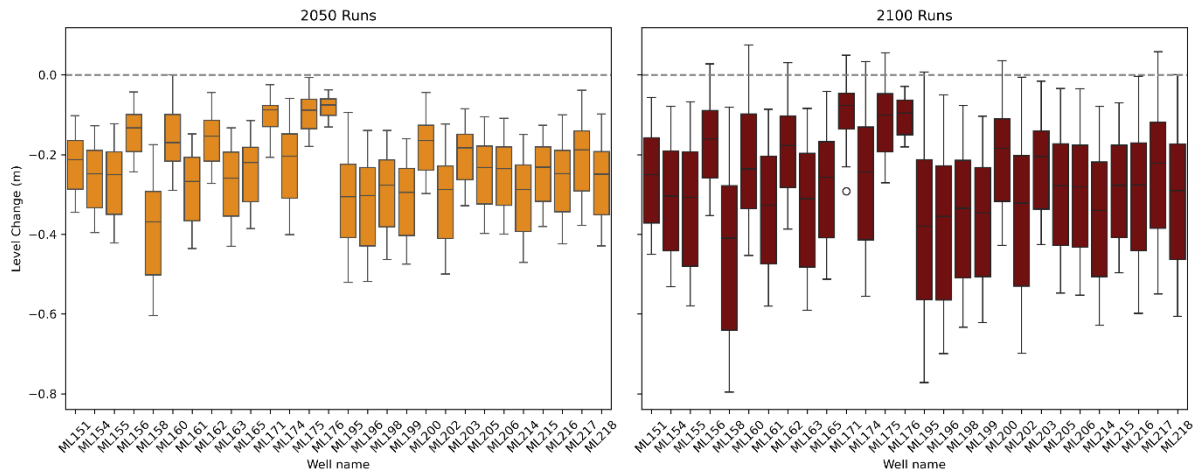
Change in Groundwater Levels for Kapellen Wells



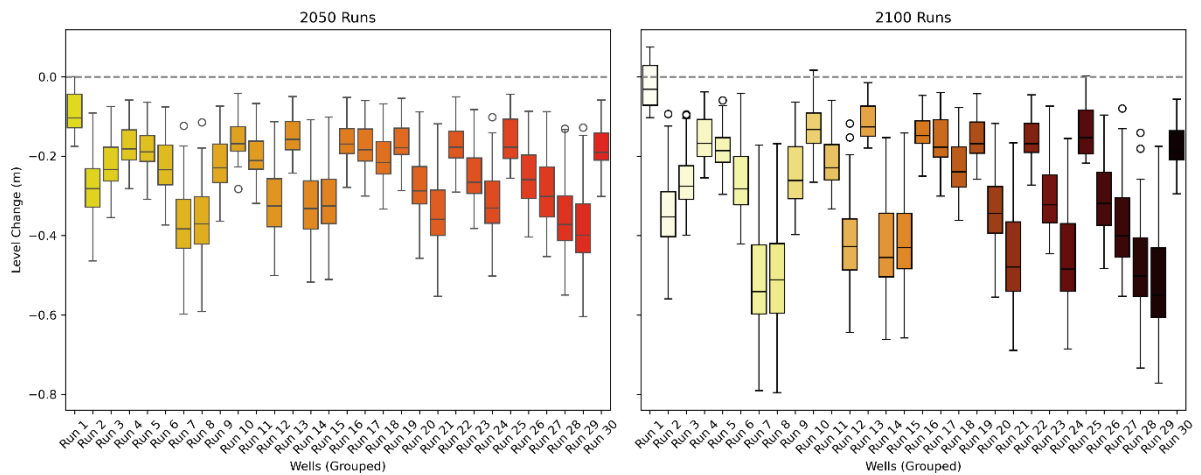
Change in Groundwater Levels for Kapellen



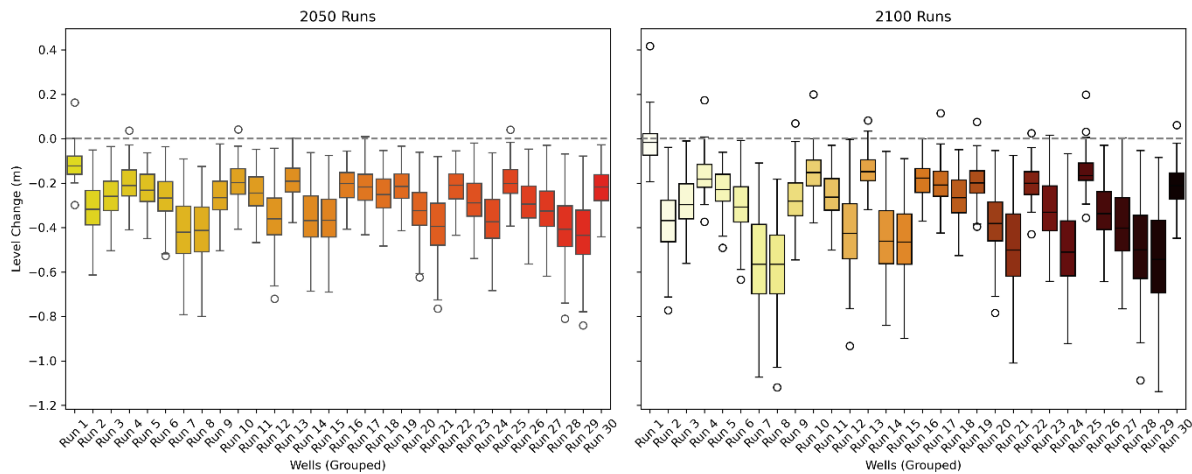
Change in Groundwater Levels for Meerle Wells



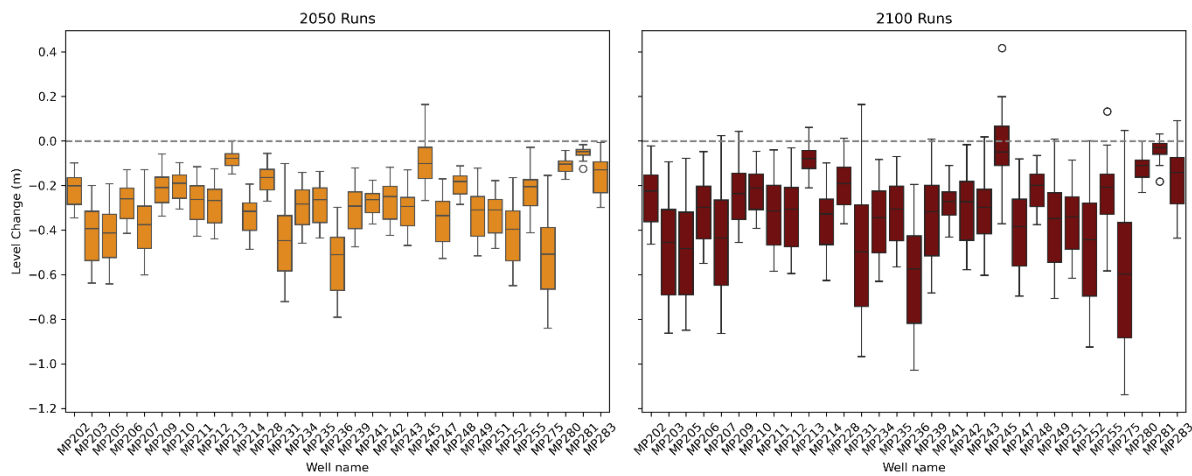
Change in Groundwater Levels for Meerle



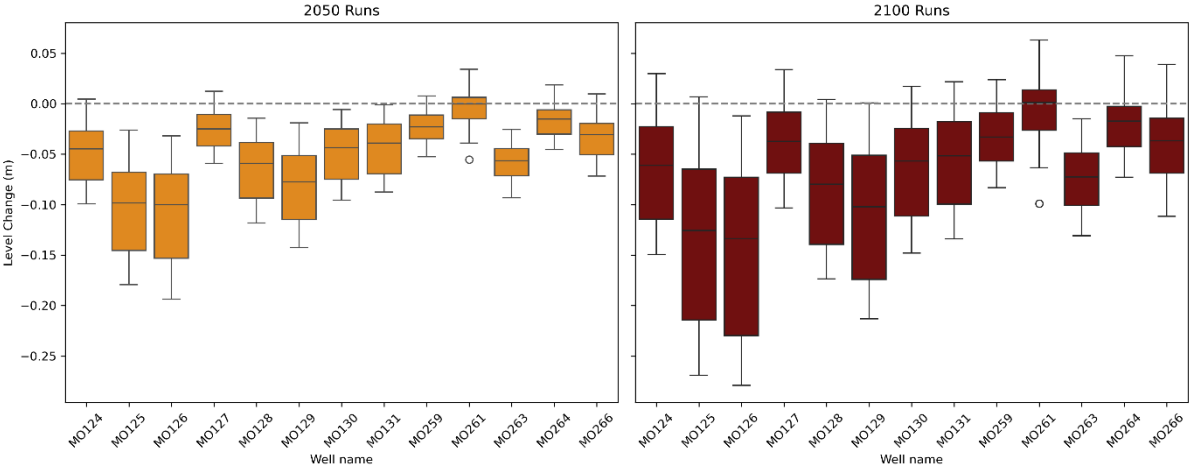
Change in Groundwater Levels for Merksplas



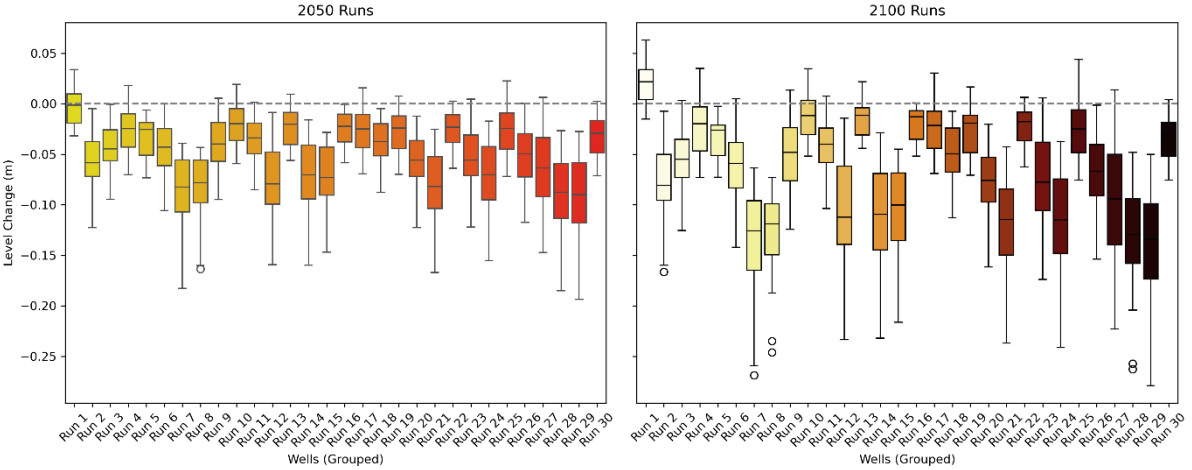
Change in Groundwater Levels for Merksplas Wells



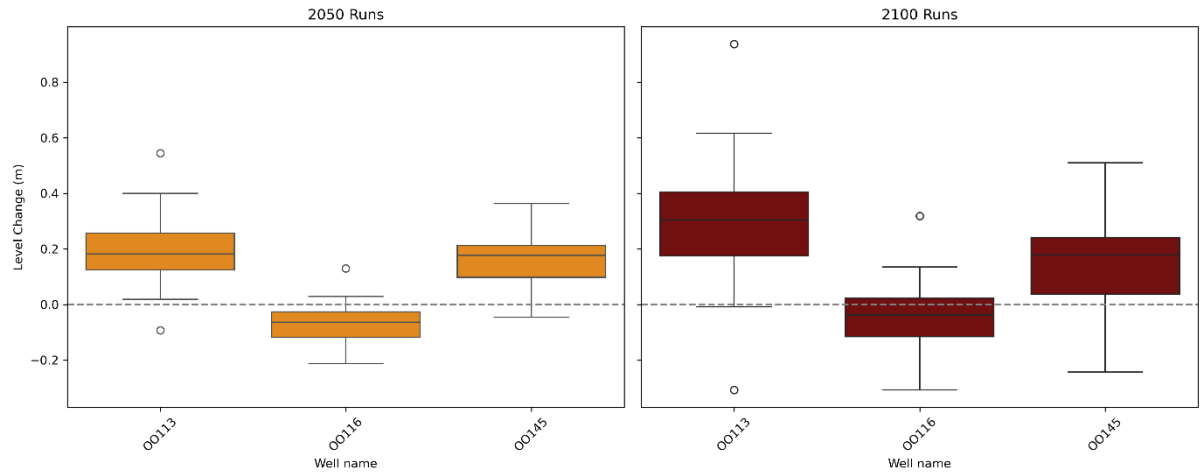
Change in Groundwater Levels for Mol Wells



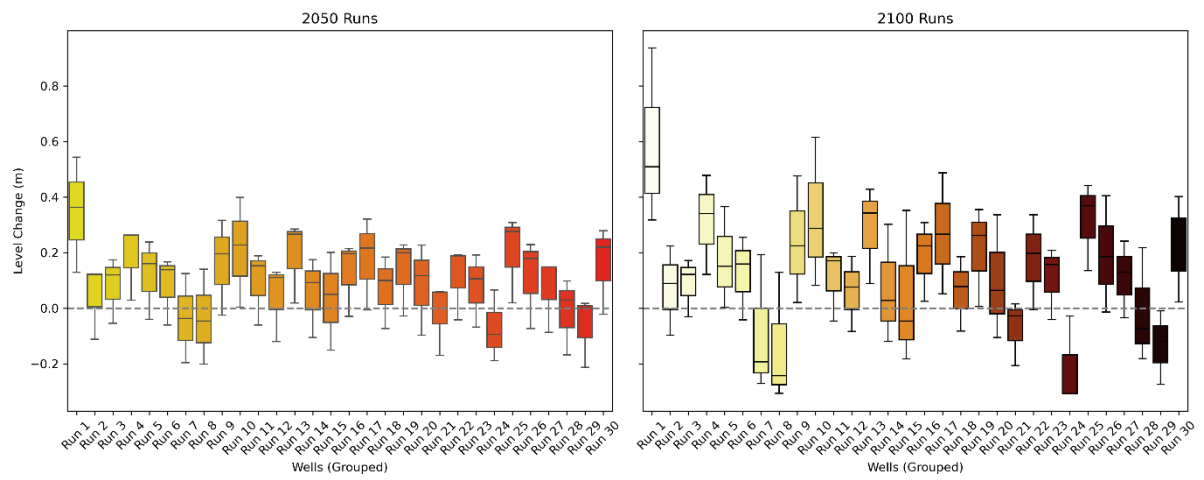
Change in Groundwater Levels for Mol



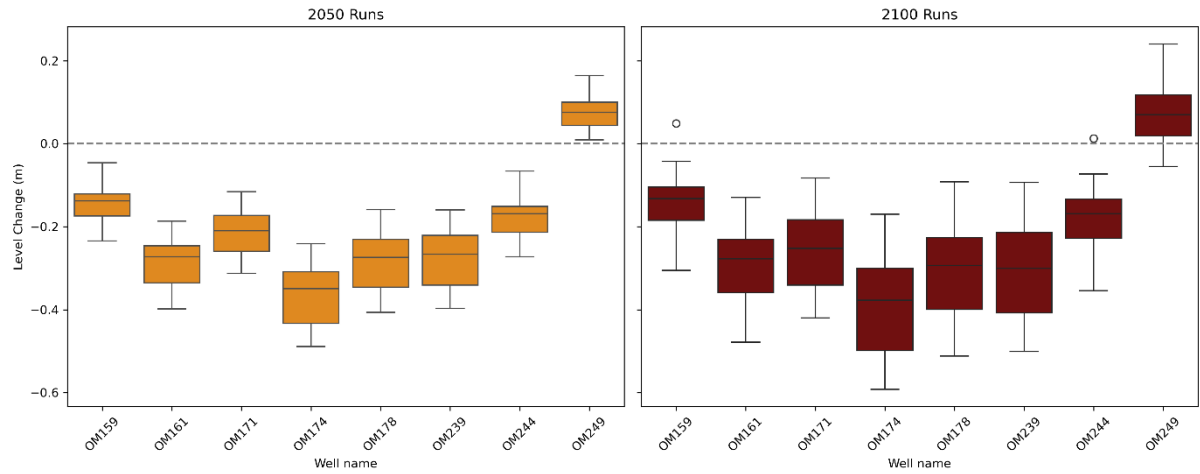
Change in Groundwater Levels for Olen Wells



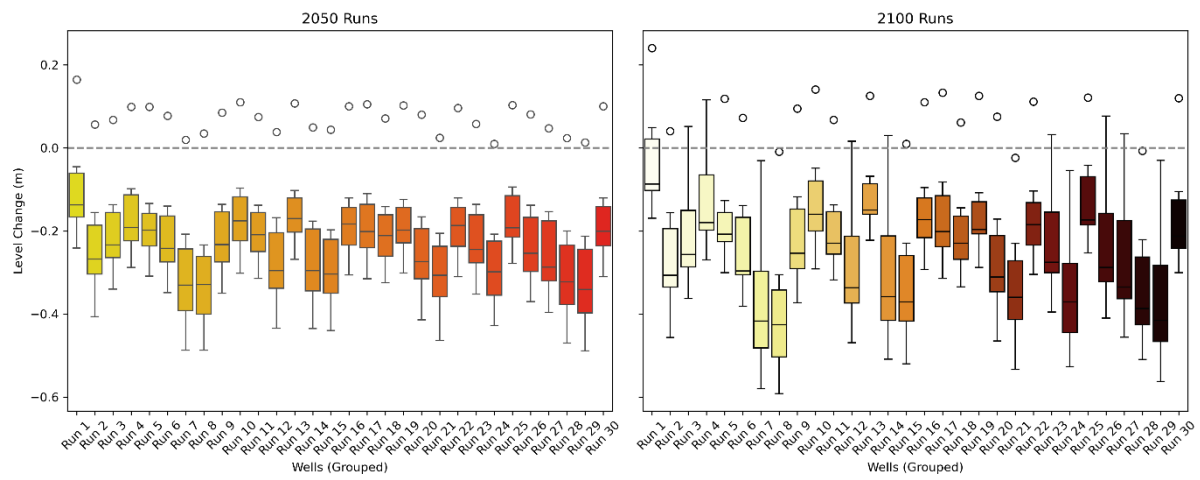
Change in Groundwater Levels for Olen



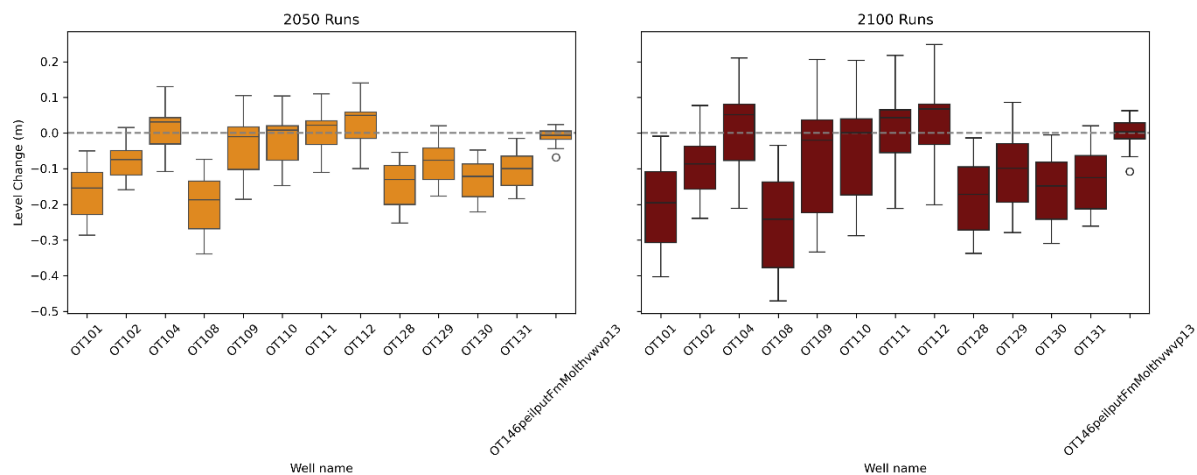
Change in Groundwater Levels for Oostmalle Wells



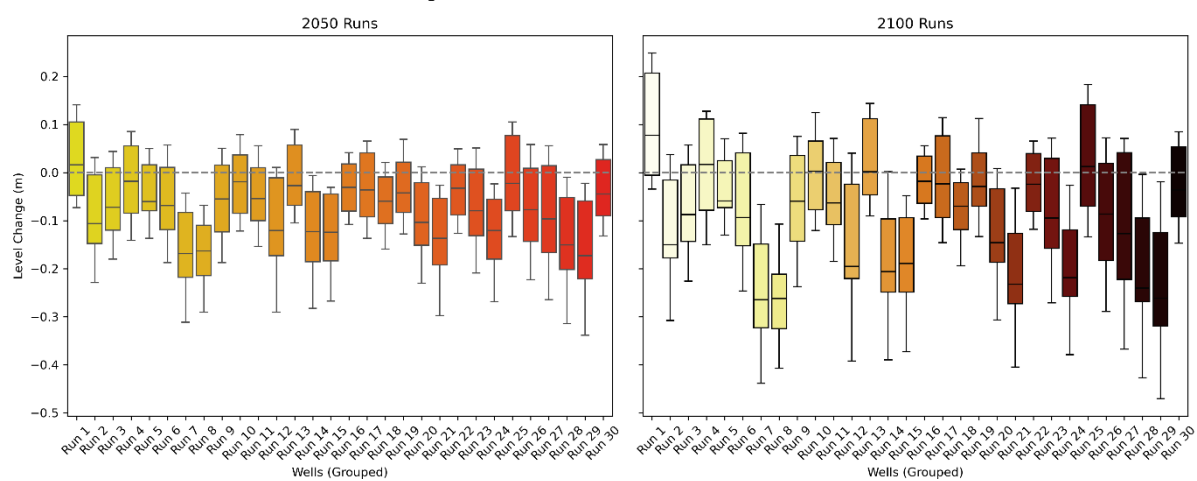
Change in Groundwater Levels for Oostmalle



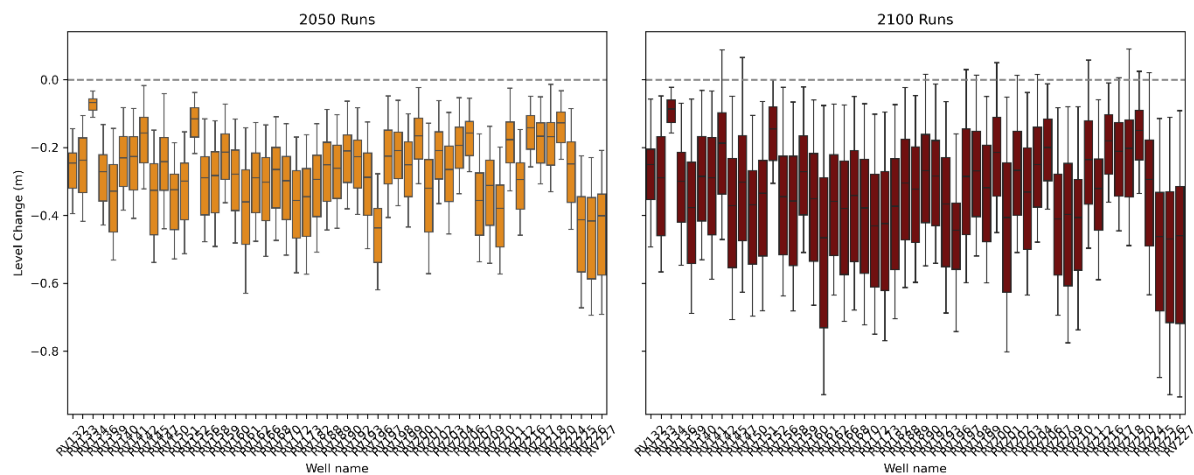
Change in Groundwater Levels for OudTurnhout Wells



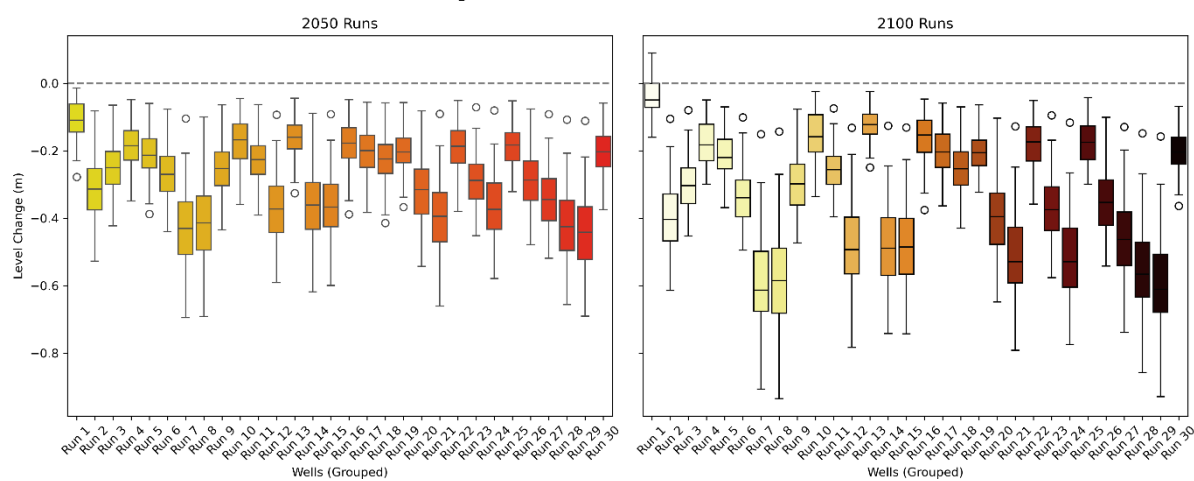
Change in Groundwater Levels for OudTurnhout



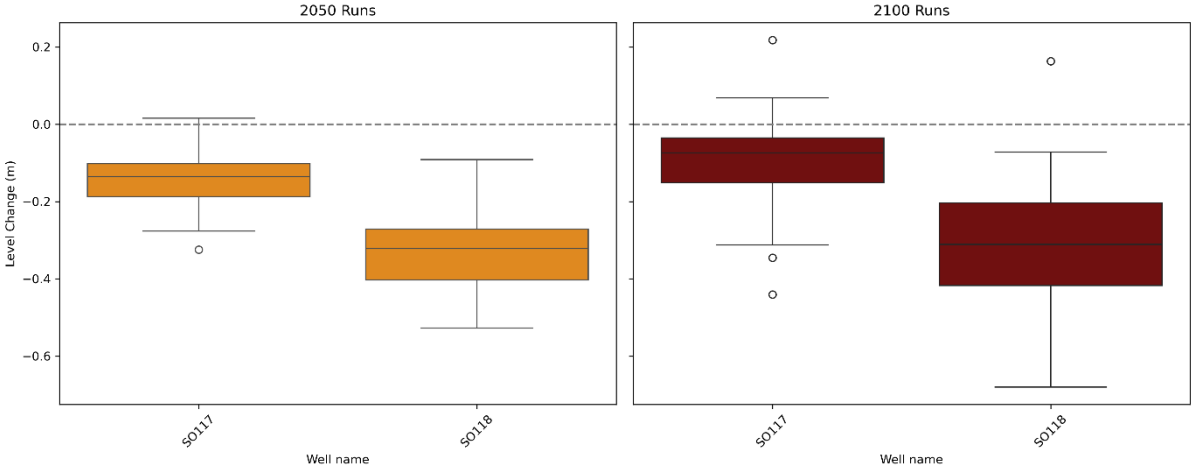
Change in Groundwater Levels for Ravels Wells



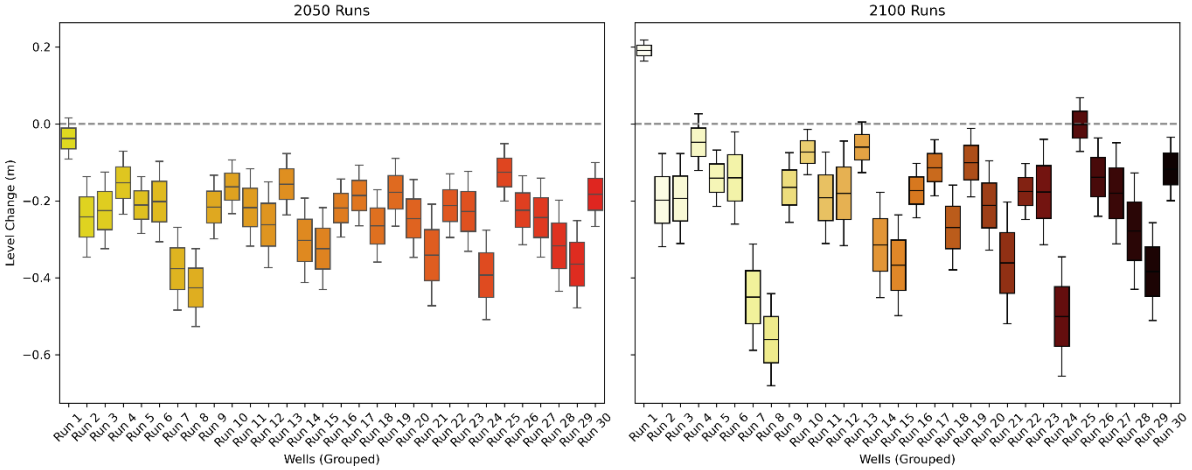
Change in Groundwater Levels for Ravels



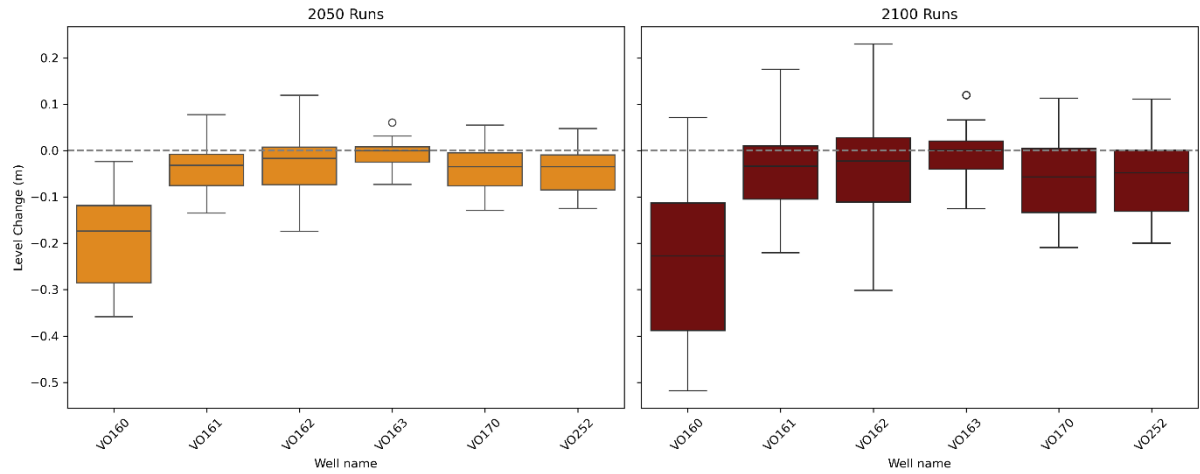
Change in Groundwater Levels for Schoten Wells



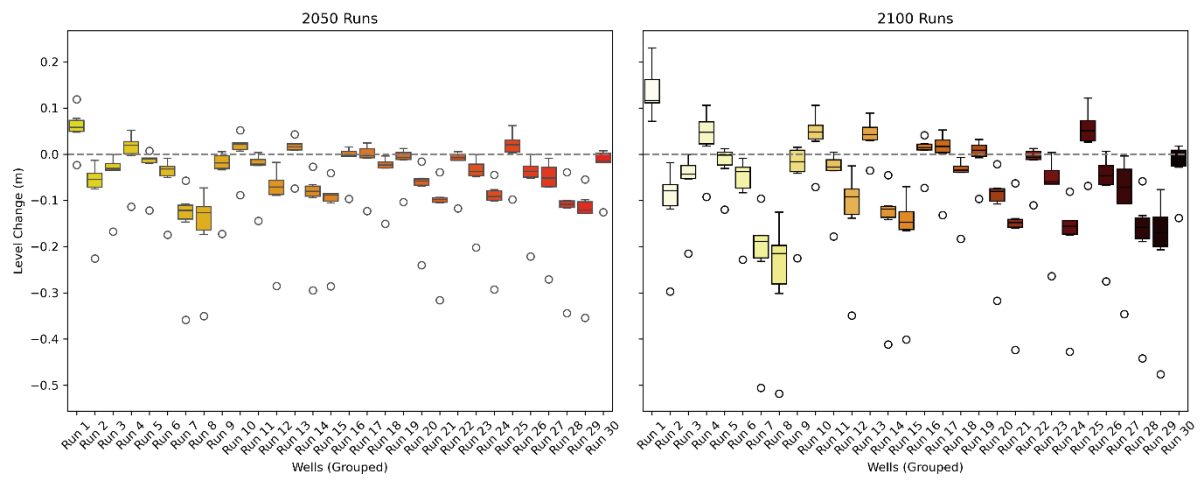
Change in Groundwater Levels for Schoten



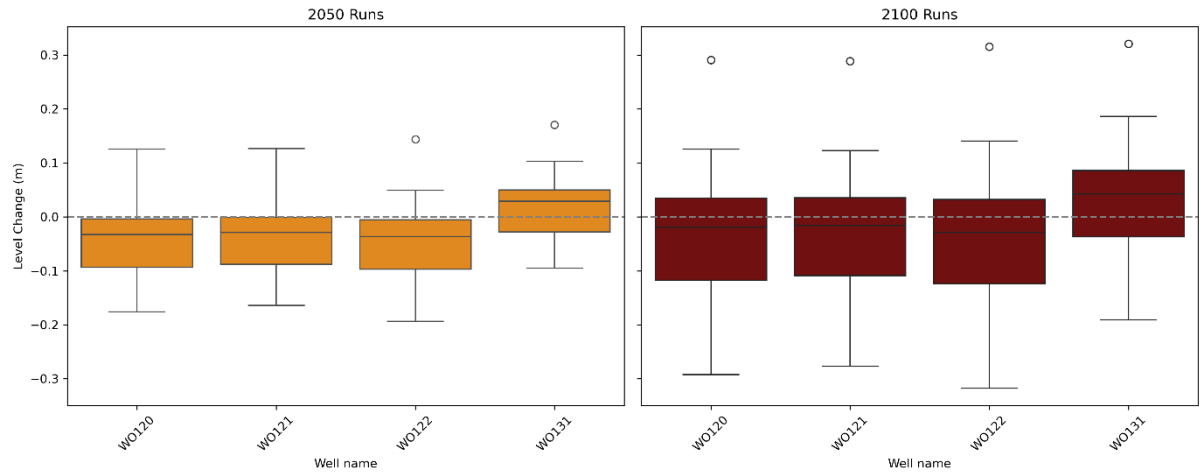
Change in Groundwater Levels for Vorst Wells



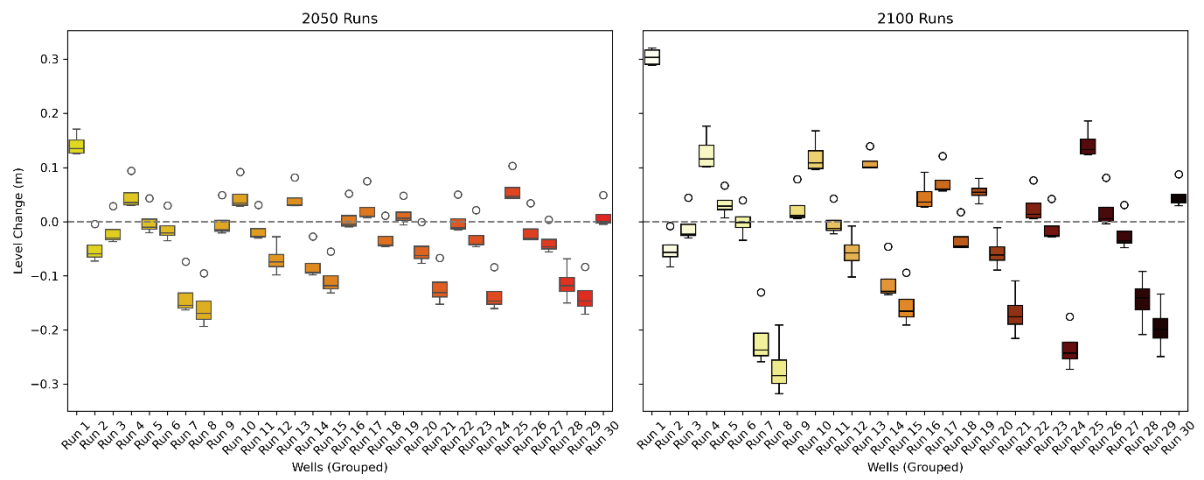
Change in Groundwater Levels for Vorst



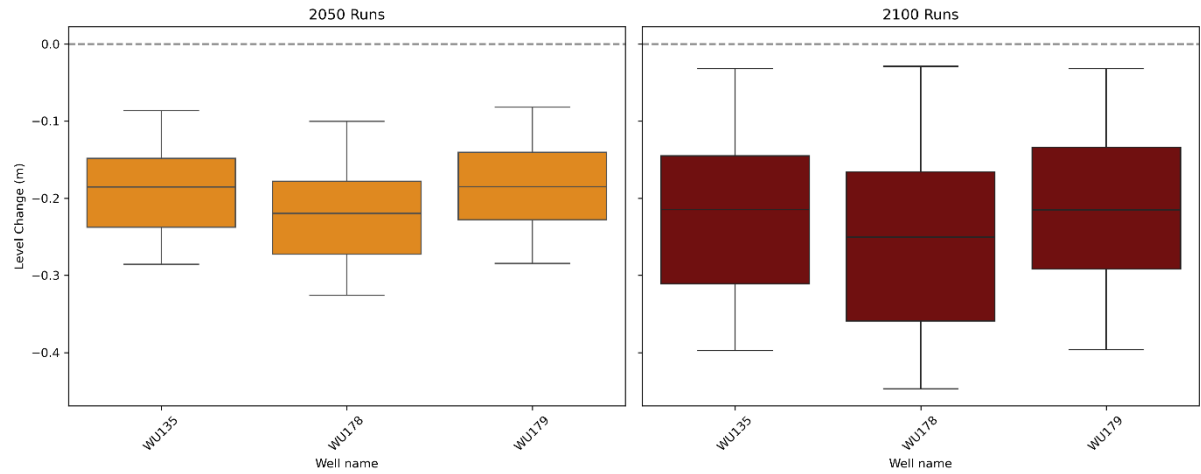
Change in Groundwater Levels for Westerlo Wells



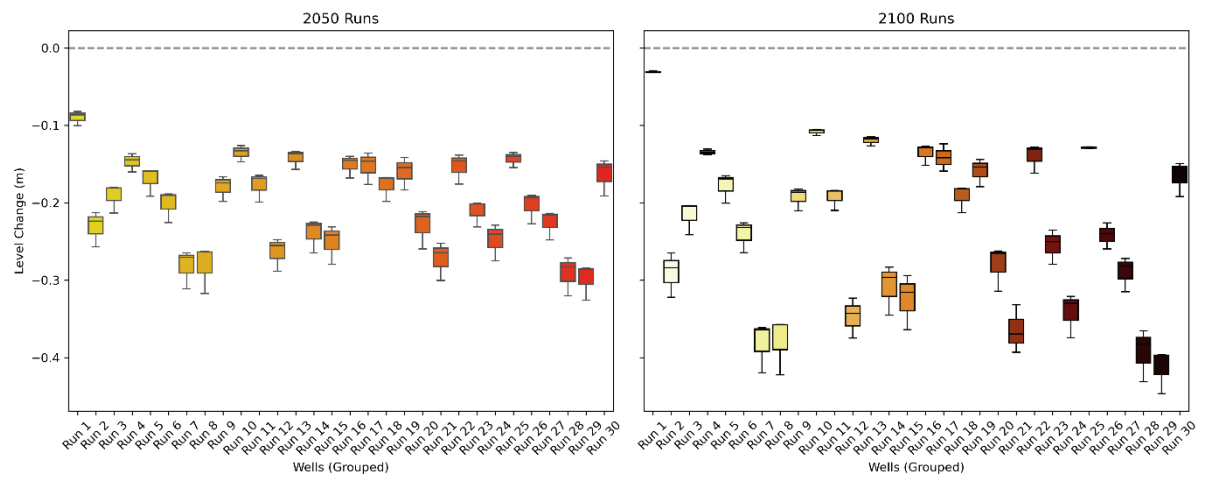
Change in Groundwater Levels for Westerlo



Change in Groundwater Levels for Wuustwezel Wells



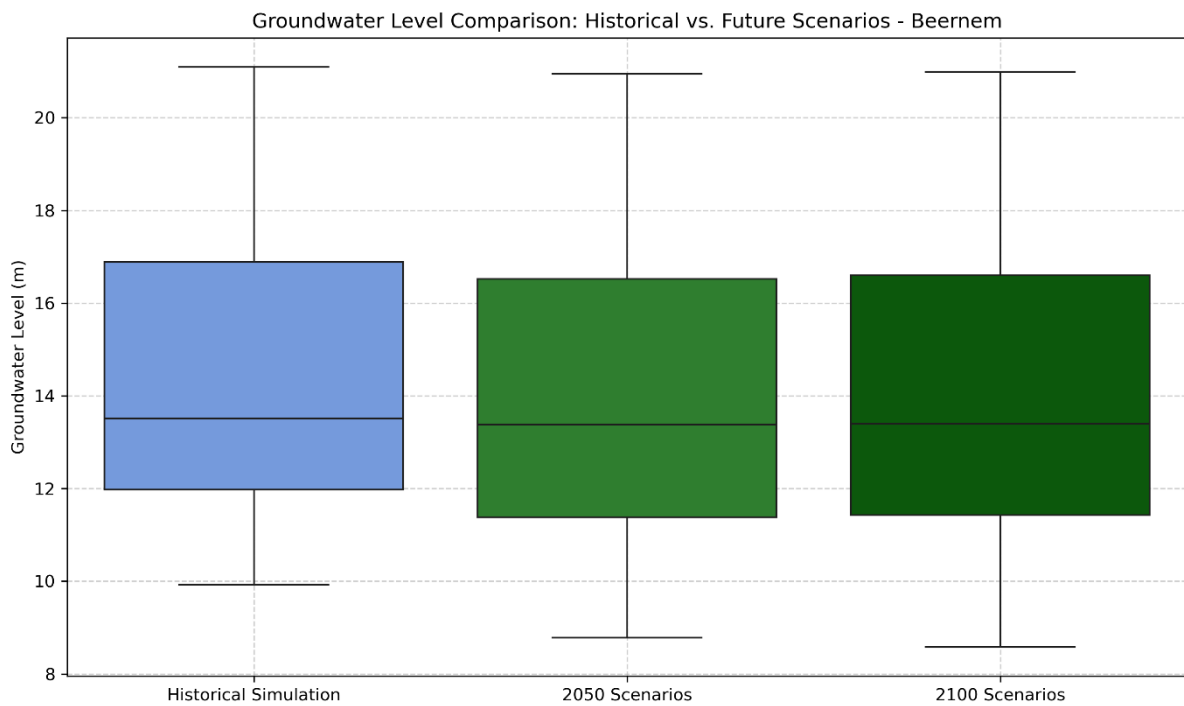
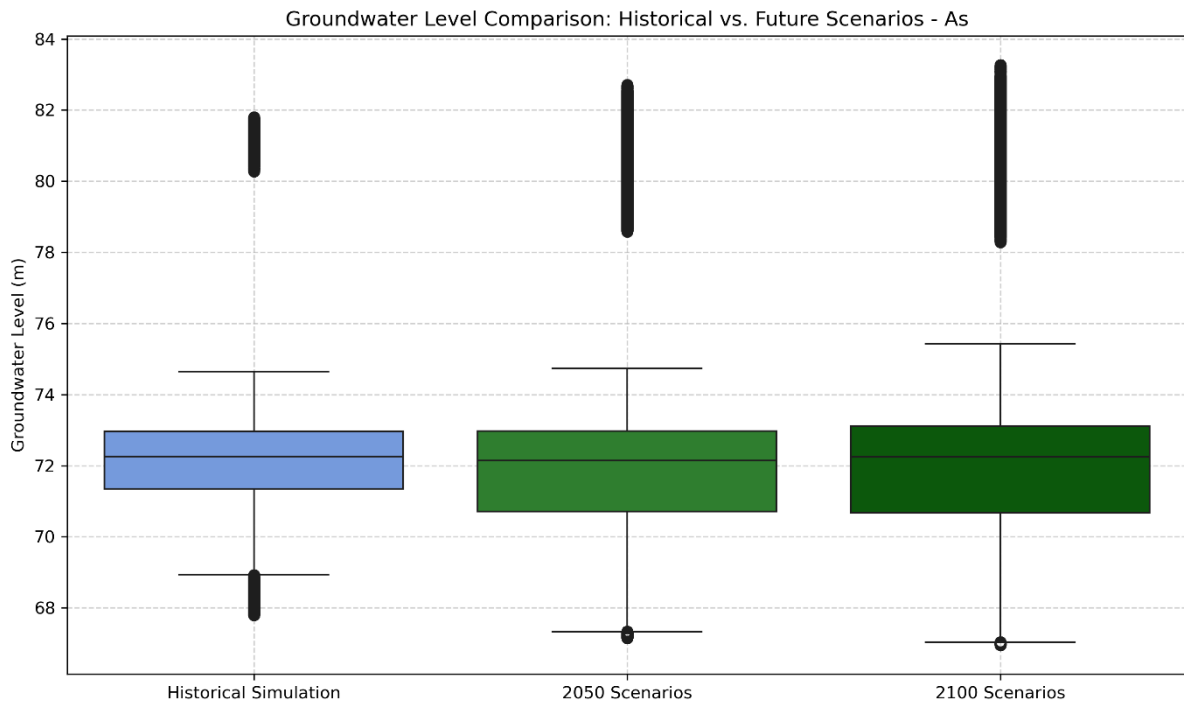
Change in Groundwater Levels for Wuustwezel

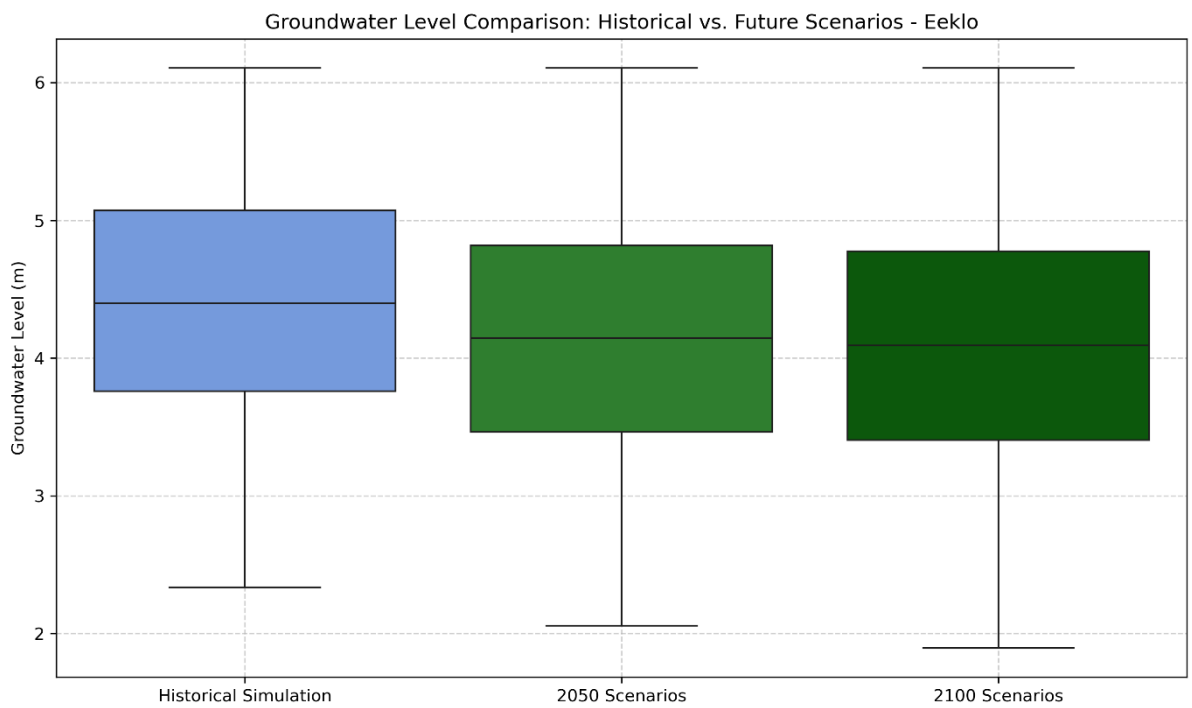
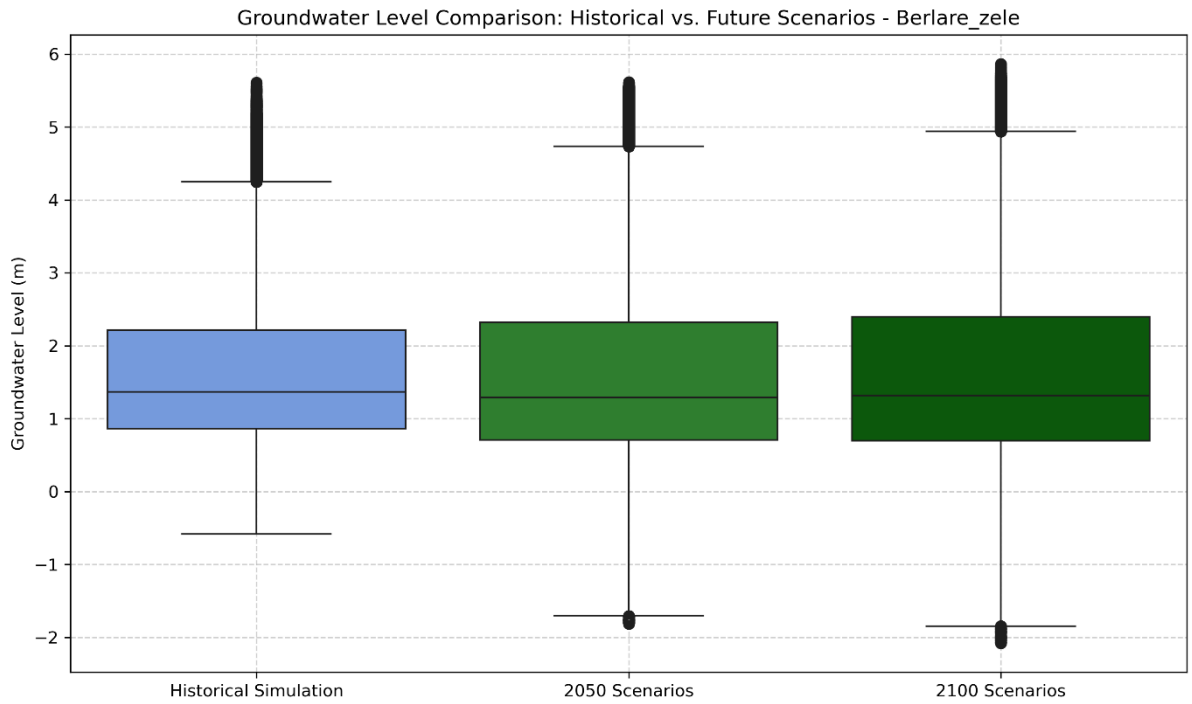


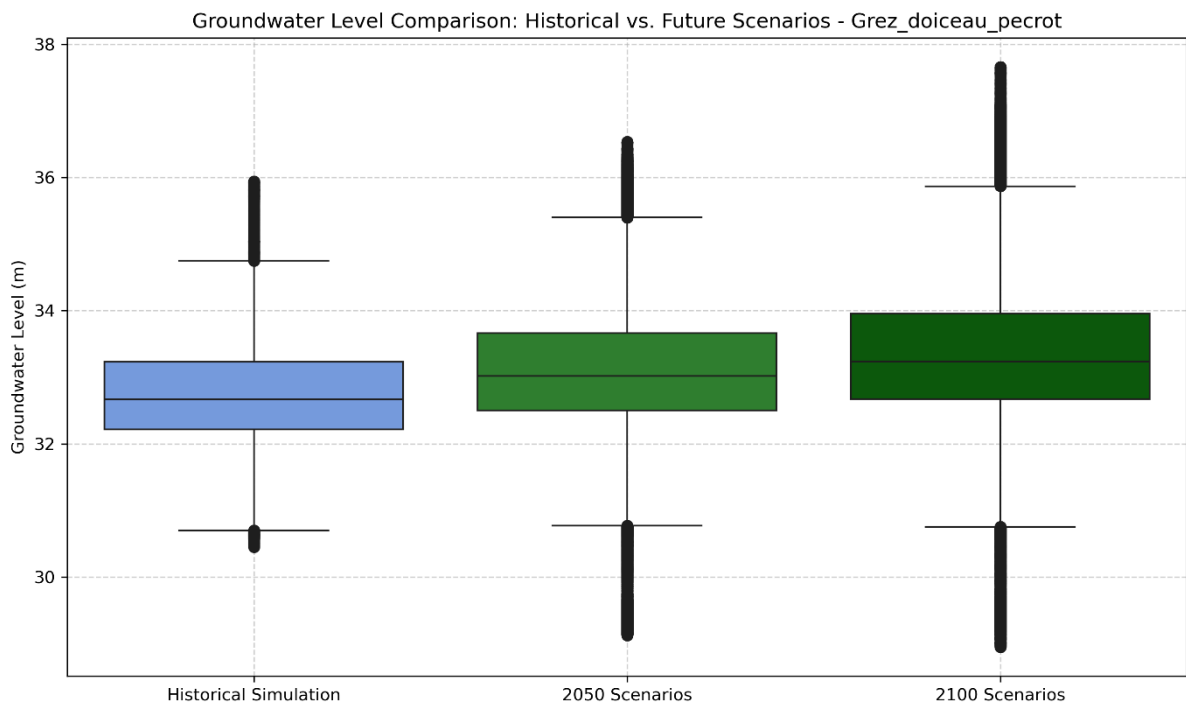
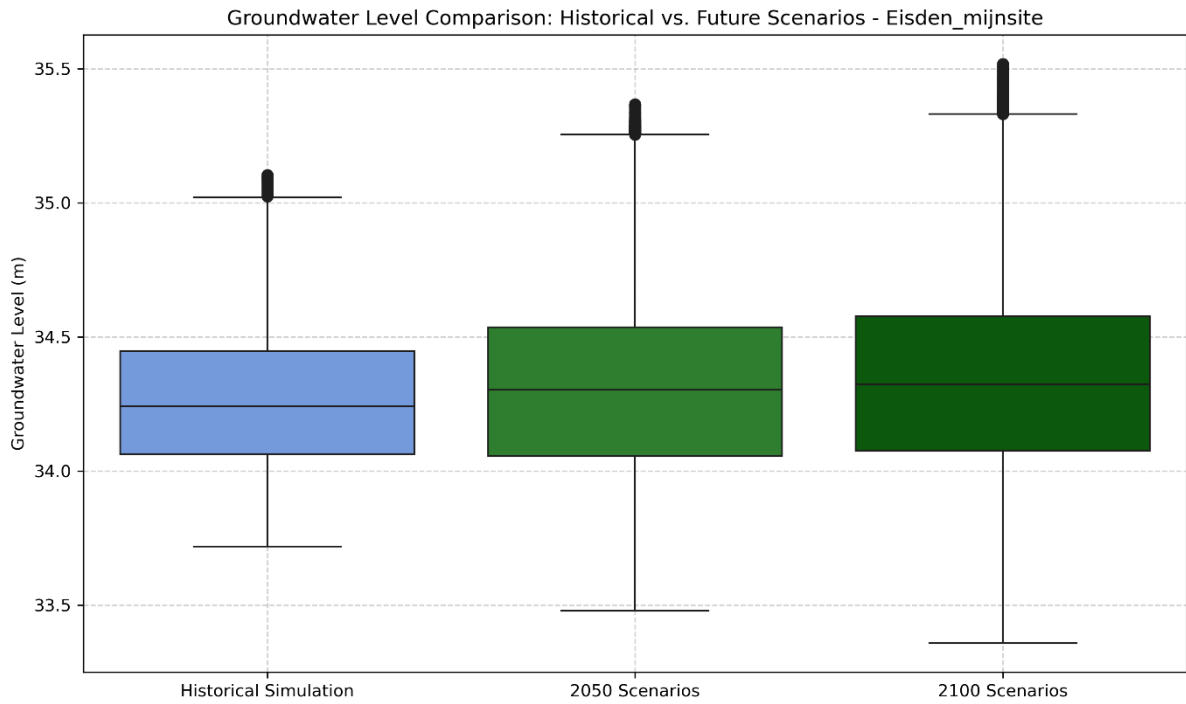
10.2 Appendix B: De Watergroep results

10.2.1 B.1 De Watergroep Groundwater Level comparison

Comparison of simulated groundwater levels under historical and future climate scenarios for three examples of group of wells.





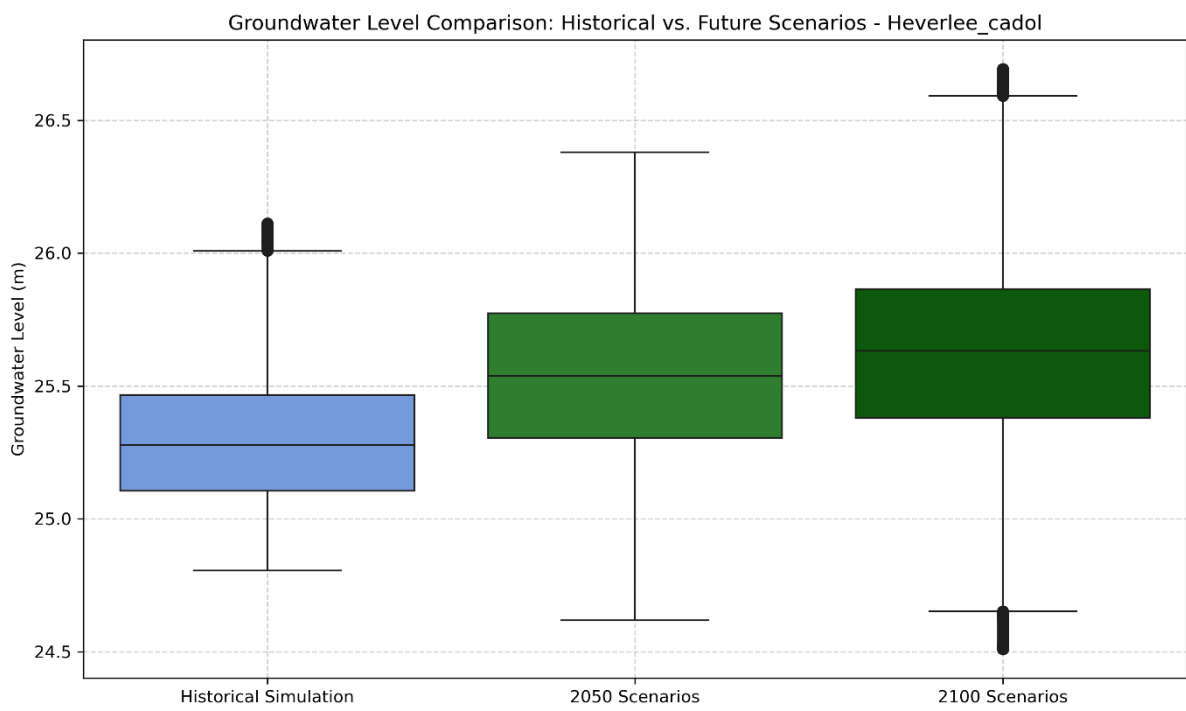
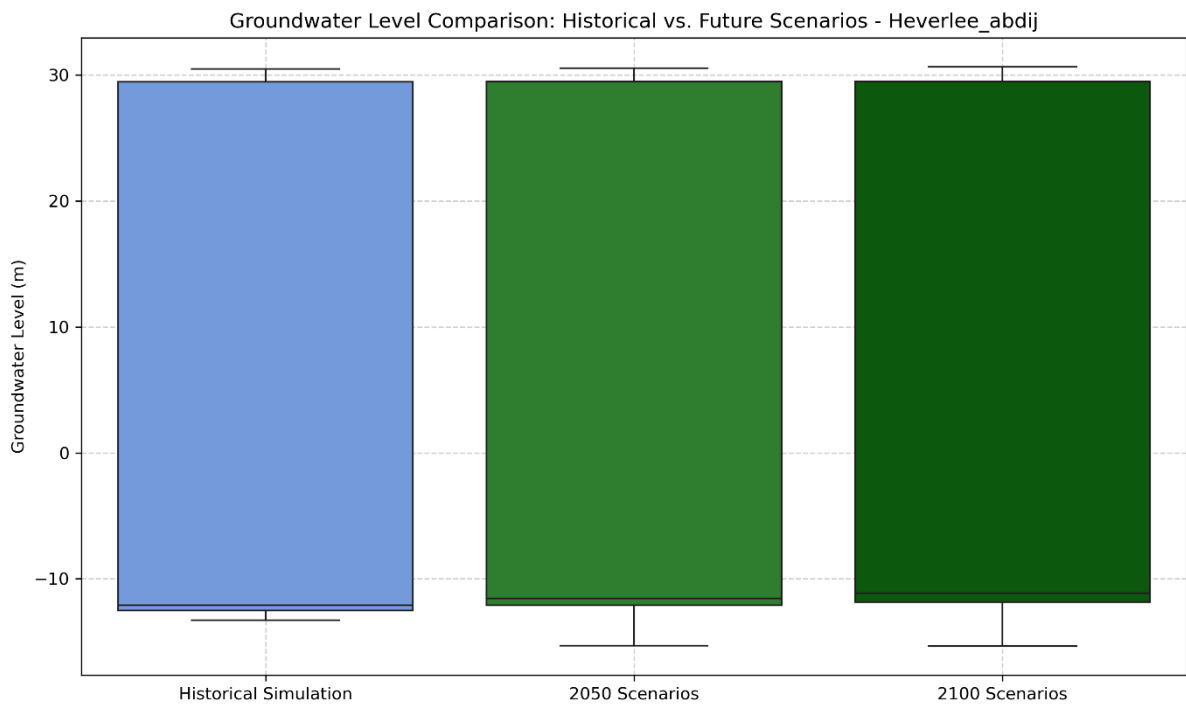


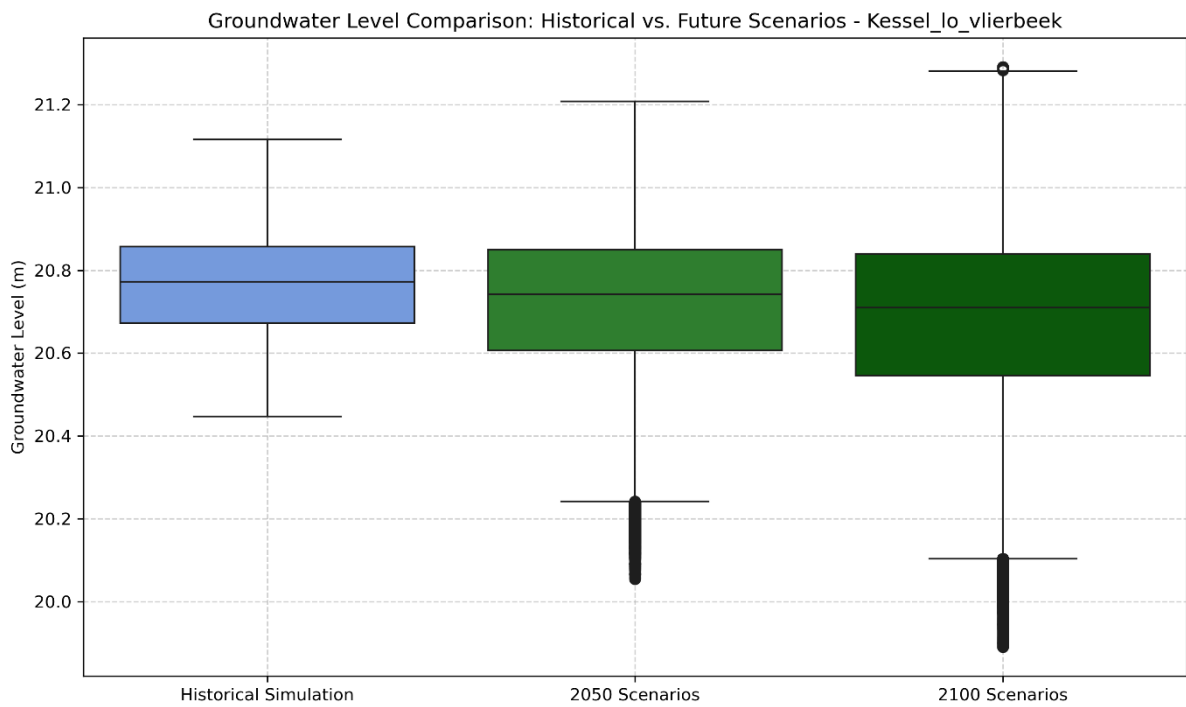
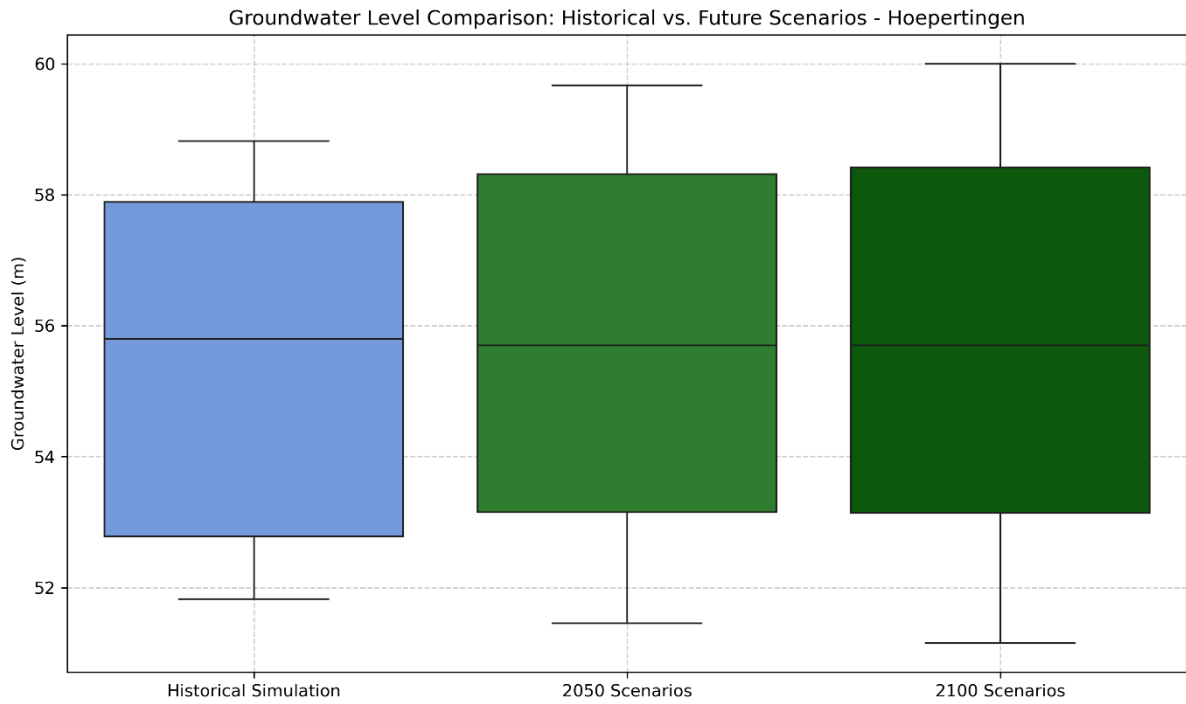
A box plot comparing groundwater levels across three scenarios. The y-axis represents 'Groundwater Level (m)' from 16 to 24. The x-axis categories are 'Historical Simulation' (blue box), '2050 Scenarios' (green box), and '2100 Scenarios' (dark green box). Each box shows the median (horizontal line), the interquartile range (the box), and whiskers extending to the minimum and maximum values. The '2050 Scenarios' and '2100 Scenarios' categories show a wider range of values, indicated by longer whiskers and vertical error bars, compared to the 'Historical Simulation'.

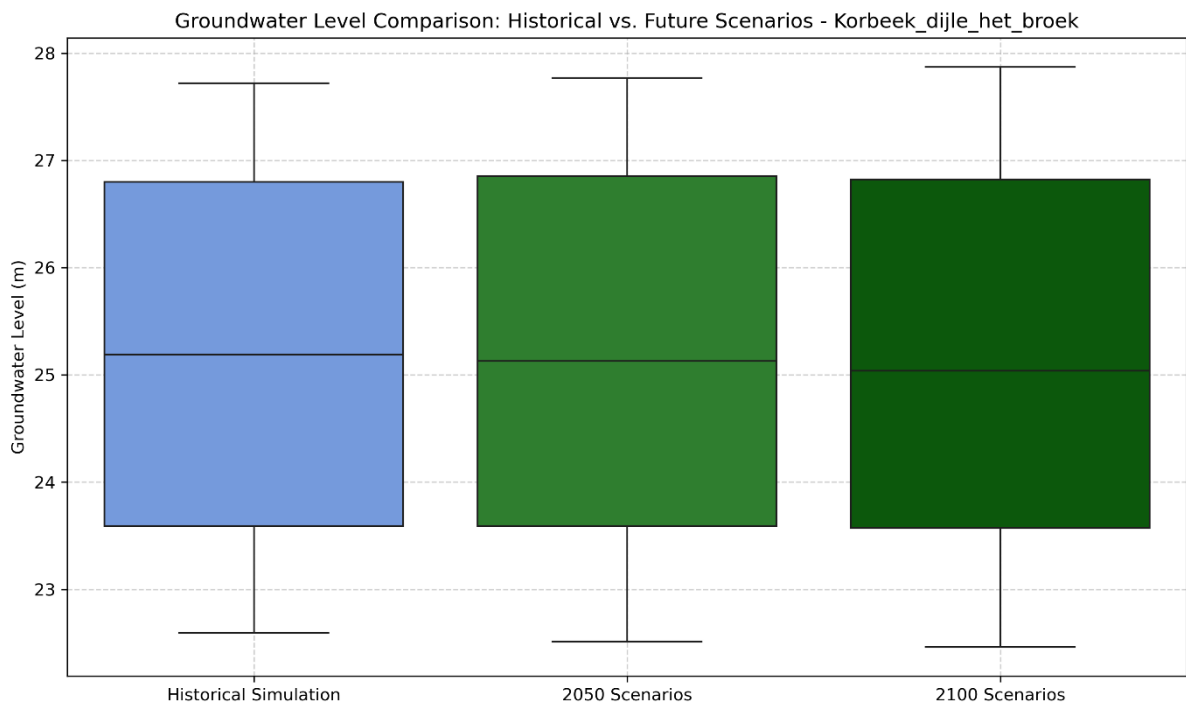
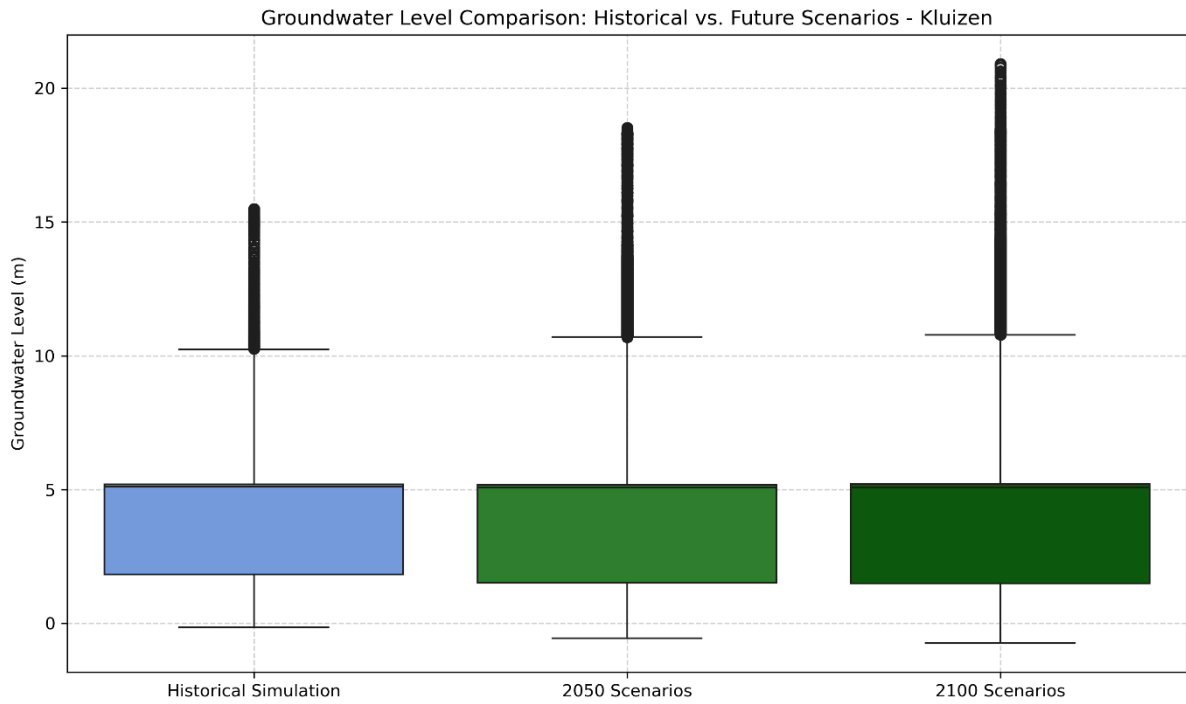
Scenario	Min (m)	Q1 (m)	Median (m)	Q3 (m)	Max (m)
Historical Simulation	18.3	19.6	20.2	20.7	22.0
2050 Scenarios	18.5	20.2	20.8	21.3	22.8
2100 Scenarios	18.5	20.3	20.9	21.5	23.2

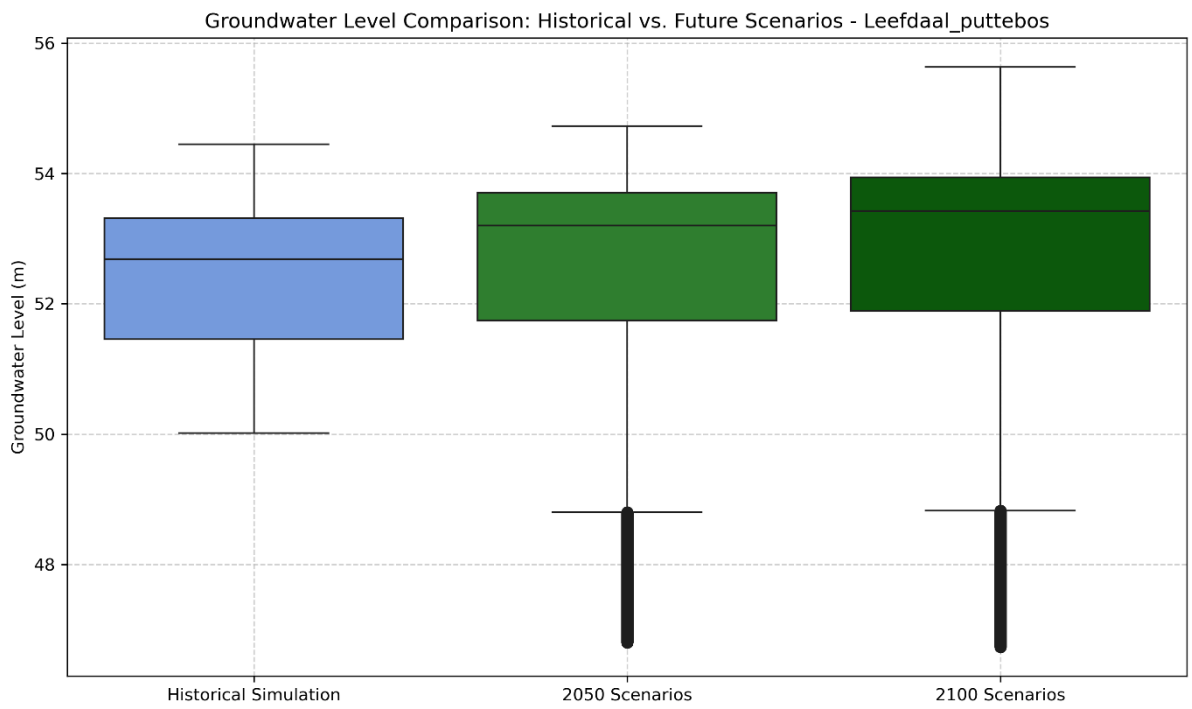
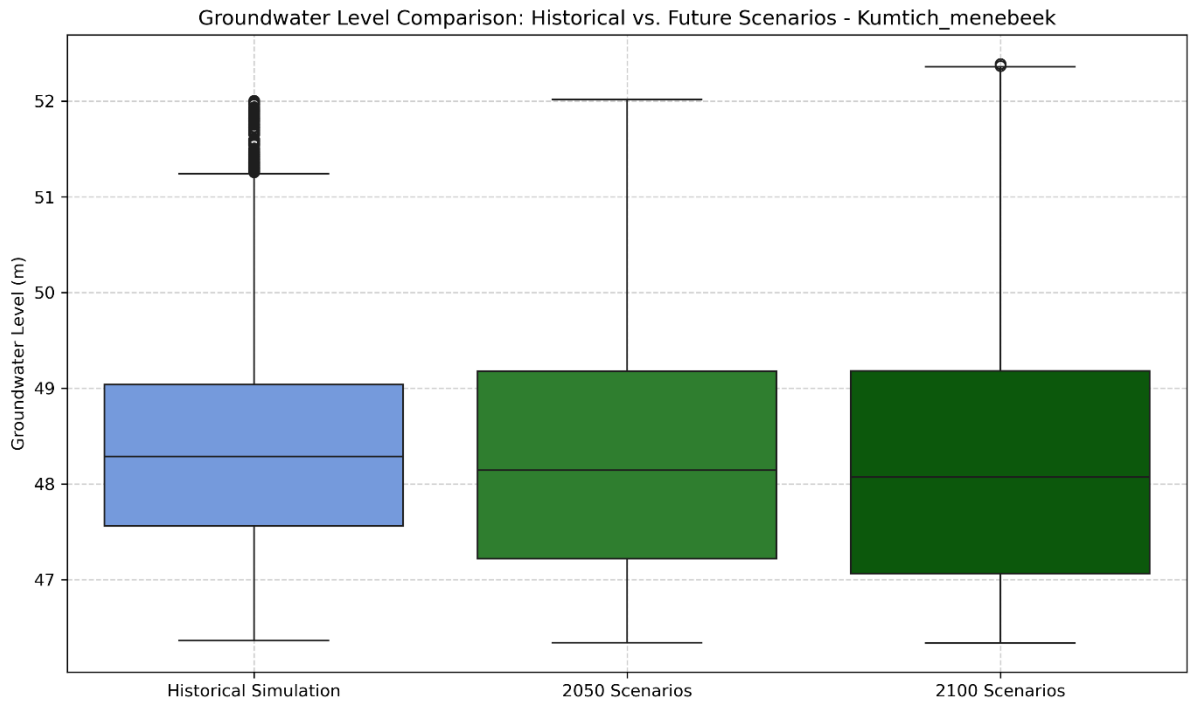
A box plot comparing groundwater levels across three scenarios: Historical Simulation, 2050 Scenarios, and 2100 Scenarios. The y-axis represents the Groundwater Level in meters (m), ranging from 20 to 45. The x-axis labels are 'Historical Simulation', '2050 Scenarios', and '2100 Scenarios'. The Historical Simulation box is blue, while the 2050 and 2100 Scenarios boxes are green. Each box shows the median (horizontal line inside the box), the interquartile range (the box itself), and the full range of the data (whiskers). The medians for all three scenarios are approximately 30.5 m. The 2100 Scenarios show a slightly higher median and a wider range compared to the 2050 Scenarios.

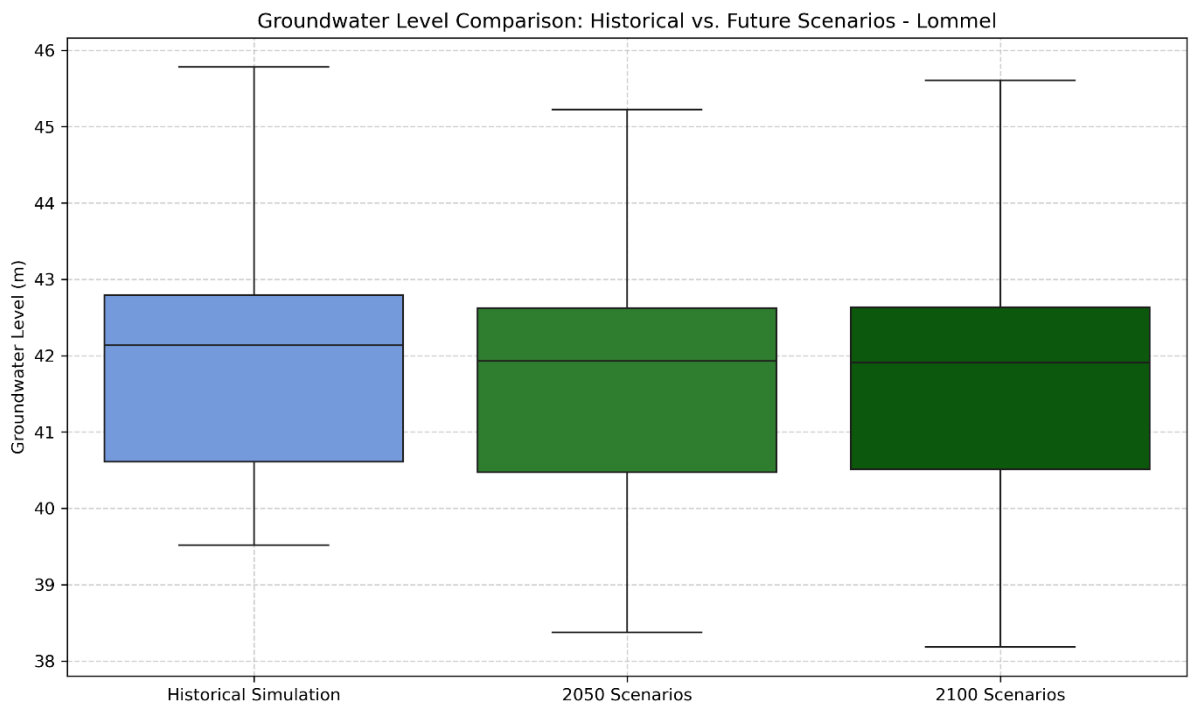
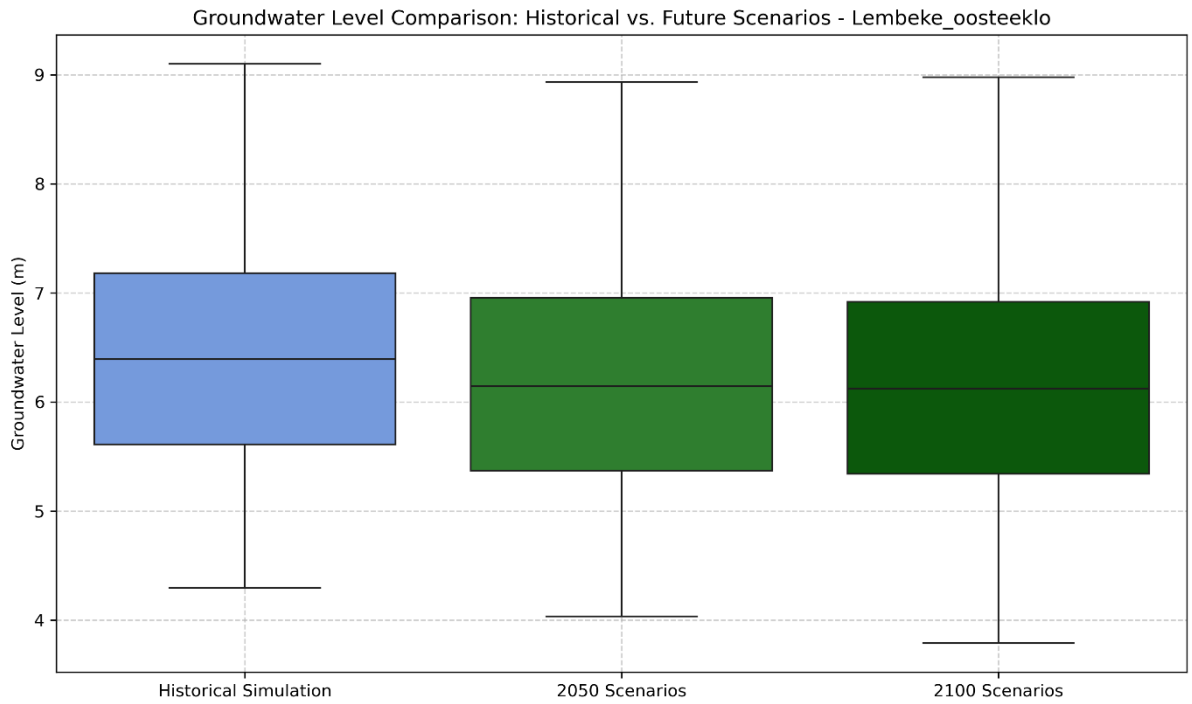
Scenario	Min	Q1	Median	Q3	Max
Historical Simulation	19.0	21.5	30.5	45.5	47.0
2050 Scenarios	19.0	21.5	30.5	45.5	47.0
2100 Scenarios	18.5	21.5	30.5	45.5	47.5

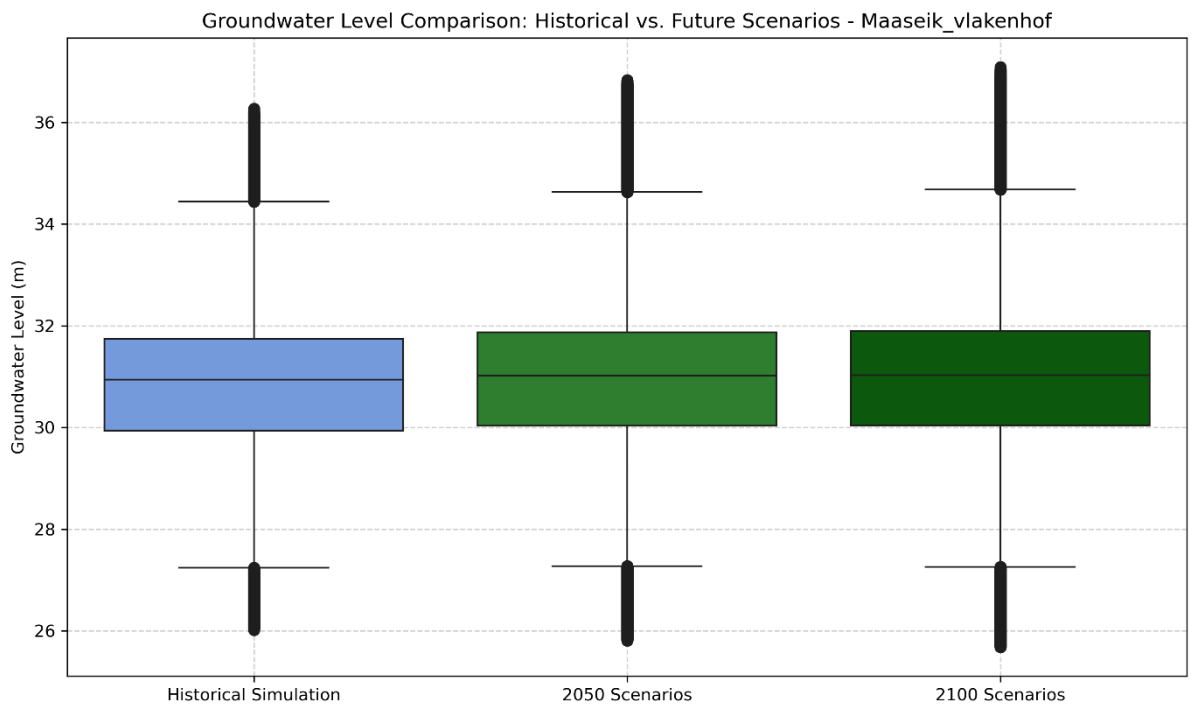
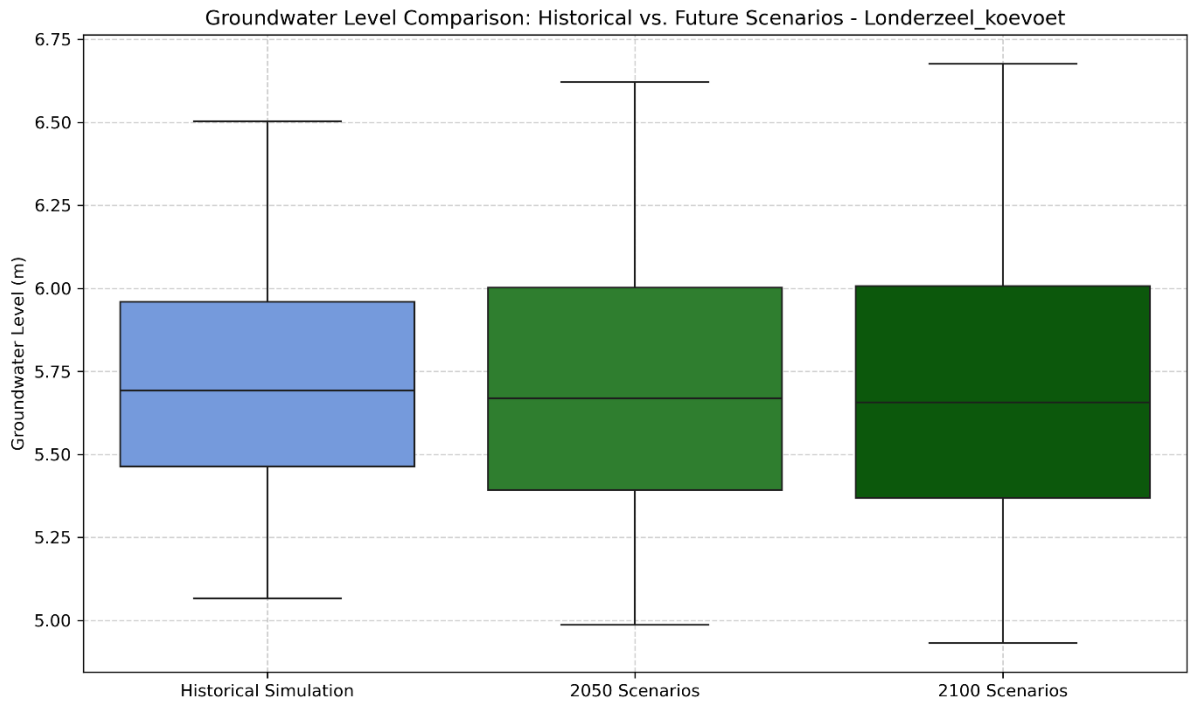


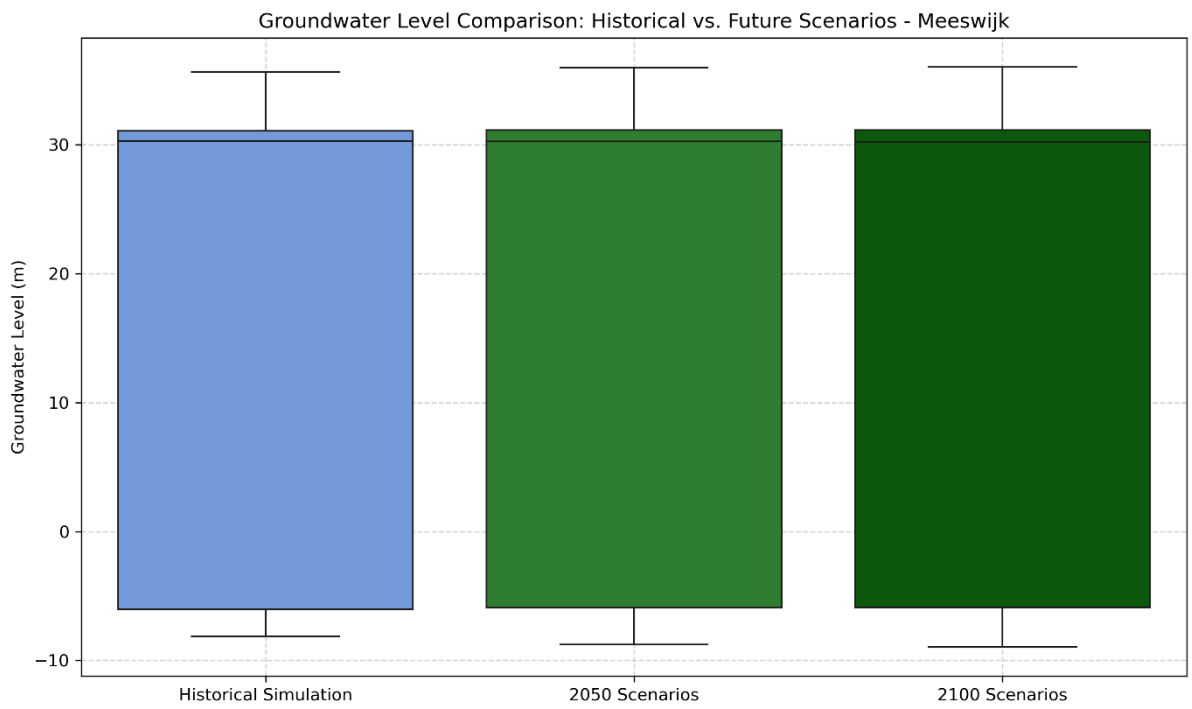
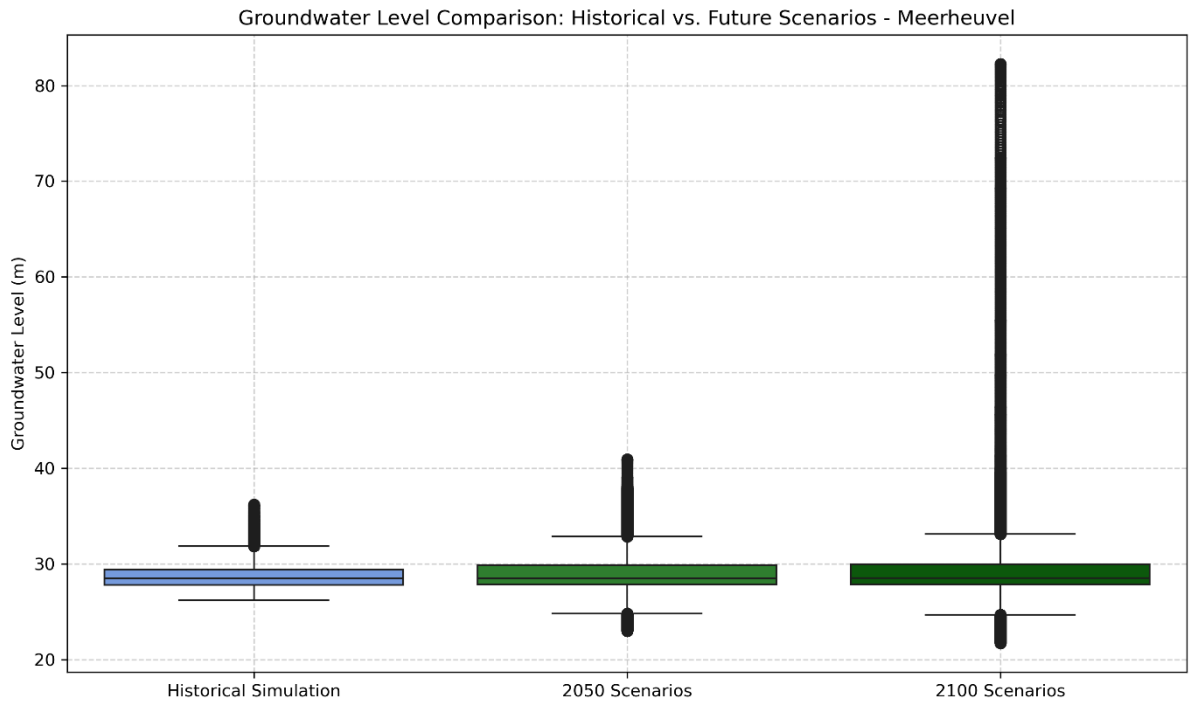


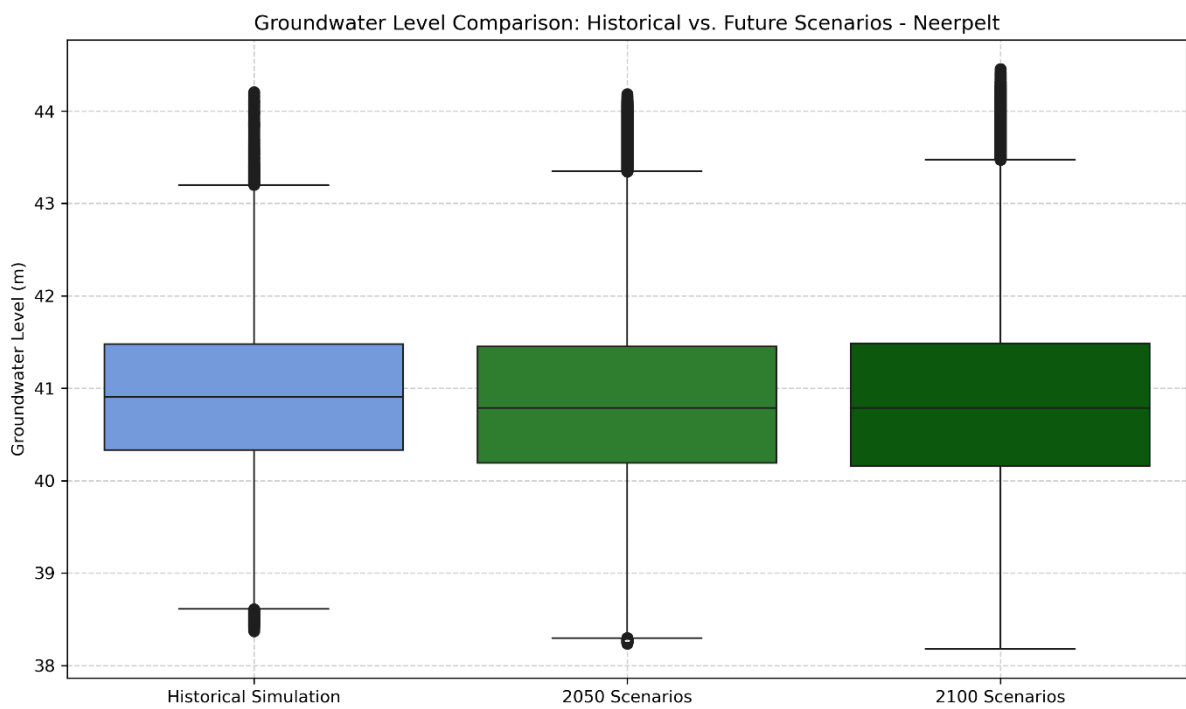
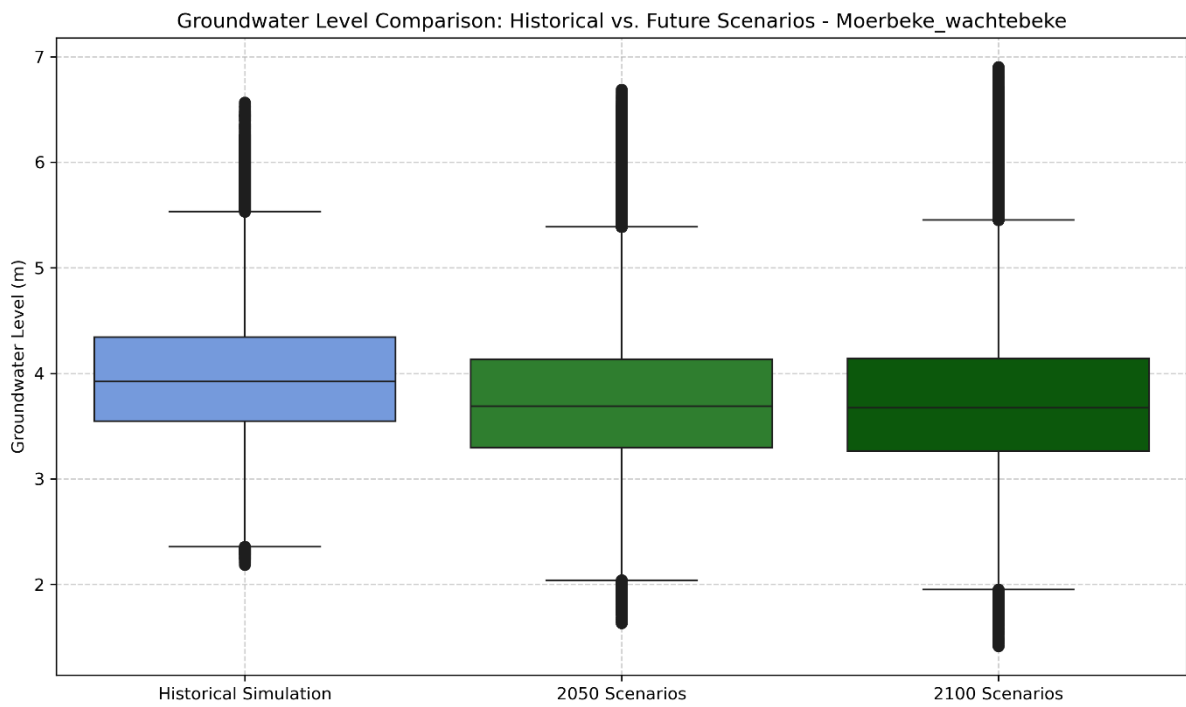


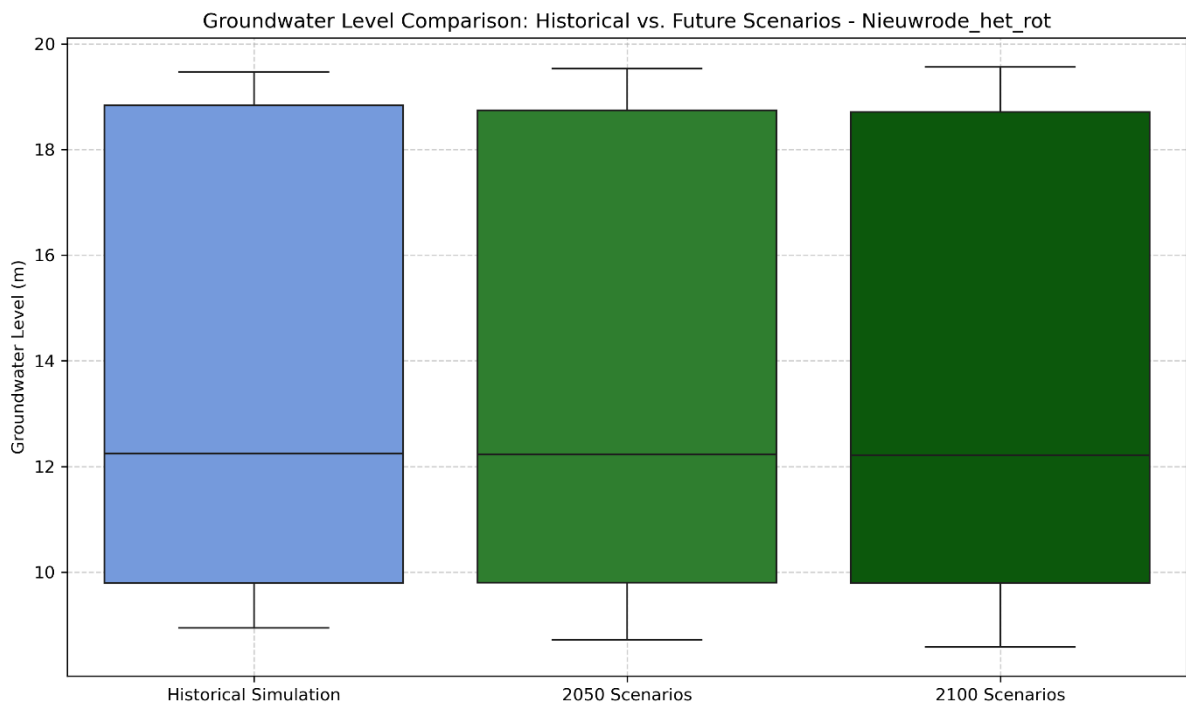
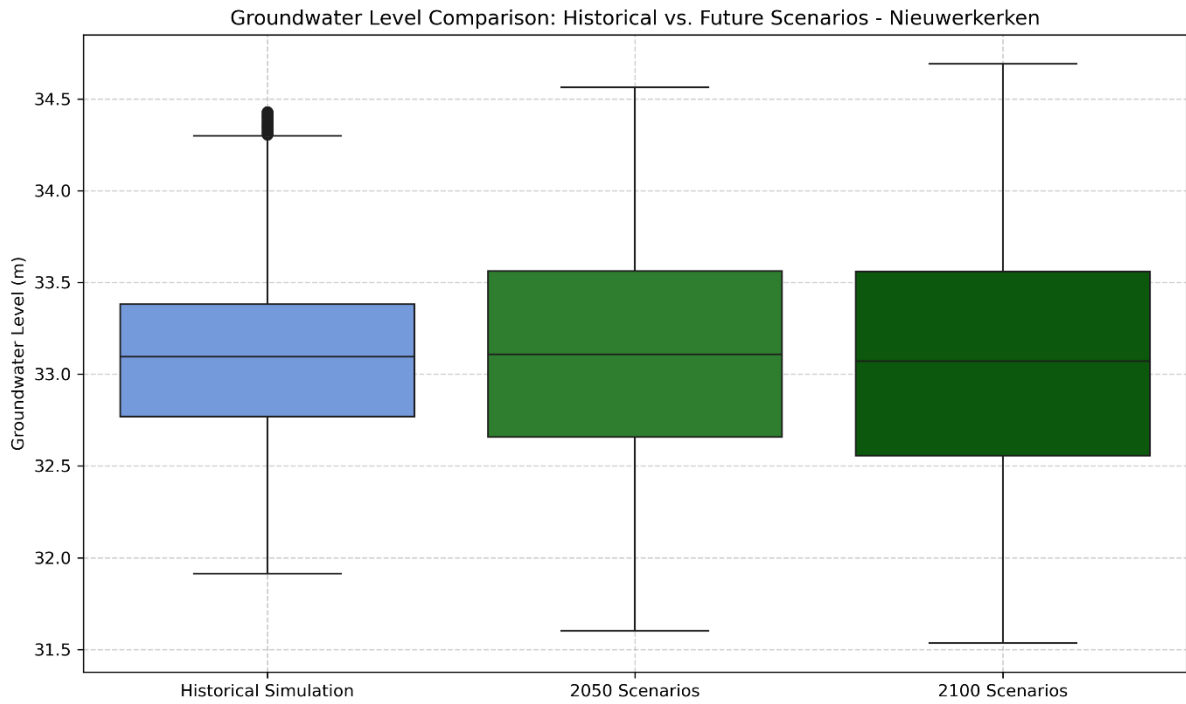


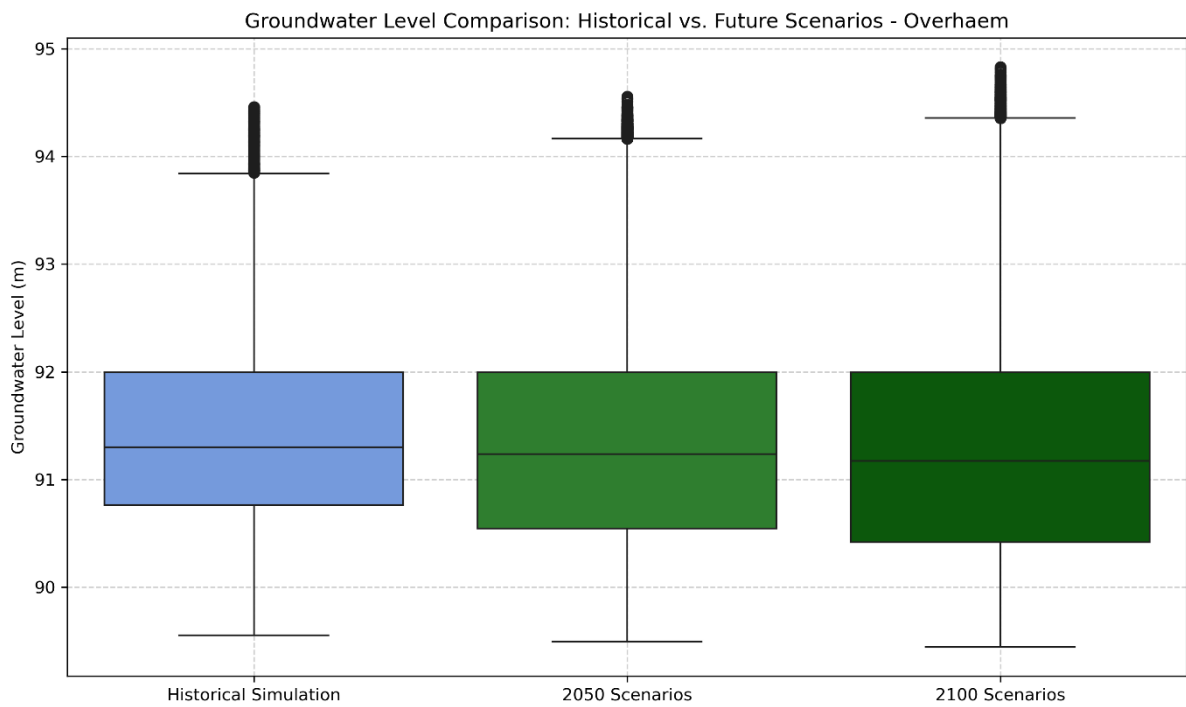
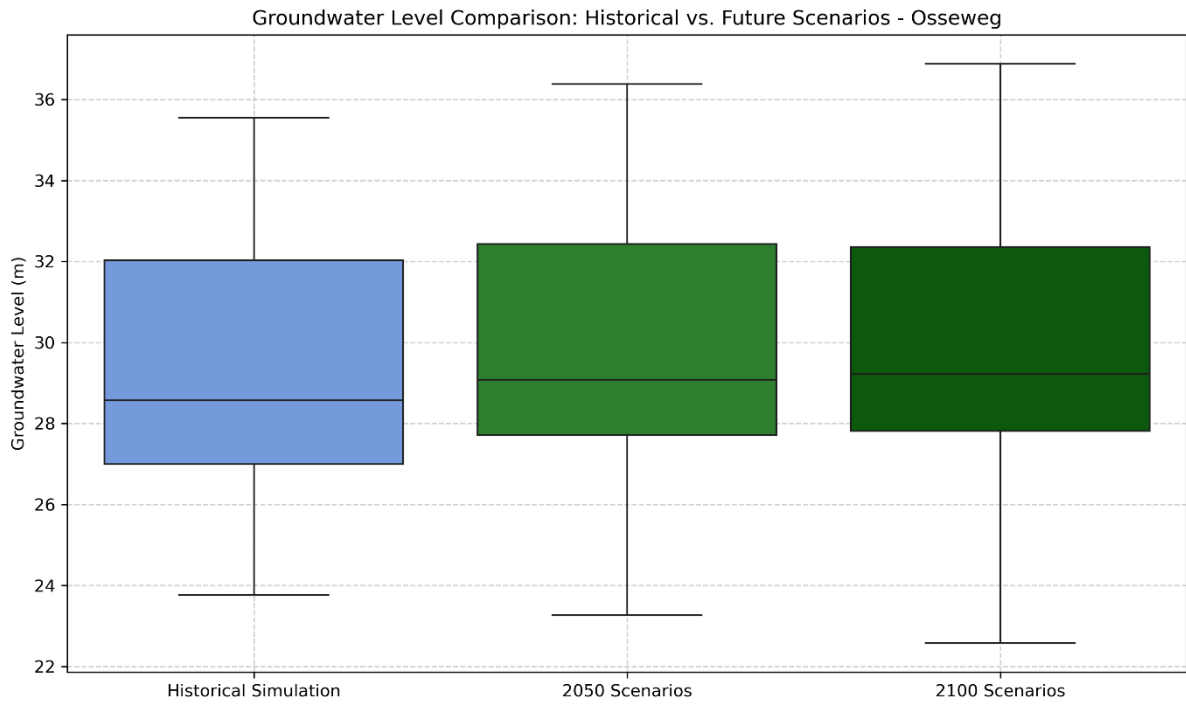


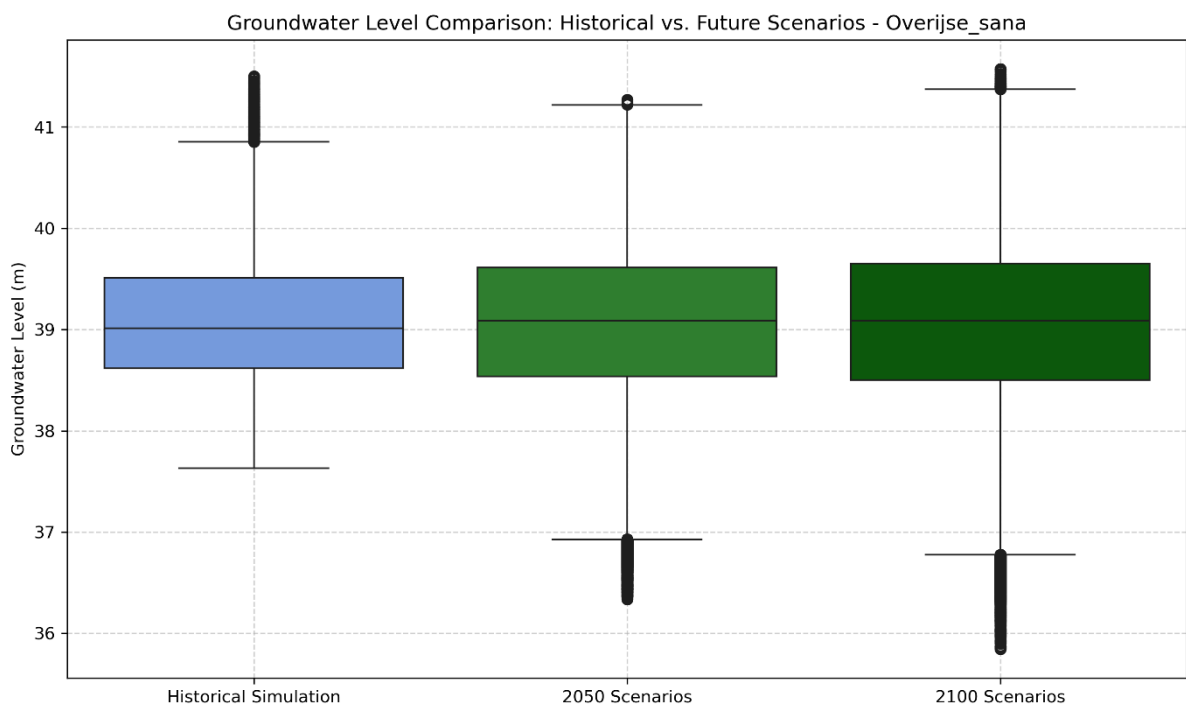
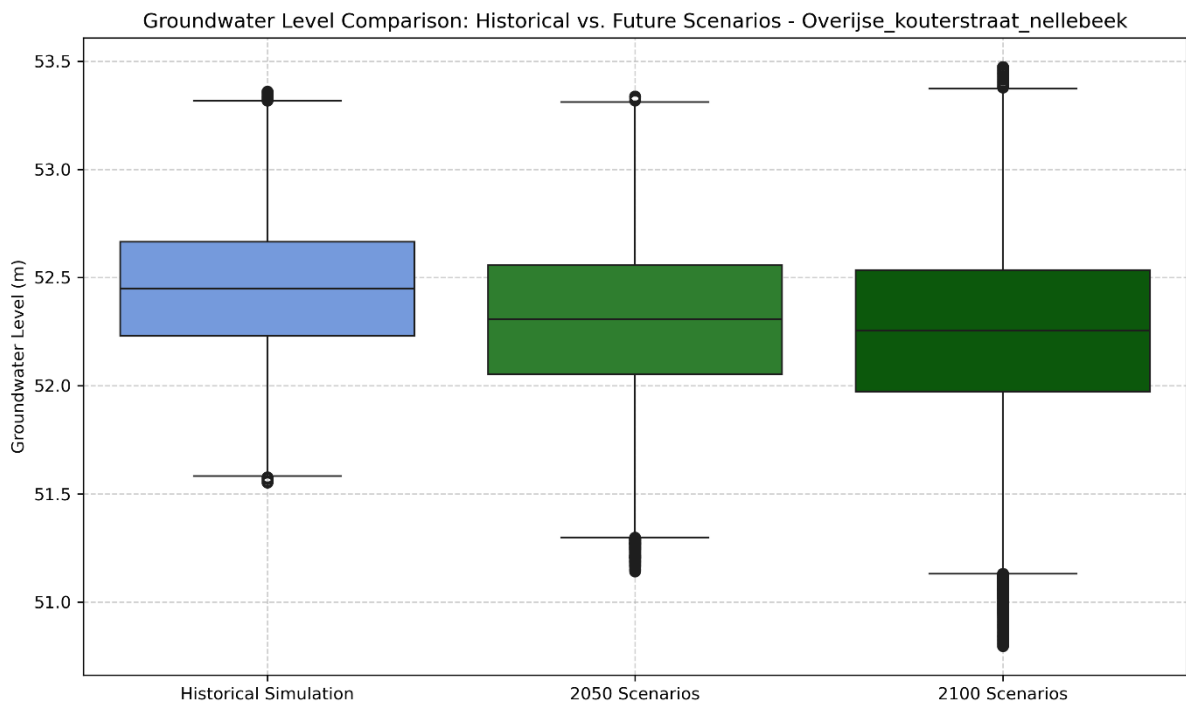


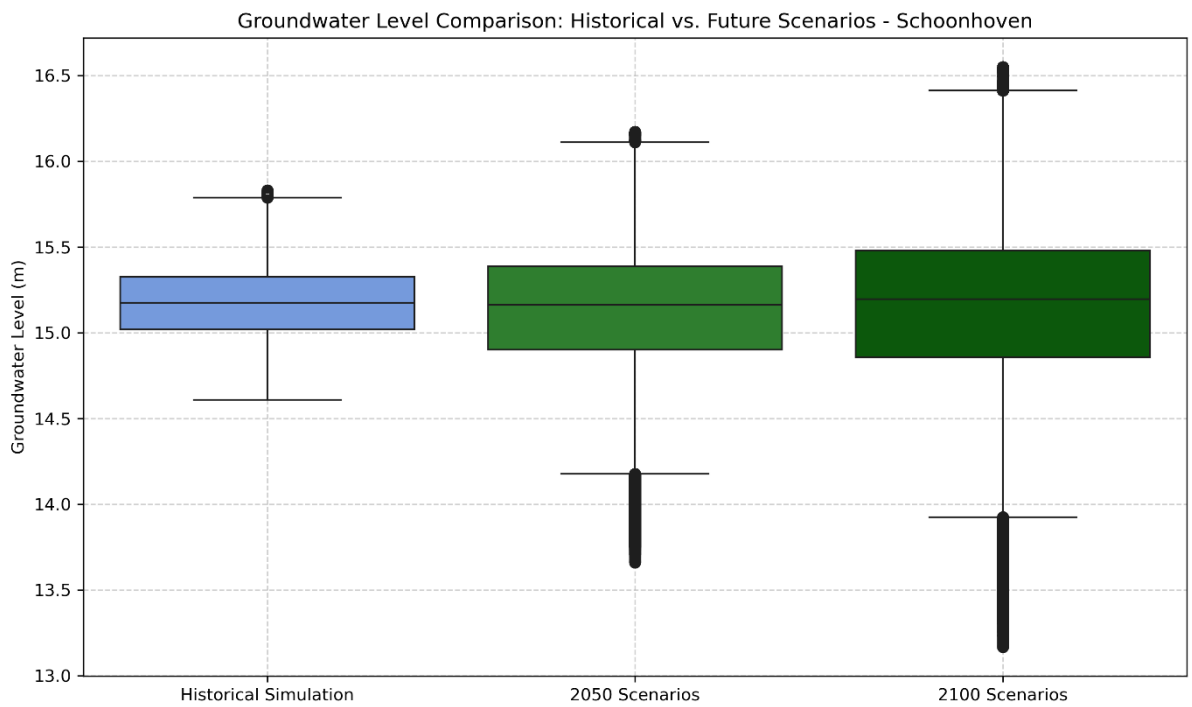
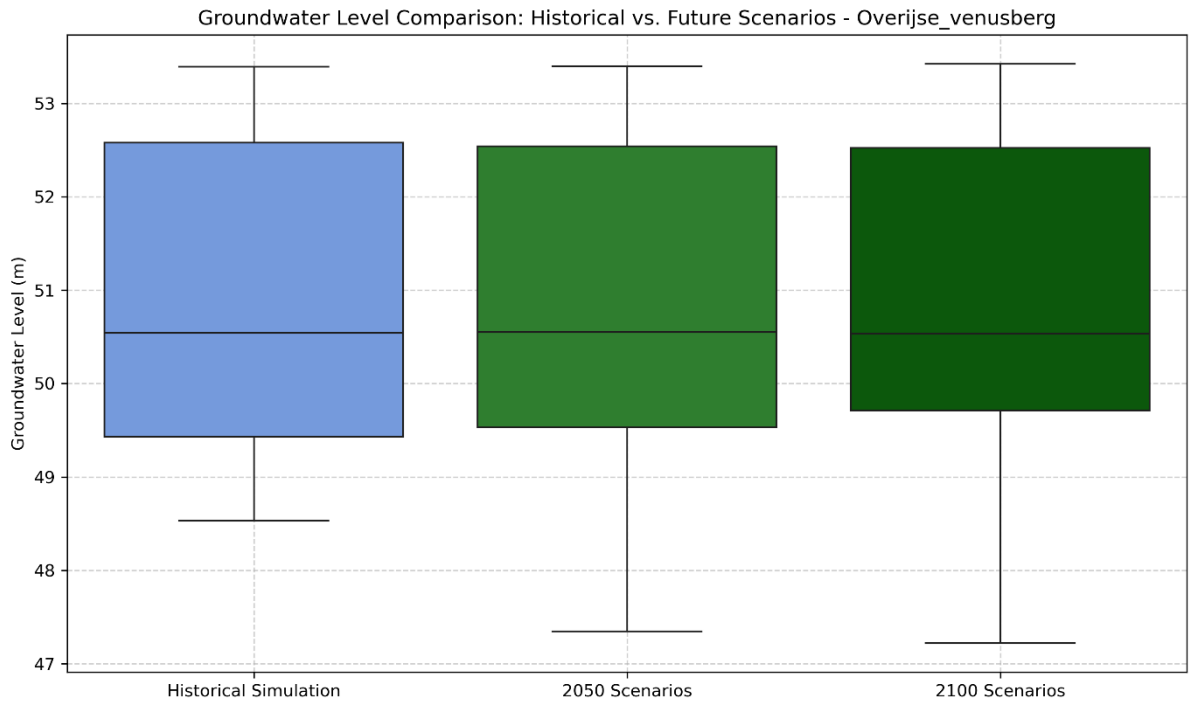


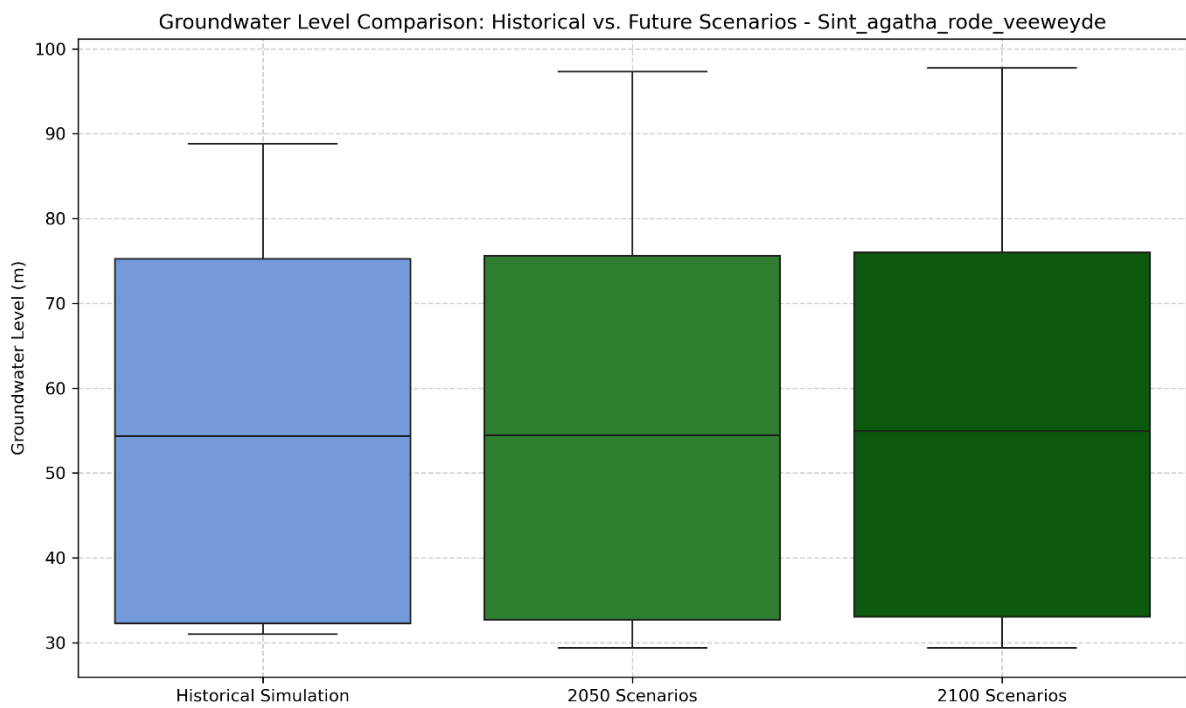
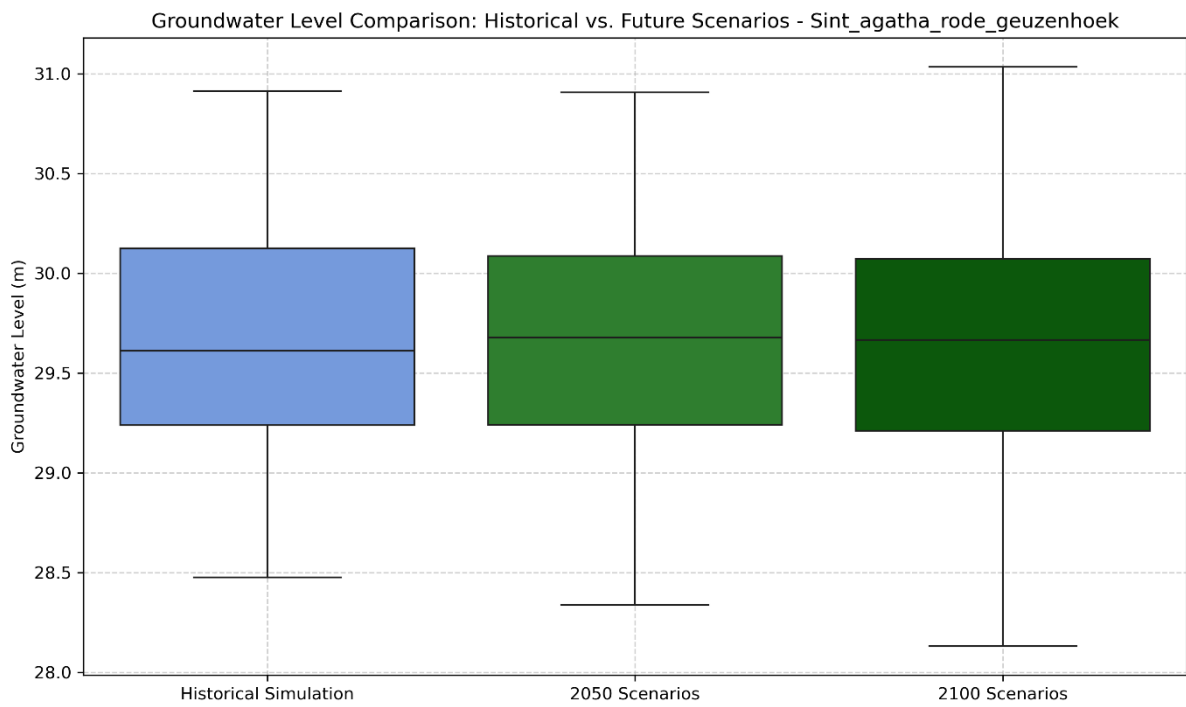


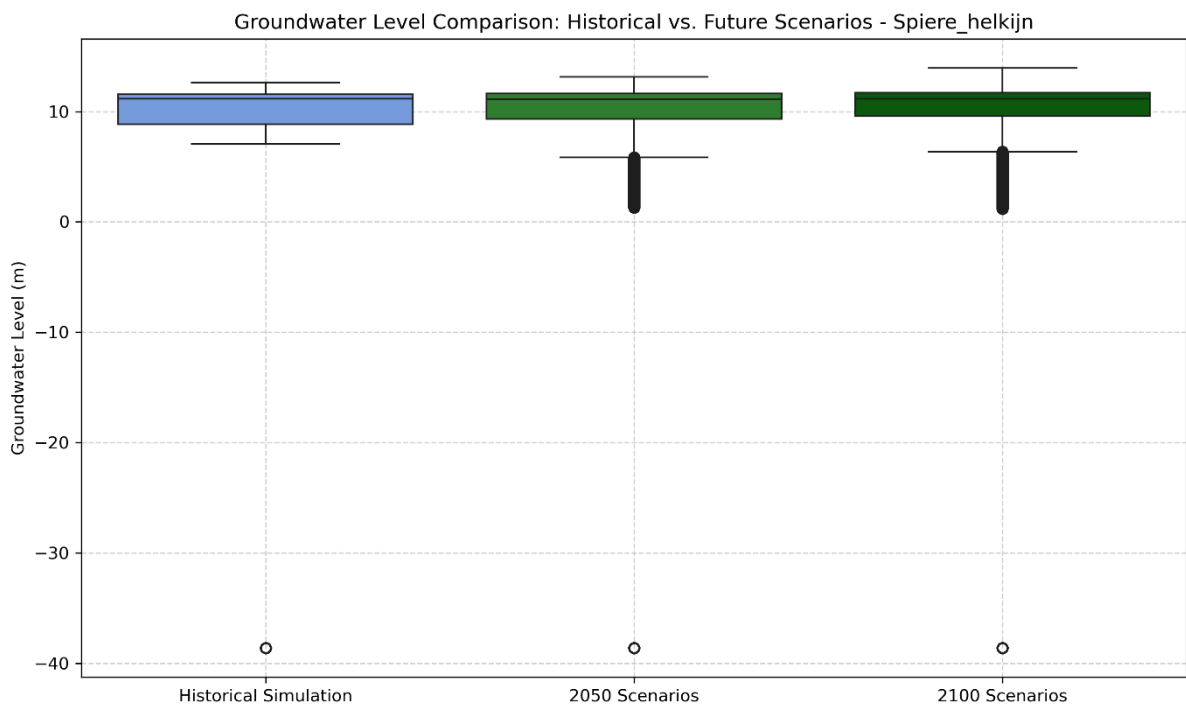
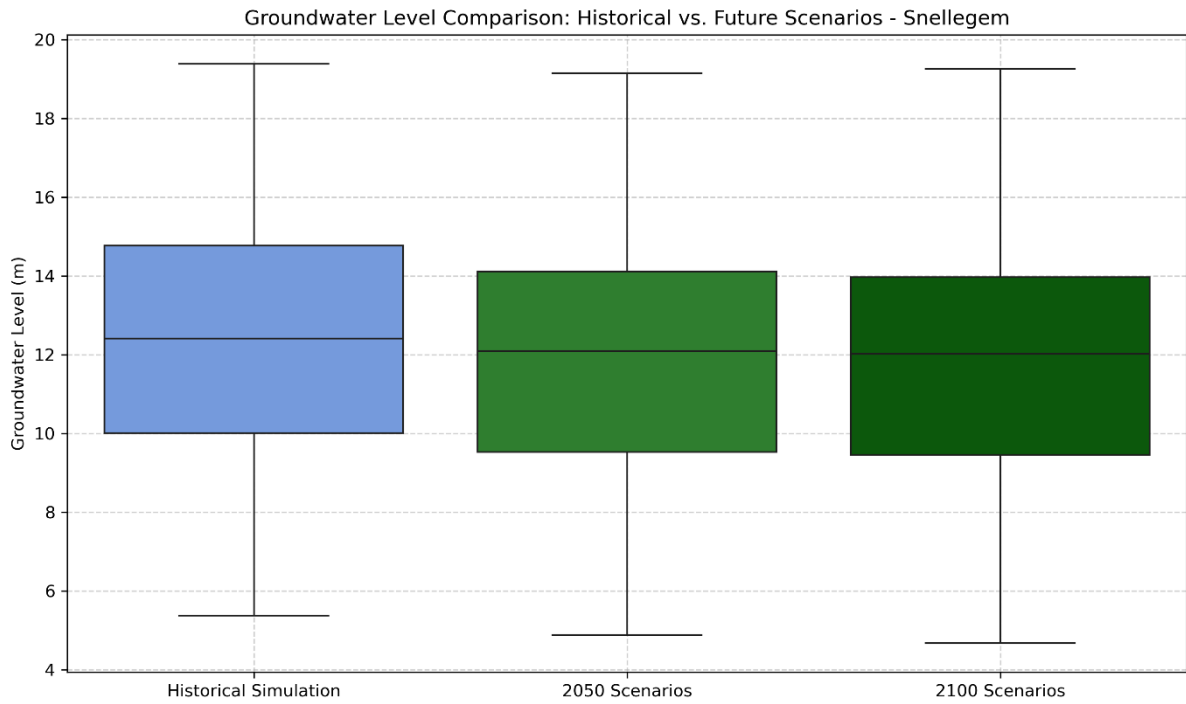


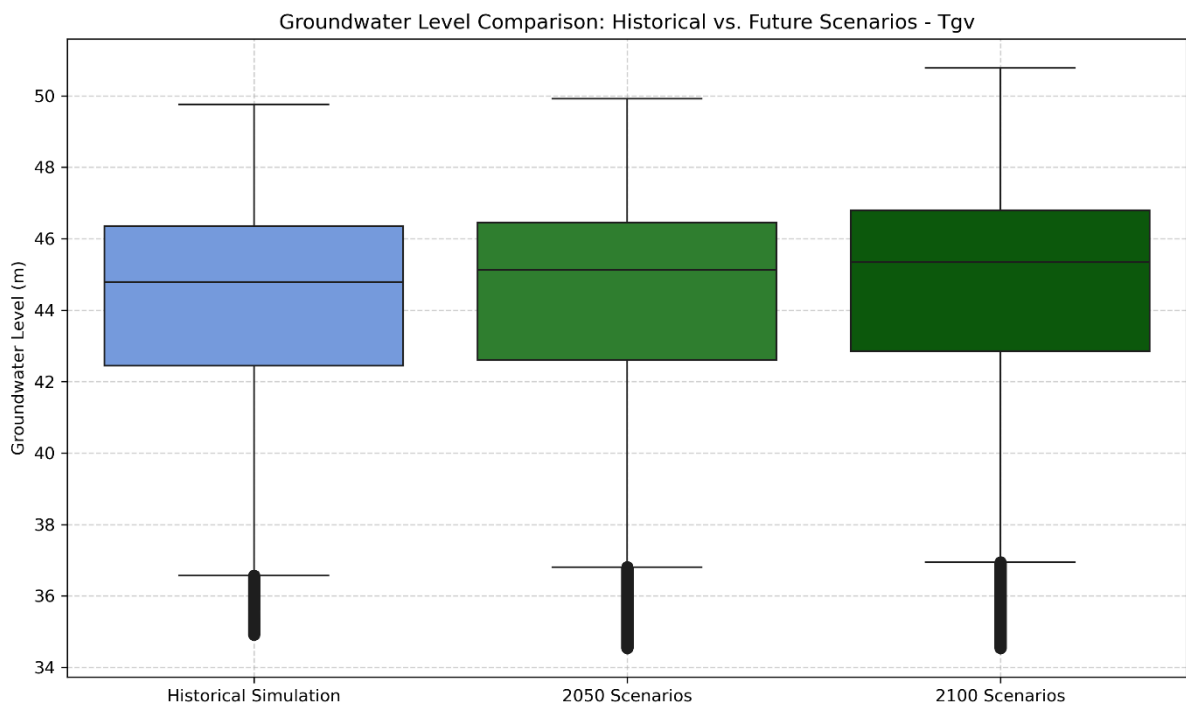
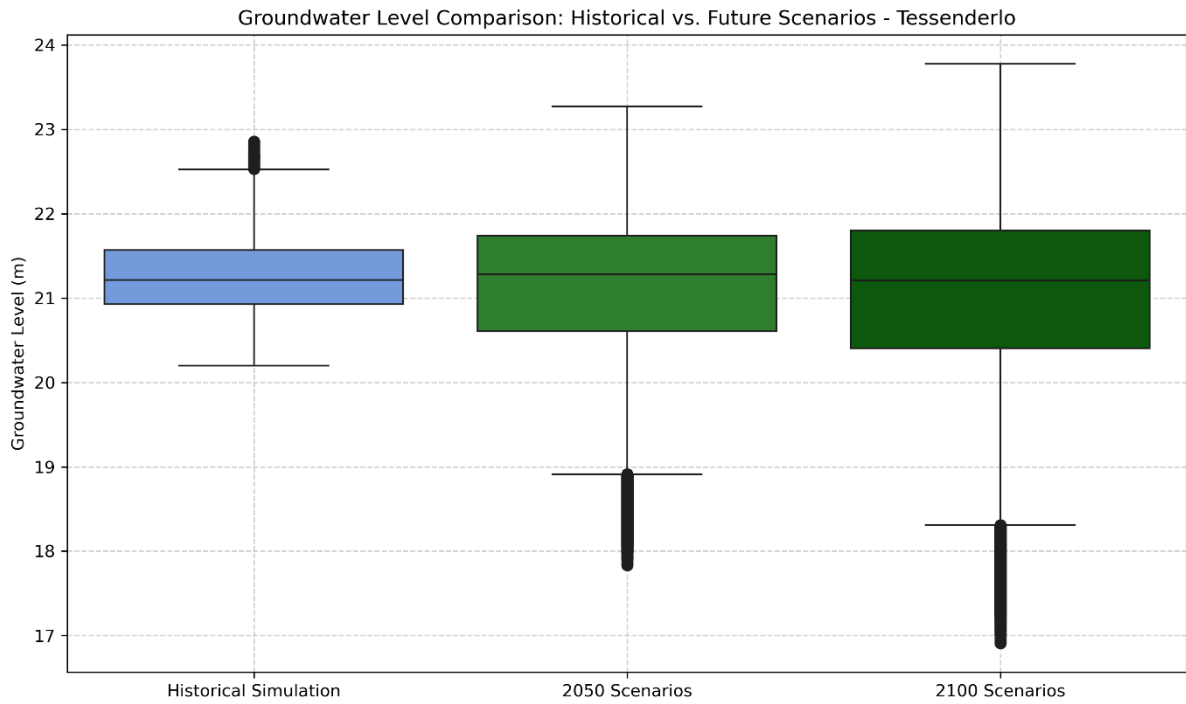


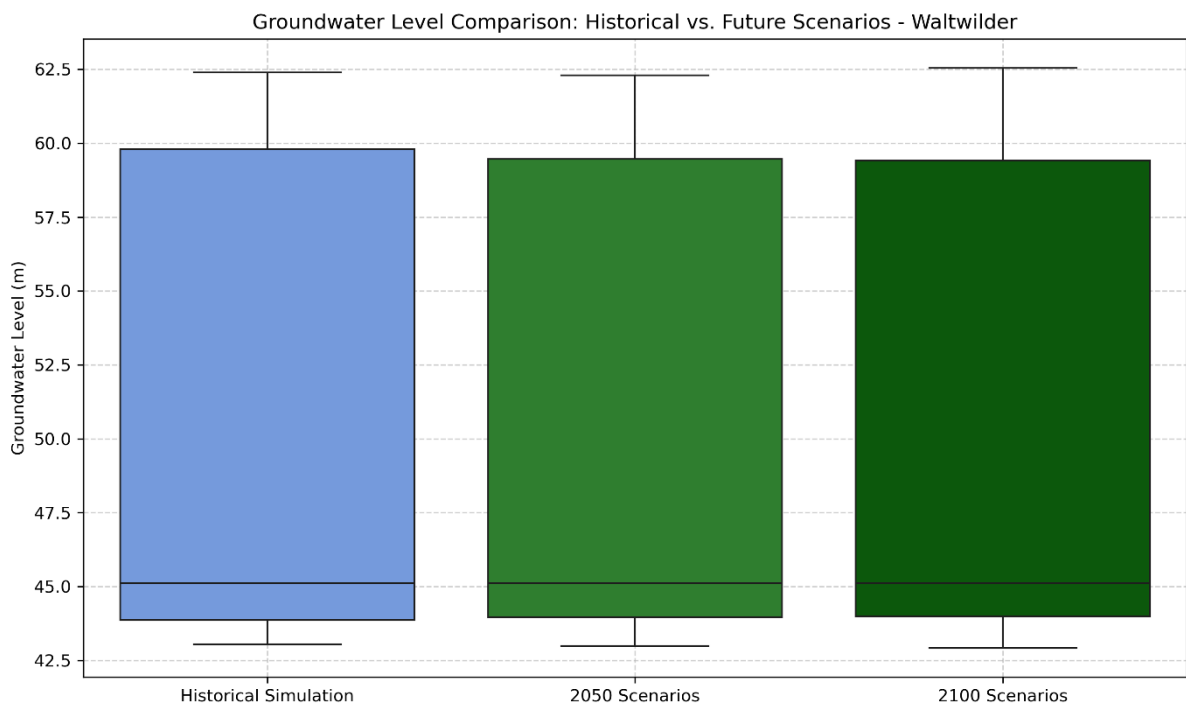
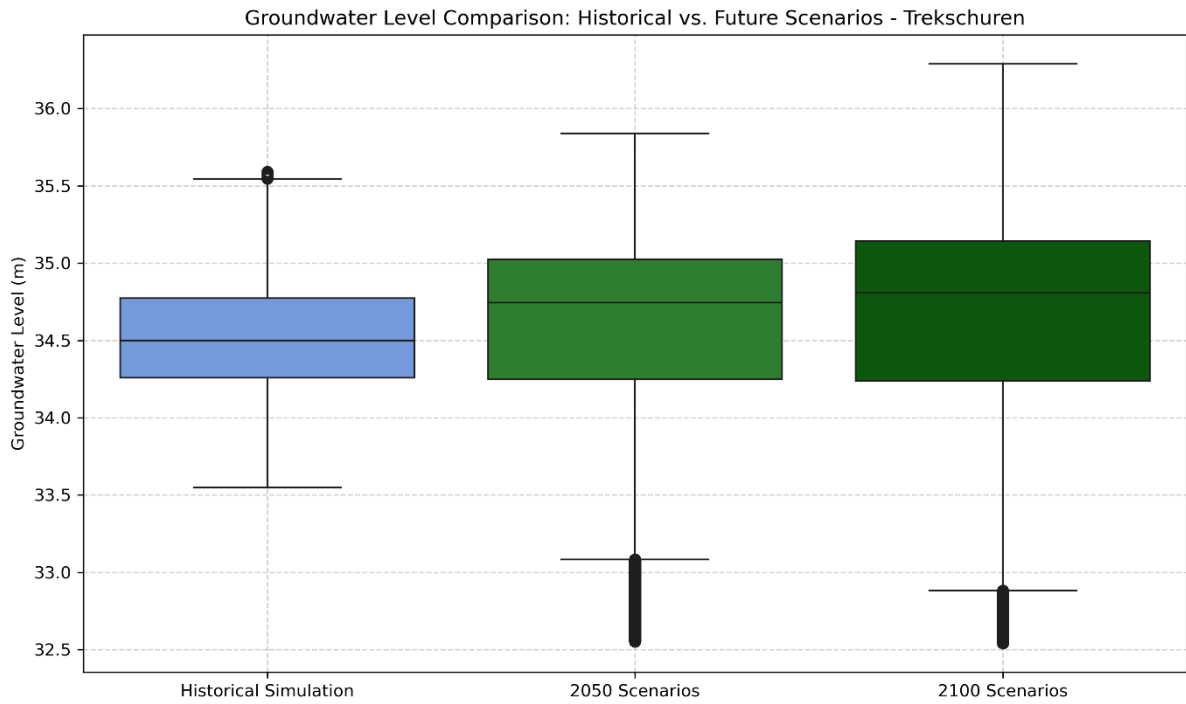


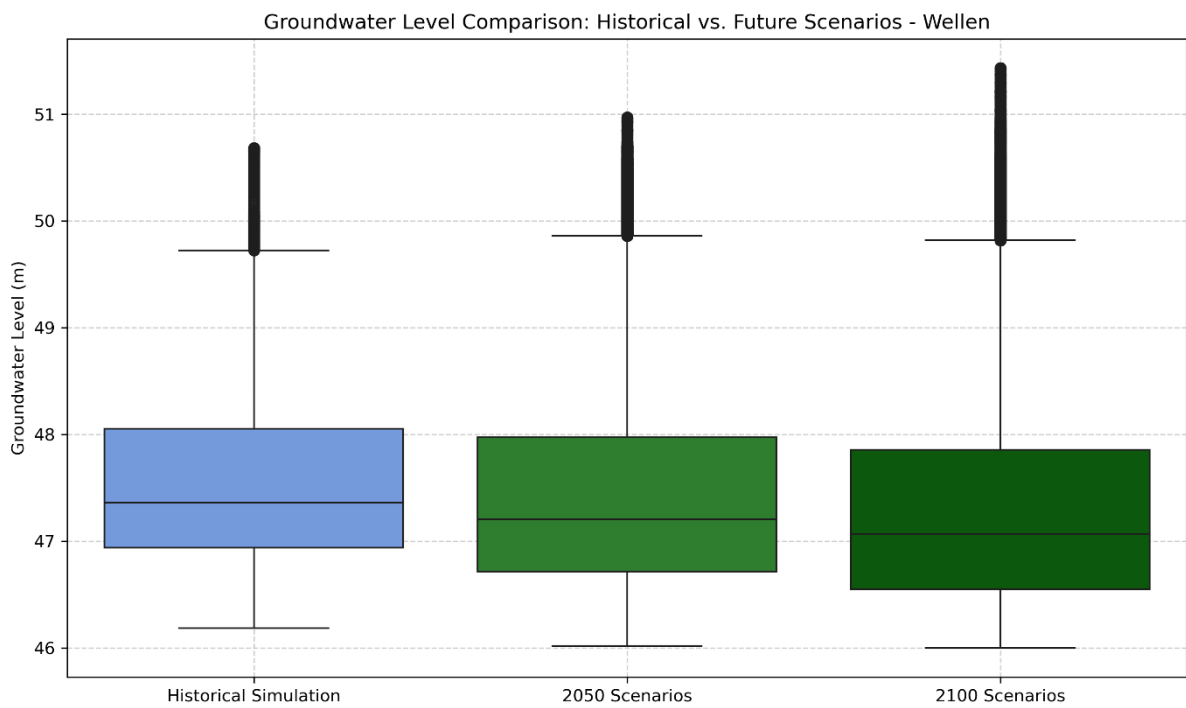
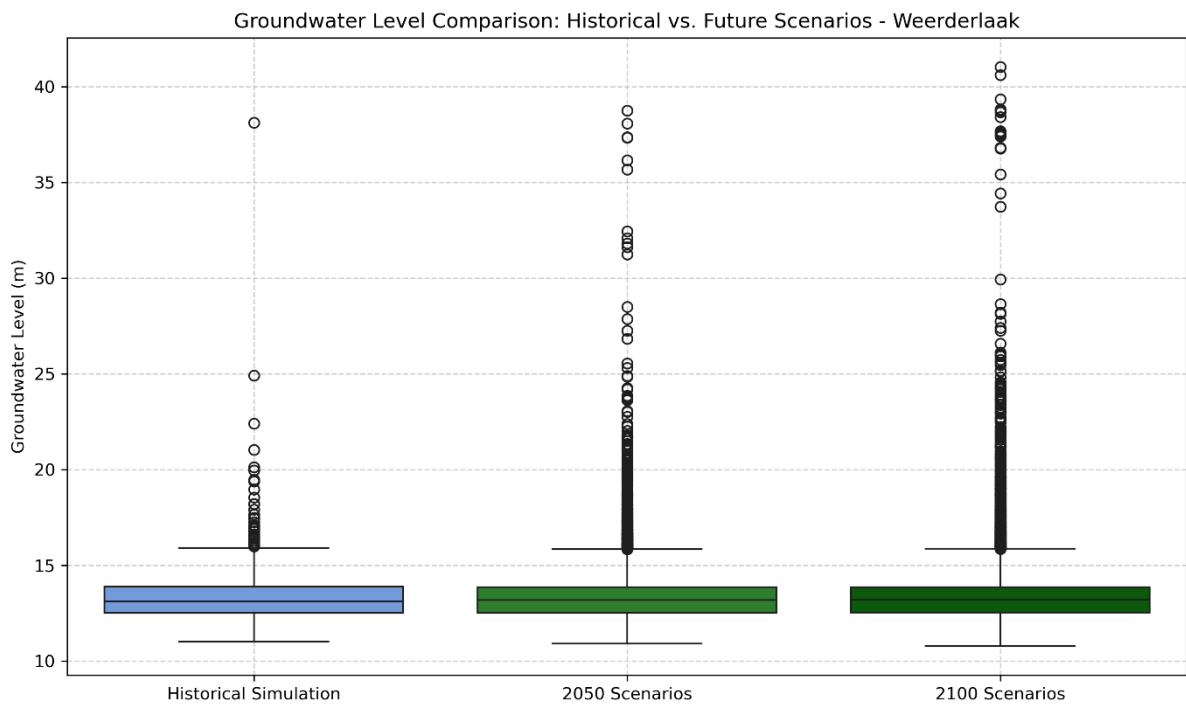


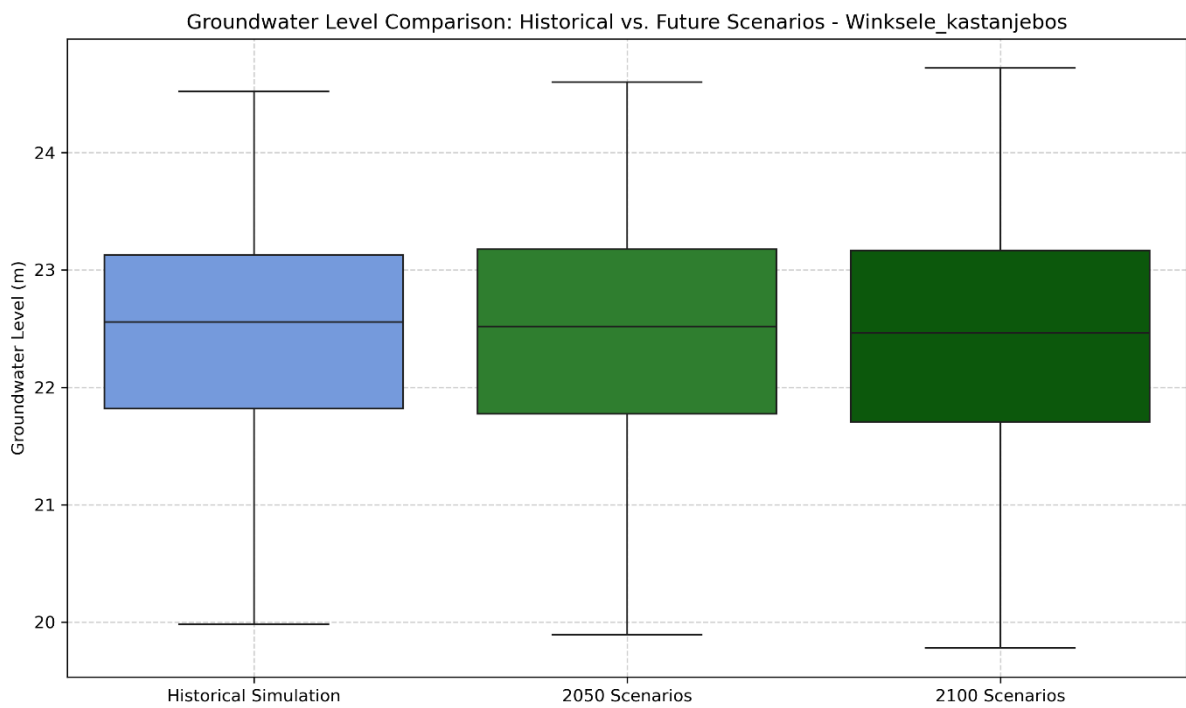
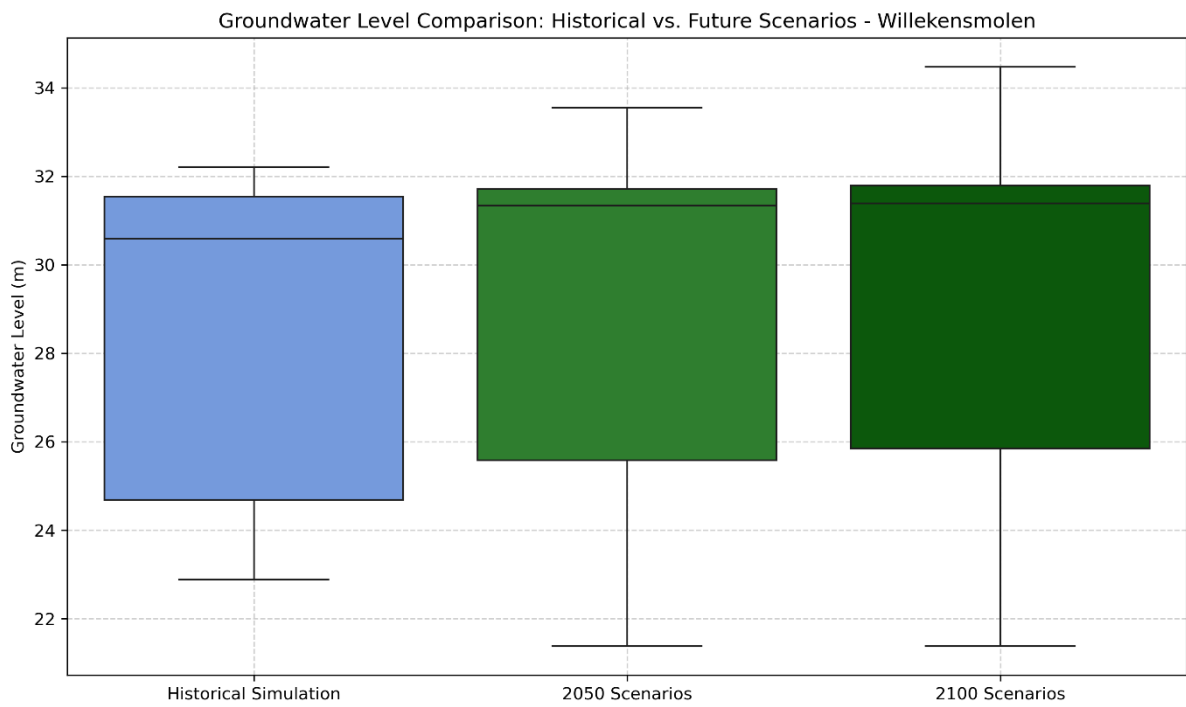


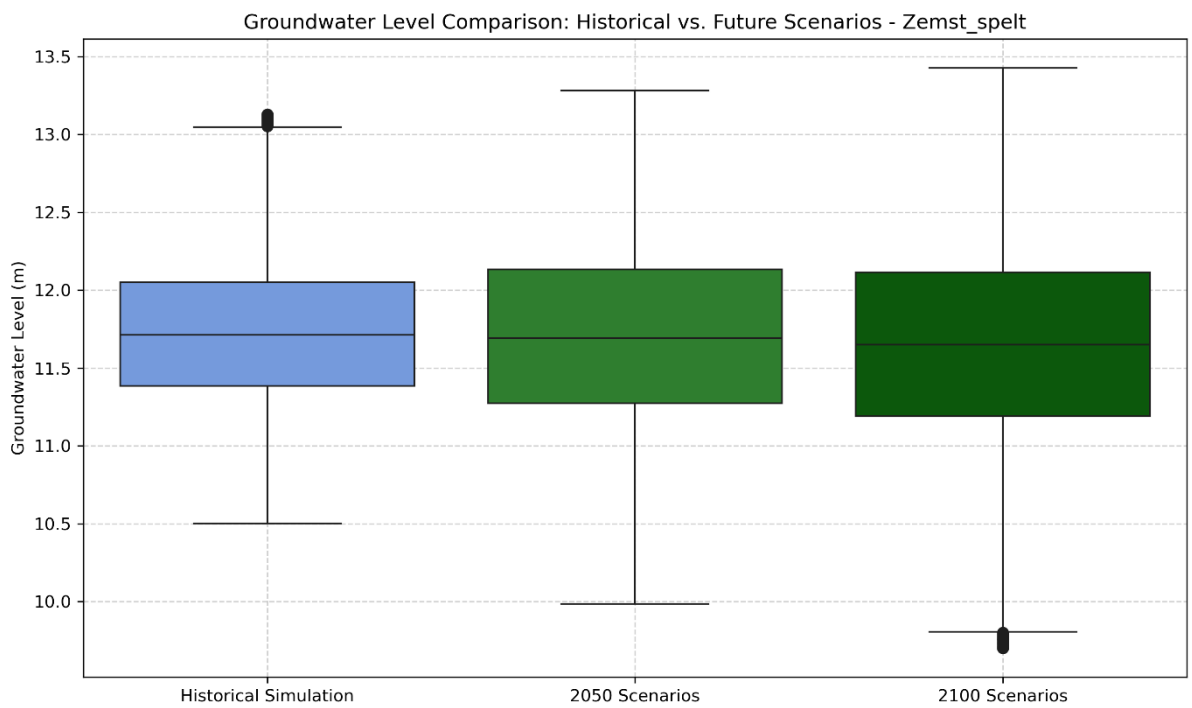
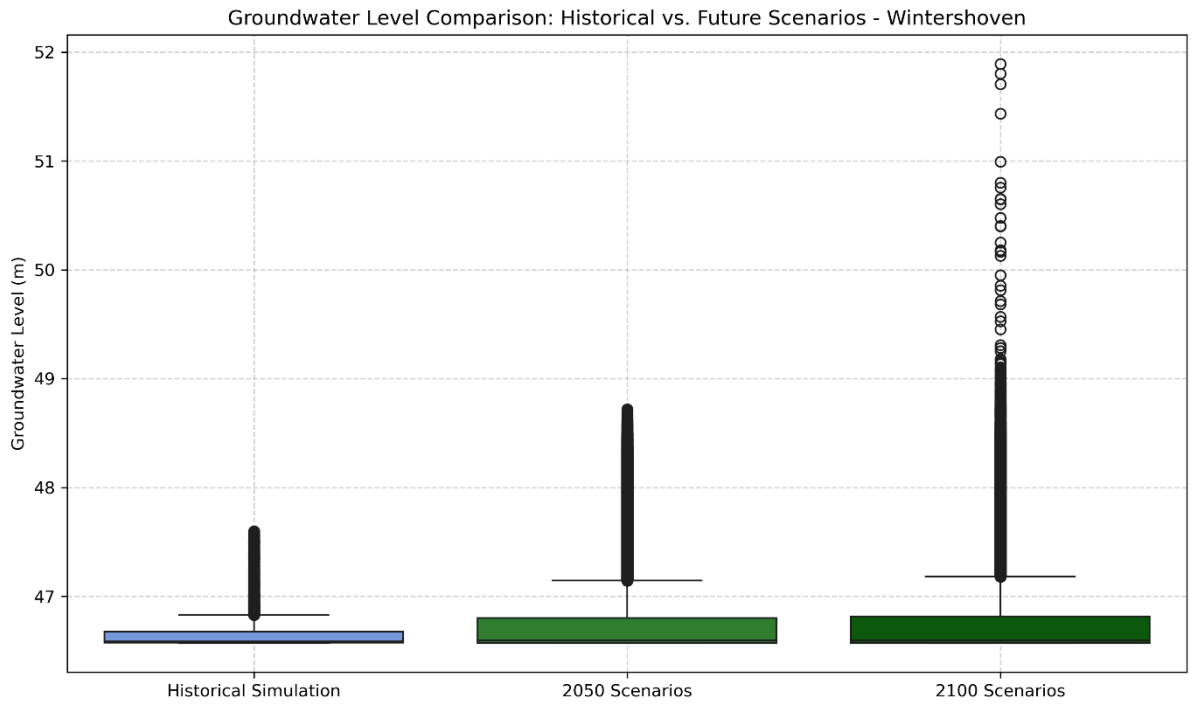


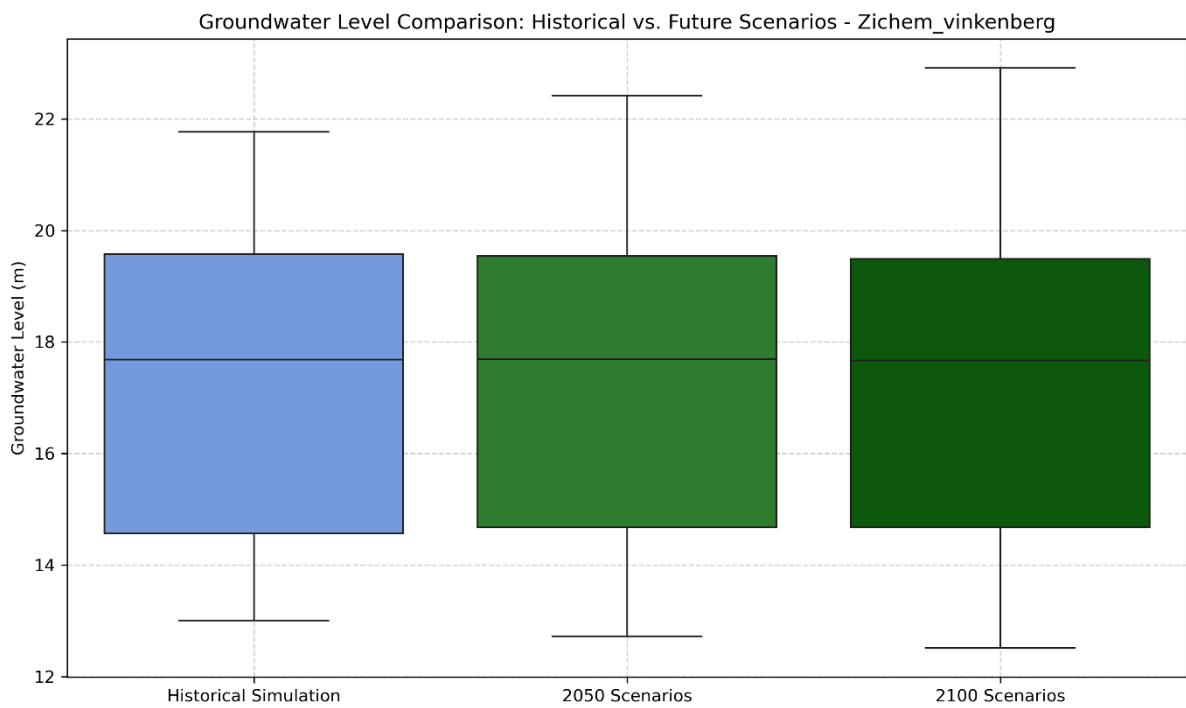
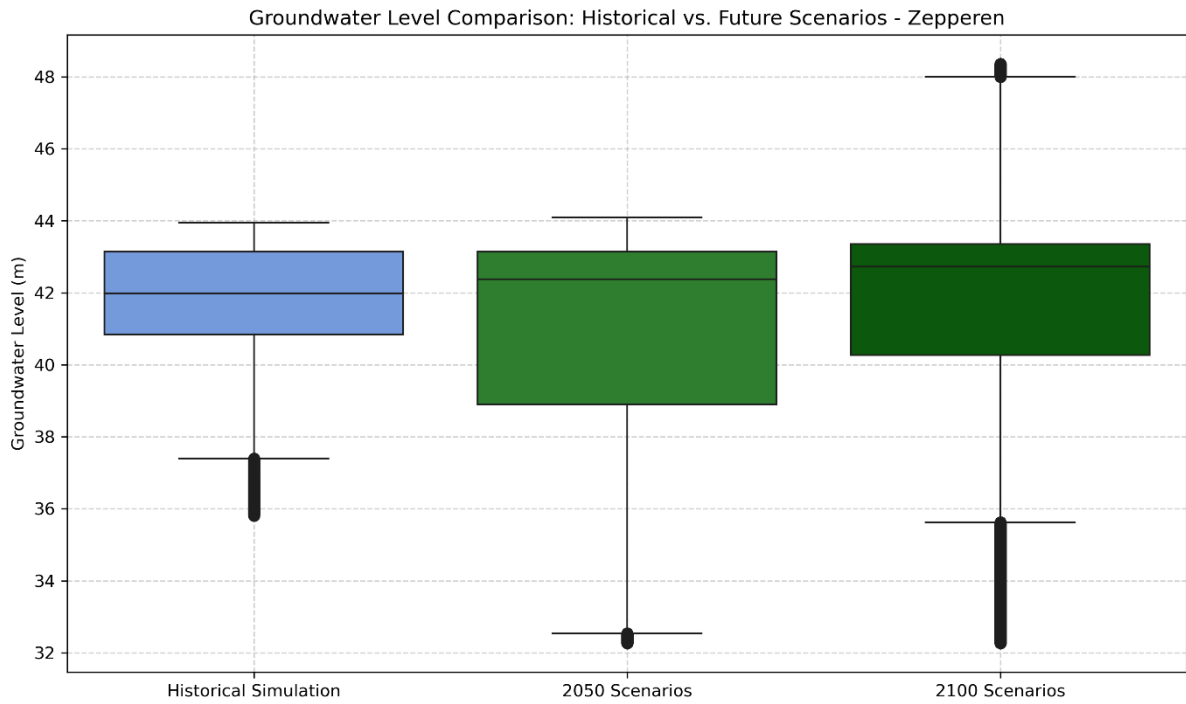


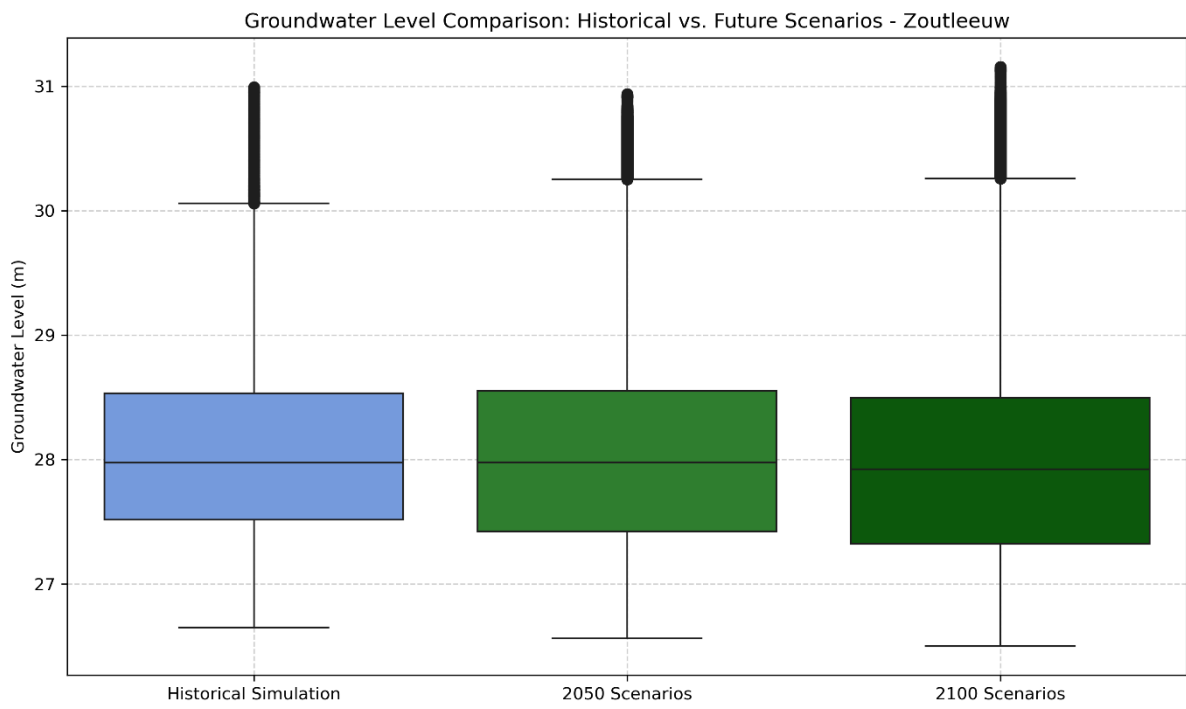






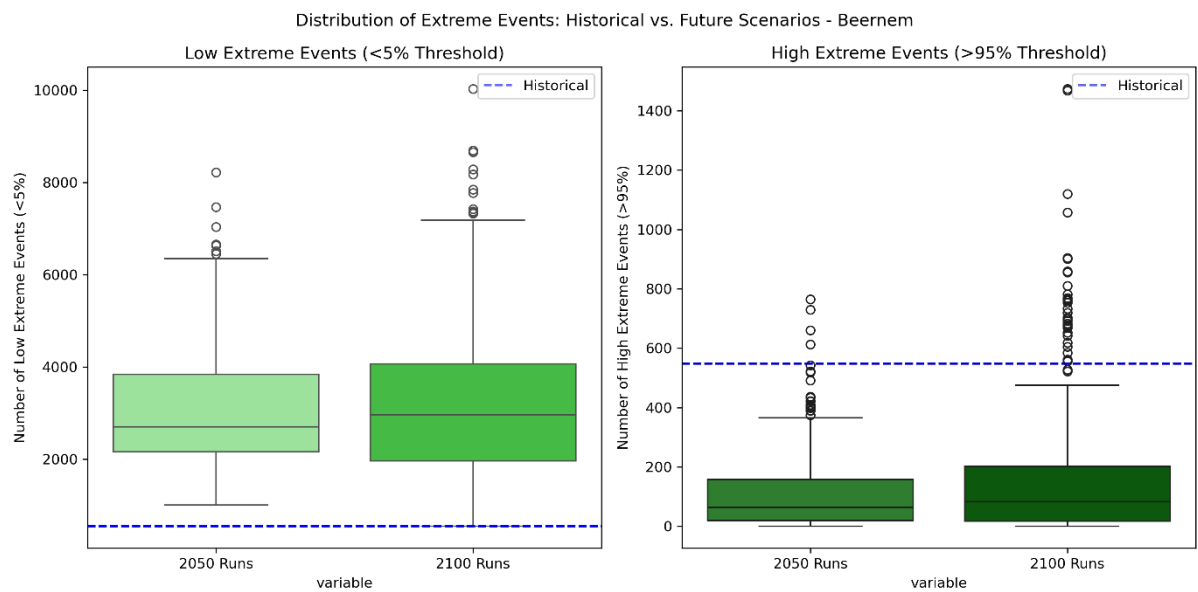
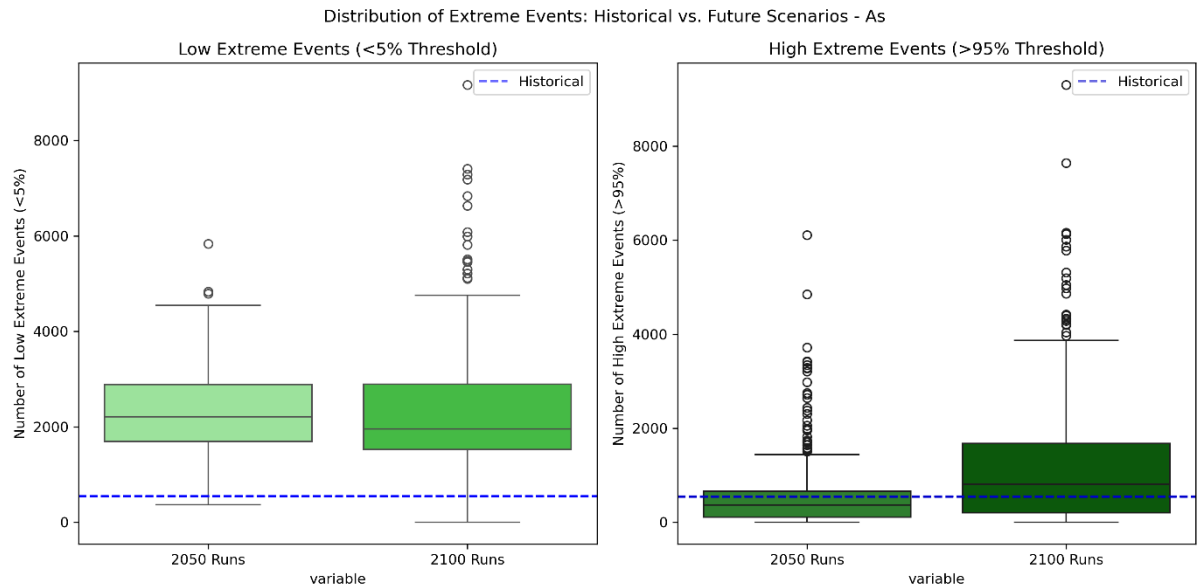




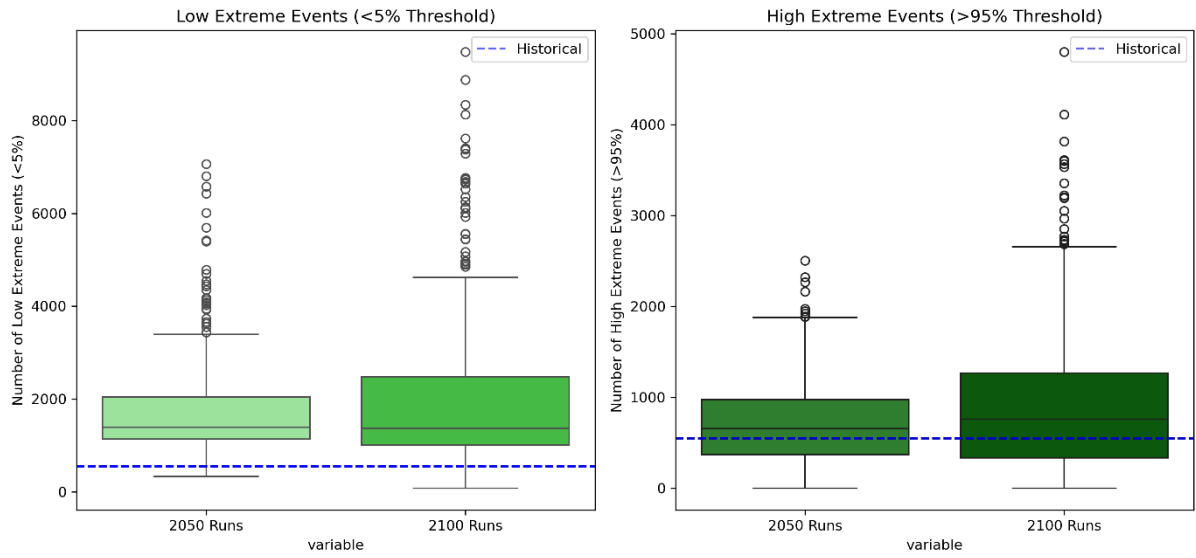


10.2.2 B.2 De Watergroep Distribution of Extreme Events

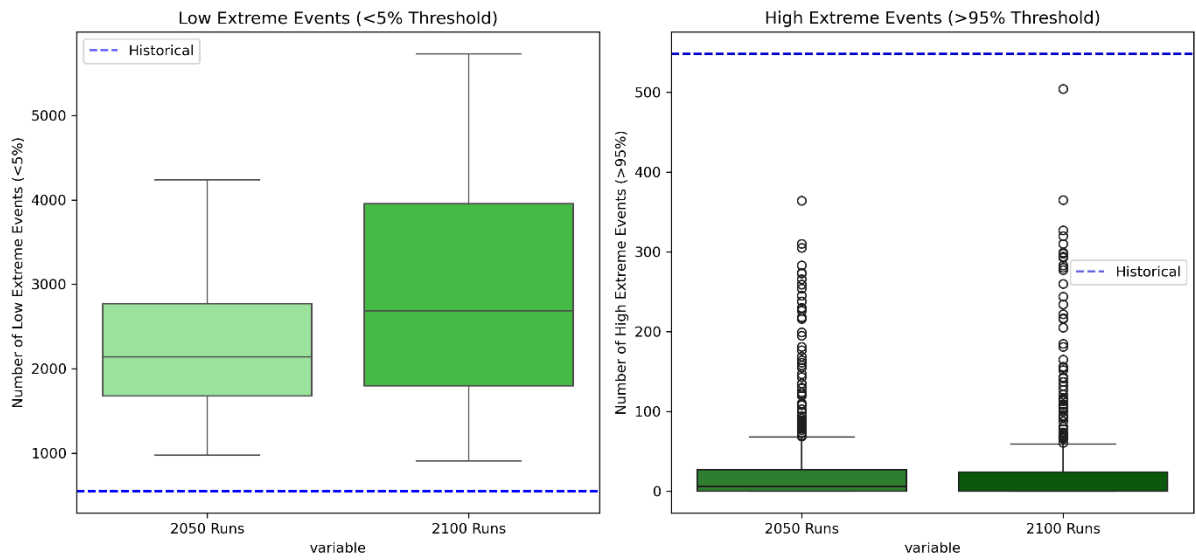
Distribution of extreme groundwater level events under future scenarios for the Hoogstraten group of wells.



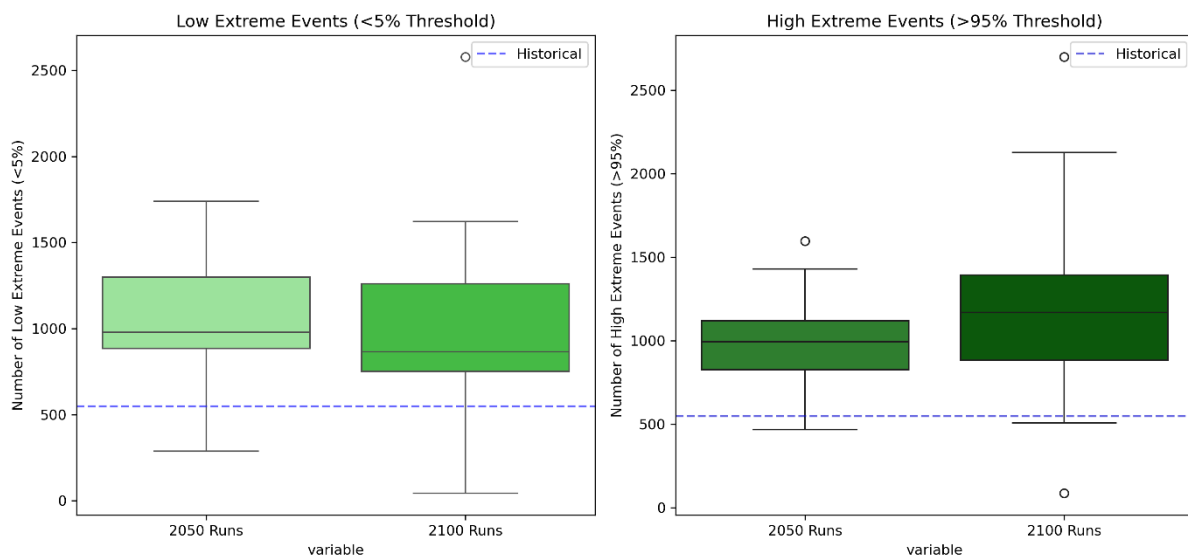
Distribution of Extreme Events: Historical vs. Future Scenarios - Berlare_zele



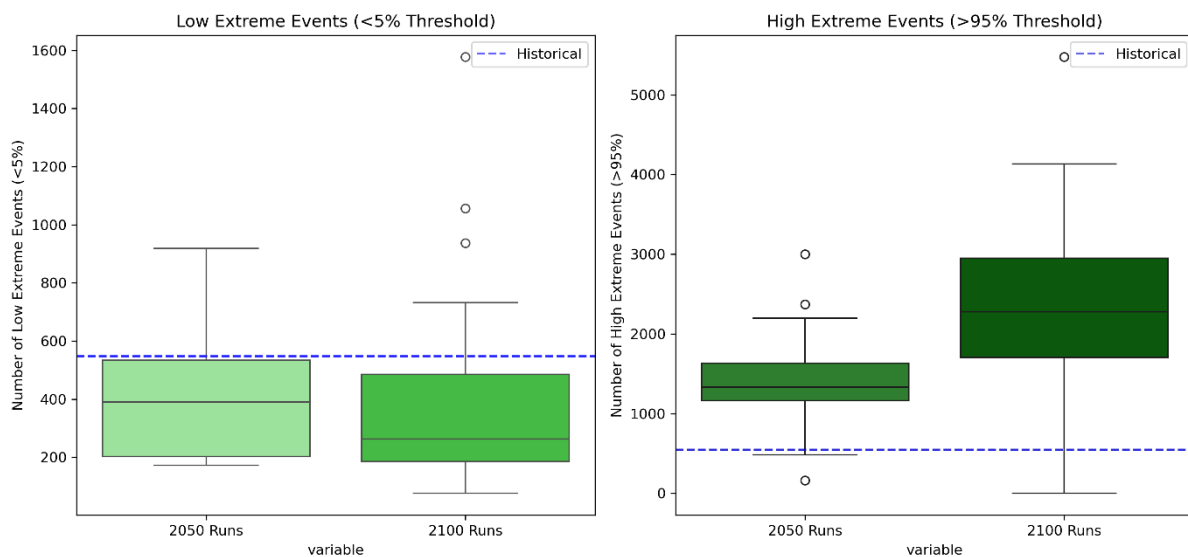
Distribution of Extreme Events: Historical vs. Future Scenarios - Eeklo



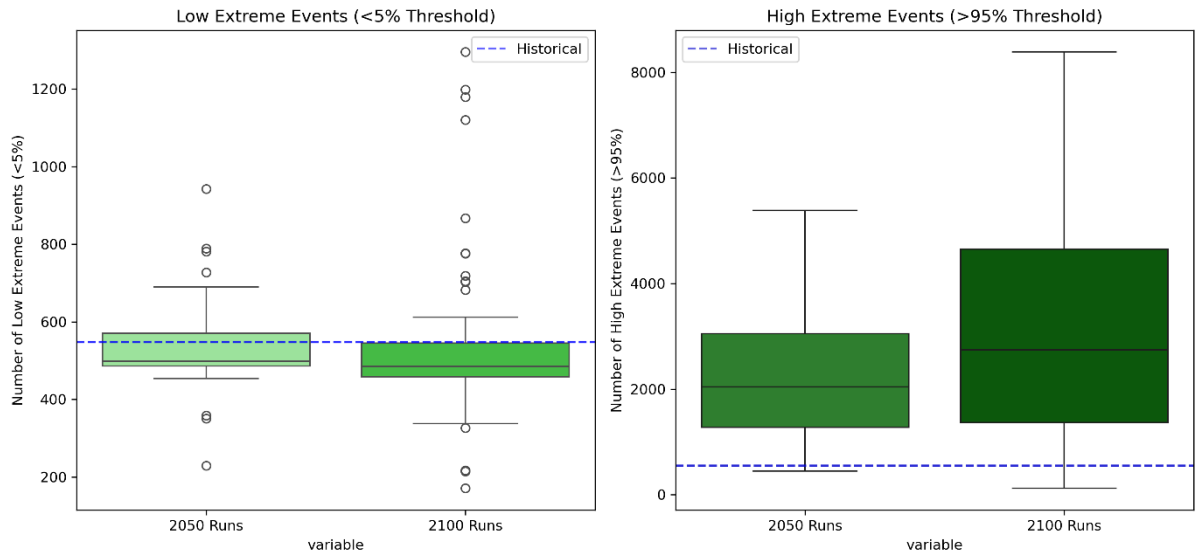
Distribution of Extreme Events: Historical vs. Future Scenarios - Eisdén_mijnsite



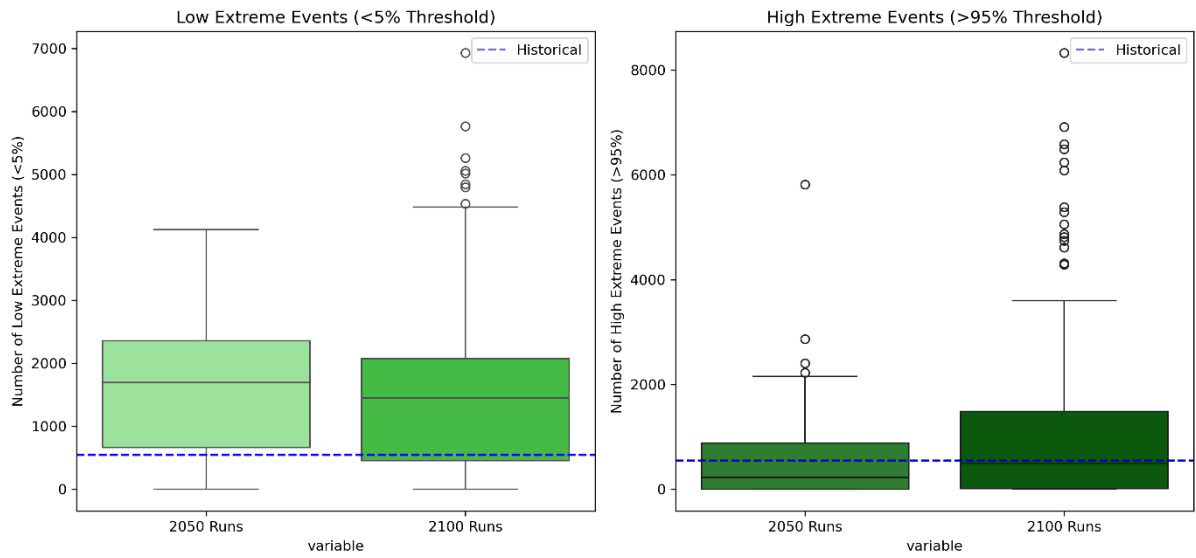
Distribution of Extreme Events: Historical vs. Future Scenarios - Grez_doiceau_pecrot



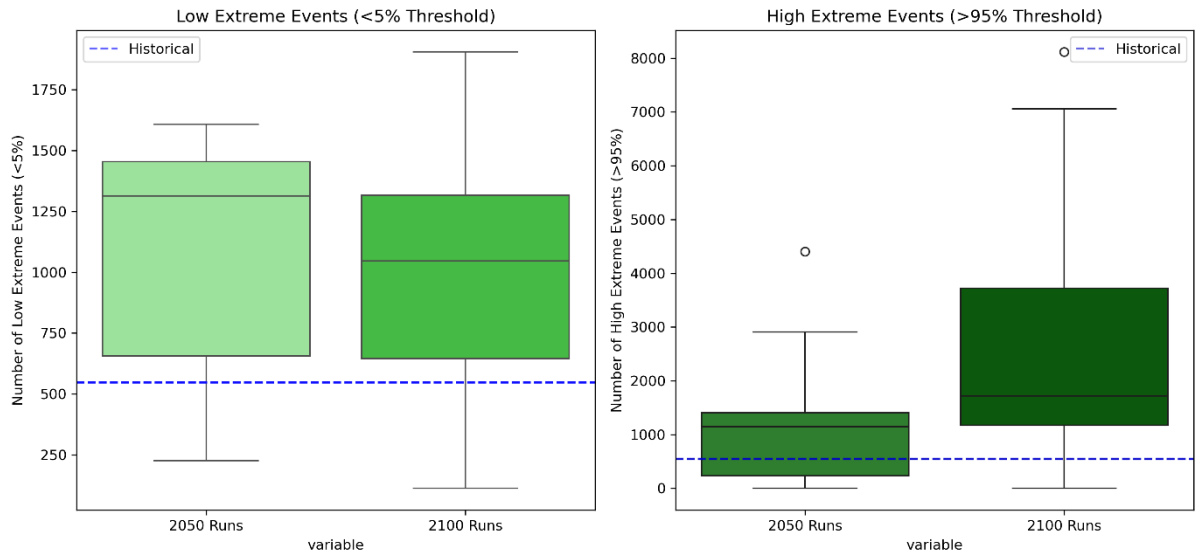
Distribution of Extreme Events: Historical vs. Future Scenarios - Herent_bijlok



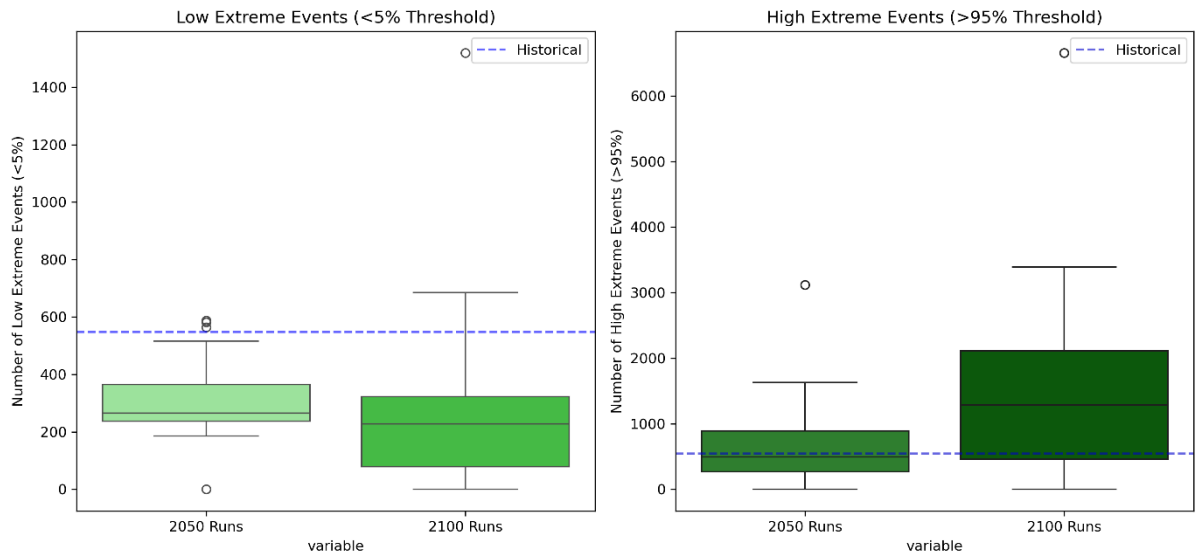
Distribution of Extreme Events: Historical vs. Future Scenarios - Heusden_zolder



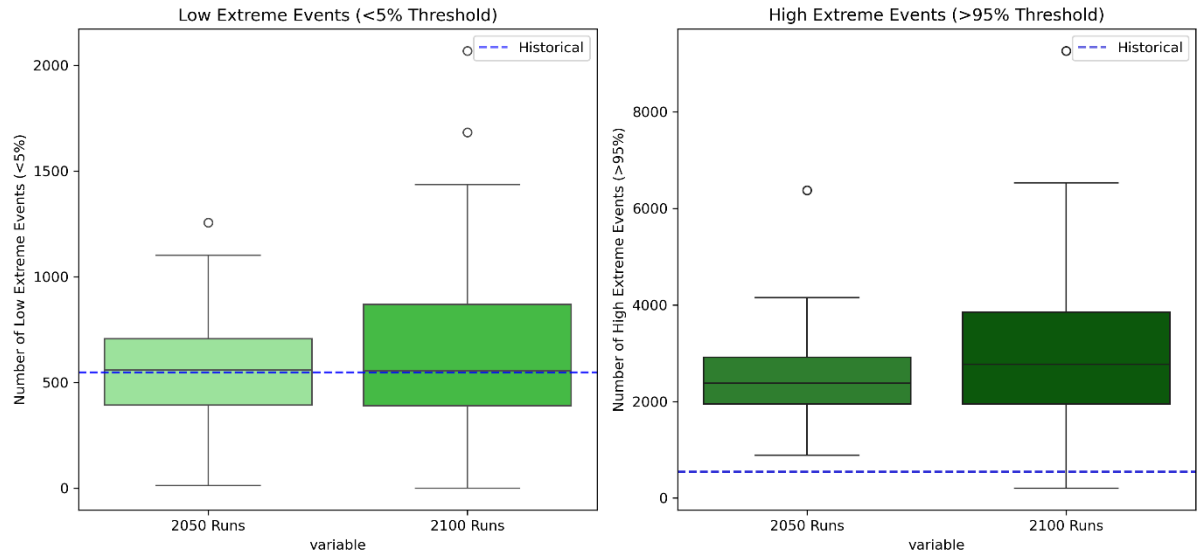
Distribution of Extreme Events: Historical vs. Future Scenarios - Heverlee_abdij



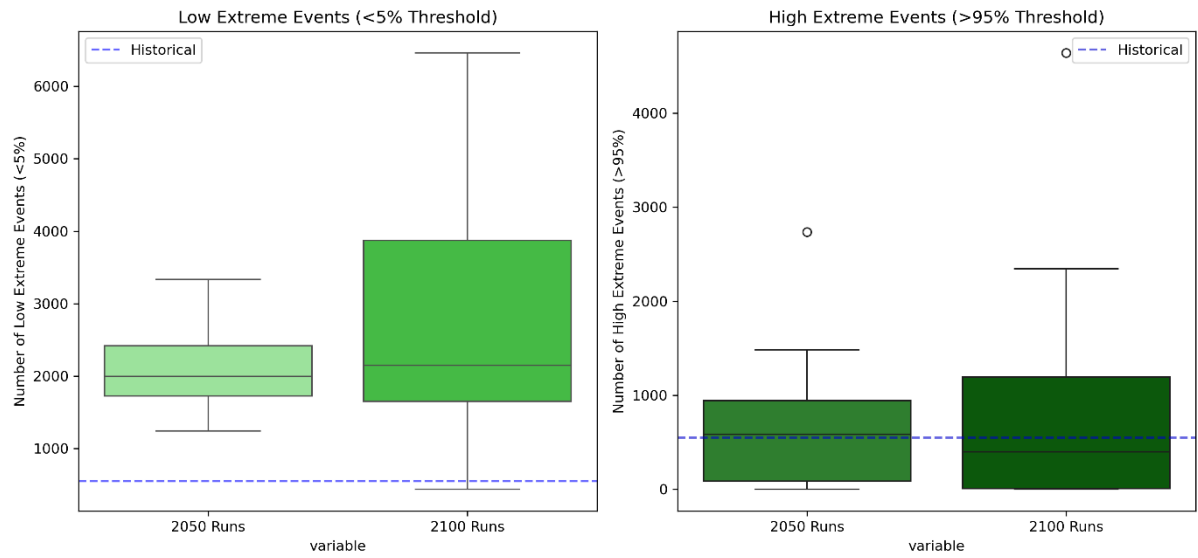
Distribution of Extreme Events: Historical vs. Future Scenarios - Heverlee_cadol



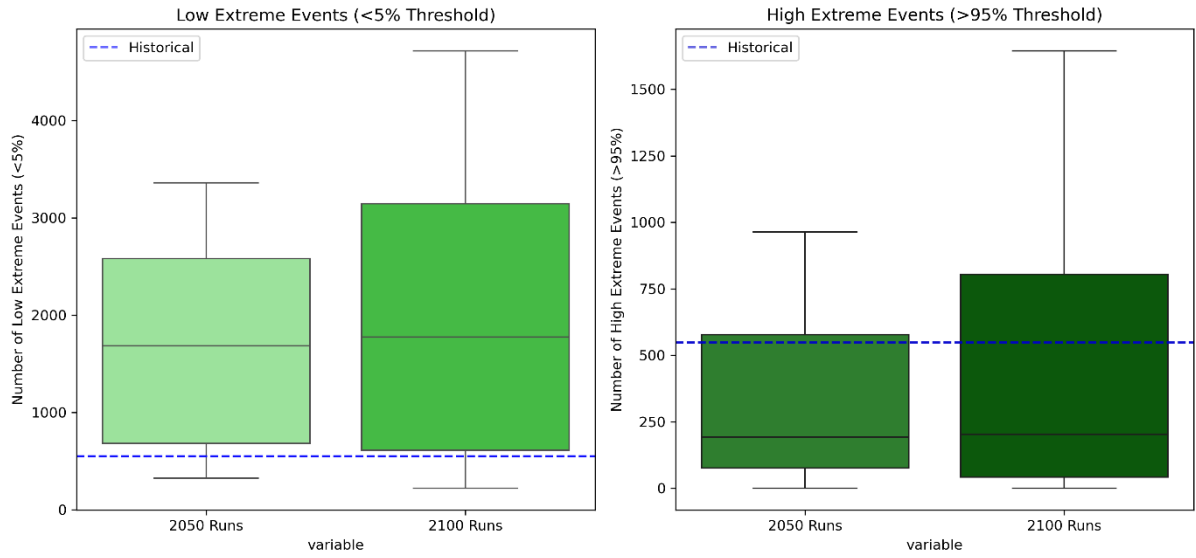
Distribution of Extreme Events: Historical vs. Future Scenarios - Hoepertingen



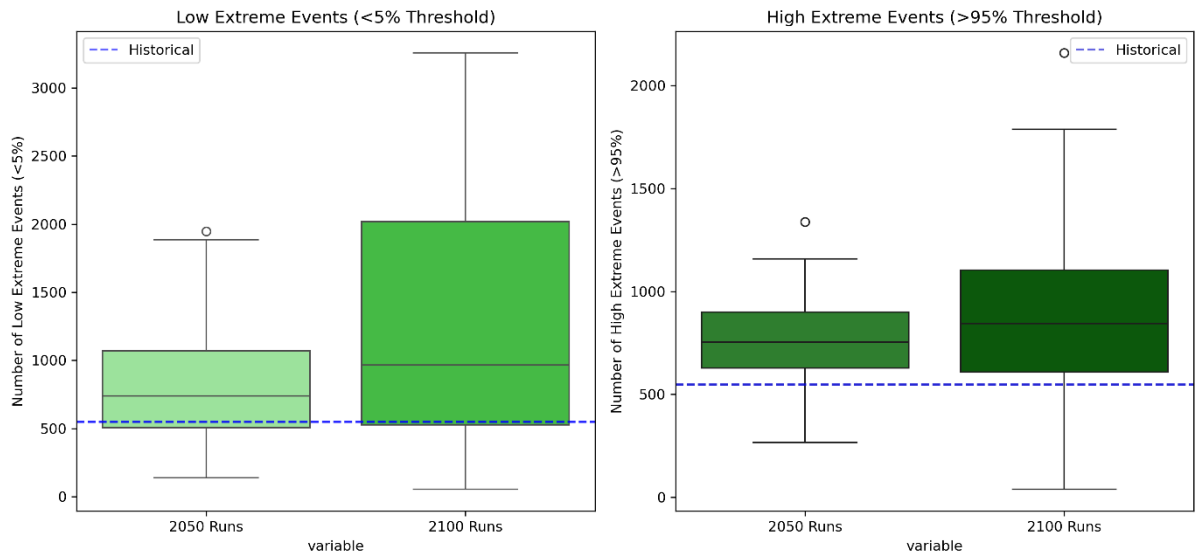
Distribution of Extreme Events: Historical vs. Future Scenarios - Kessel_lo_vlierbeek



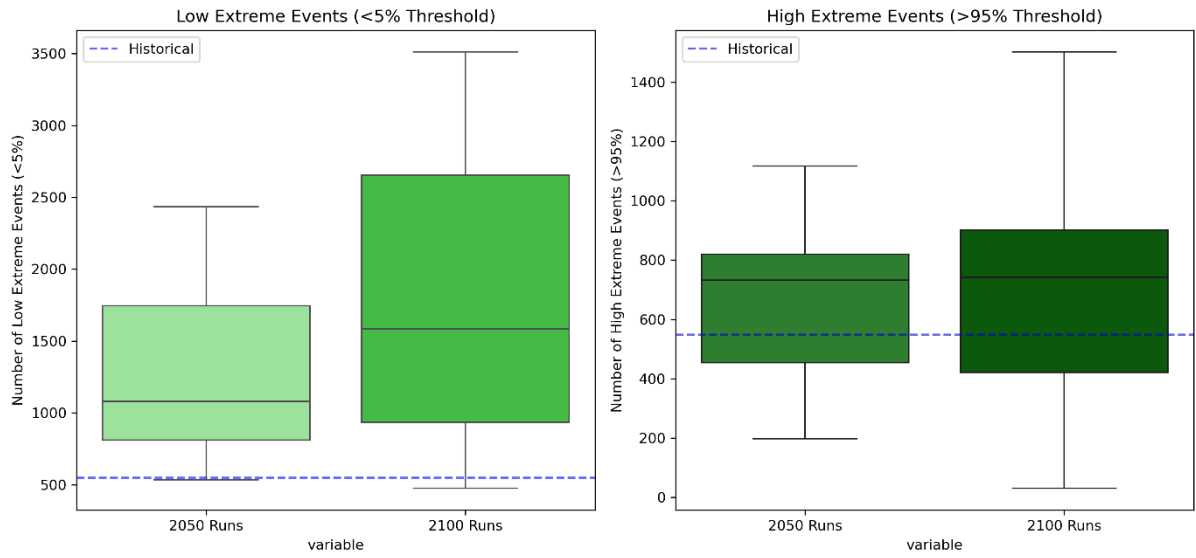
Distribution of Extreme Events: Historical vs. Future Scenarios - Kluizen



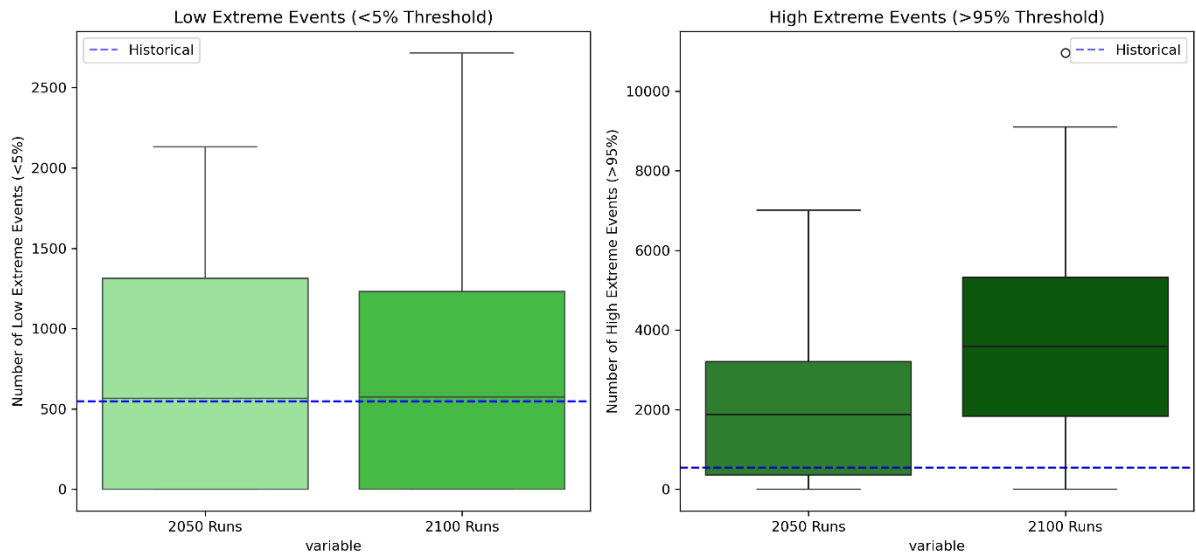
Distribution of Extreme Events: Historical vs. Future Scenarios - Korbeek_dijle_het_broek



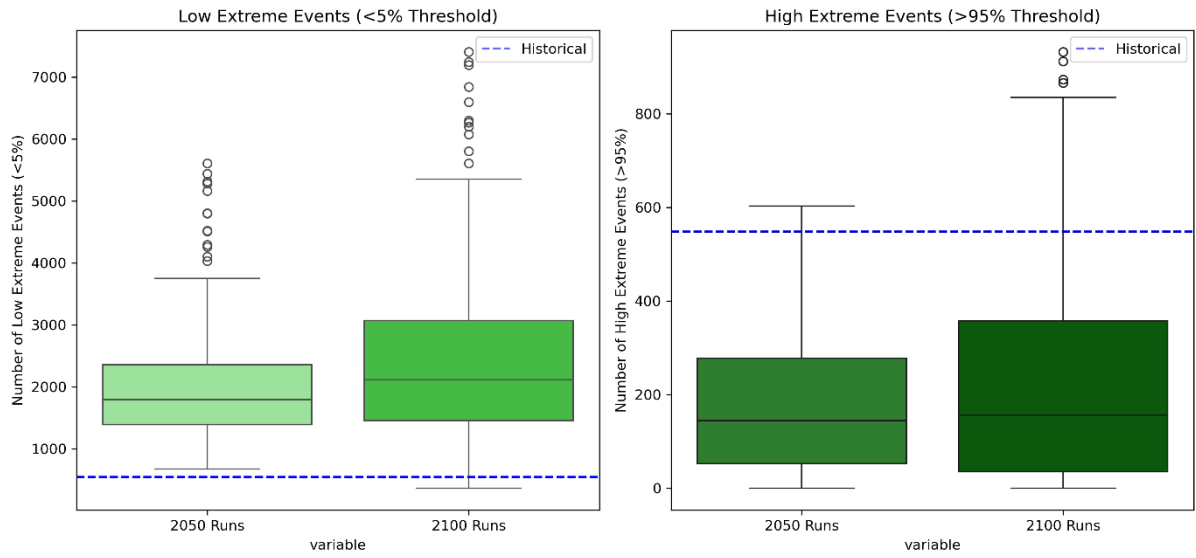
Distribution of Extreme Events: Historical vs. Future Scenarios - Kuntich_menebeek



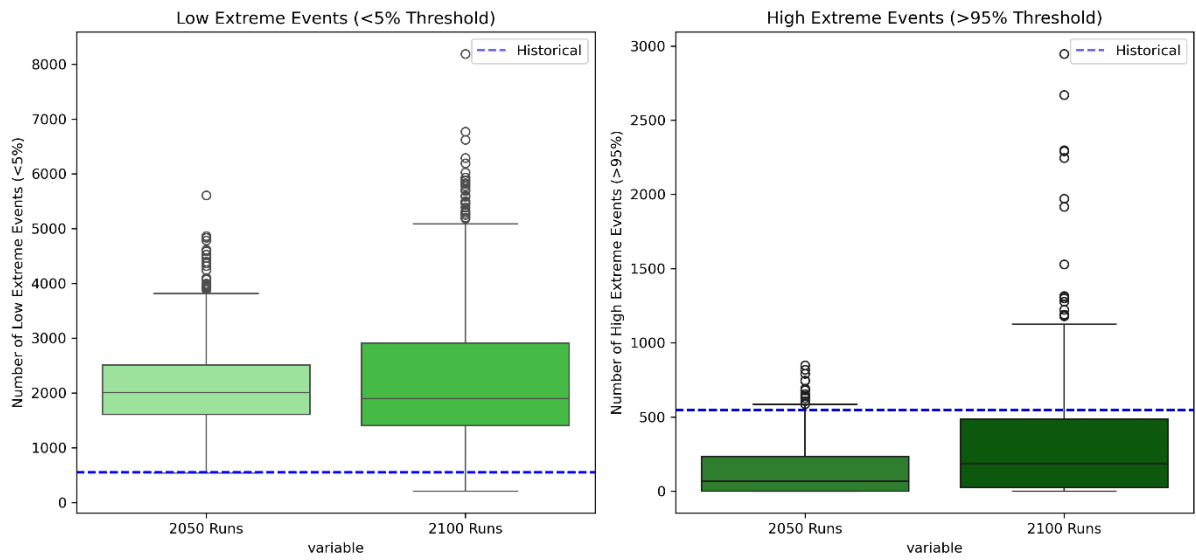
Distribution of Extreme Events: Historical vs. Future Scenarios - Leefdaal_puttebos



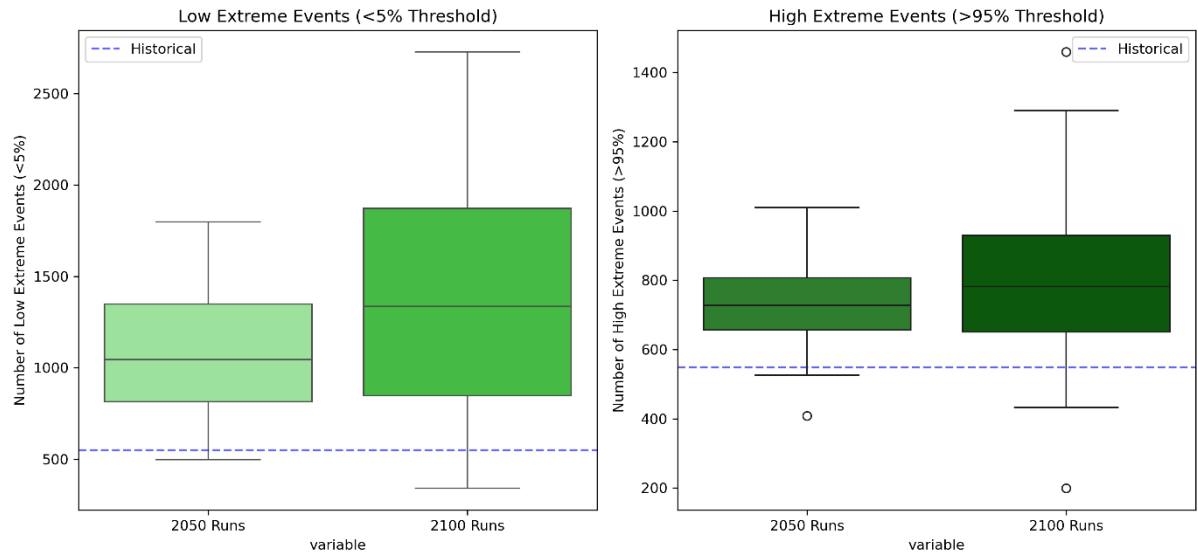
Distribution of Extreme Events: Historical vs. Future Scenarios - Lembeke_oosteeklo



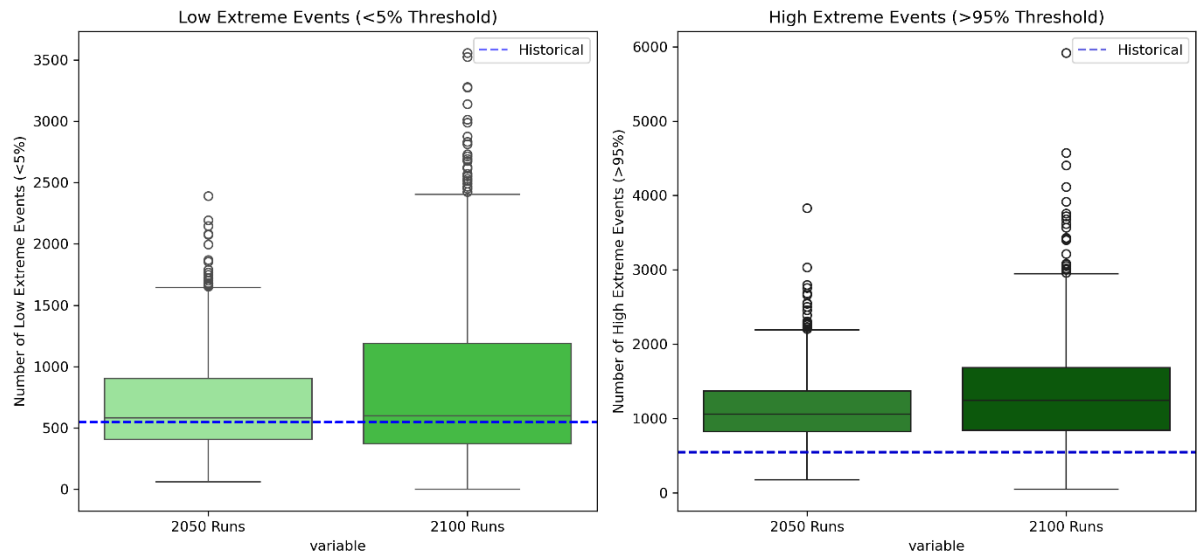
Distribution of Extreme Events: Historical vs. Future Scenarios - Lommel



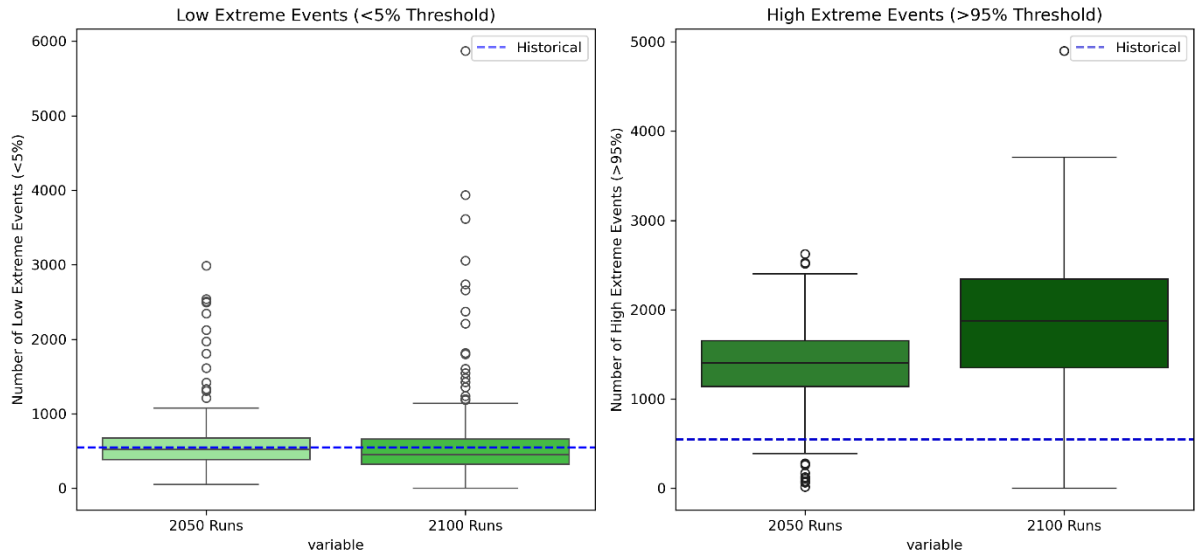
Distribution of Extreme Events: Historical vs. Future Scenarios - Londerzeel_koevoet



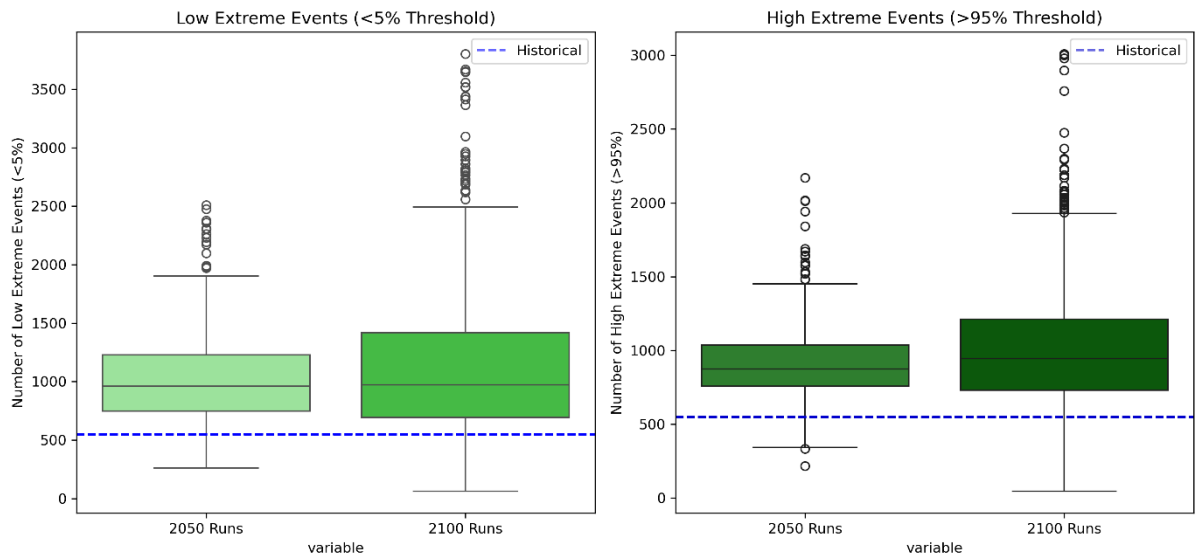
Distribution of Extreme Events: Historical vs. Future Scenarios - Maaseik_vlakenhof



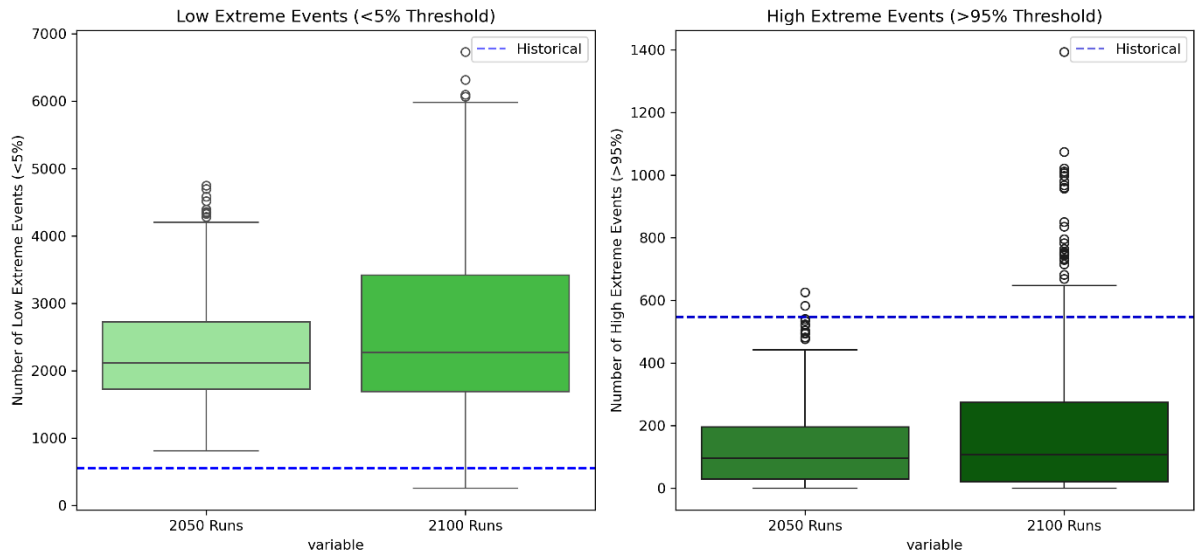
Distribution of Extreme Events: Historical vs. Future Scenarios - Meerheuvcl



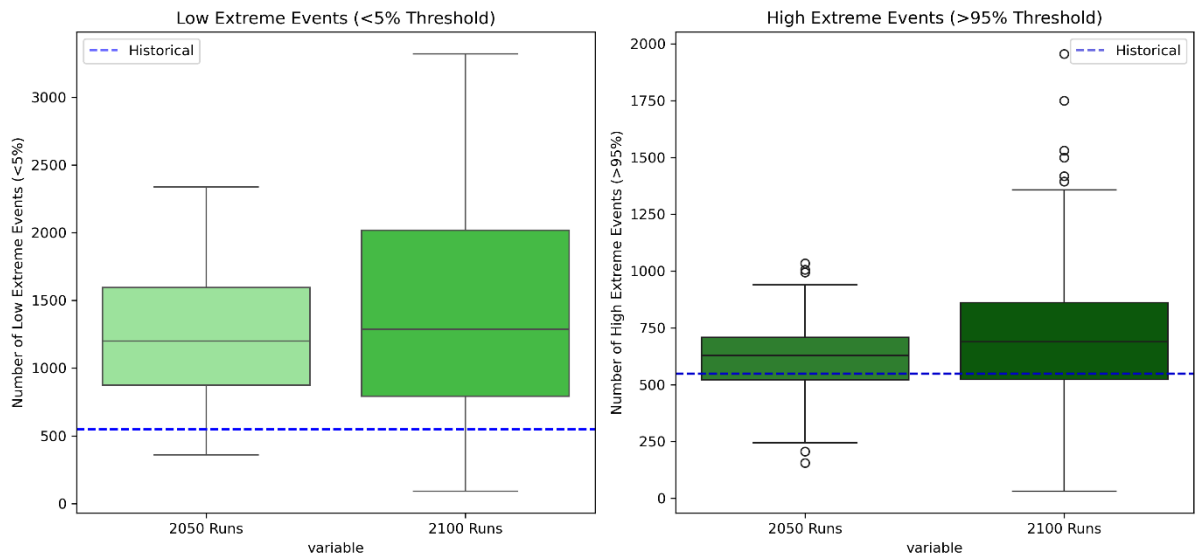
Distribution of Extreme Events: Historical vs. Future Scenarios - Meeswijk



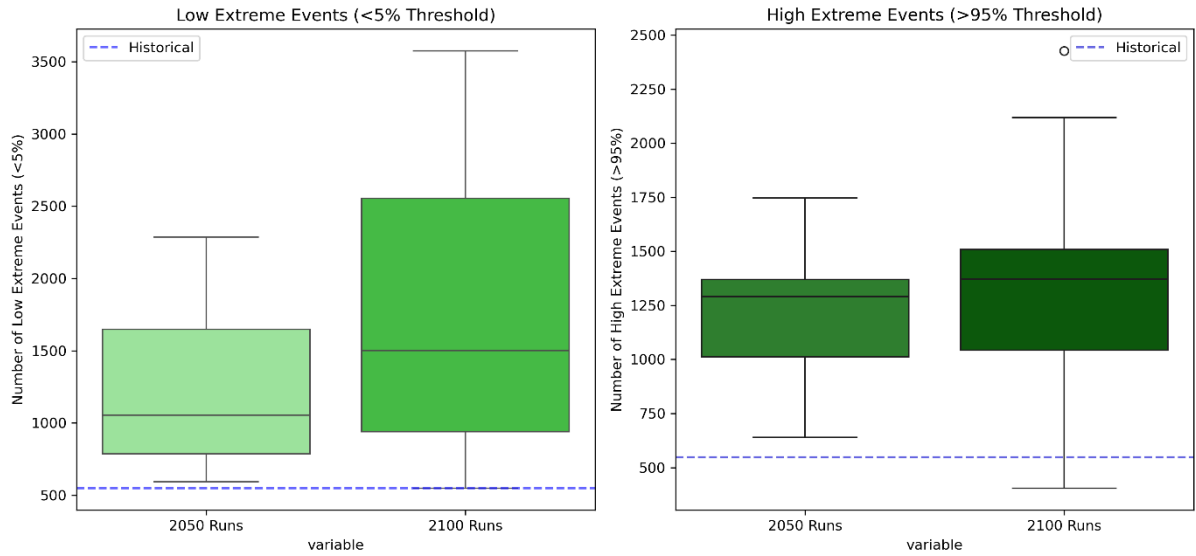
Distribution of Extreme Events: Historical vs. Future Scenarios - Moerbeke_wachtebeke



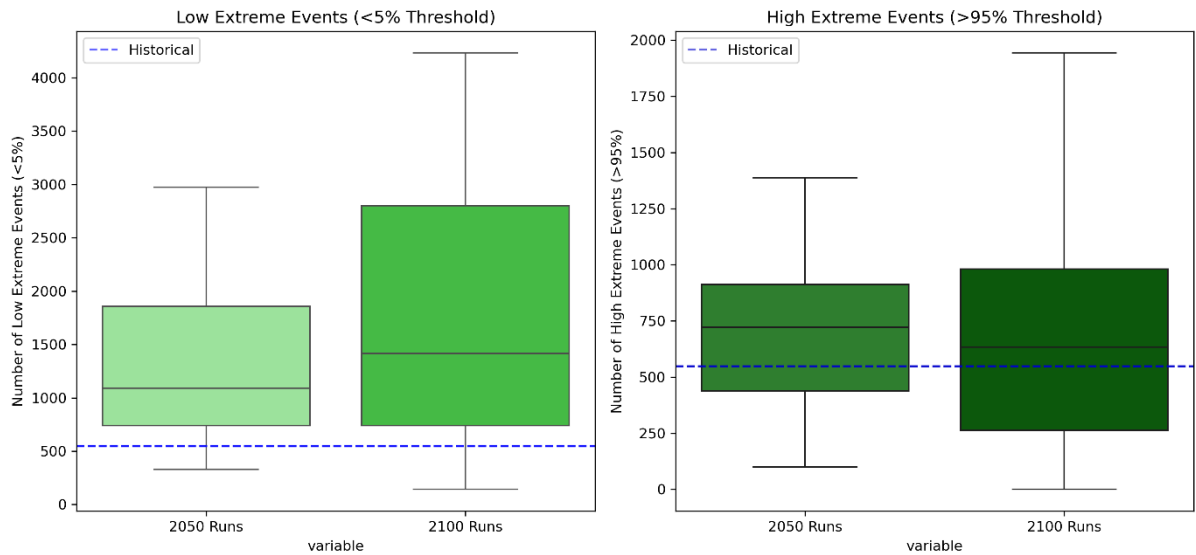
Distribution of Extreme Events: Historical vs. Future Scenarios - Neerpelt



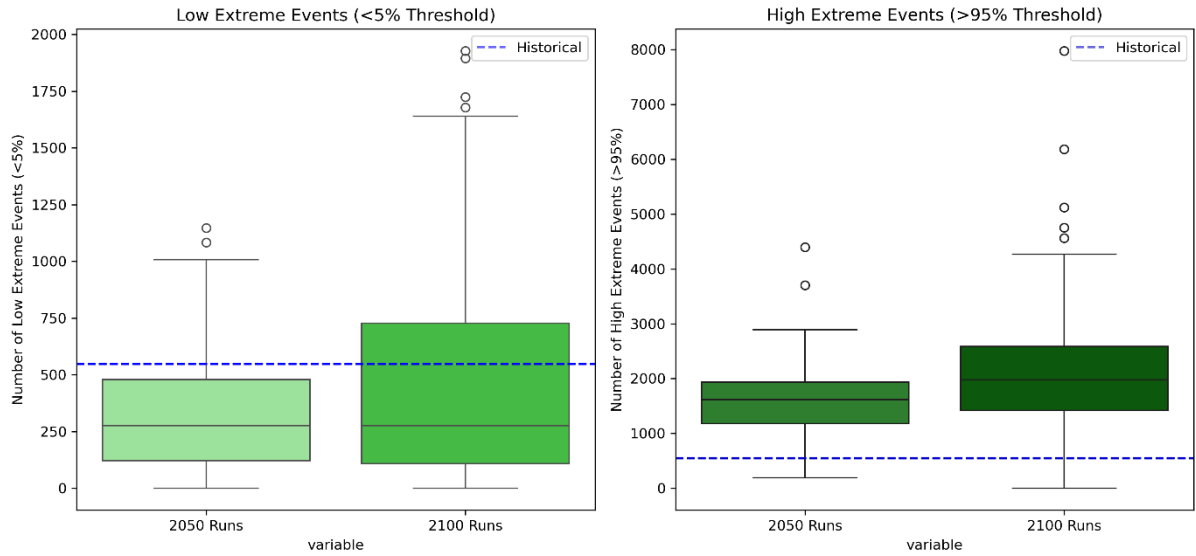
Distribution of Extreme Events: Historical vs. Future Scenarios - Nieuwerkerken



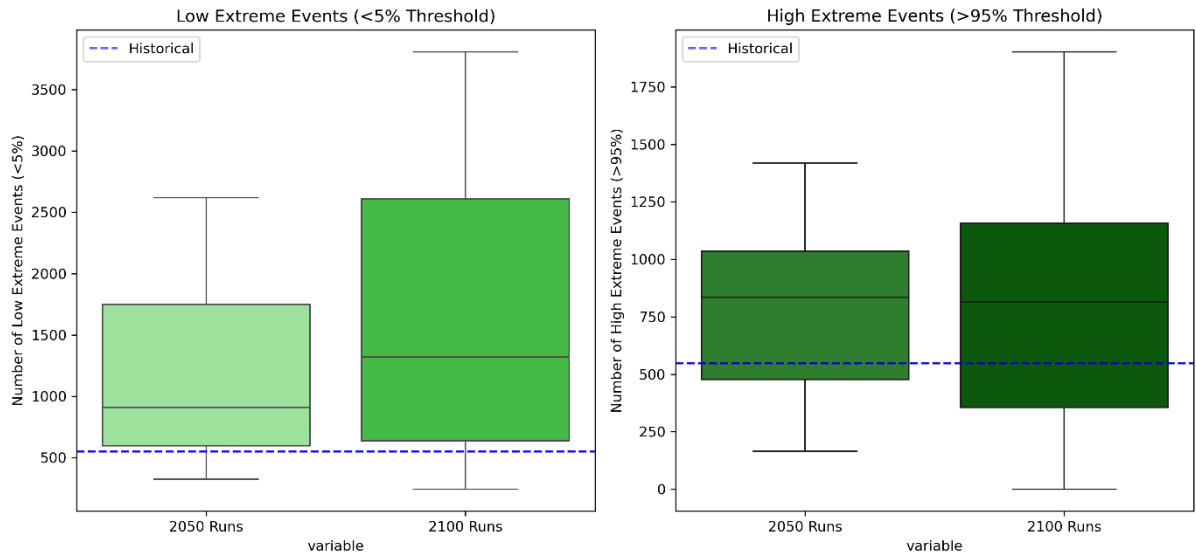
Distribution of Extreme Events: Historical vs. Future Scenarios - Nieuwrode_het_rot



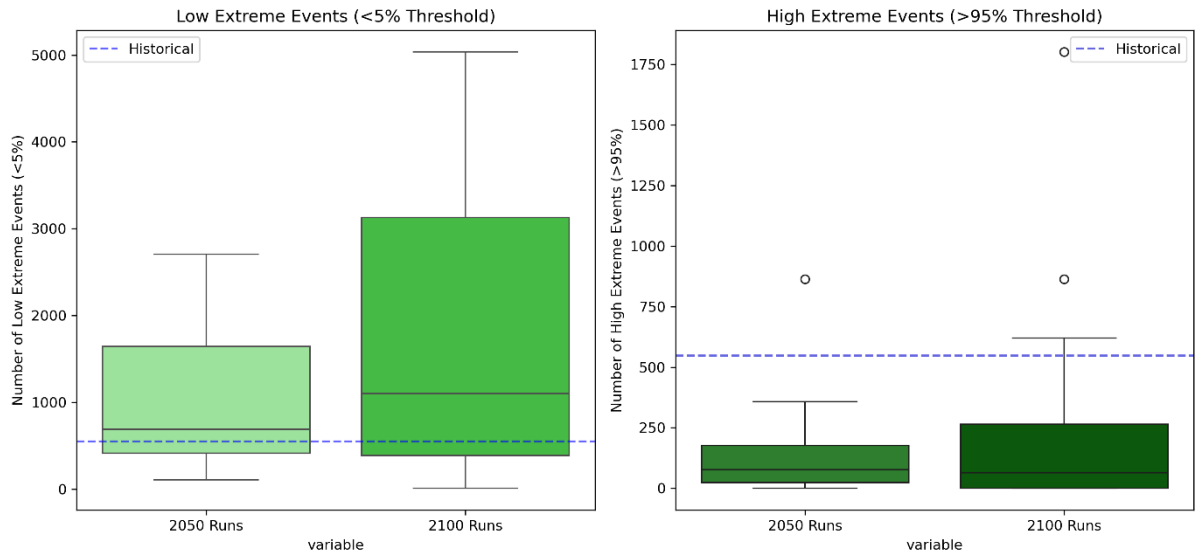
Distribution of Extreme Events: Historical vs. Future Scenarios - Osseweg



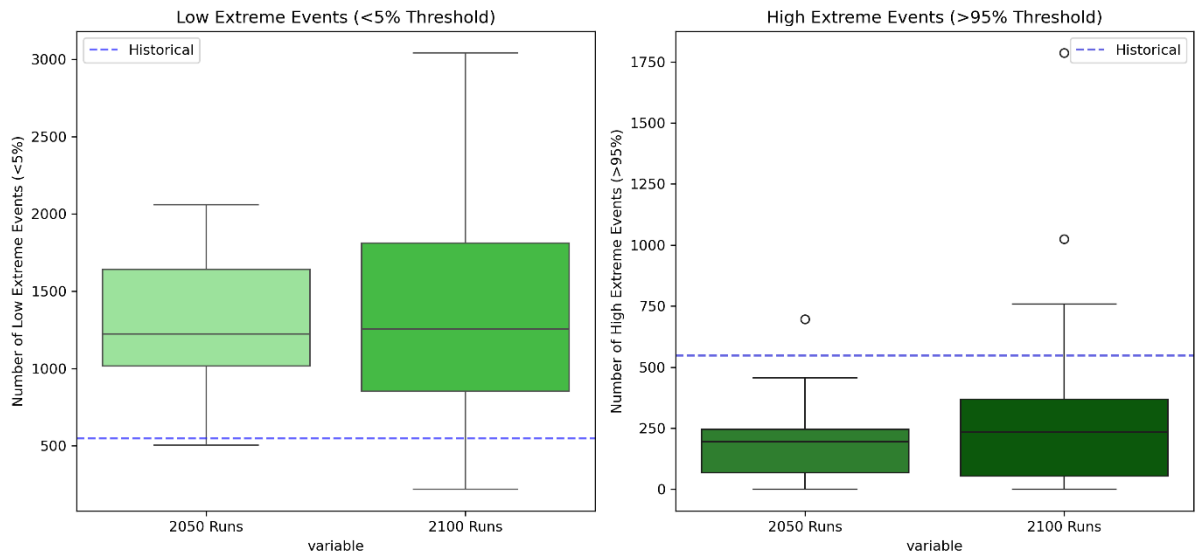
Distribution of Extreme Events: Historical vs. Future Scenarios - Overhaem



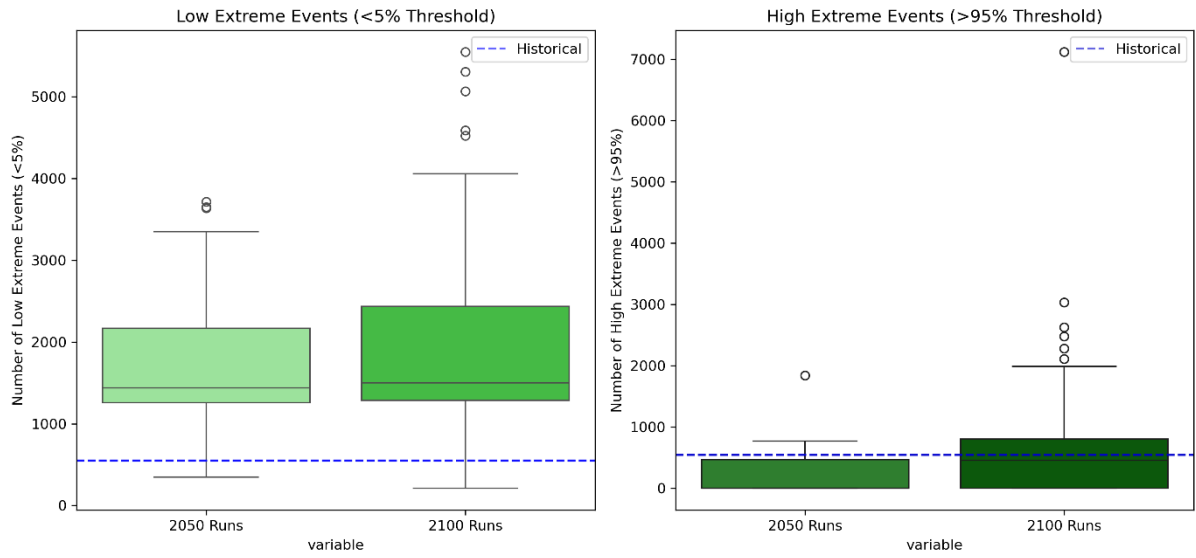
Distribution of Extreme Events: Historical vs. Future Scenarios - Overijse_kouterstraat_nellebeek



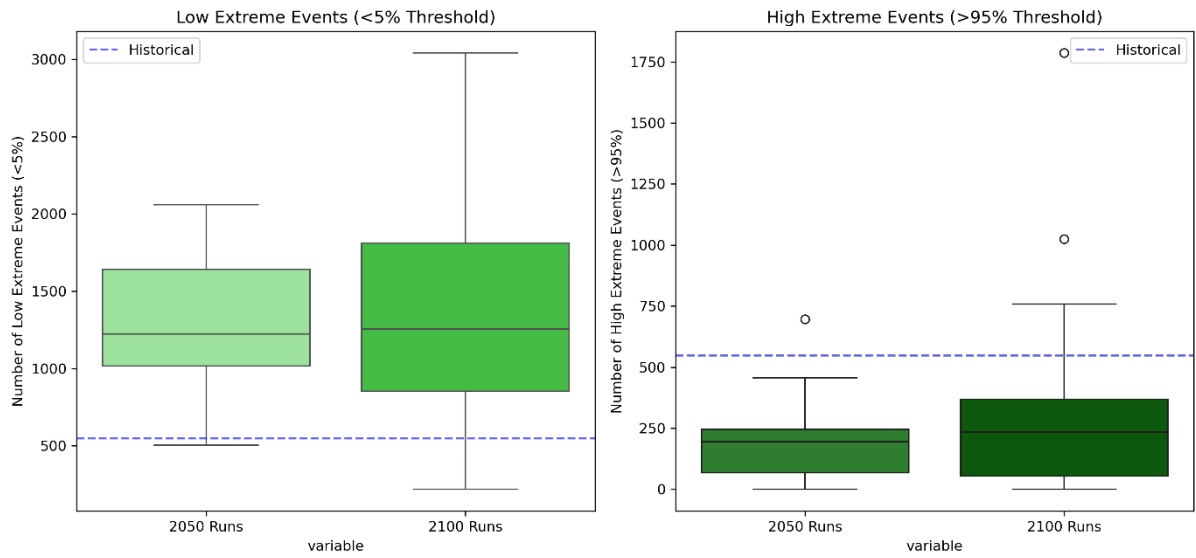
Distribution of Extreme Events: Historical vs. Future Scenarios - Overijse_sana



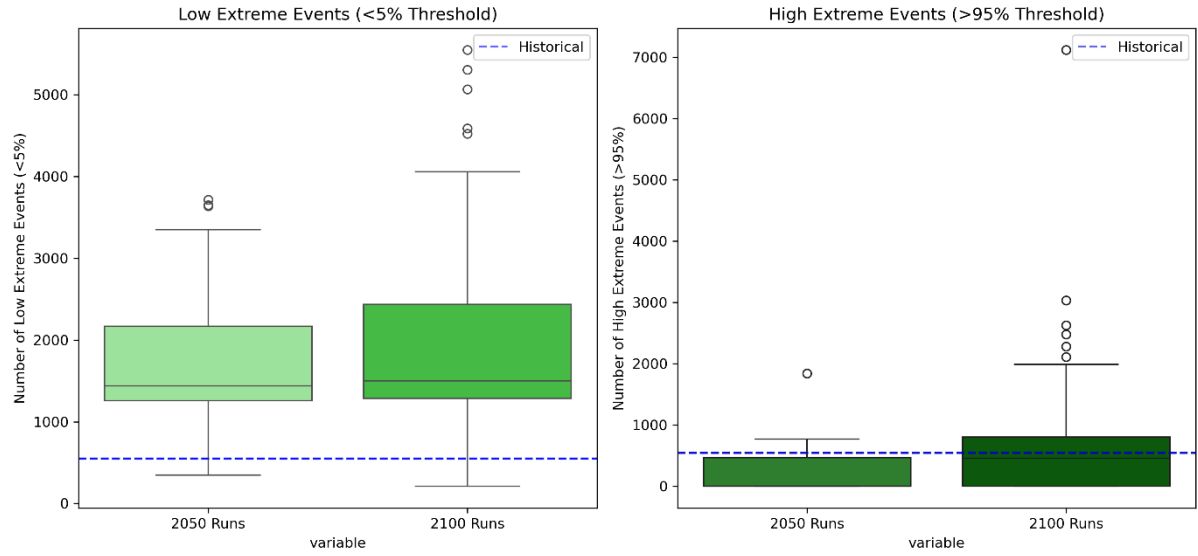
Distribution of Extreme Events: Historical vs. Future Scenarios - Overijse_venusberg



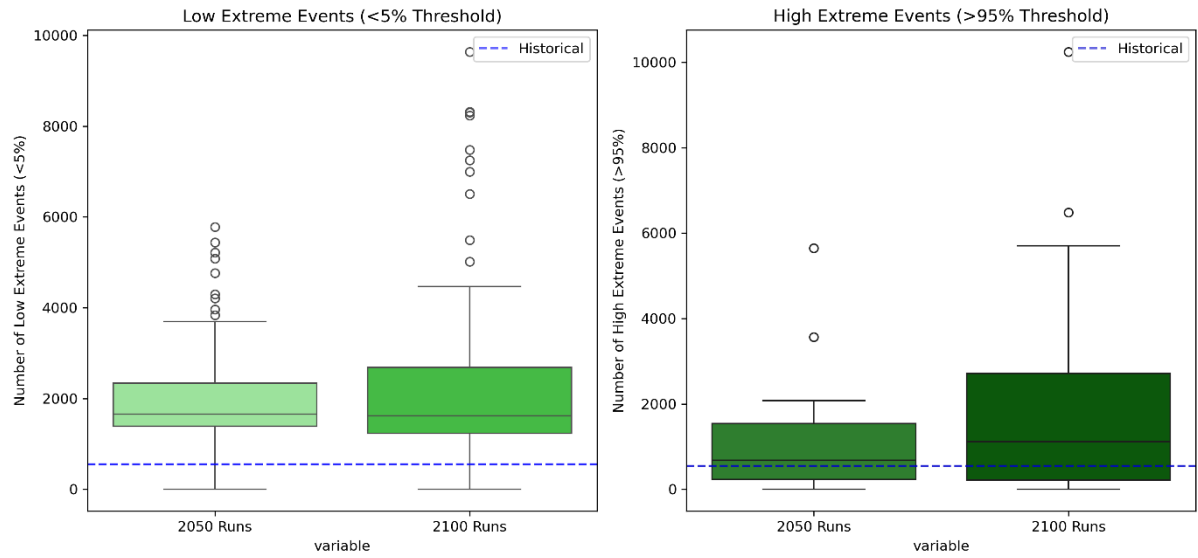
Distribution of Extreme Events: Historical vs. Future Scenarios - Overijse_sana



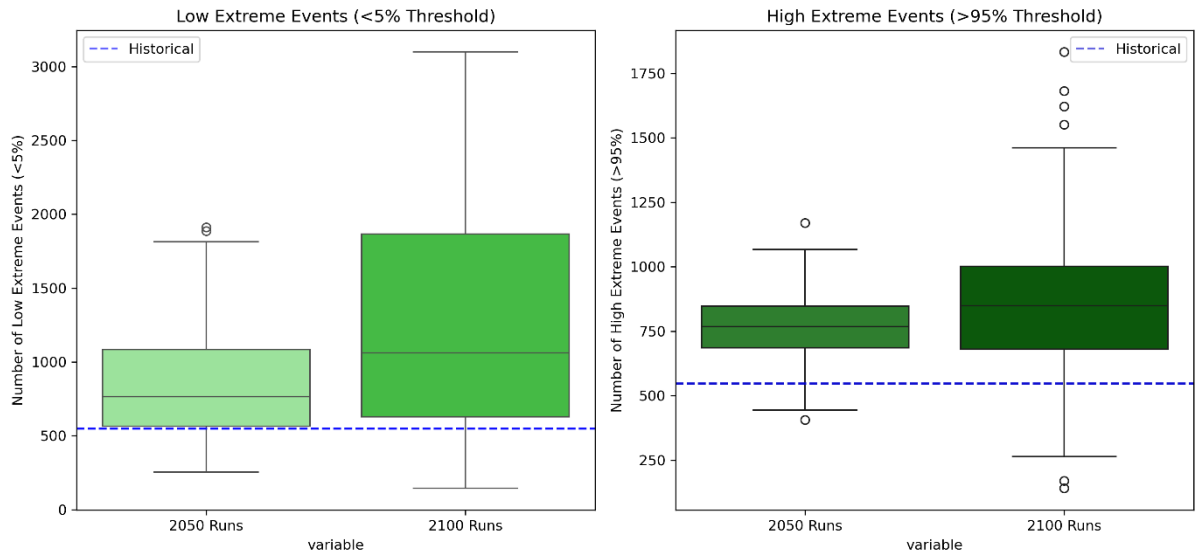
Distribution of Extreme Events: Historical vs. Future Scenarios - Overijse_venusberg



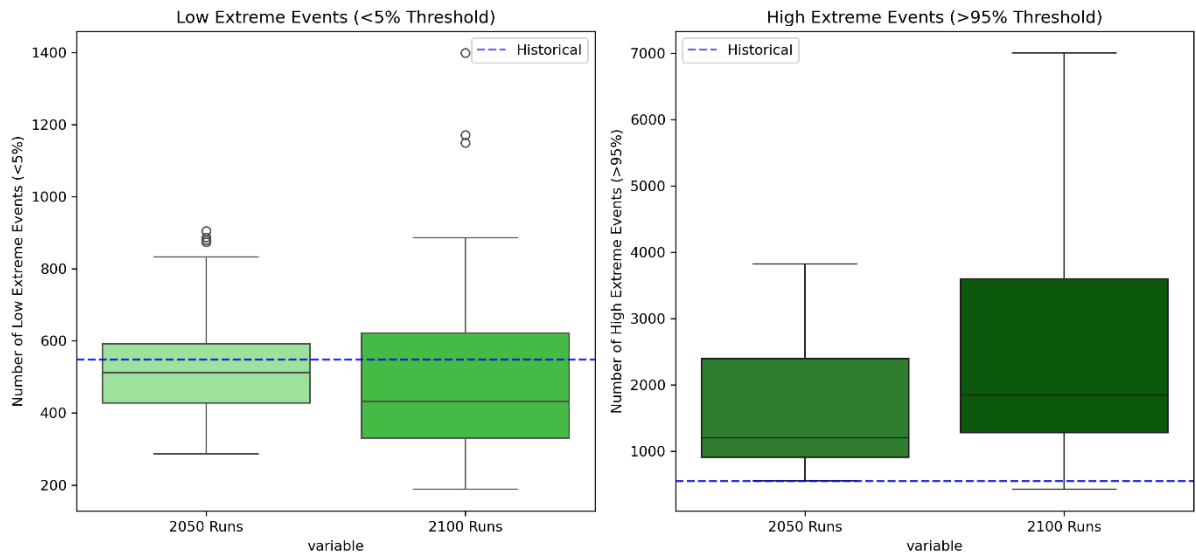
Distribution of Extreme Events: Historical vs. Future Scenarios - Schoonhoven



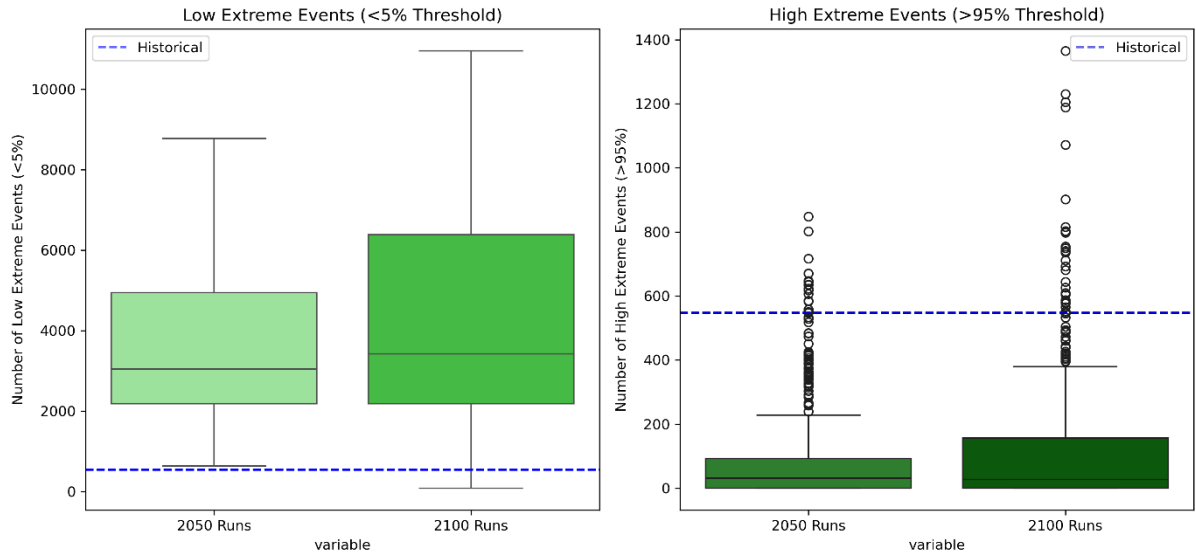
Distribution of Extreme Events: Historical vs. Future Scenarios - Sint_agatha_rode_geuzenhoek



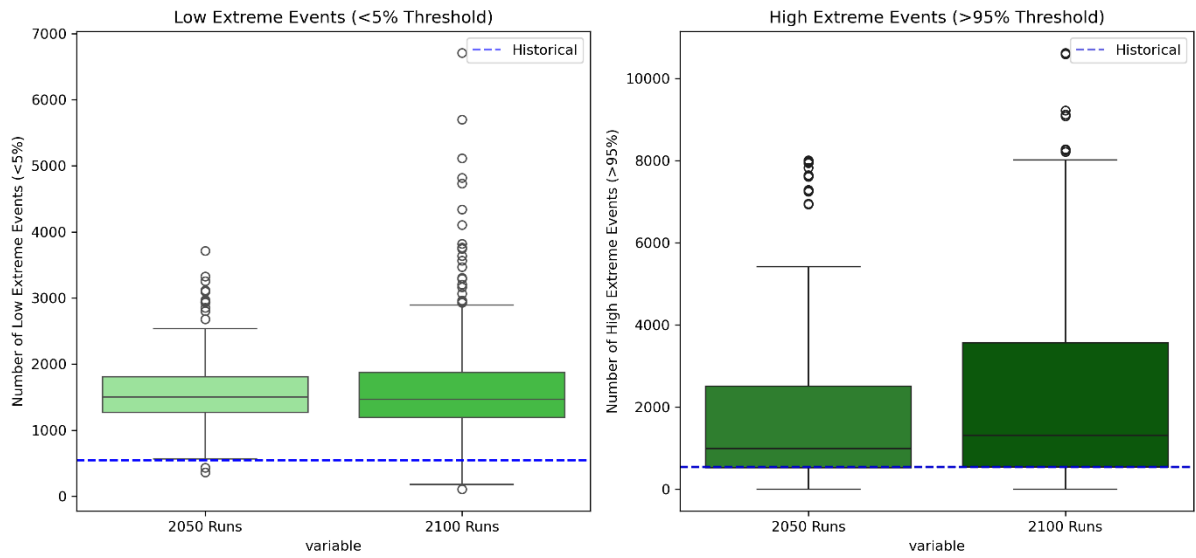
Distribution of Extreme Events: Historical vs. Future Scenarios - Sint_agatha_rode_veeweyde



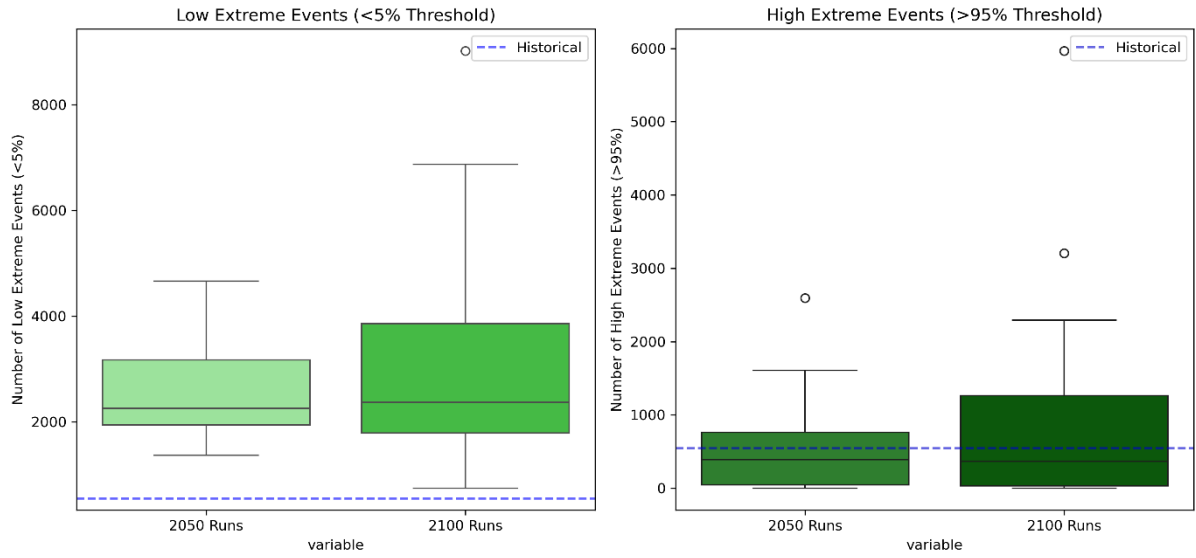
Distribution of Extreme Events: Historical vs. Future Scenarios - Snellegem



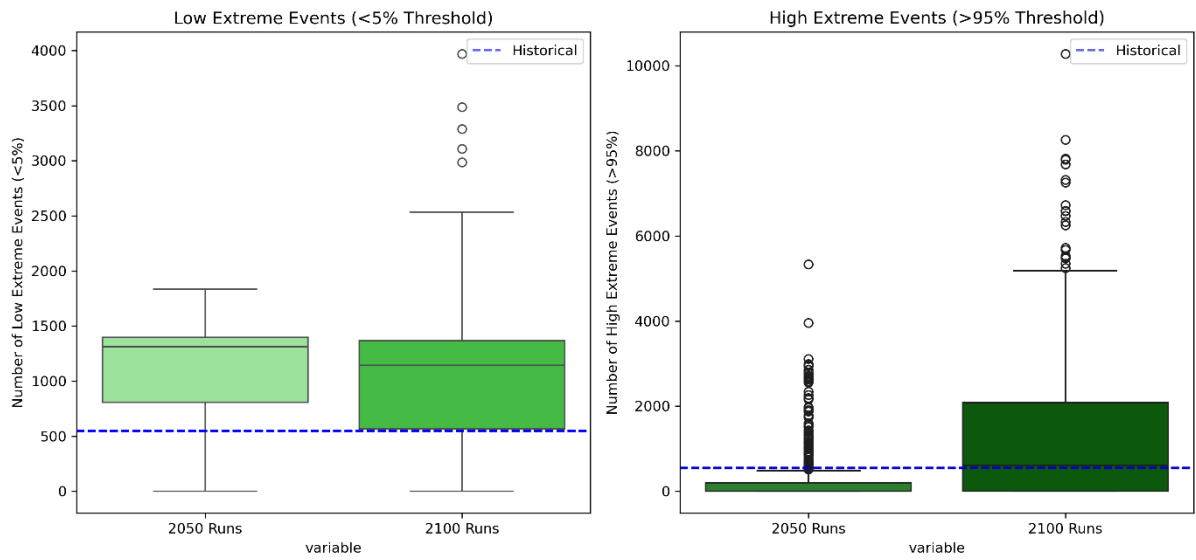
Distribution of Extreme Events: Historical vs. Future Scenarios - Spiere_helkijn



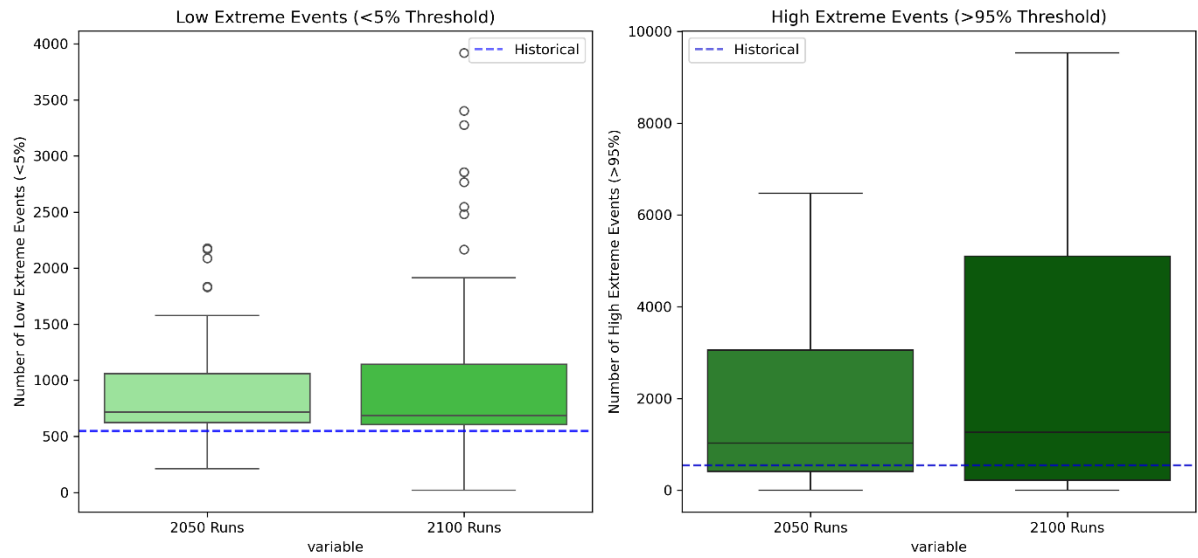
Distribution of Extreme Events: Historical vs. Future Scenarios - Tessenderlo



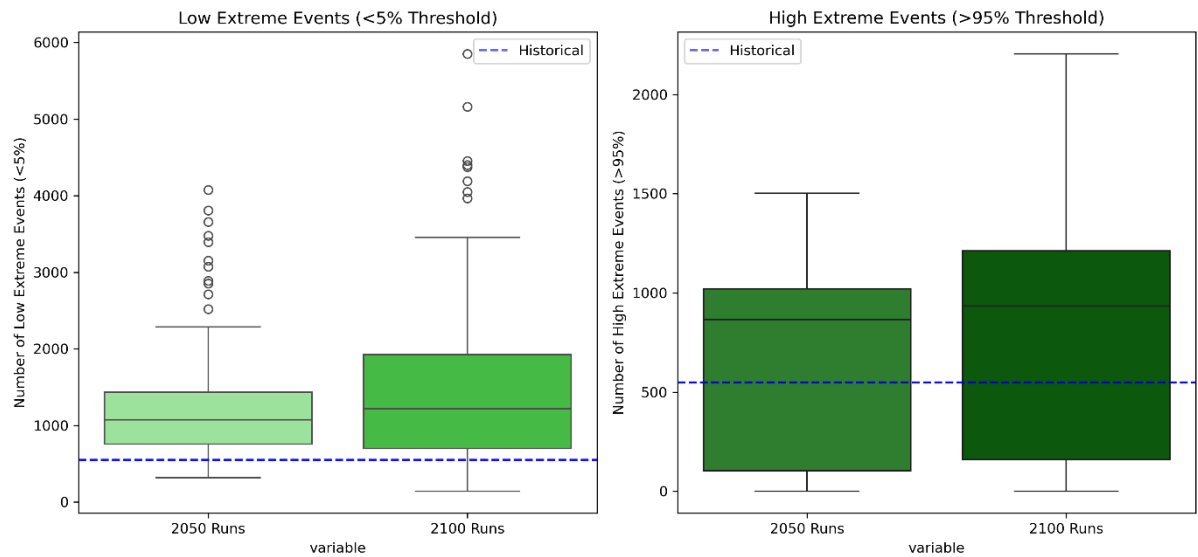
Distribution of Extreme Events: Historical vs. Future Scenarios - Tgv



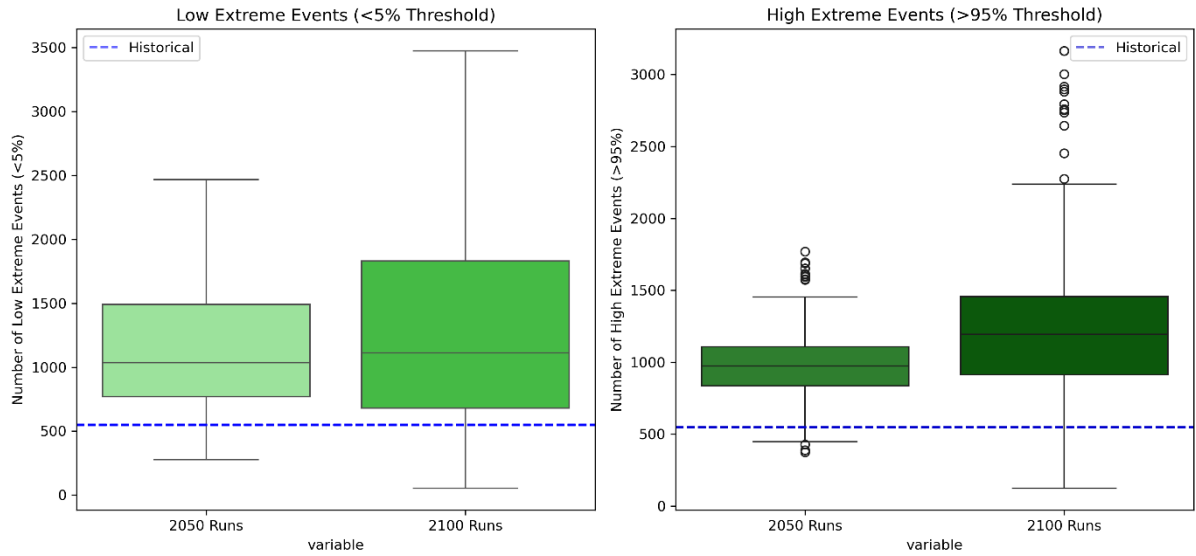
Distribution of Extreme Events: Historical vs. Future Scenarios - Trekschuren



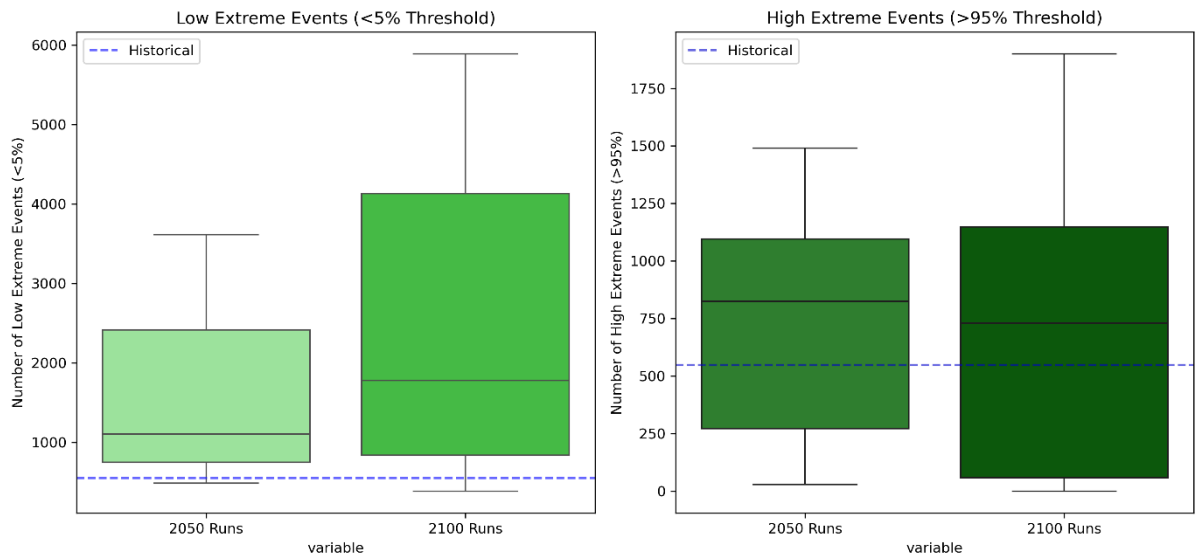
Distribution of Extreme Events: Historical vs. Future Scenarios - Waltwilder



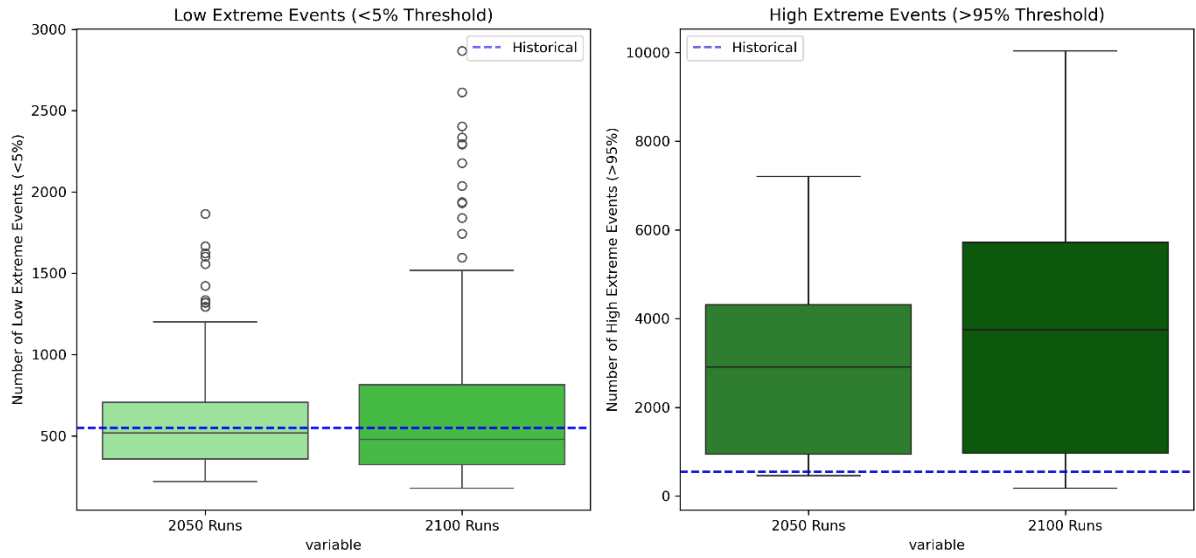
Distribution of Extreme Events: Historical vs. Future Scenarios - Weerderlaak



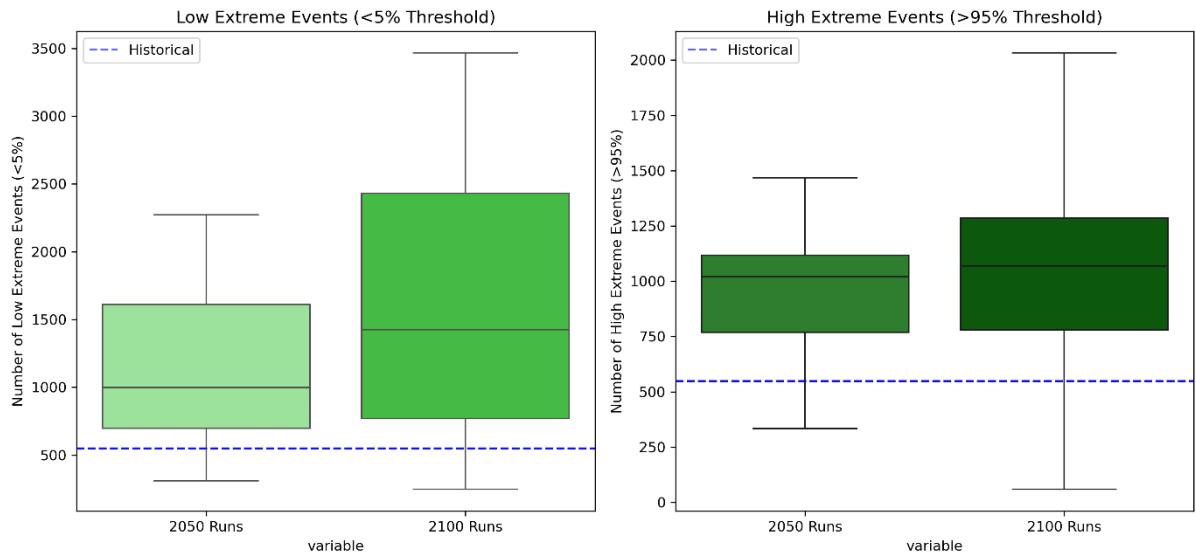
Distribution of Extreme Events: Historical vs. Future Scenarios - Wellen



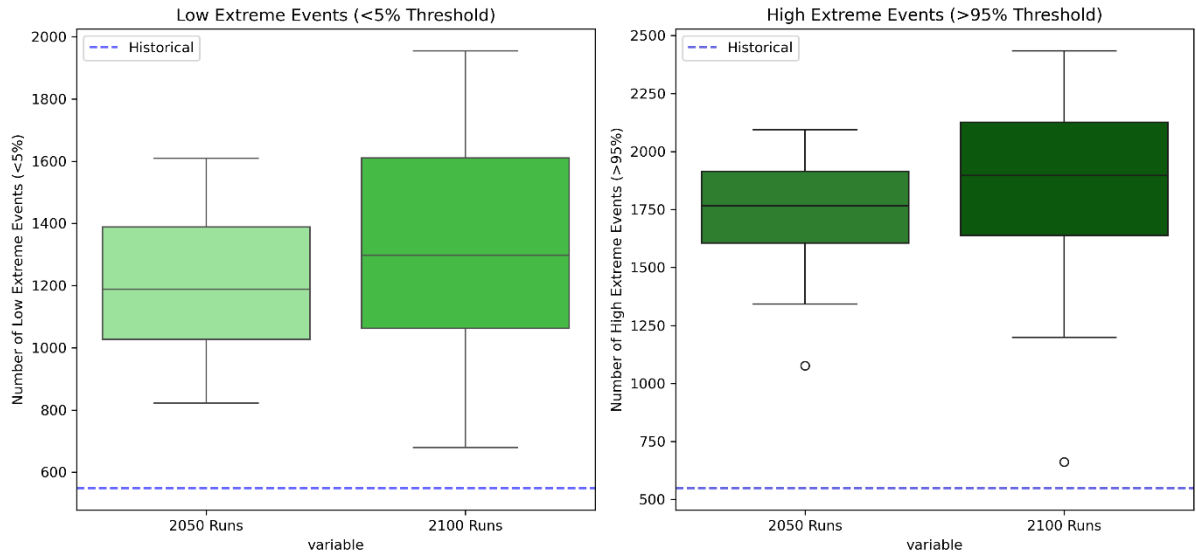
Distribution of Extreme Events: Historical vs. Future Scenarios - Willekensmolen



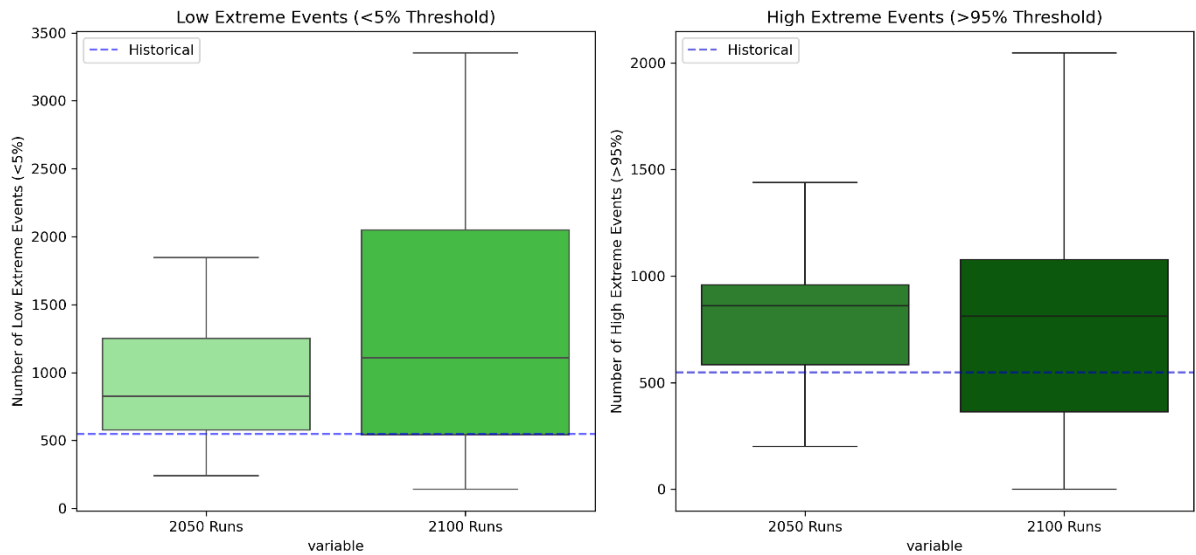
Distribution of Extreme Events: Historical vs. Future Scenarios - Winksele_kastanjebo



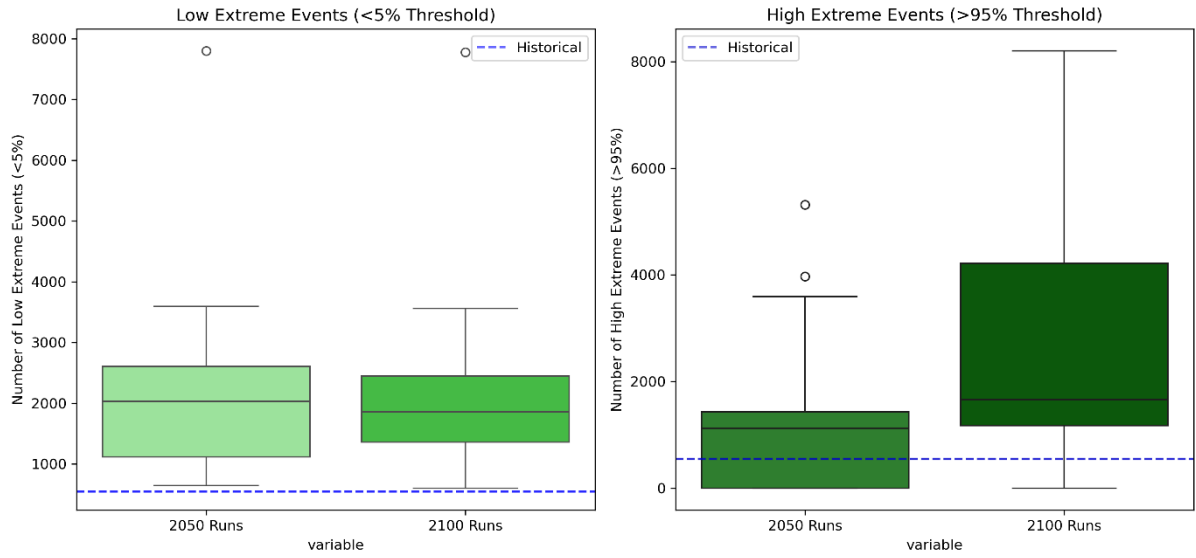
Distribution of Extreme Events: Historical vs. Future Scenarios - Wintershoven



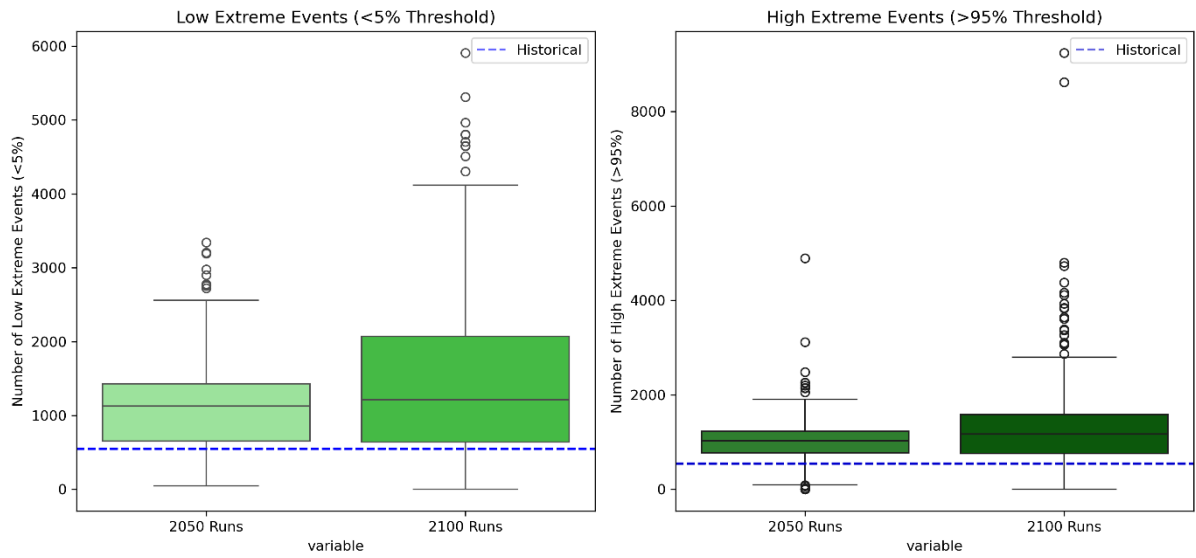
Distribution of Extreme Events: Historical vs. Future Scenarios - Zemst_spl



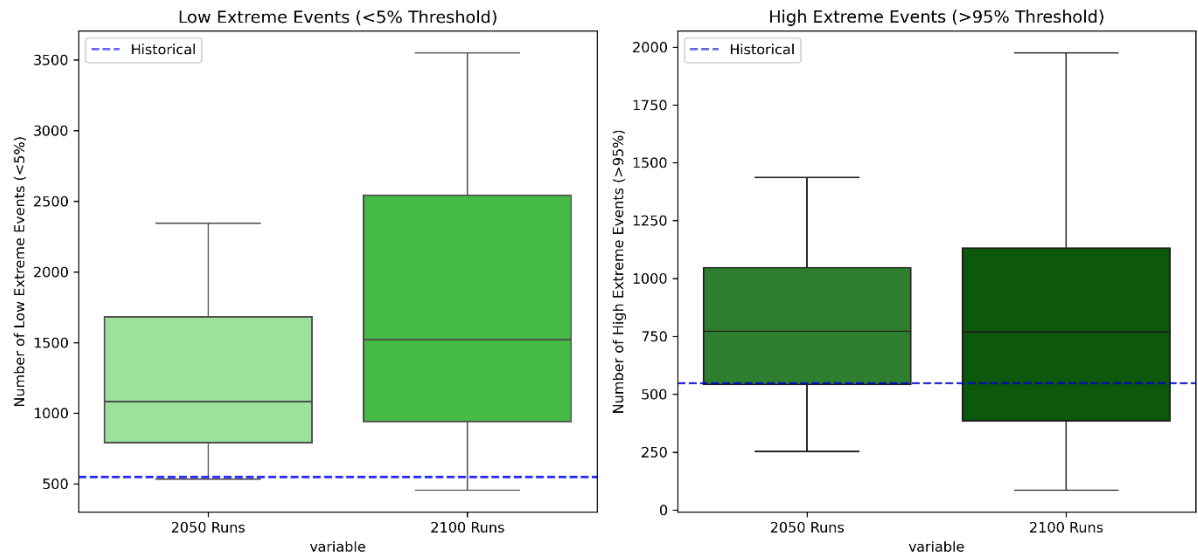
Distribution of Extreme Events: Historical vs. Future Scenarios - Zepperen



Distribution of Extreme Events: Historical vs. Future Scenarios - Zichem_vinkenberg

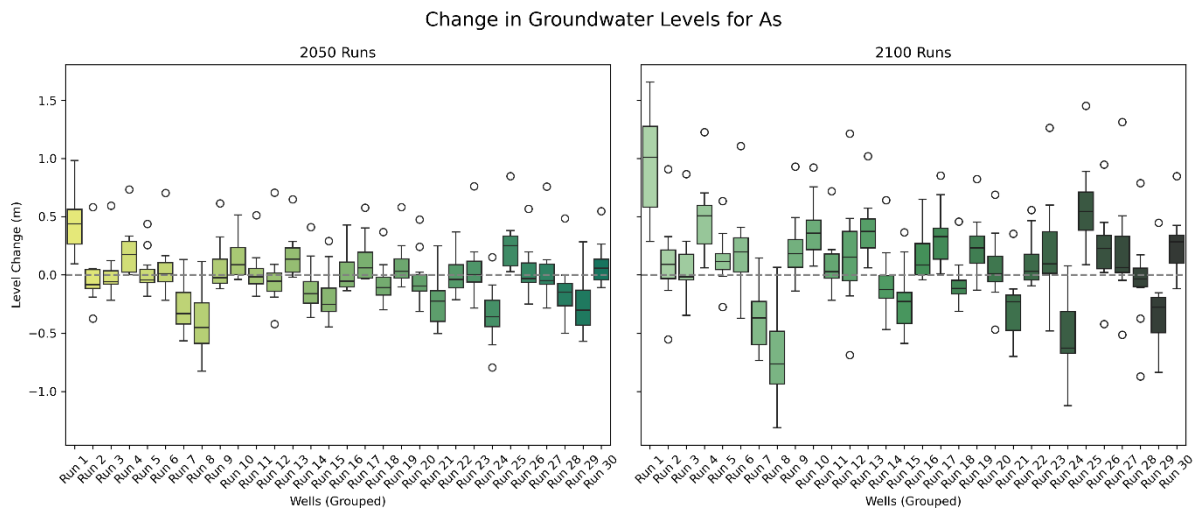
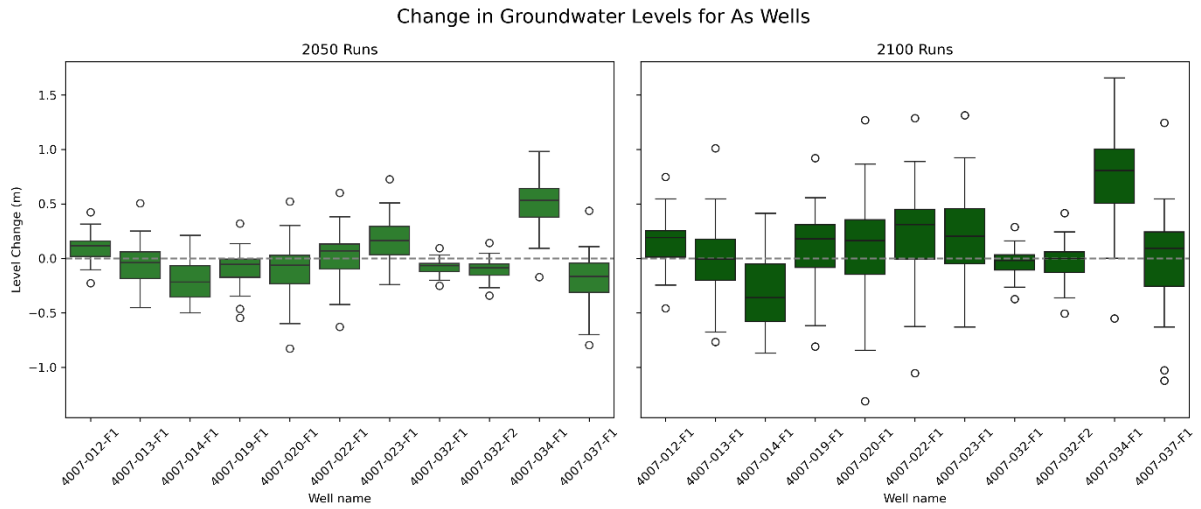


Distribution of Extreme Events: Historical vs. Future Scenarios - Zoutleeuw

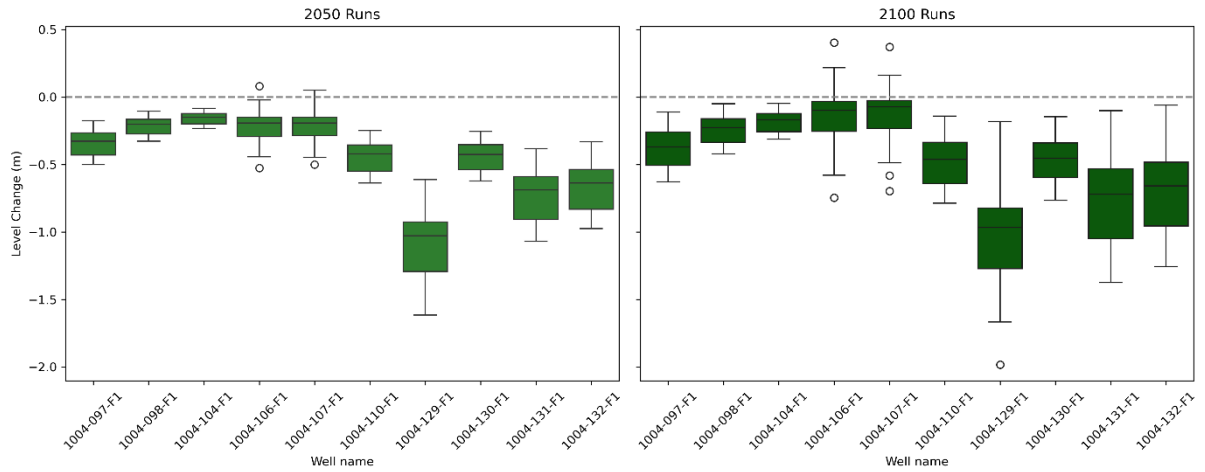


10.2.3 B.3 De Watergroep Projected change in groundwater levels

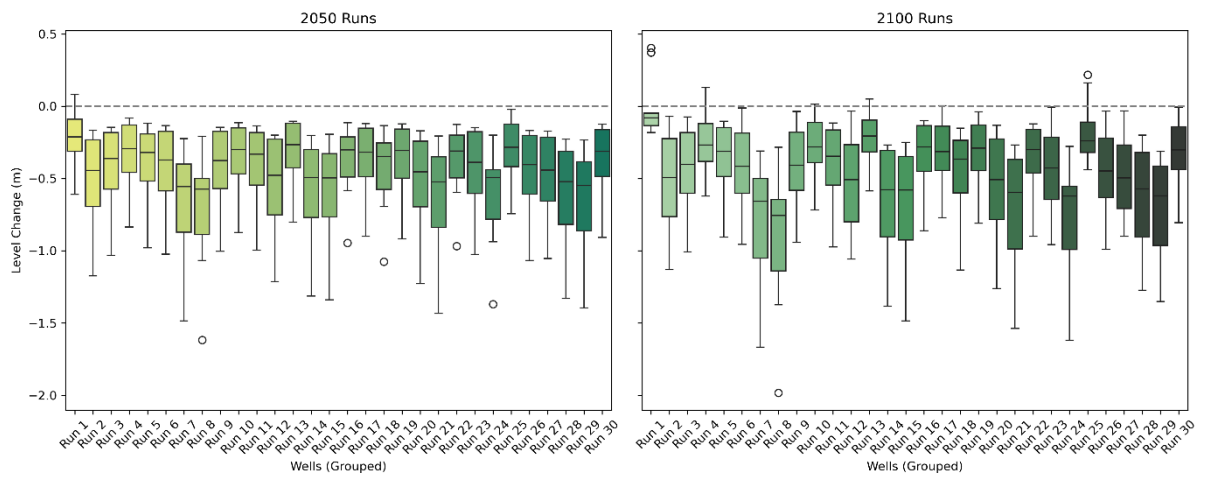
Projected change in groundwater levels across a) individual wells for aggregated simulation runs (2050 and 2100).



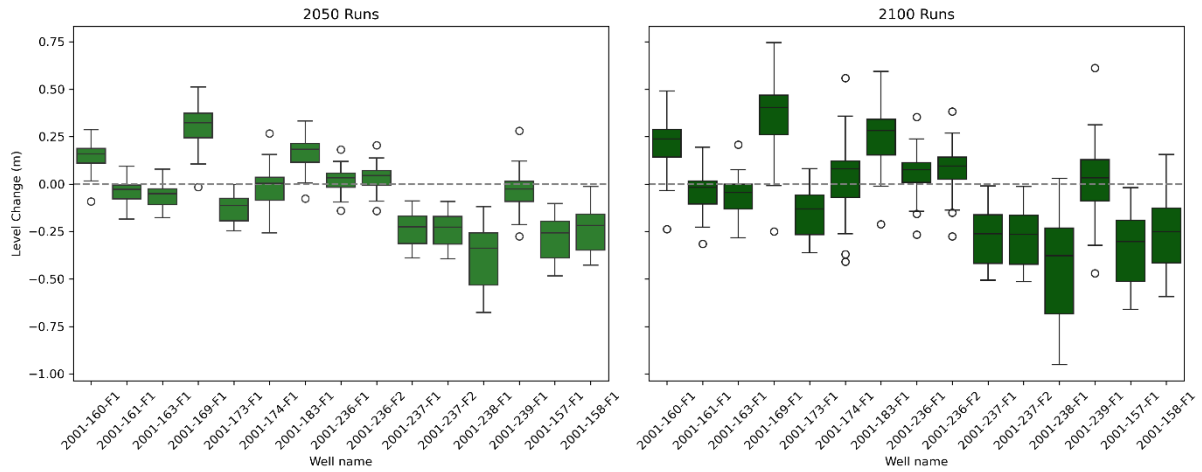
Change in Groundwater Levels for beernem Wells



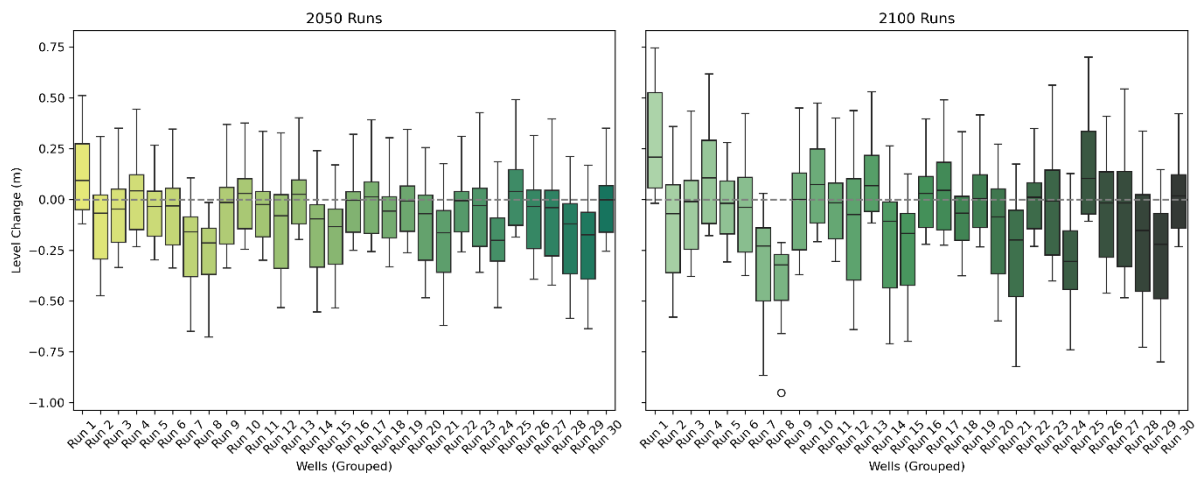
Change in Groundwater Levels for beernem



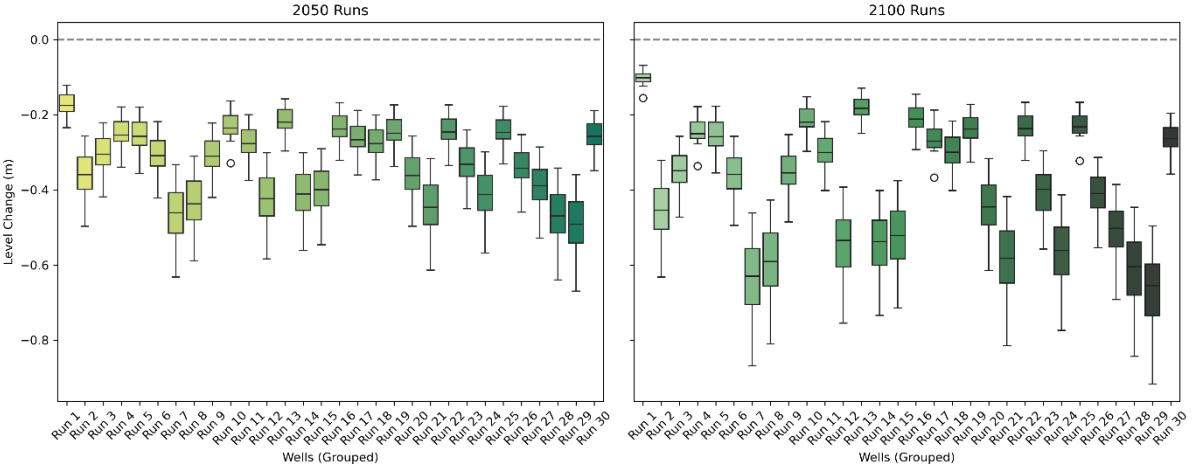
Change in Groundwater Levels for berlare_zele Wells



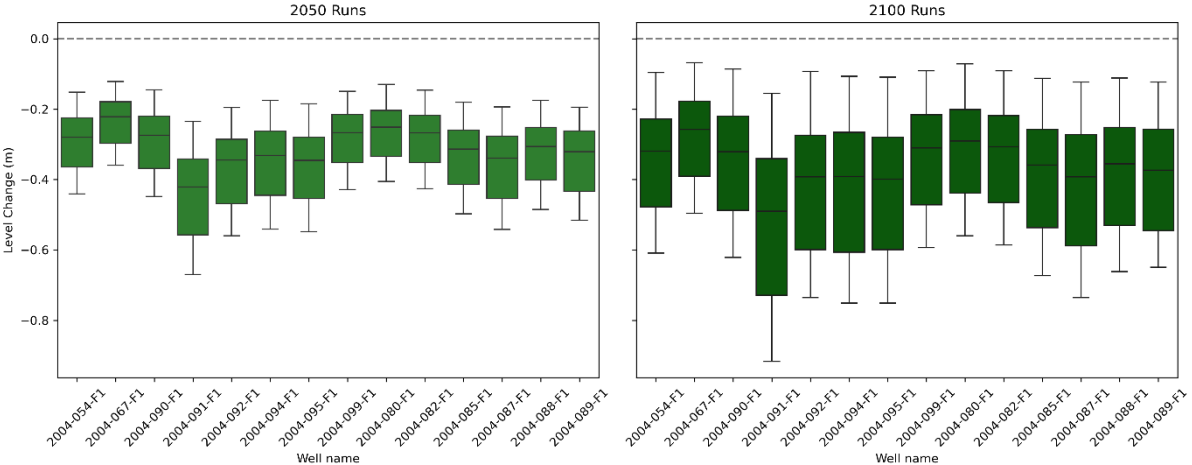
Change in Groundwater Levels for berlare_zele



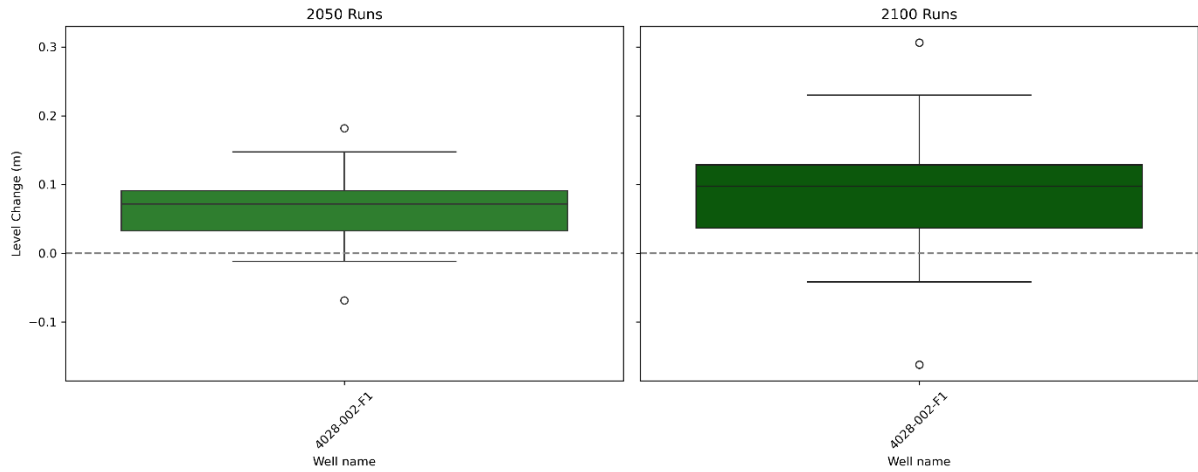
Change in Groundwater Levels for eeklo



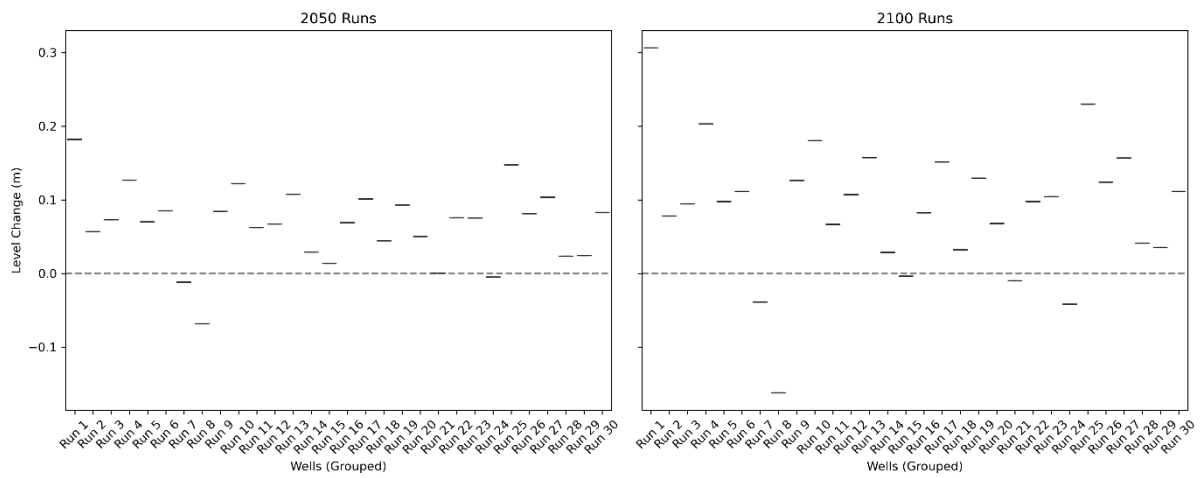
Change in Groundwater Levels for eeklo Wells



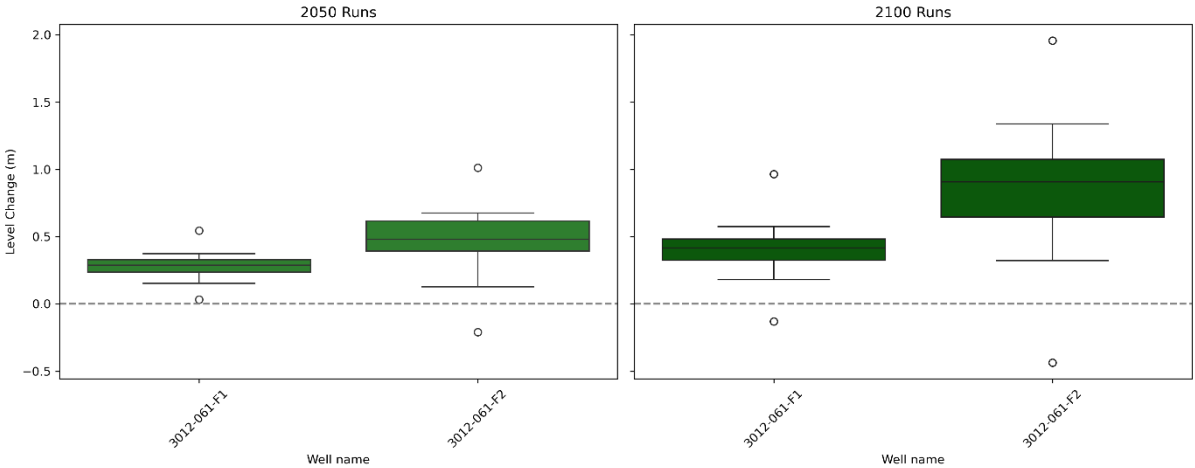
Change in Groundwater Levels for eisdén_mijnsite Wells



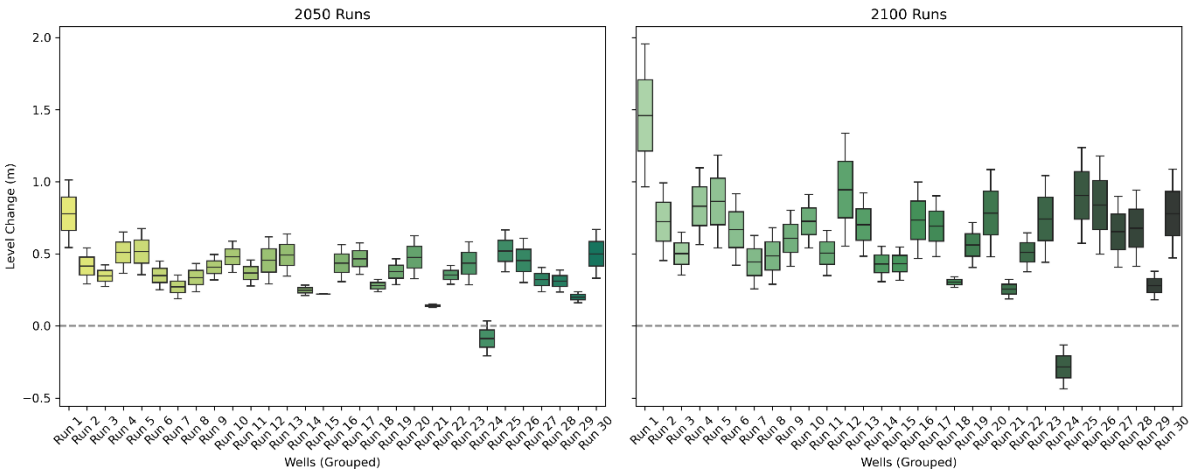
Change in Groundwater Levels for eisdén_mijnsite



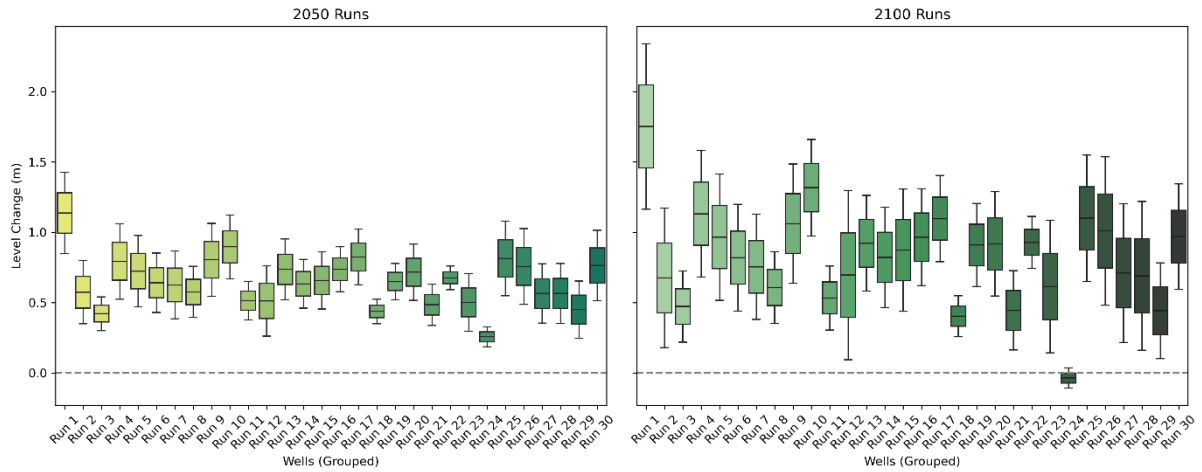
Change in Groundwater Levels for grez_doiceau_pecrot Wells



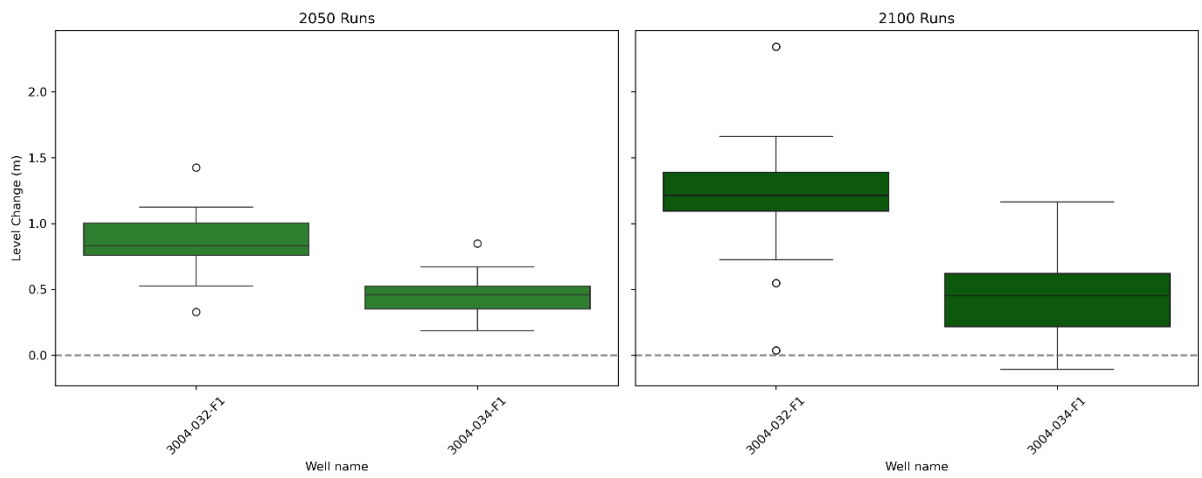
Change in Groundwater Levels for grez_doiceau_pecrot



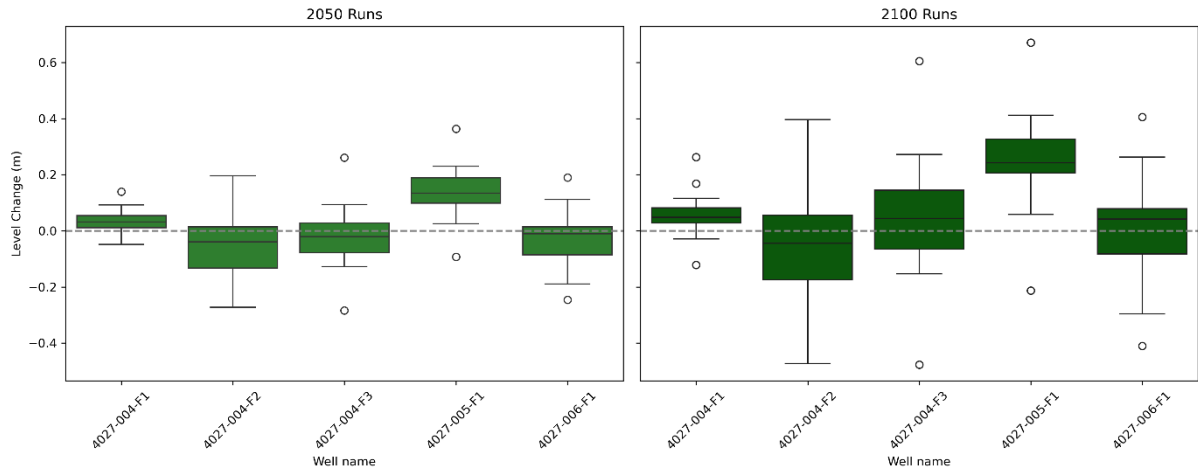
Change in Groundwater Levels for herent_bijlok



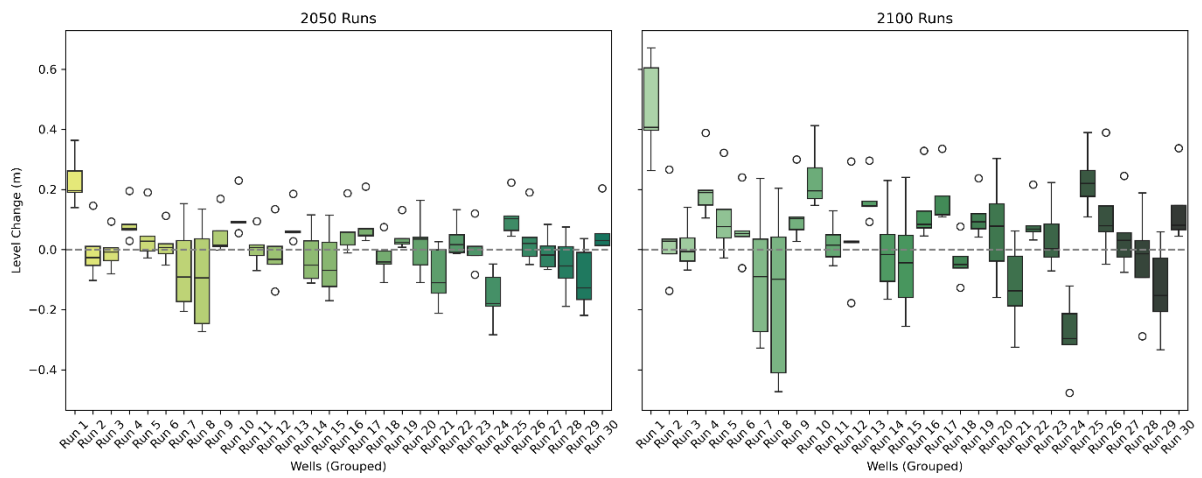
Change in Groundwater Levels for herent_bijlok Wells



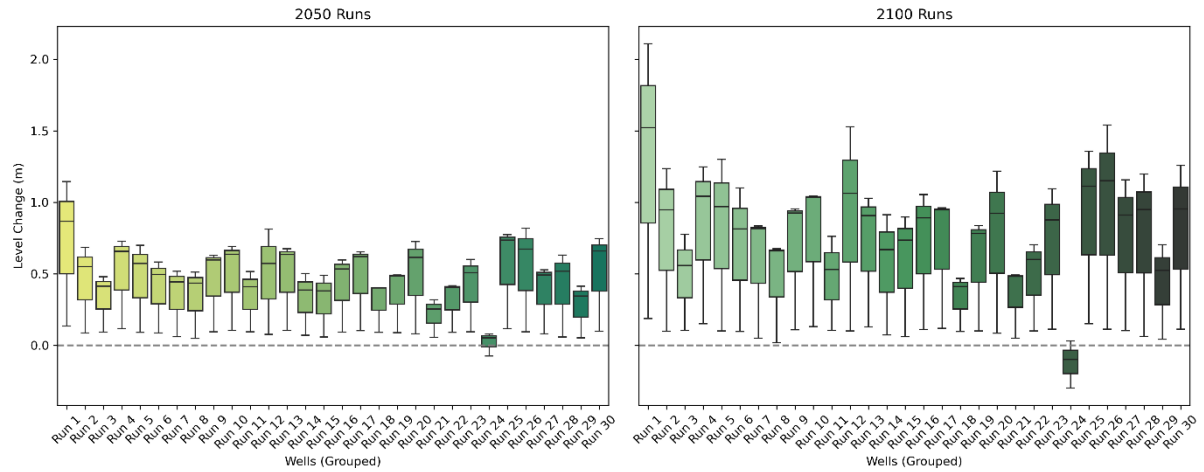
Change in Groundwater Levels for heusden_zolder Wells



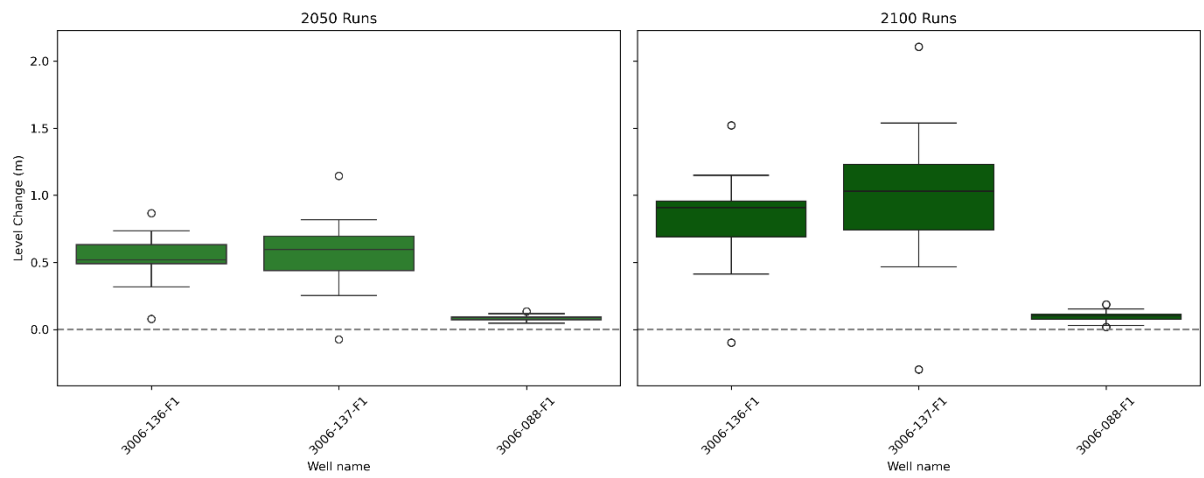
Change in Groundwater Levels for heusden_zolder



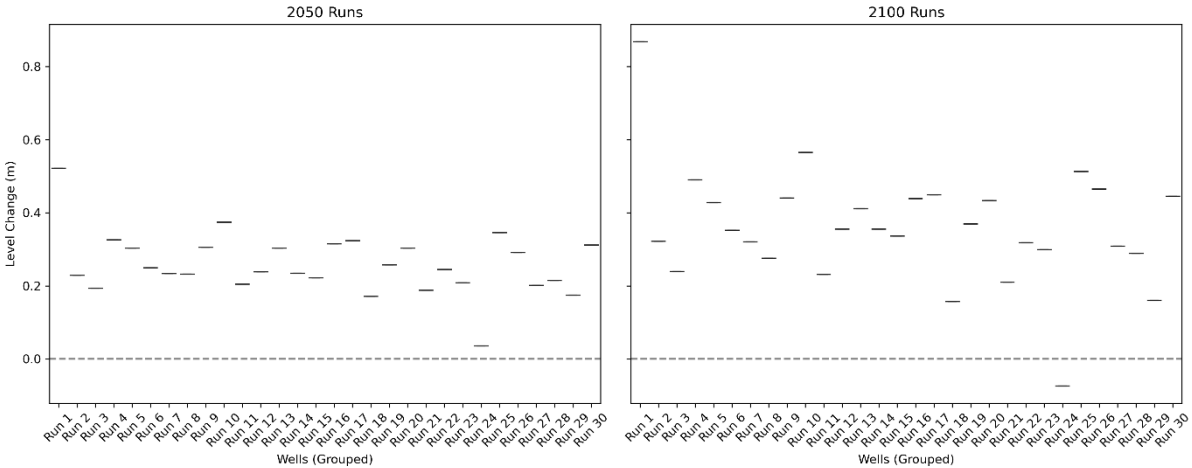
Change in Groundwater Levels for heverlee_abdij



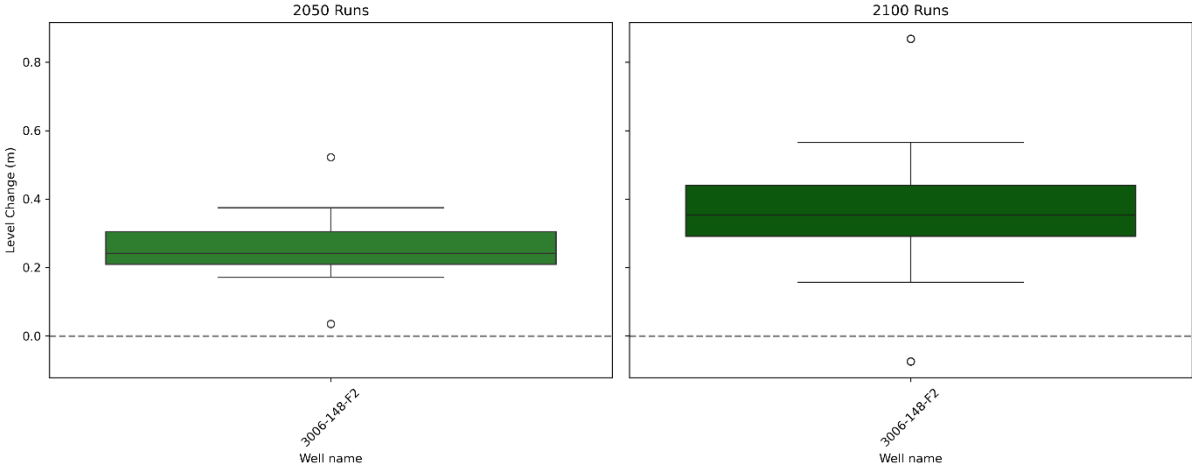
Change in Groundwater Levels for heverlee_abdij Wells



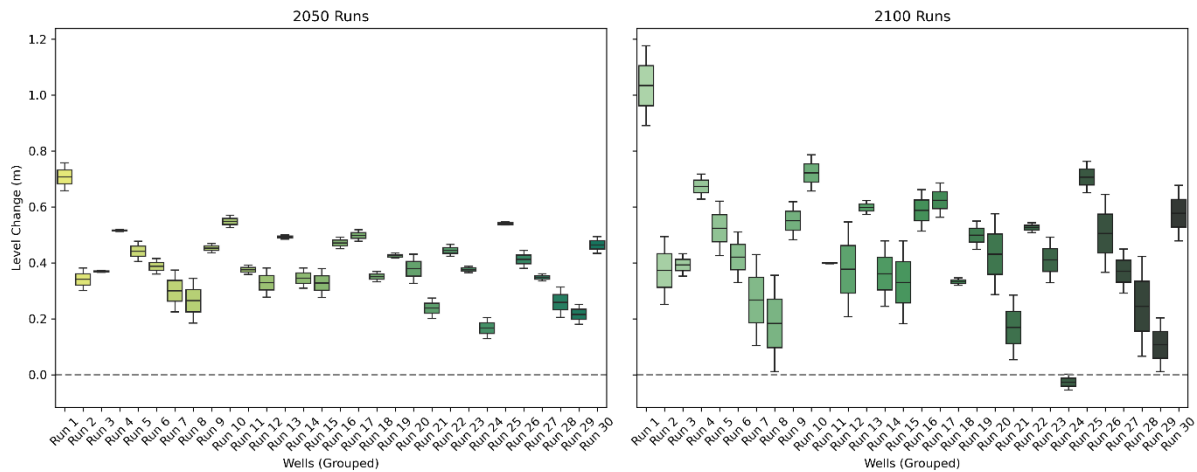
Change in Groundwater Levels for heverlee_cadol



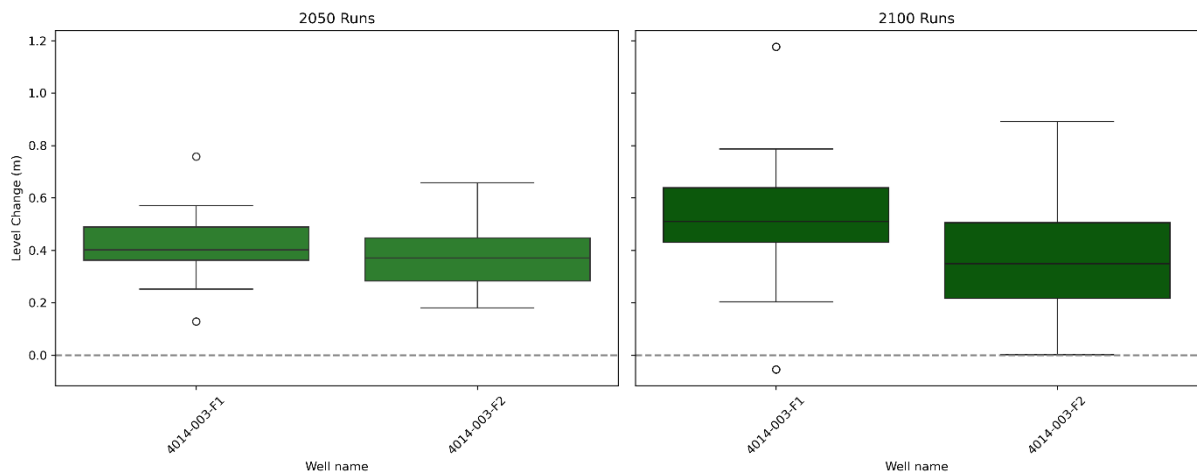
Change in Groundwater Levels for heverlee_cadol Wells



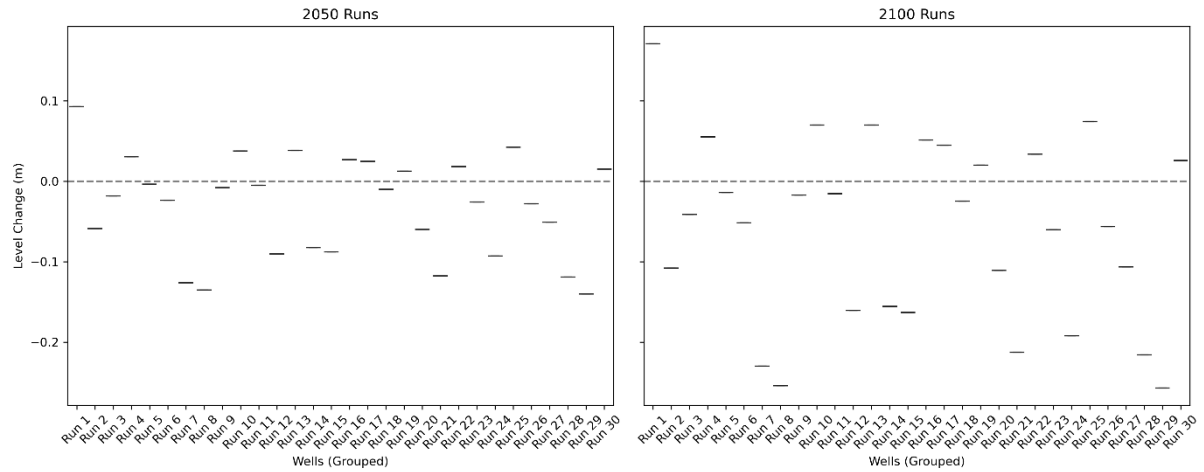
Change in Groundwater Levels for hoeptertingen



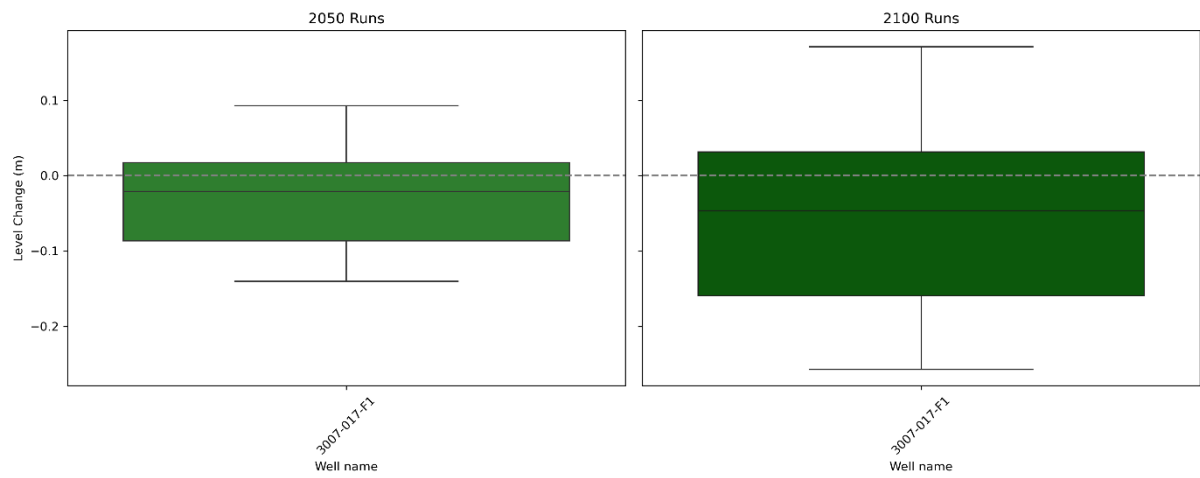
Change in Groundwater Levels for hoeptertingen Wells



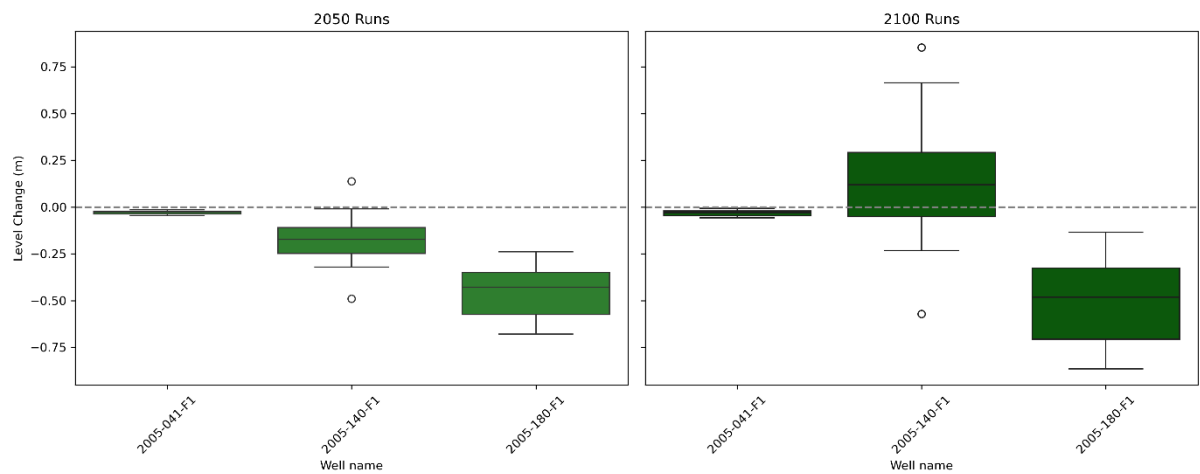
Change in Groundwater Levels for kessel_lo_vlierbeek



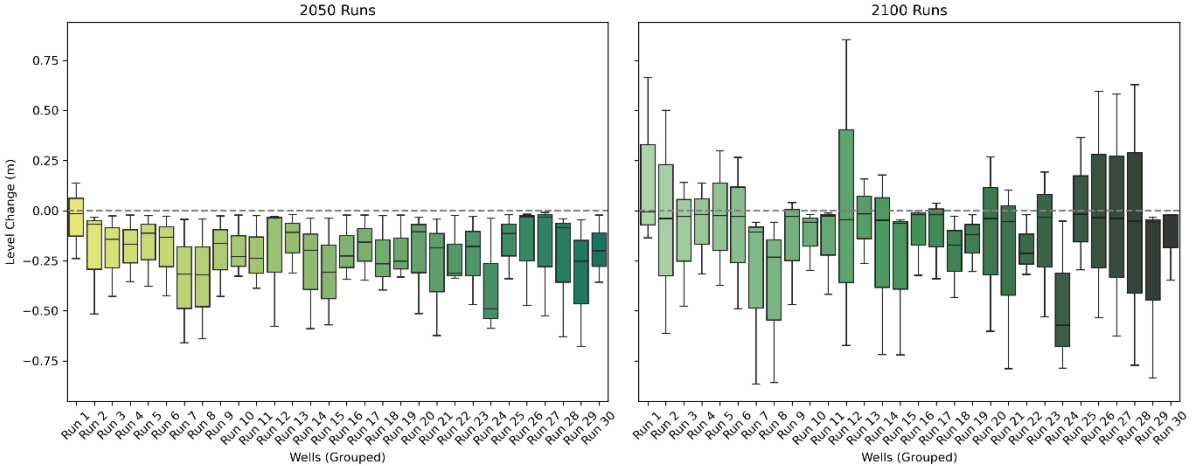
Change in Groundwater Levels for kessel_lo_vlierbeek Wells



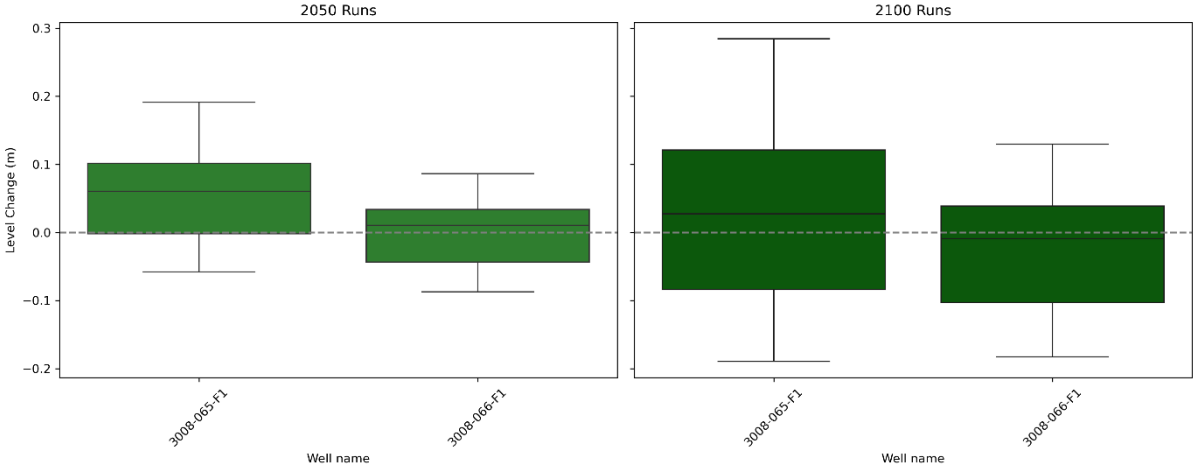
Change in Groundwater Levels for kluizen Wells



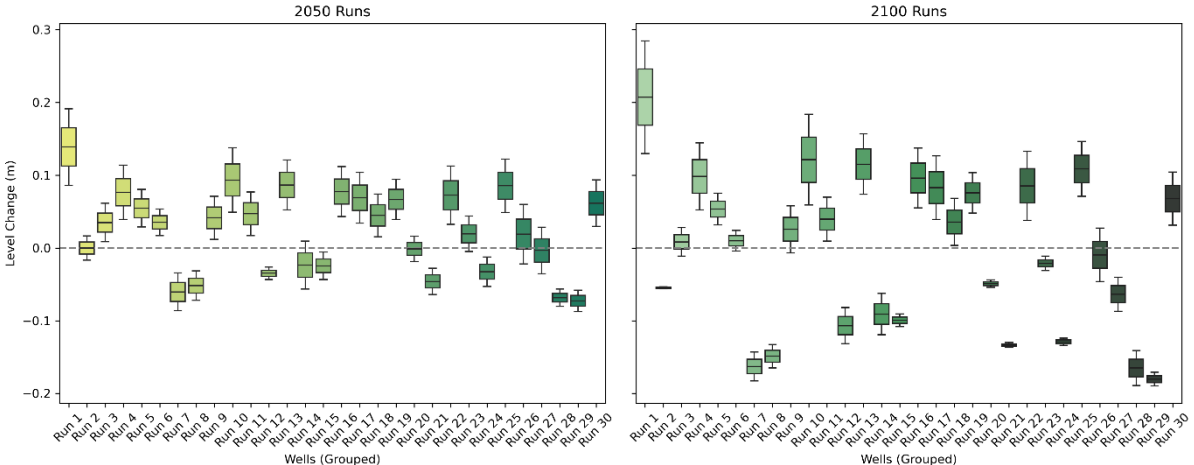
Change in Groundwater Levels for kluizen



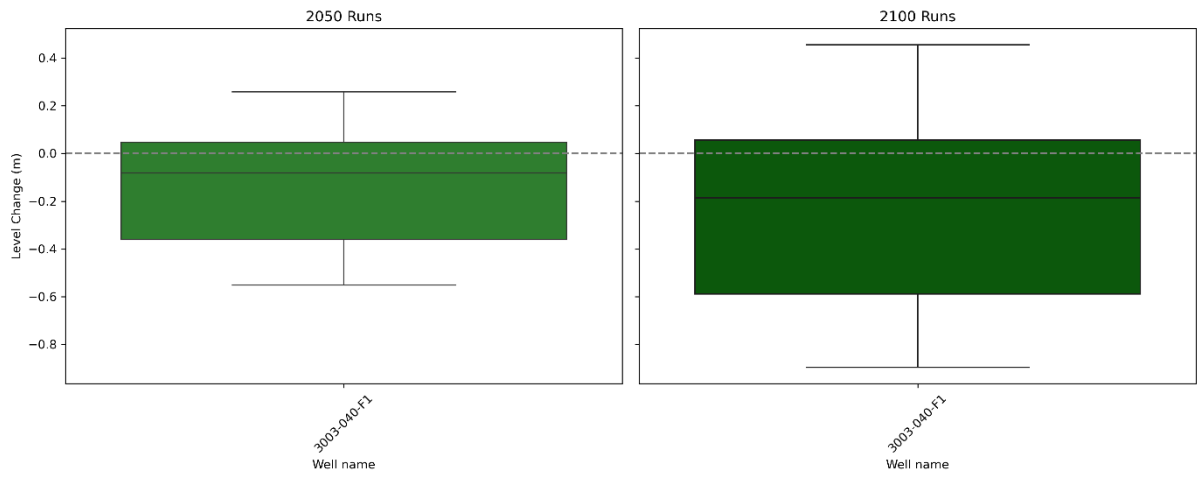
Change in Groundwater Levels for korbeek_dijle_het_broek Wells



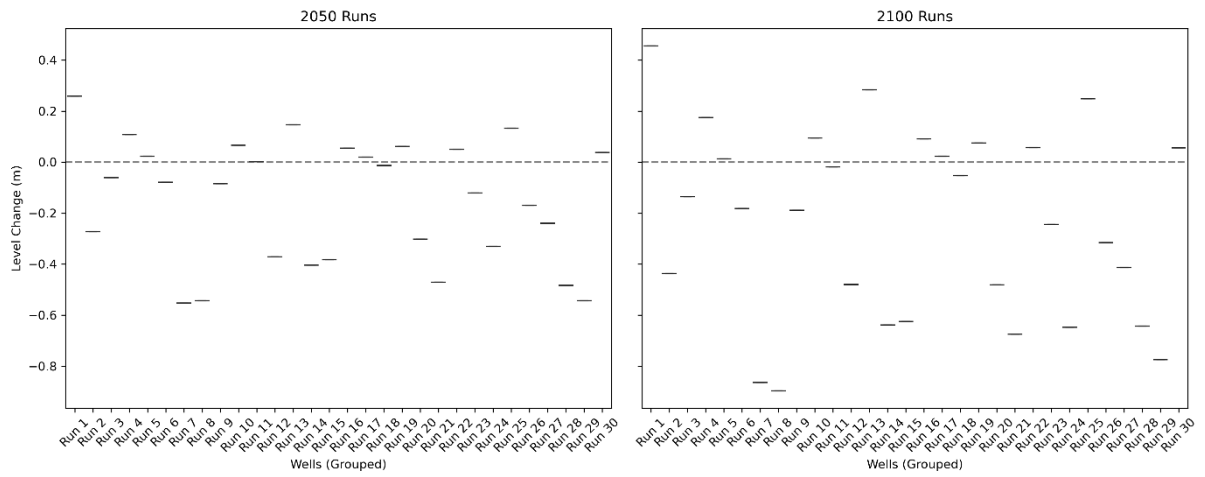
Change in Groundwater Levels for korbeek_dijle_het_broek



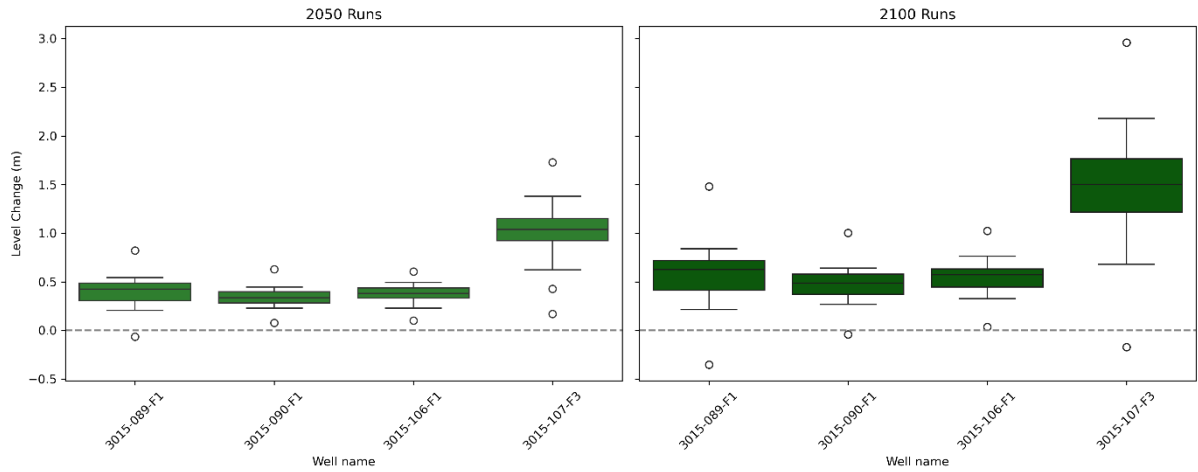
Change in Groundwater Levels for kumtich_menebeek Wells



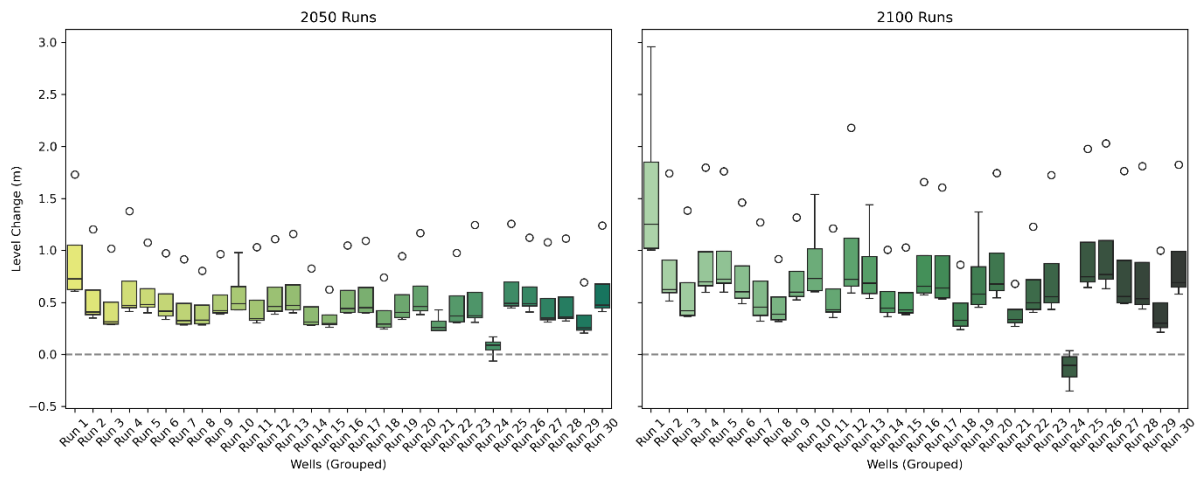
Change in Groundwater Levels for kumtich_menebeek



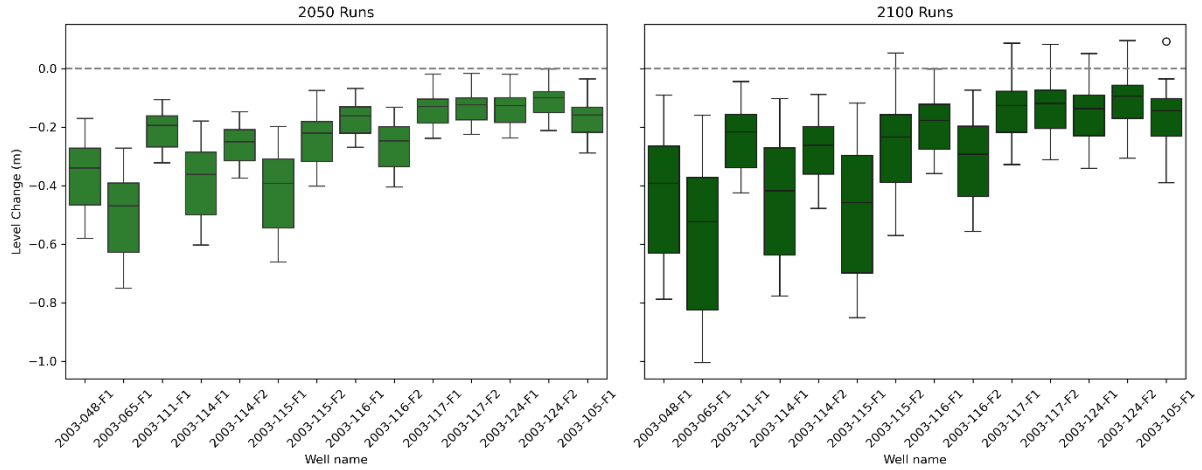
Change in Groundwater Levels for leefdaal_puttebos Wells



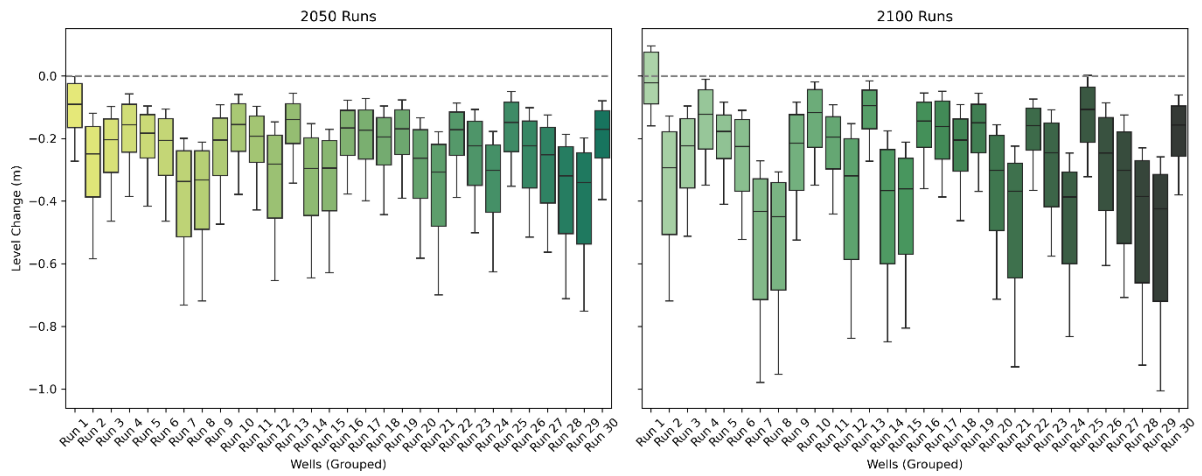
Change in Groundwater Levels for leefdaal_puttebos



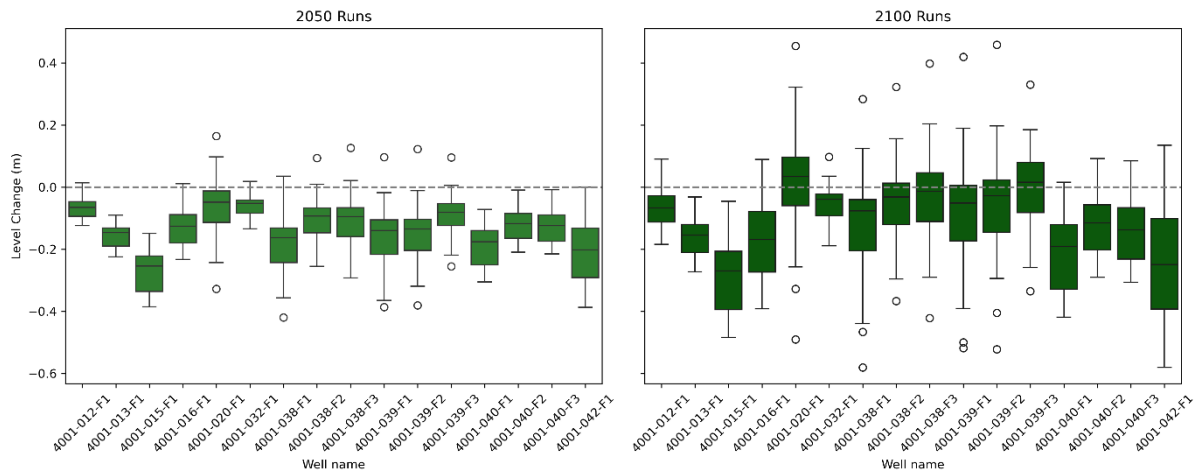
Change in Groundwater Levels for lembeke_oosteeklo Wells



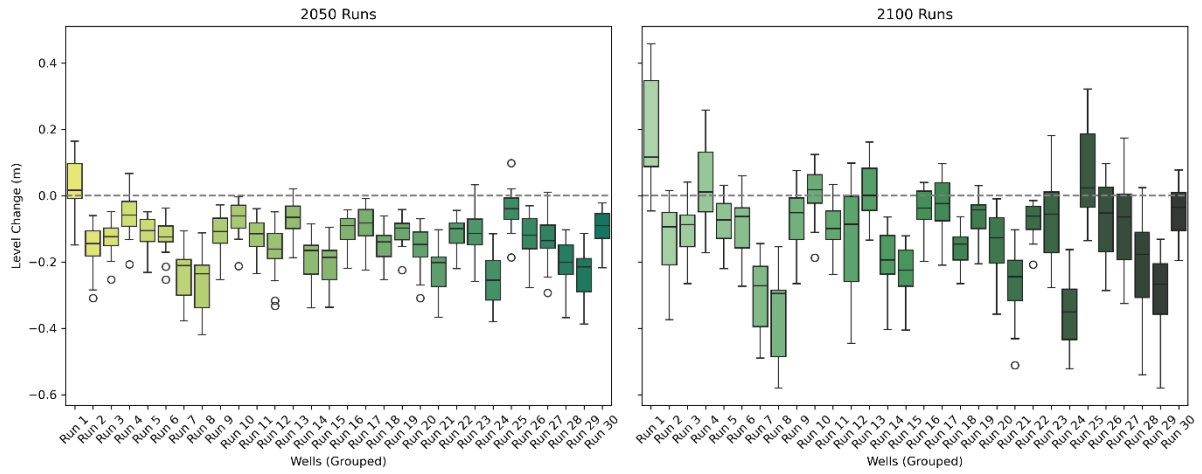
Change in Groundwater Levels for lembeke_oosteeklo



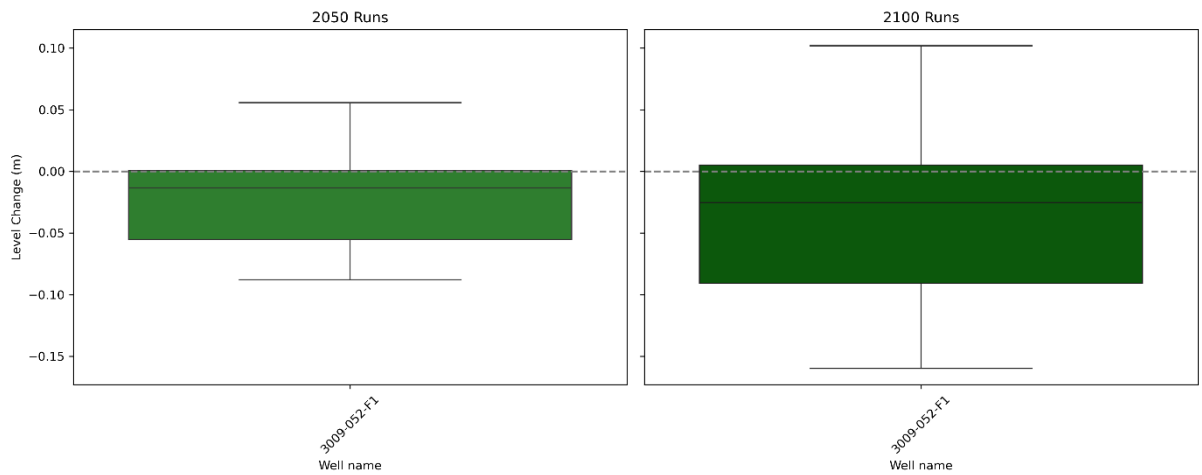
Change in Groundwater Levels for lommel Wells



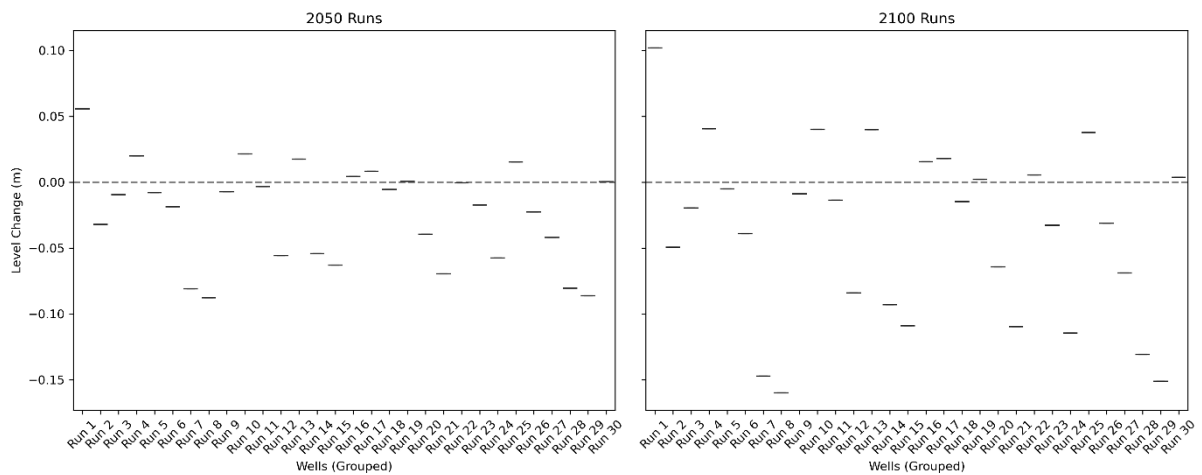
Change in Groundwater Levels for IJssel



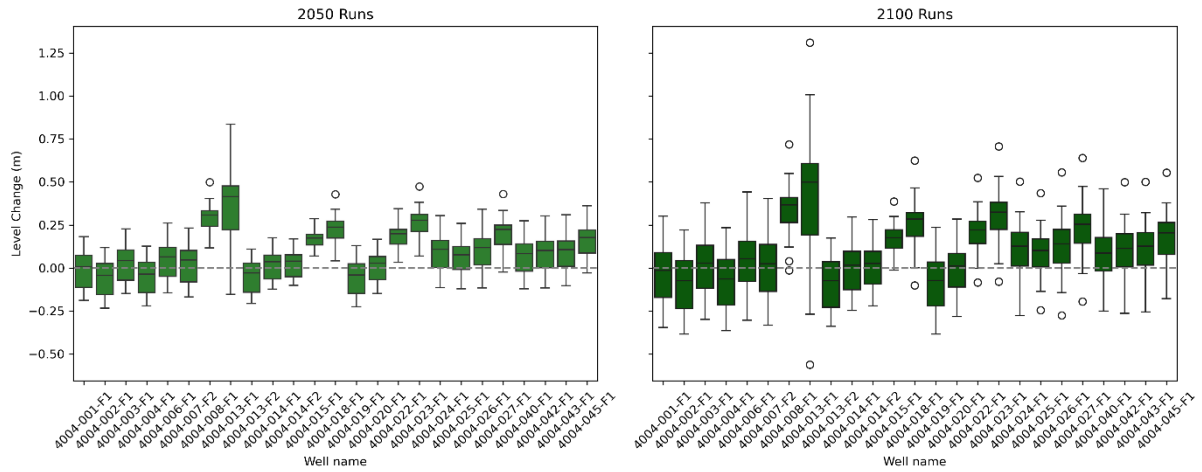
Change in Groundwater Levels for IJssel_koevoet Wells



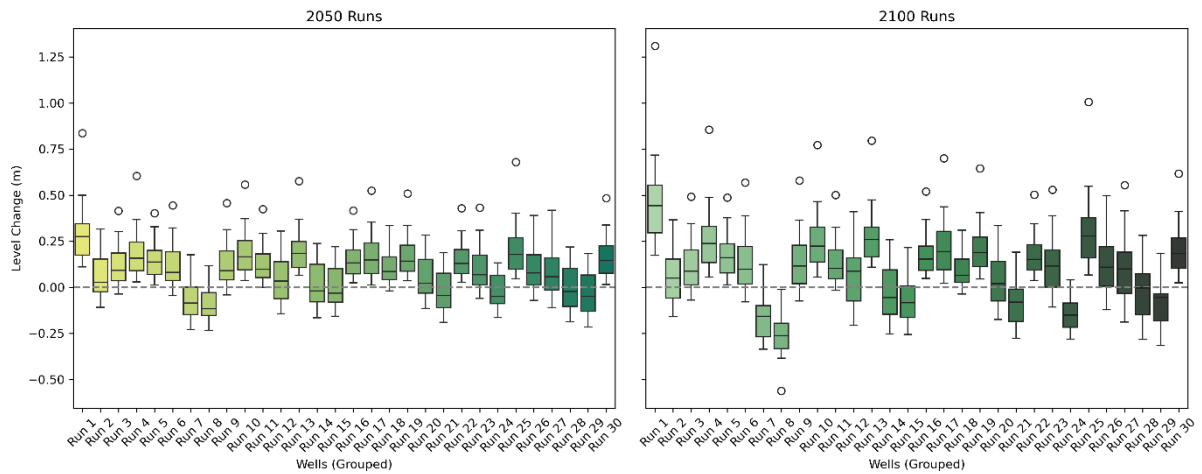
Change in Groundwater Levels for IJssel_koevoet



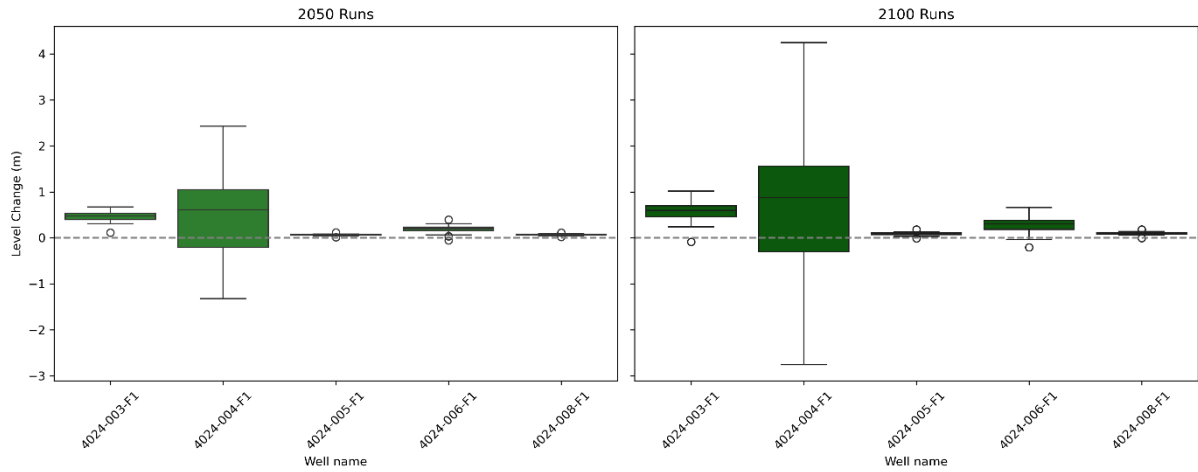
Change in Groundwater Levels for maaseik_vlakenhof Wells



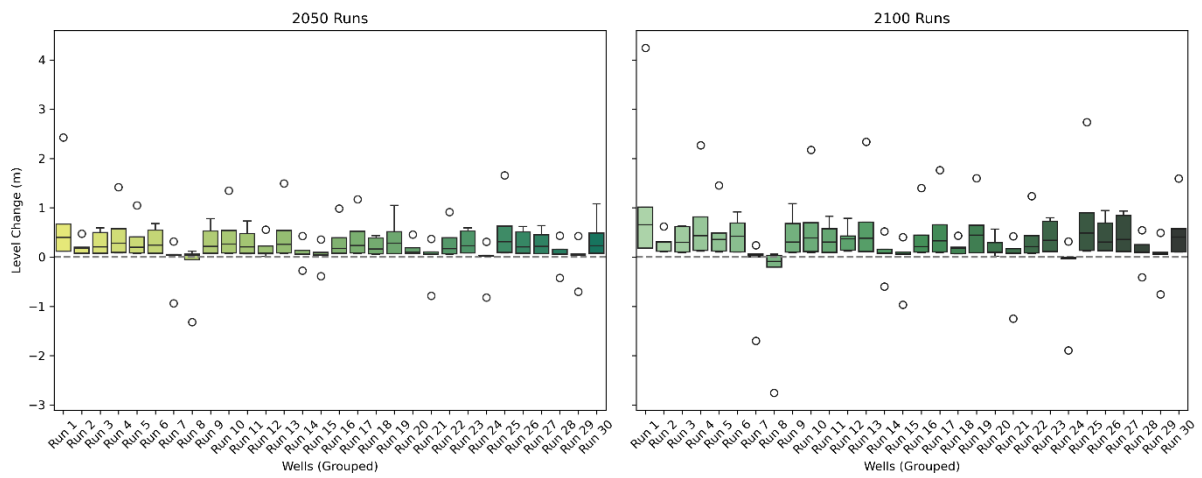
Change in Groundwater Levels for maaseik_vlakenhof



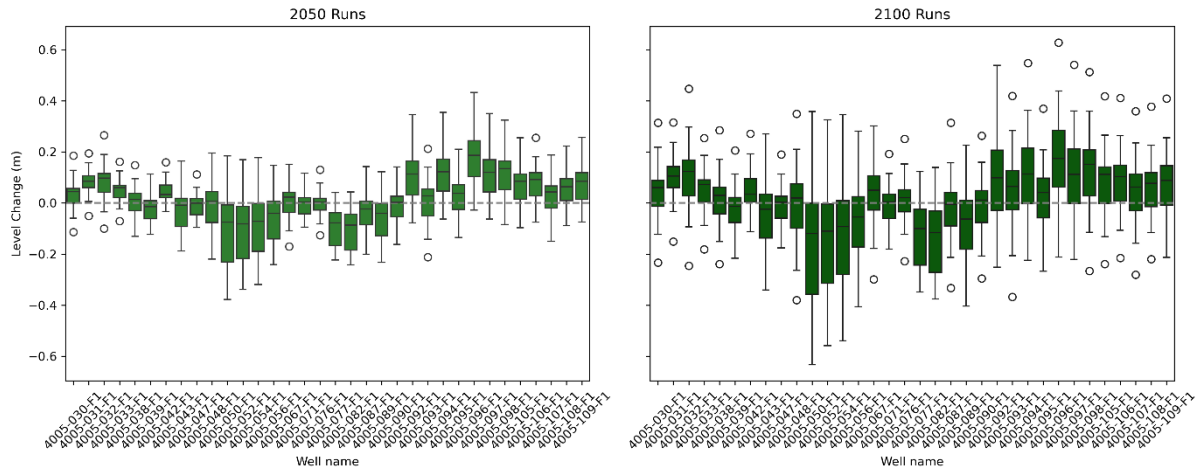
Change in Groundwater Levels for meerheuvel Wells



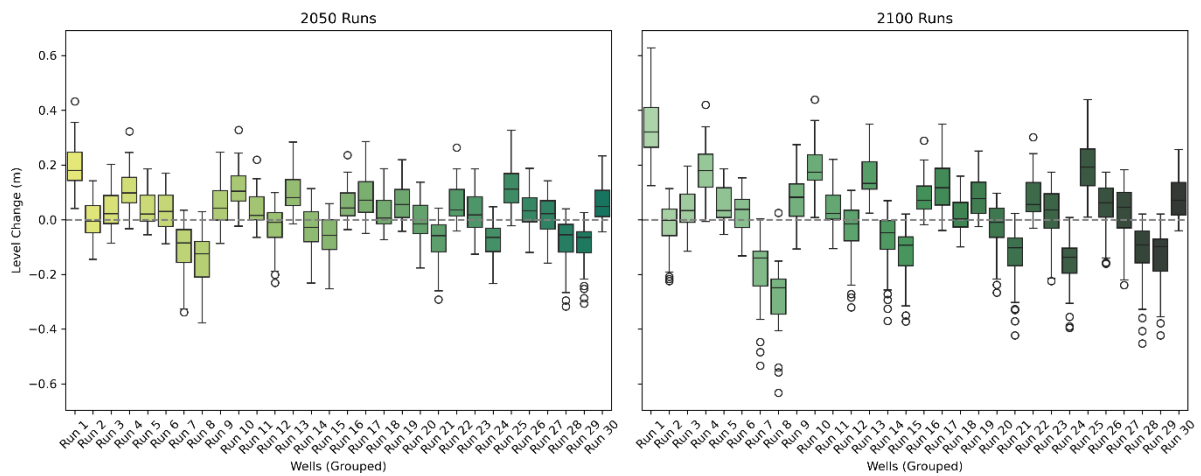
Change in Groundwater Levels for meerheuvel



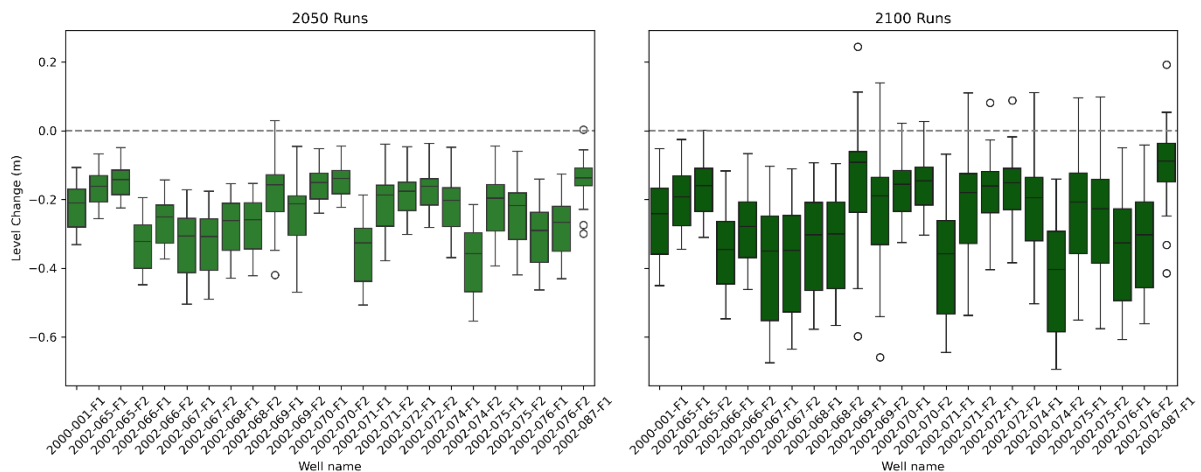
Change in Groundwater Levels for meeswijk Wells



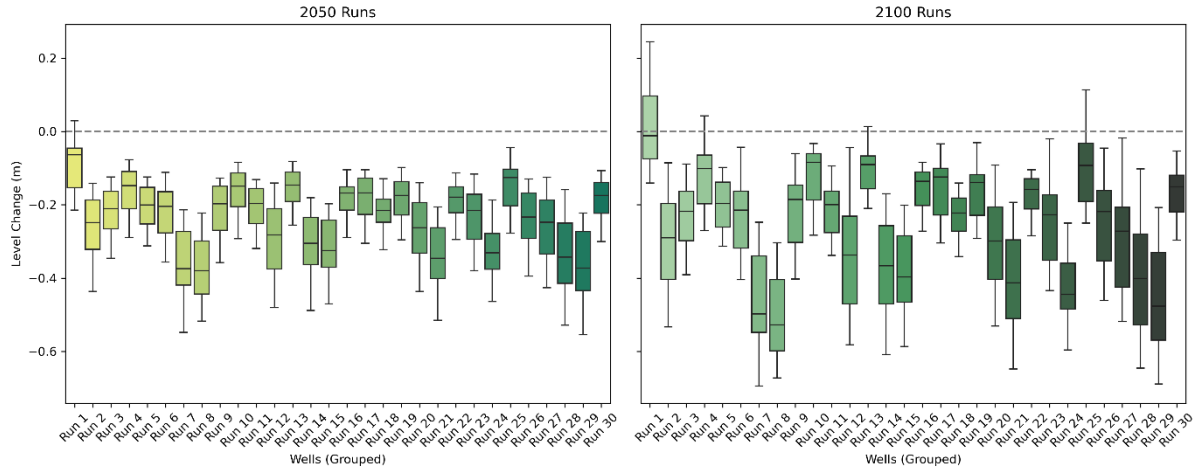
Change in Groundwater Levels for meeswijk



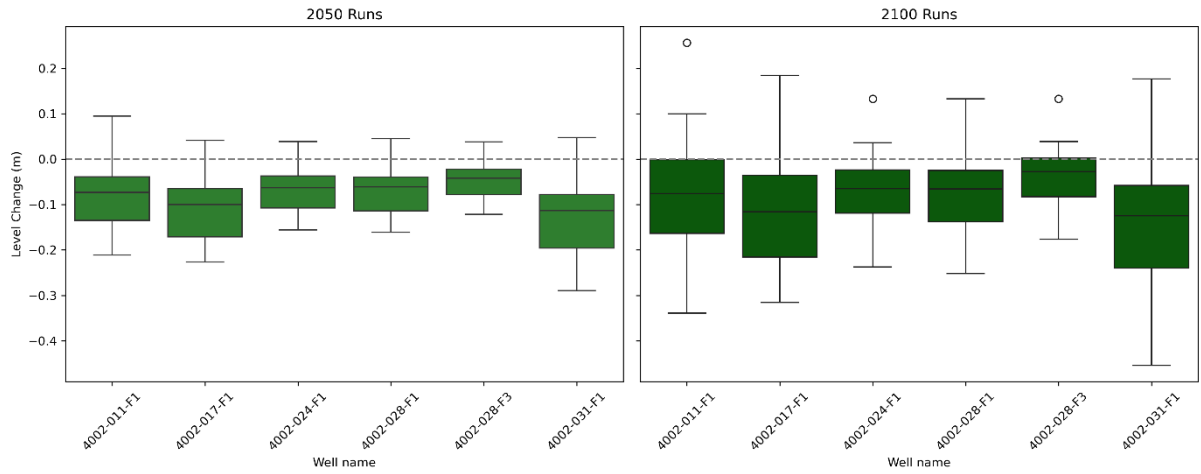
Change in Groundwater Levels for moerbeke_wachtebeke Wells



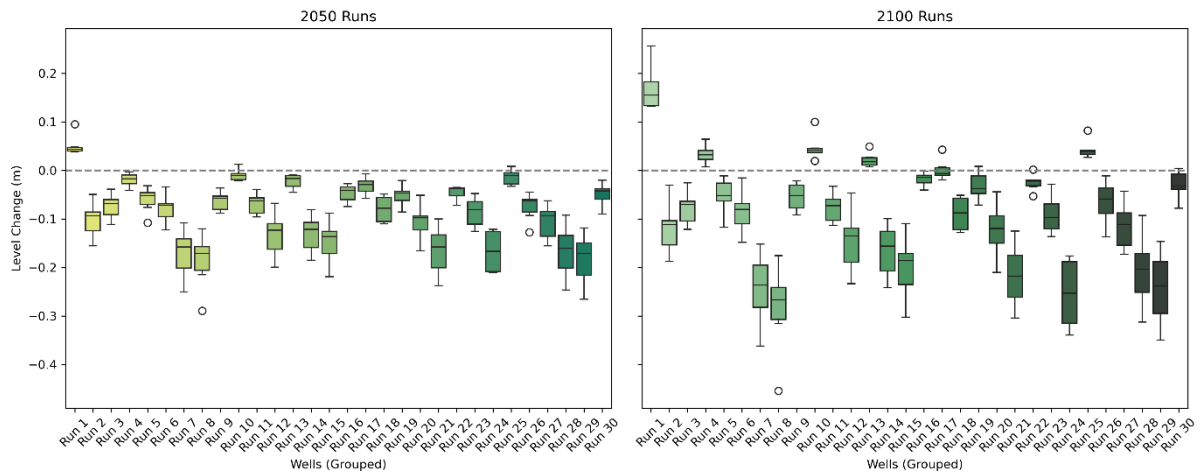
Change in Groundwater Levels for moerbeke_wachtebeke



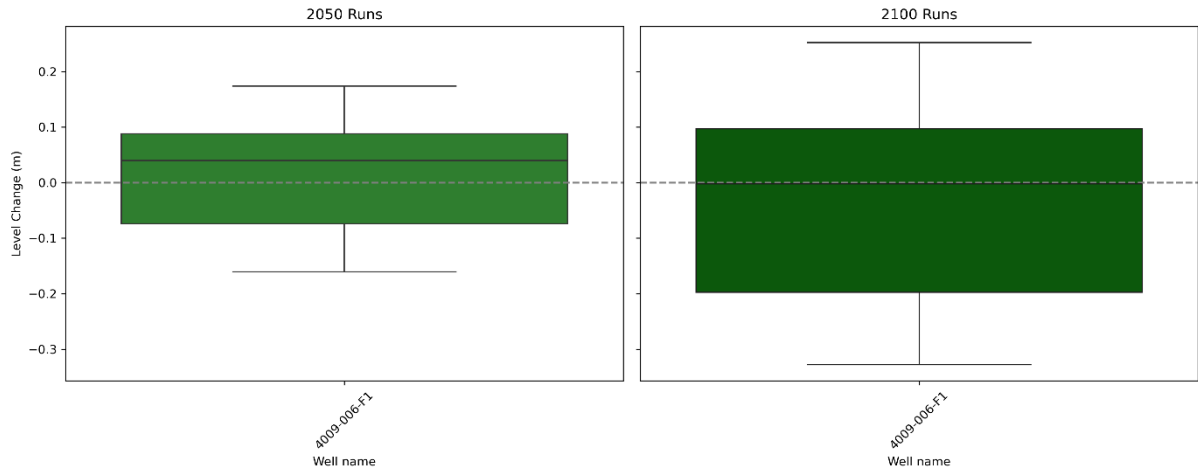
Change in Groundwater Levels for neerpelt Wells



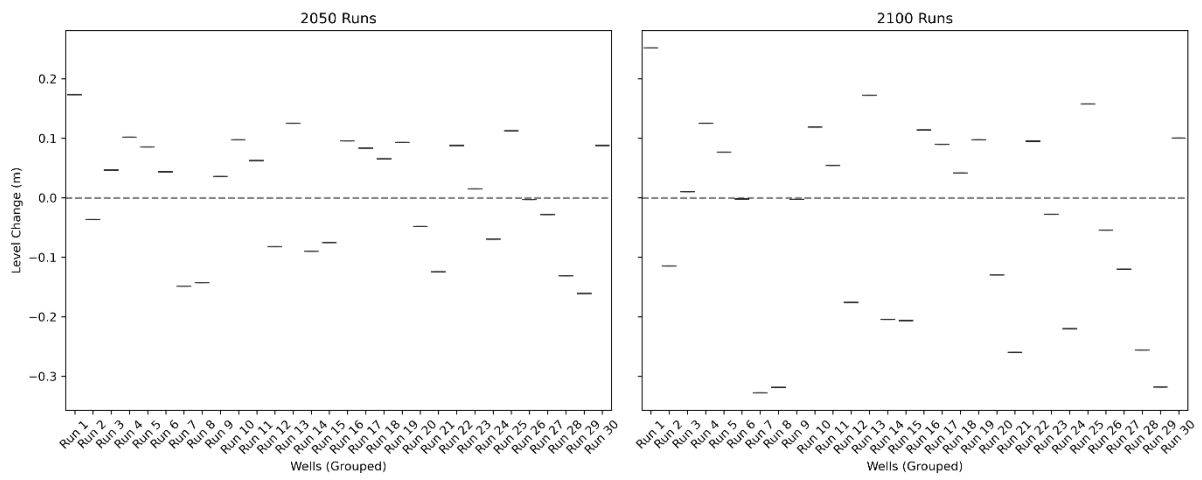
Change in Groundwater Levels for neerpelt



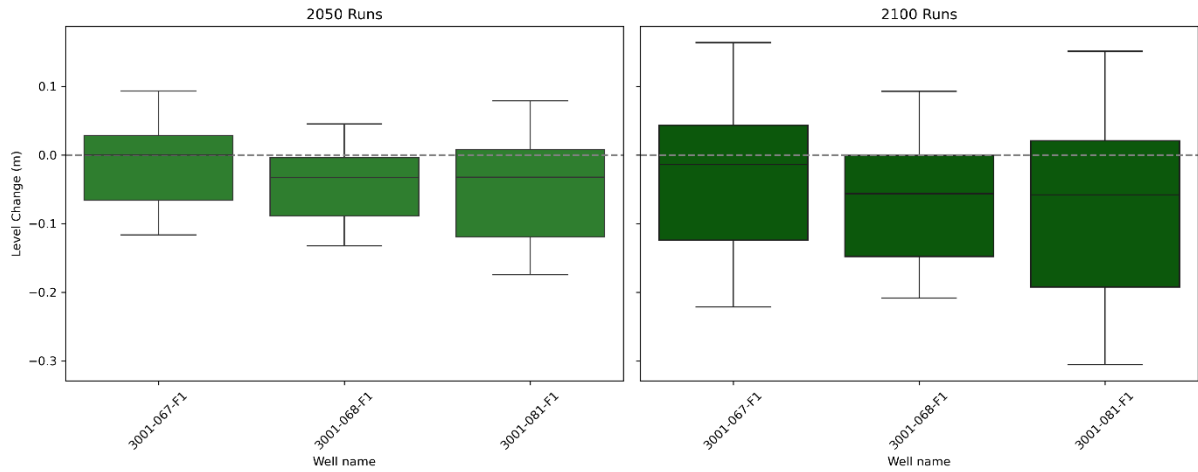
Change in Groundwater Levels for nieuwerkerken Wells



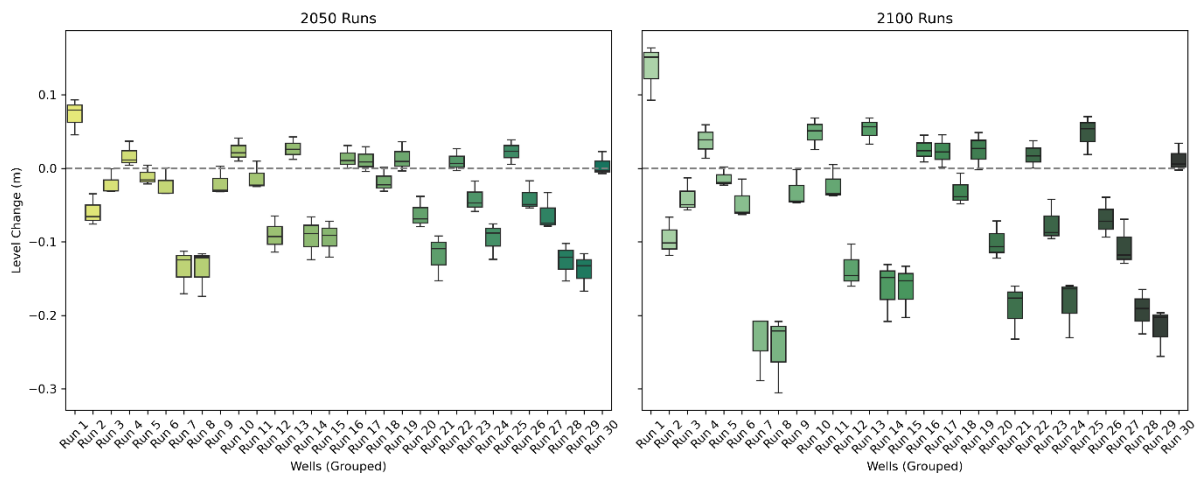
Change in Groundwater Levels for nieuwerkerken Wells (Grouped)



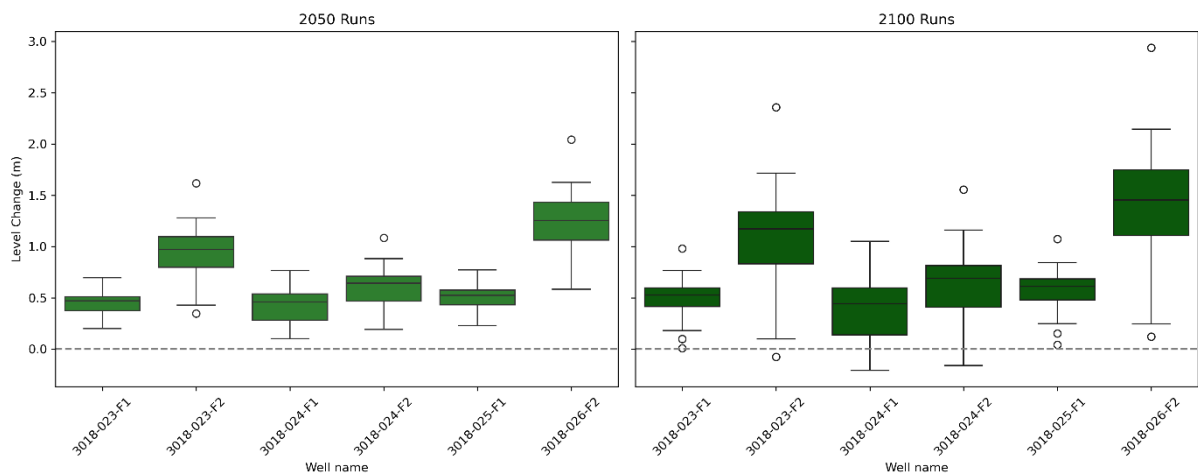
Change in Groundwater Levels for nieuwrode_het_rot Wells



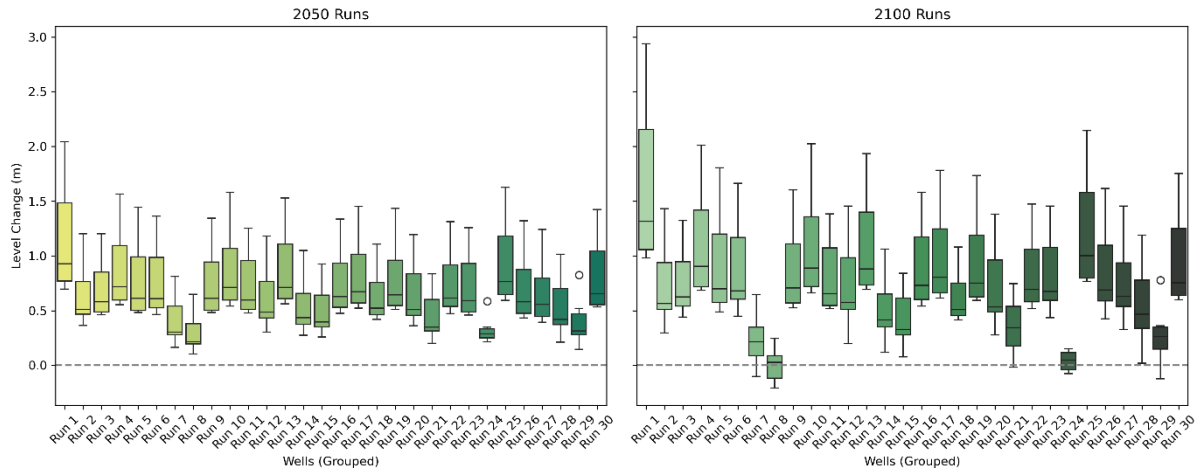
Change in Groundwater Levels for nieuwrode_het_rot



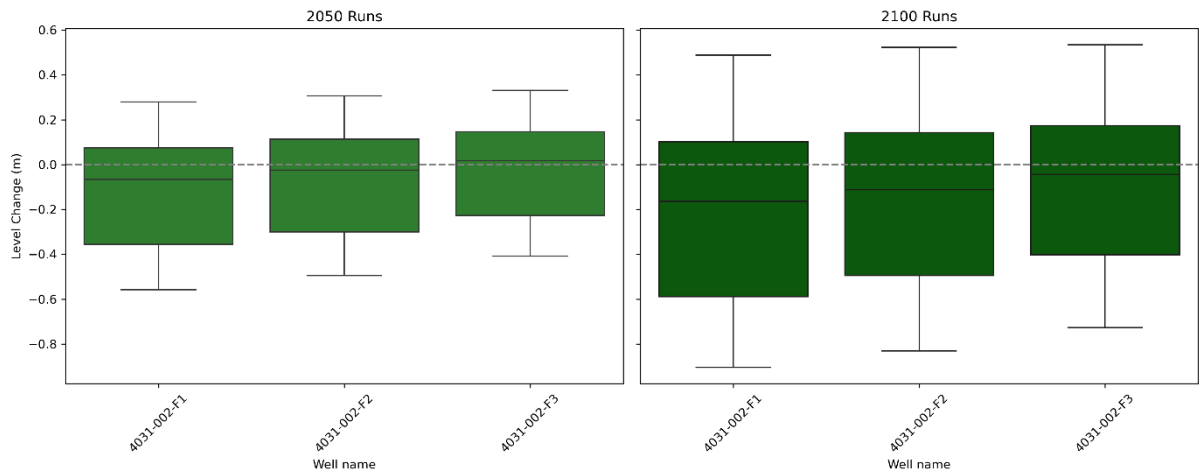
Change in Groundwater Levels for osseweg Wells



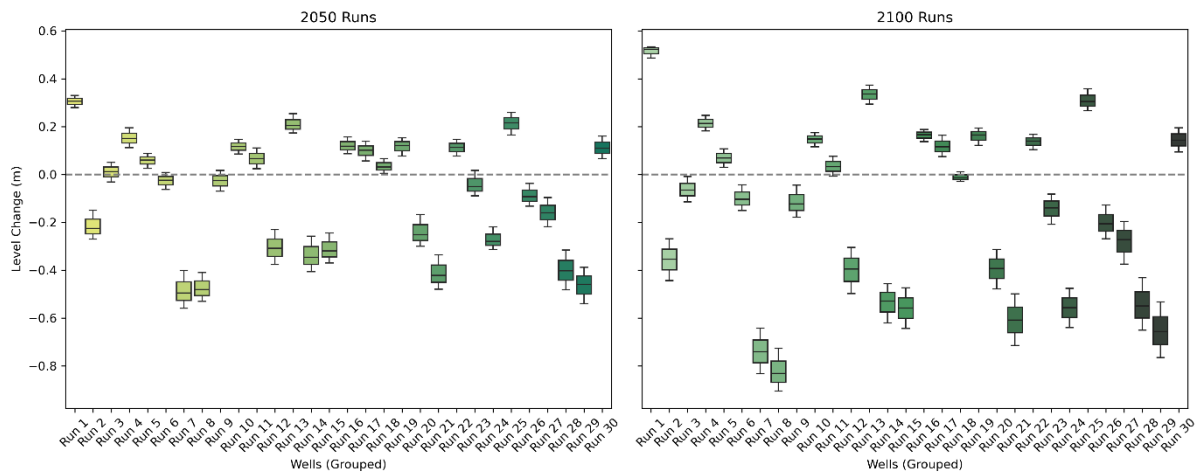
Change in Groundwater Levels for osseweg



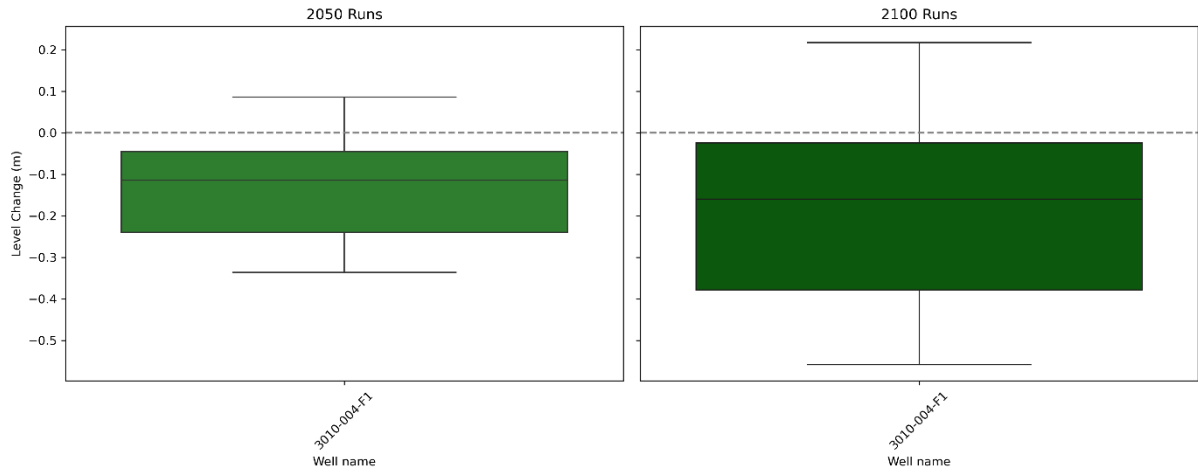
Change in Groundwater Levels for overhaem Wells



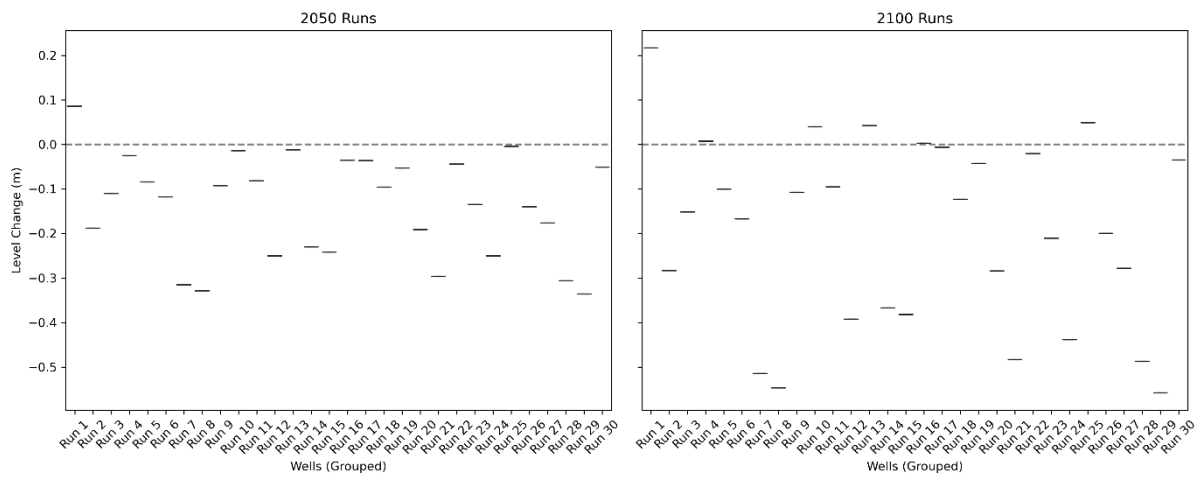
Change in Groundwater Levels for overhaem



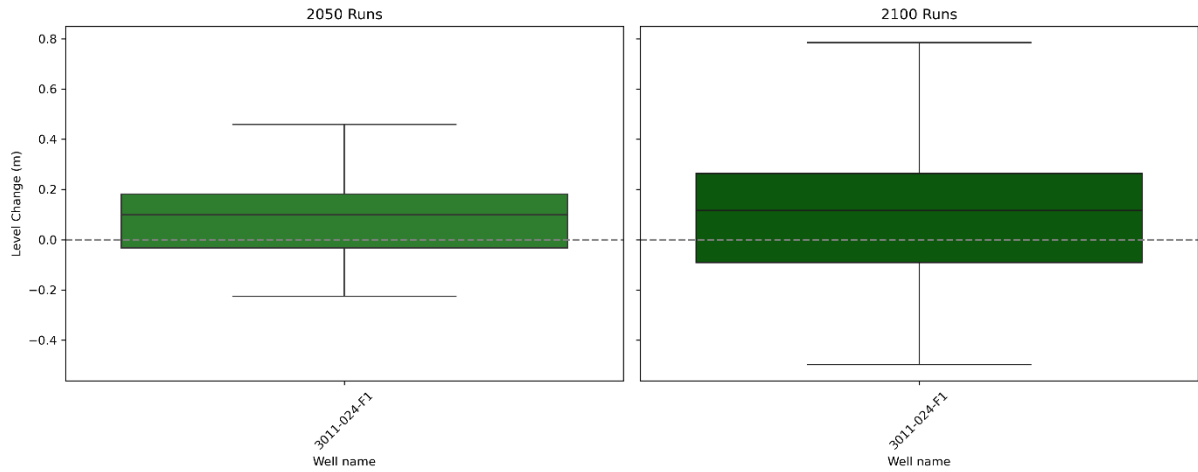
Change in Groundwater Levels for overijse_kouterstraat_nellebeek Wells



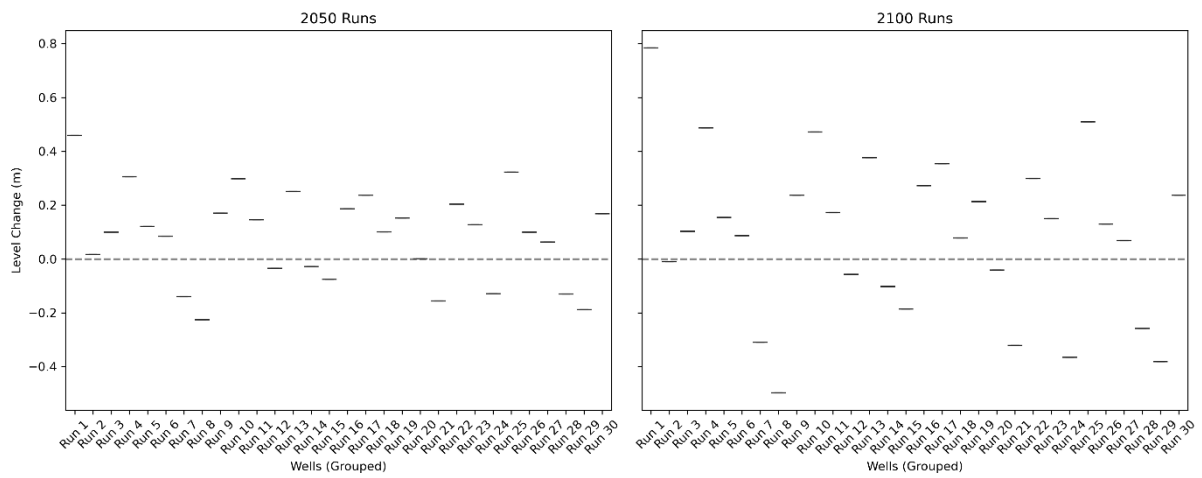
Change in Groundwater Levels for overijse_kouterstraat_nellebeek



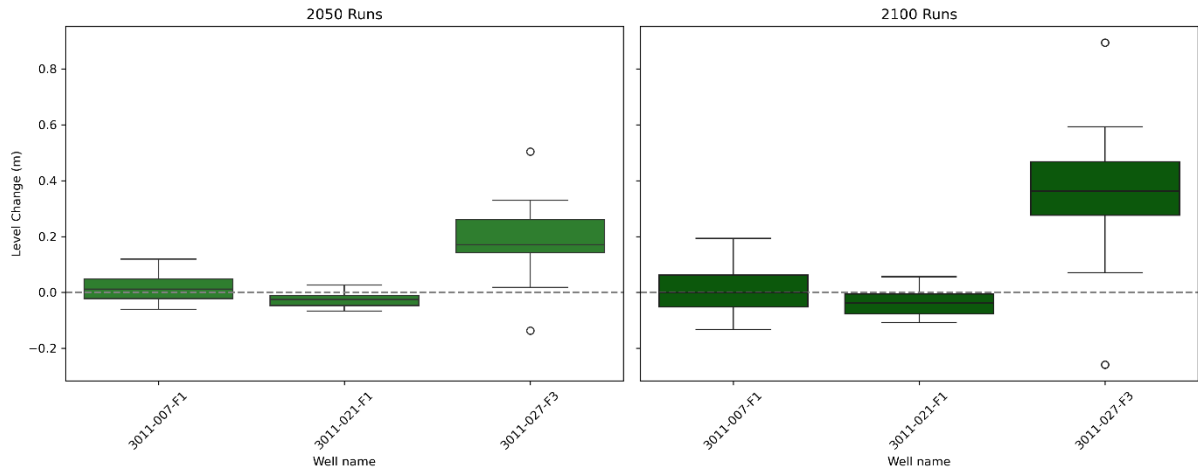
Change in Groundwater Levels for overijse_sana Wells



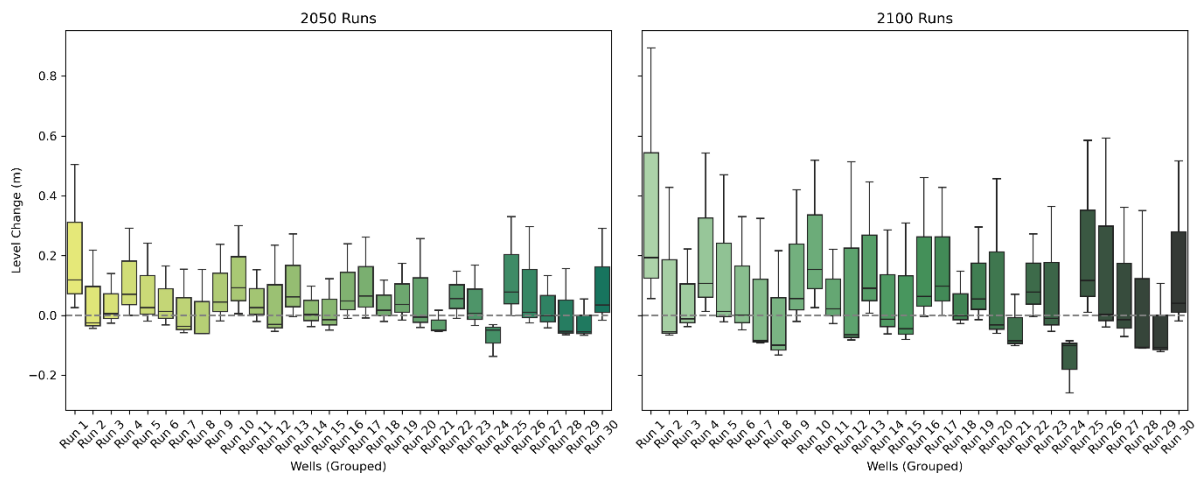
Change in Groundwater Levels for overijse_sana



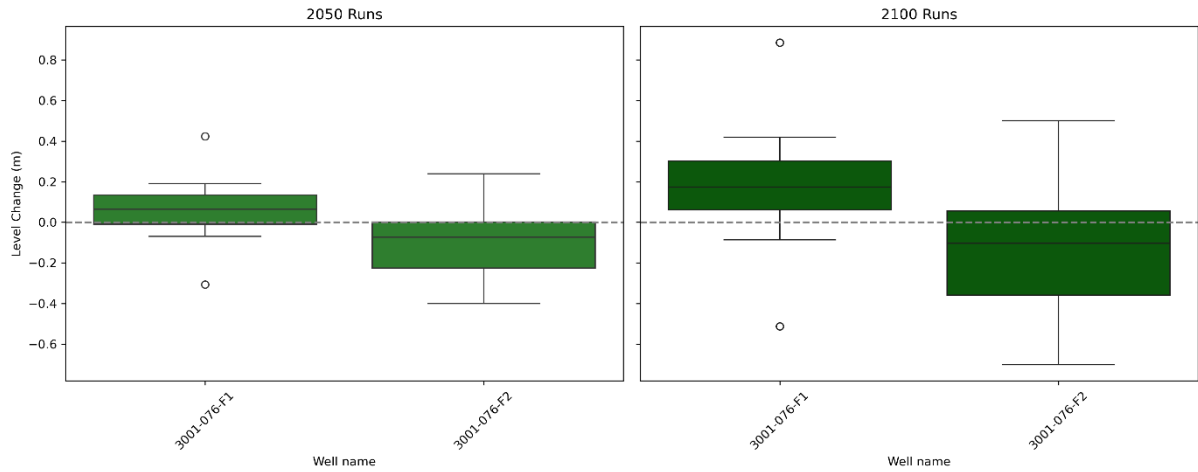
Change in Groundwater Levels for overijse_venusberg Wells



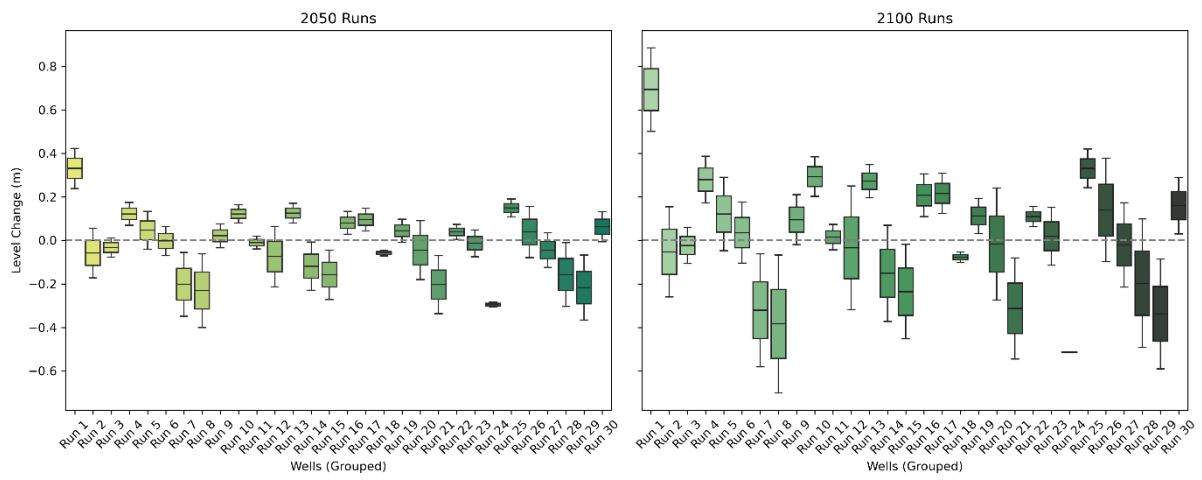
Change in Groundwater Levels for overijse_venusberg



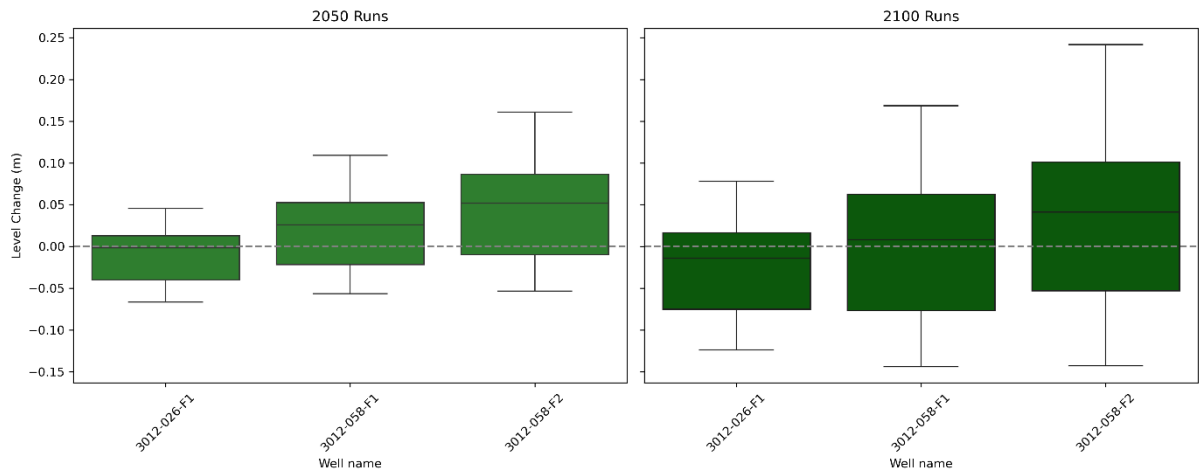
Change in Groundwater Levels for schoonhoven Wells



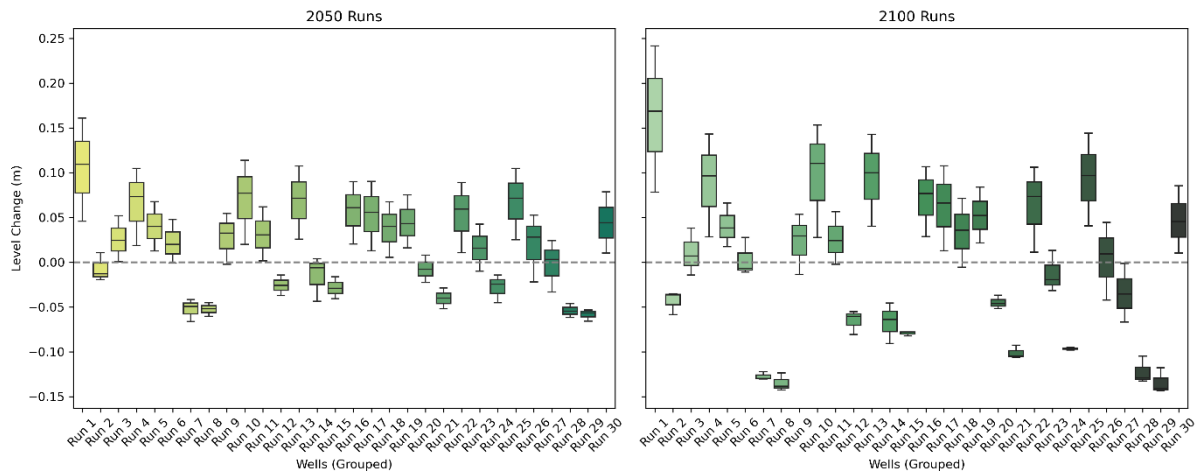
Change in Groundwater Levels for schoonhoven



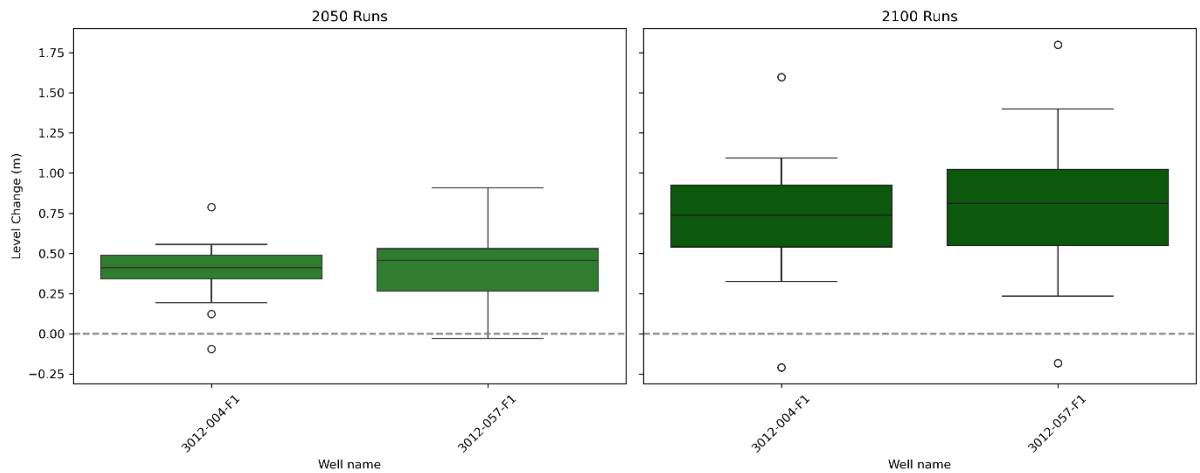
Change in Groundwater Levels for sint_agatha_rode_geuzenhoek Wells



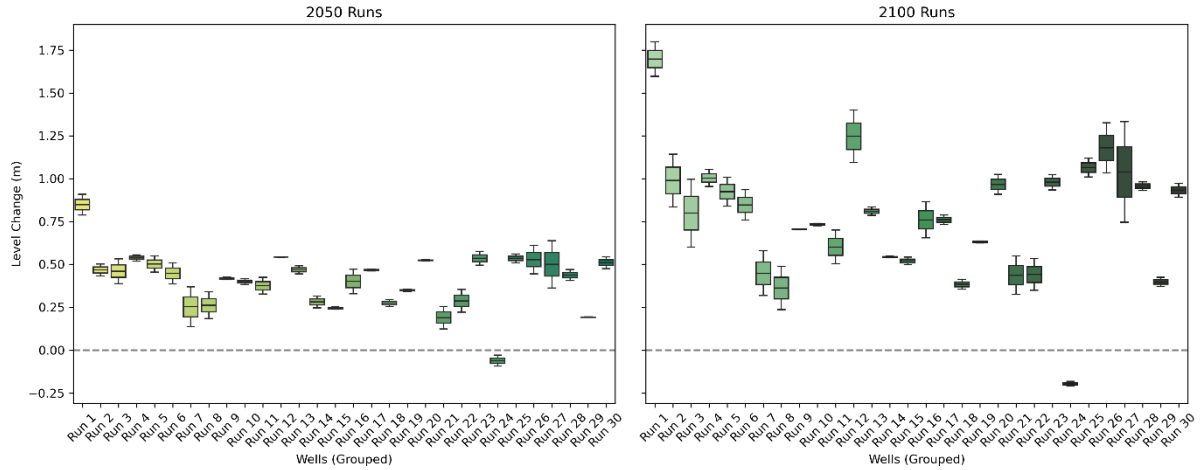
Change in Groundwater Levels for sint_agatha_rode_geuzenhoek



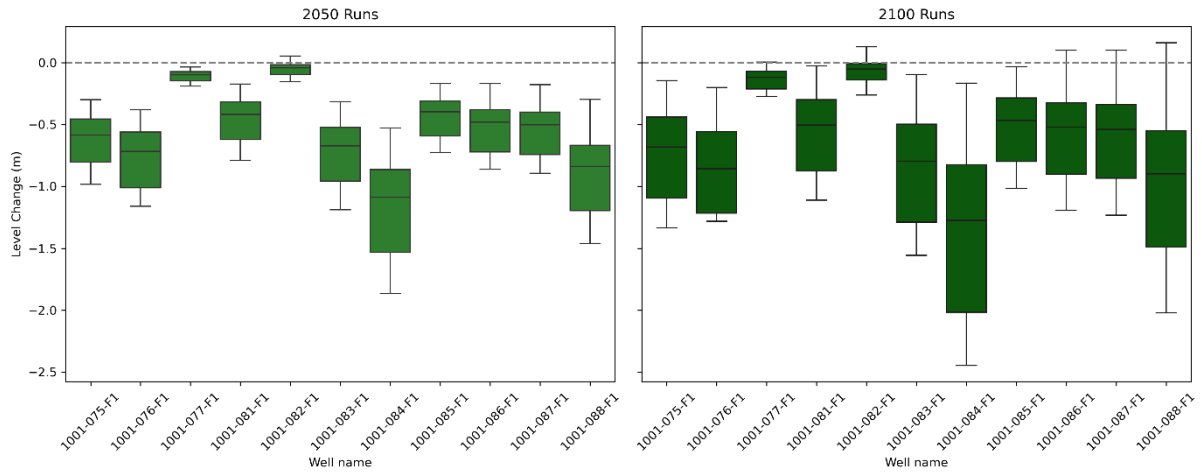
Change in Groundwater Levels for sint_agatha_rode_veeweyde Wells



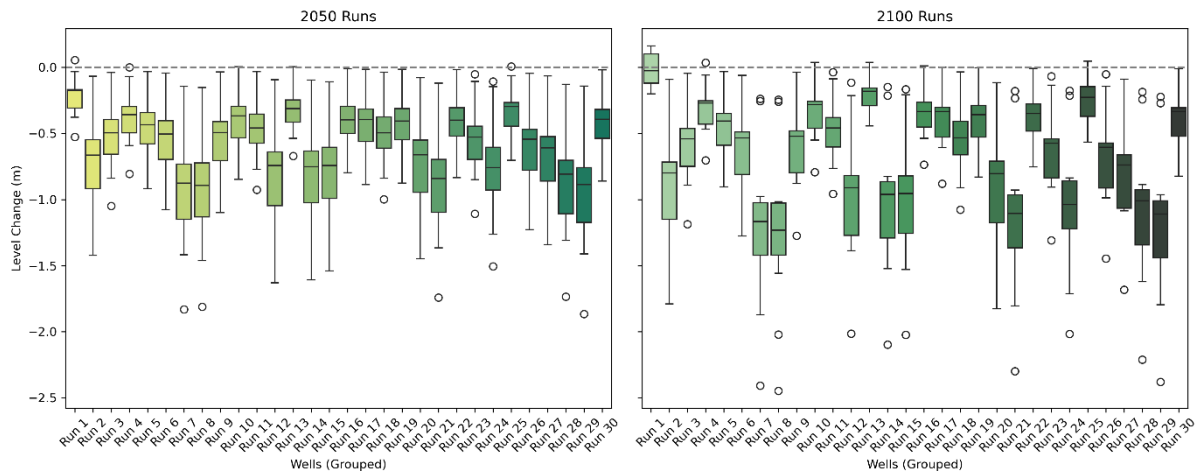
Change in Groundwater Levels for sint_agatha_rode_veeweyde



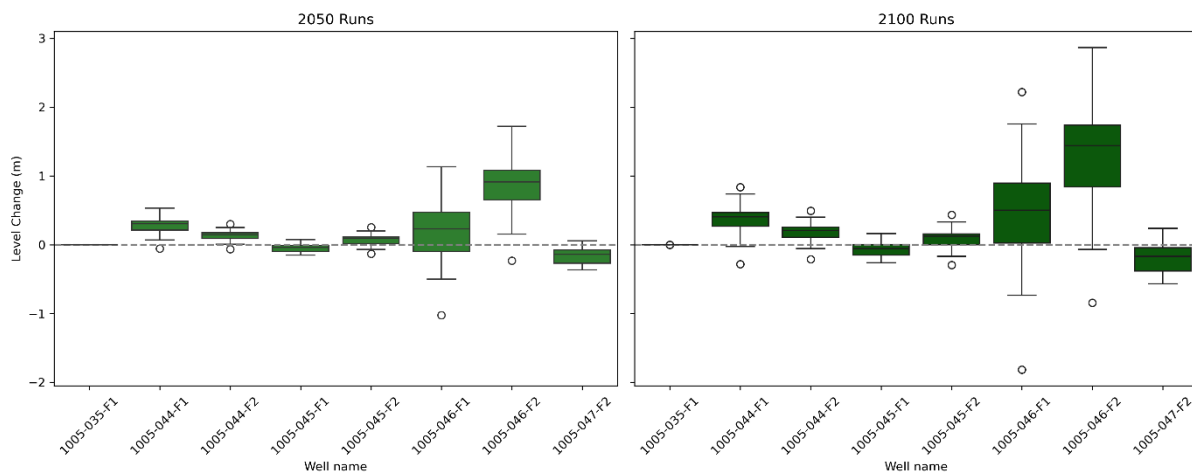
Change in Groundwater Levels for snellegem Wells



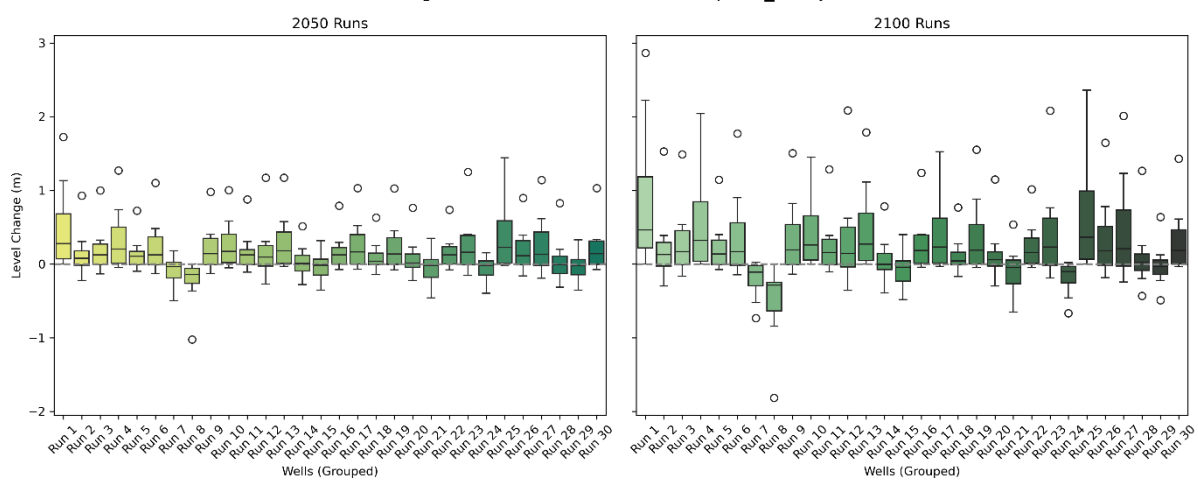
Change in Groundwater Levels for snellegem



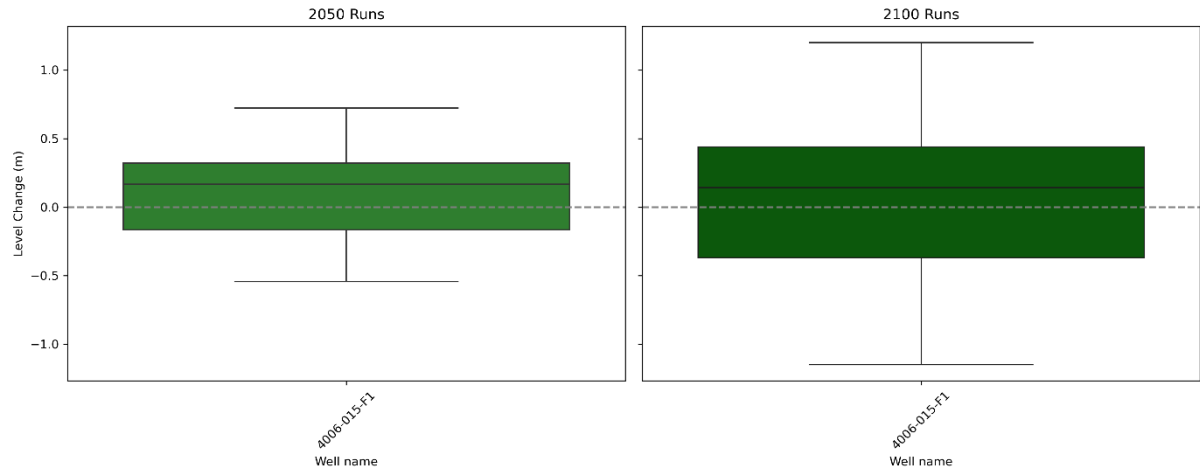
Change in Groundwater Levels for spiere_helkijn Wells



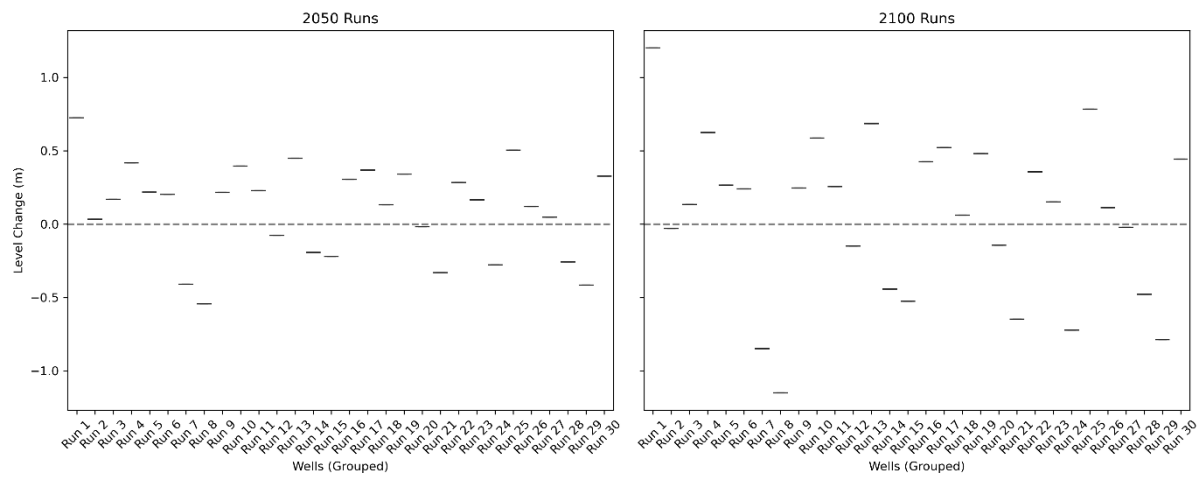
Change in Groundwater Levels for spiere_helkijn



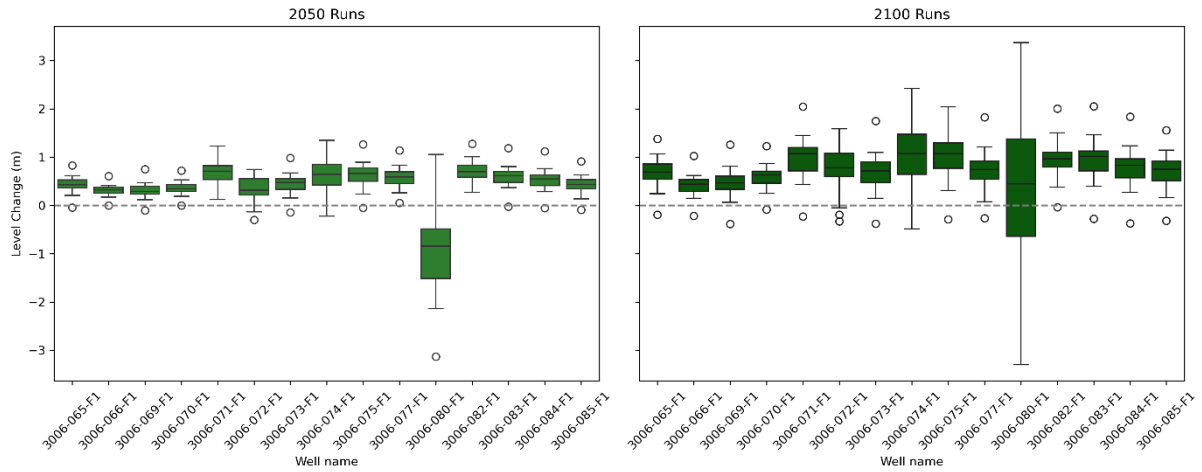
Change in Groundwater Levels for tessenderlo Wells



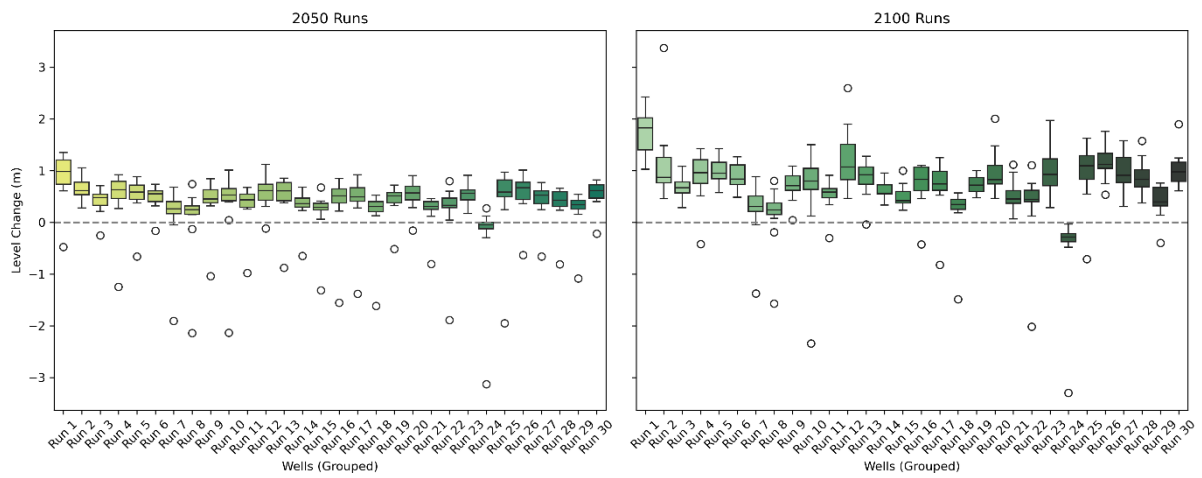
Change in Groundwater Levels for tessenderlo



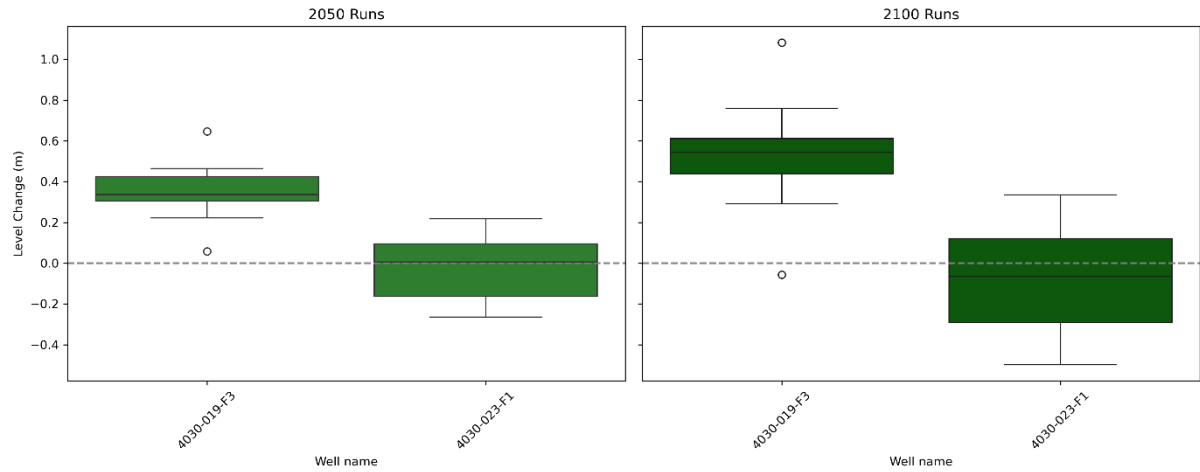
Change in Groundwater Levels for tgv Wells



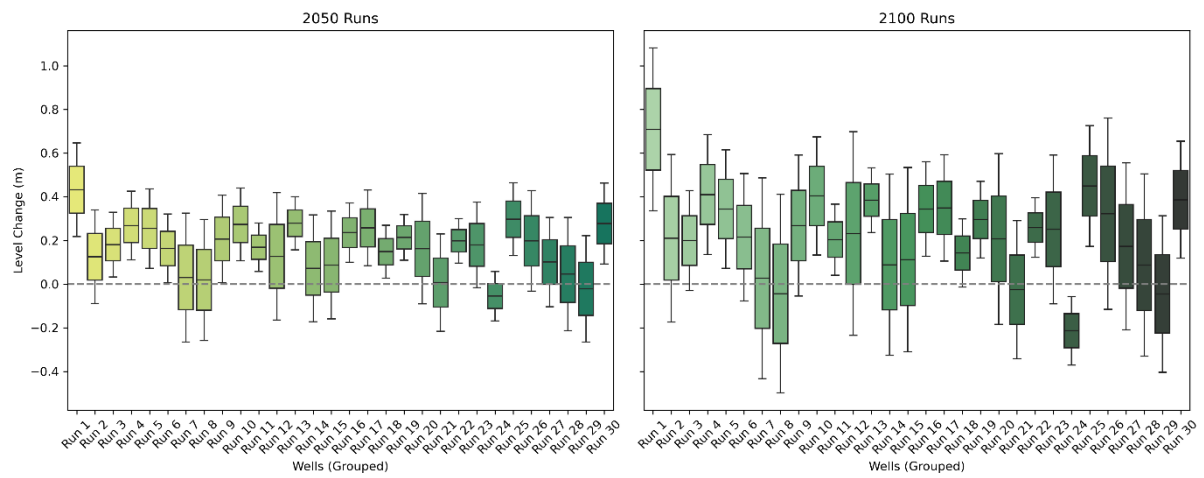
Change in Groundwater Levels for tgv



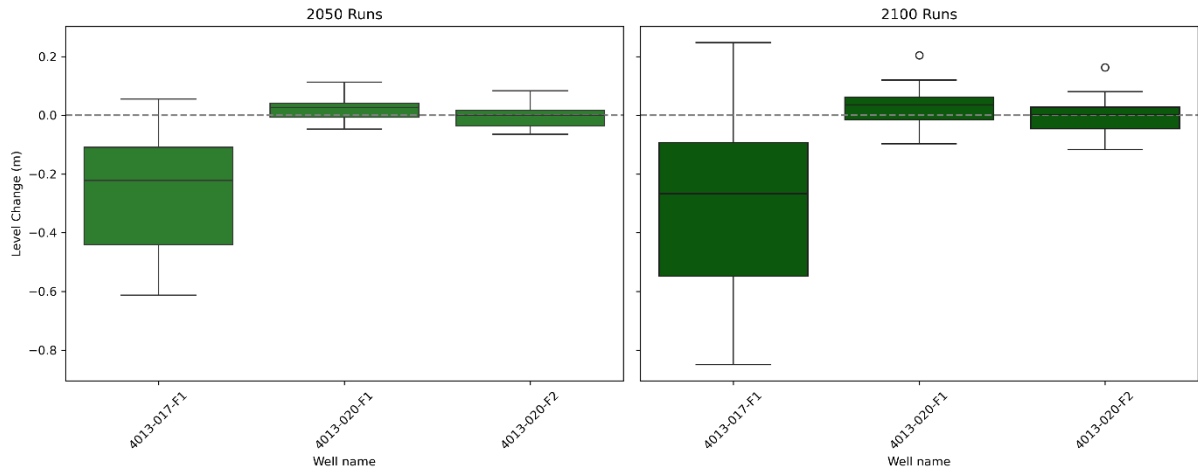
Change in Groundwater Levels for trekschuren Wells



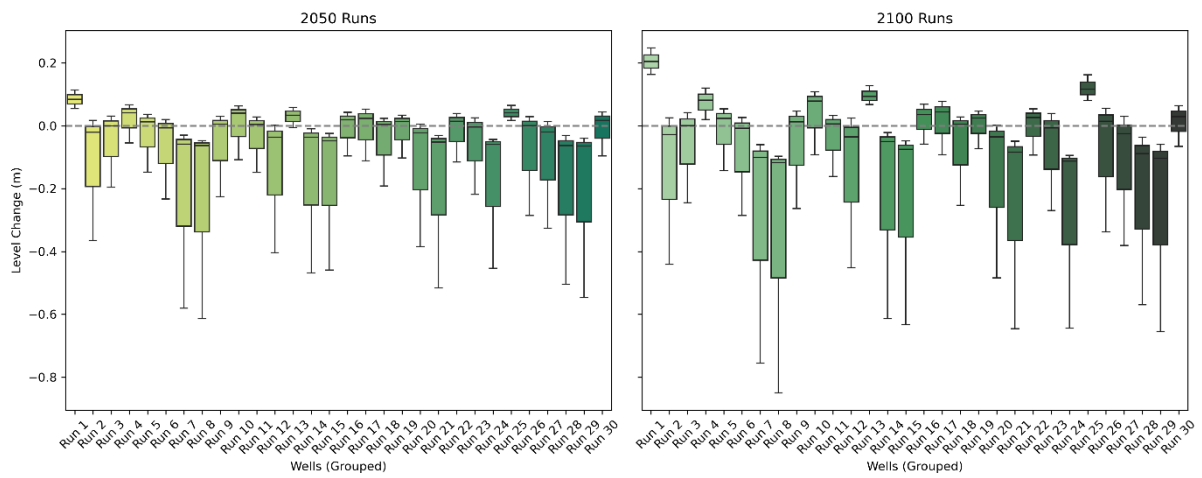
Change in Groundwater Levels for trekschuren



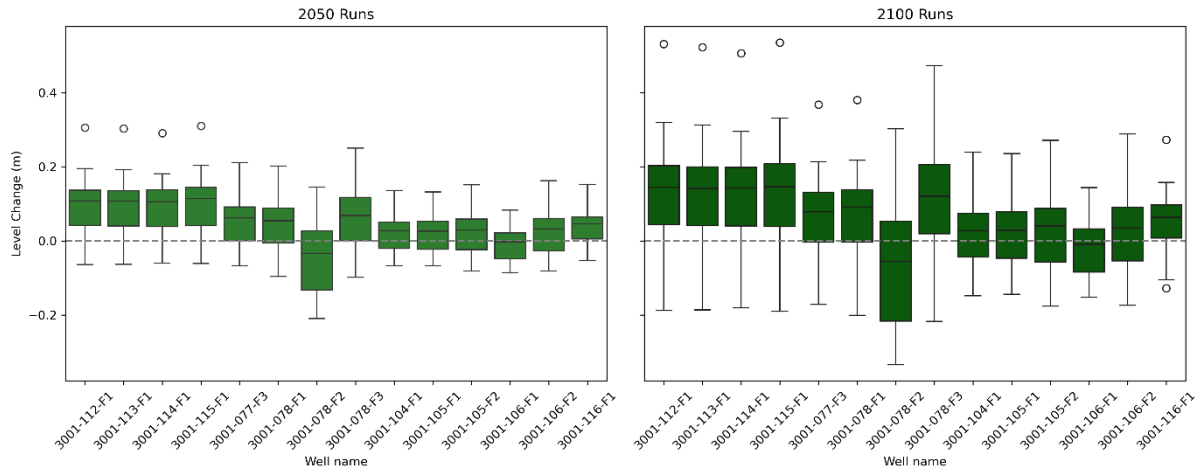
Change in Groundwater Levels for waltwilder Wells



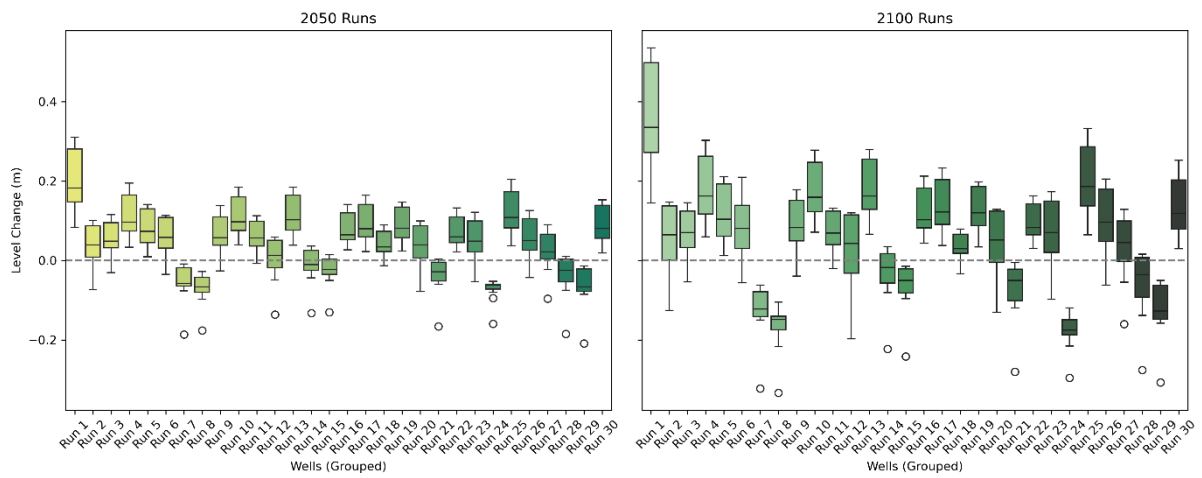
Change in Groundwater Levels for waltwilder



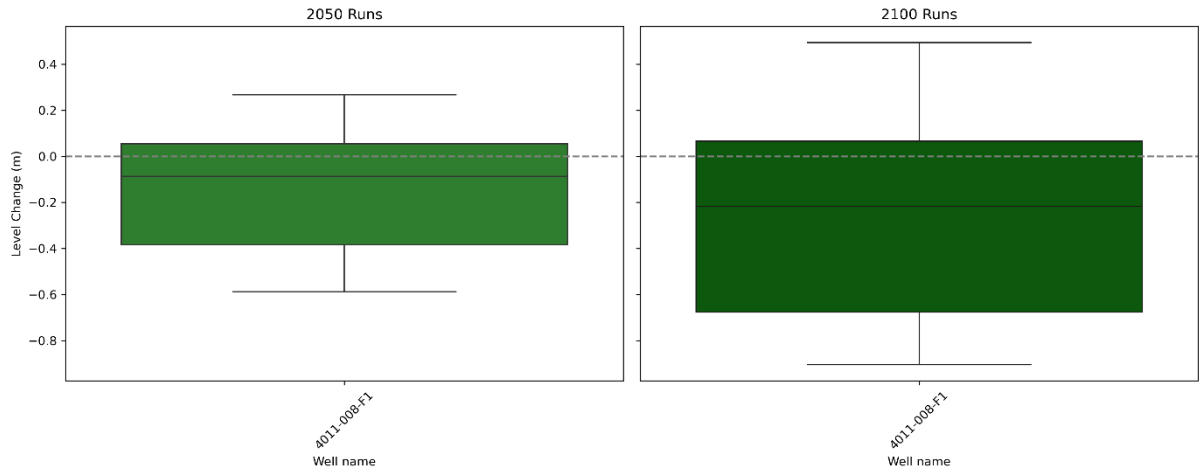
Change in Groundwater Levels for weerderlaak Wells



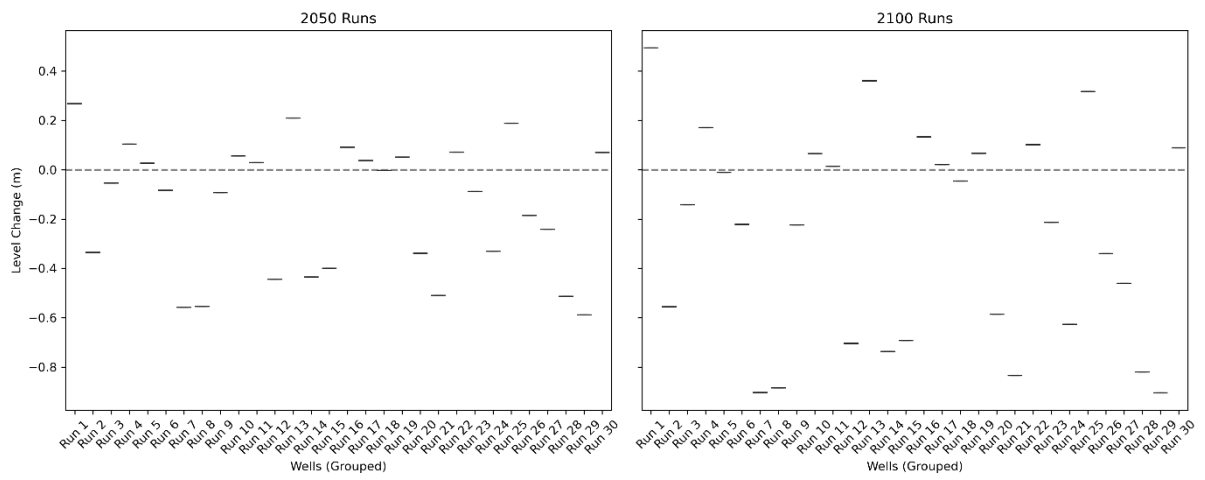
Change in Groundwater Levels for weerderlaak



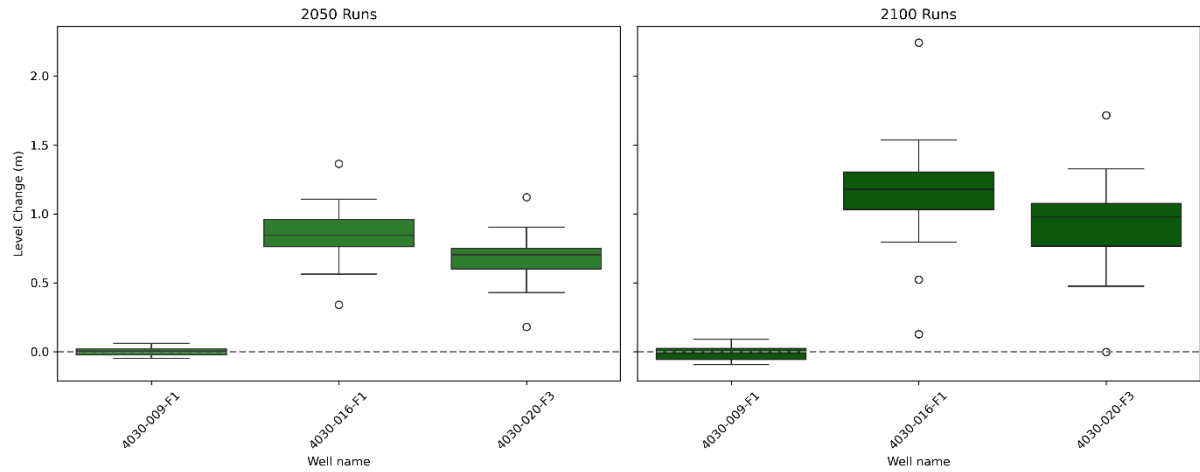
Change in Groundwater Levels for wellen Wells



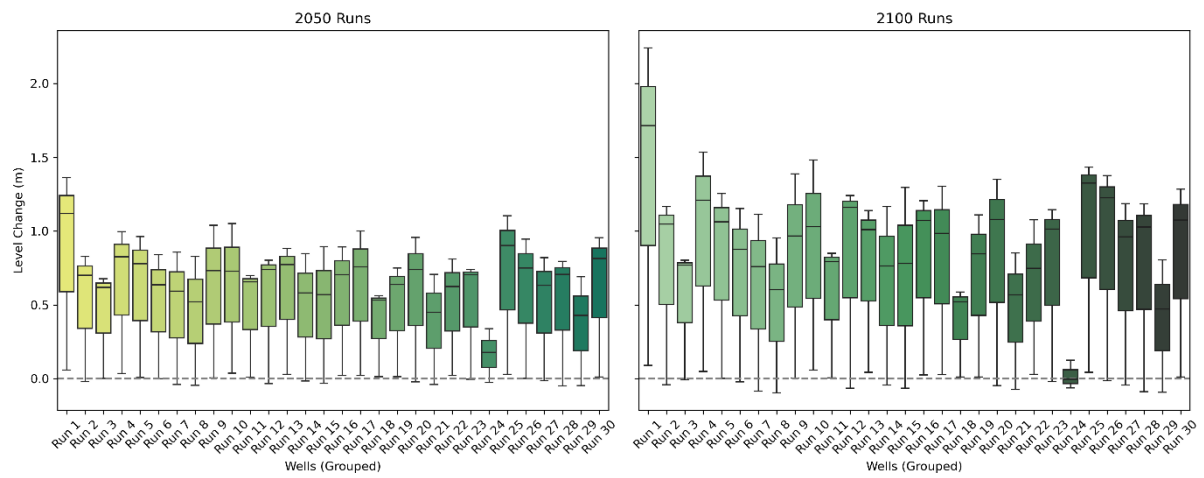
Change in Groundwater Levels for wellen



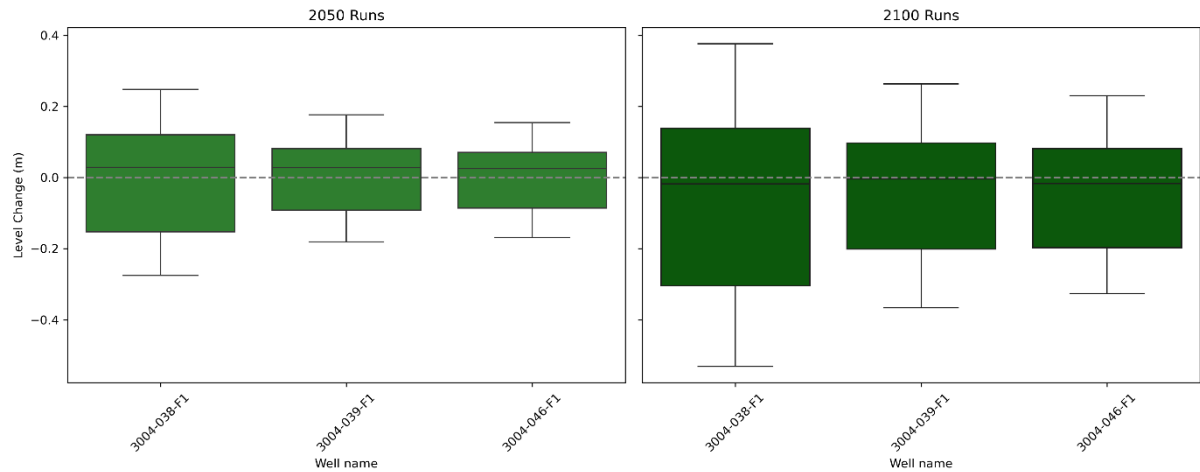
Change in Groundwater Levels for willekensmolen Wells



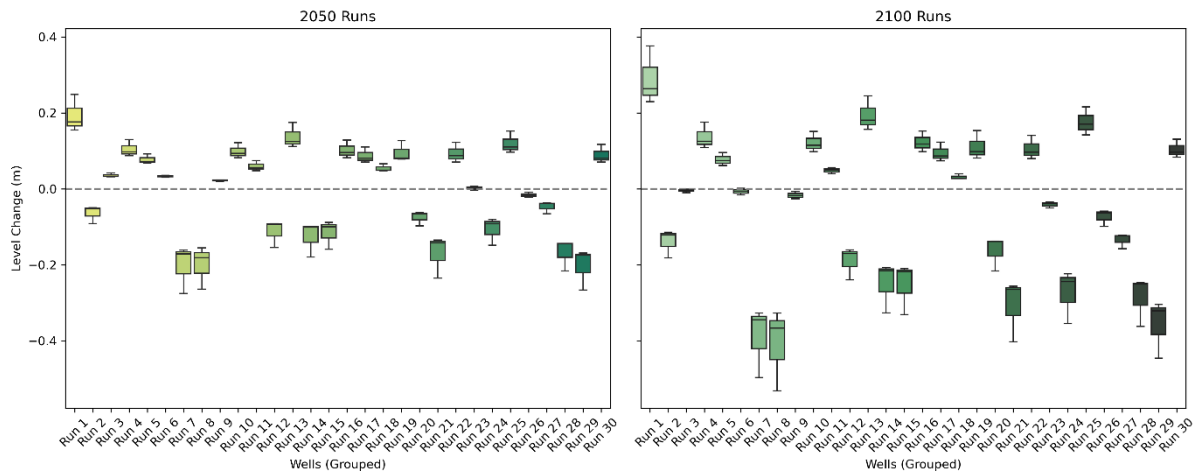
Change in Groundwater Levels for willekensmolen



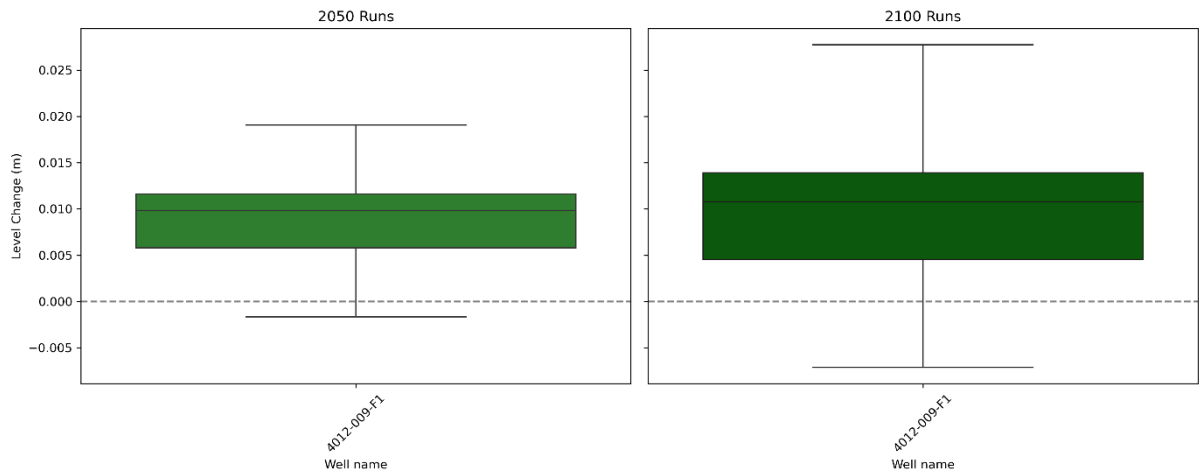
Change in Groundwater Levels for winksele_kastanjebos Wells



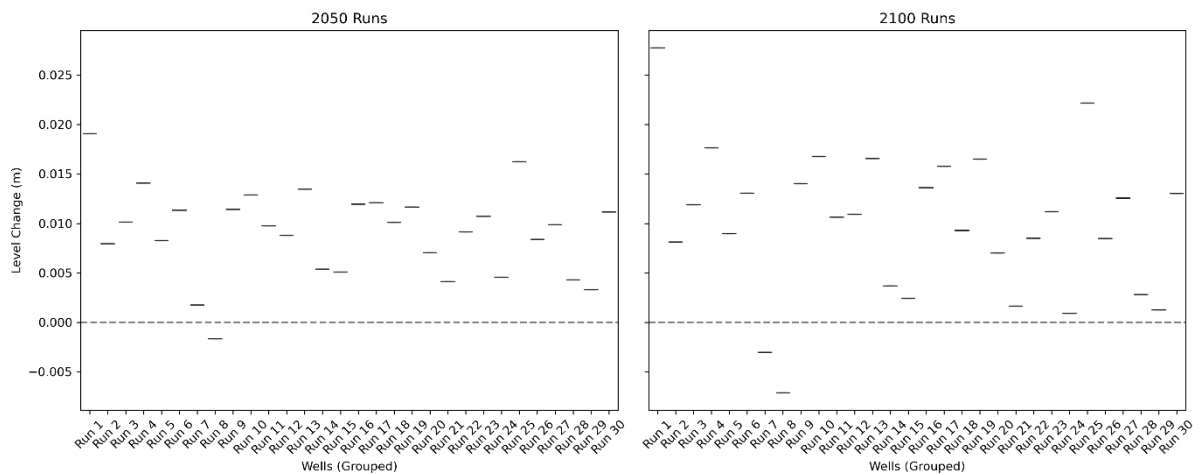
Change in Groundwater Levels for winksele_kastanjebos



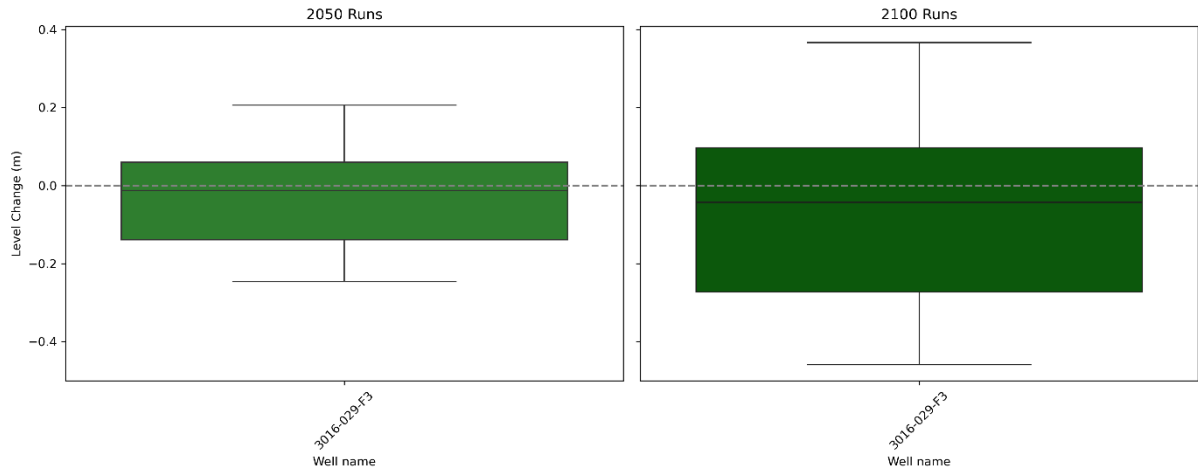
Change in Groundwater Levels for wintershoven Wells



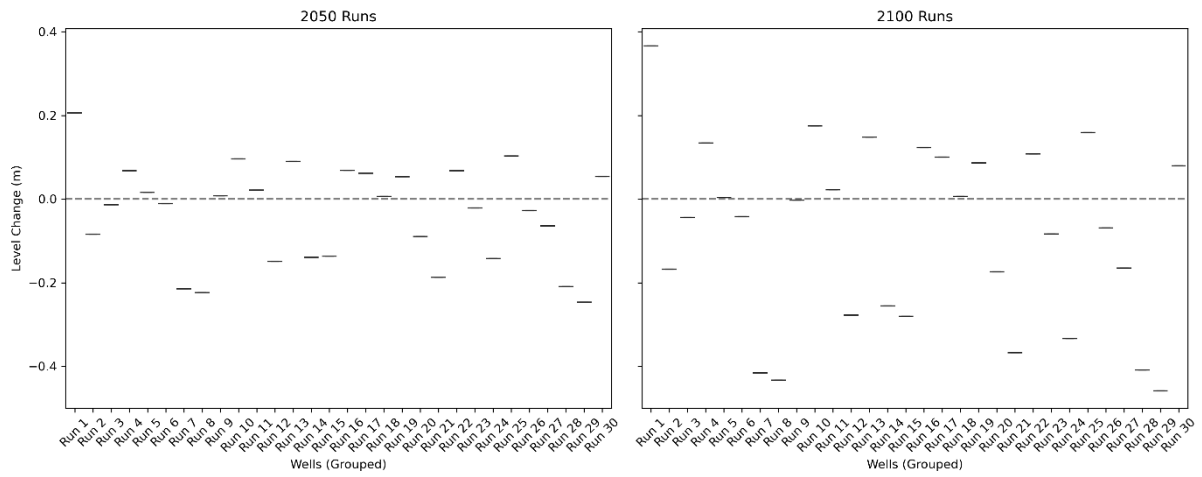
Change in Groundwater Levels for wintershoven



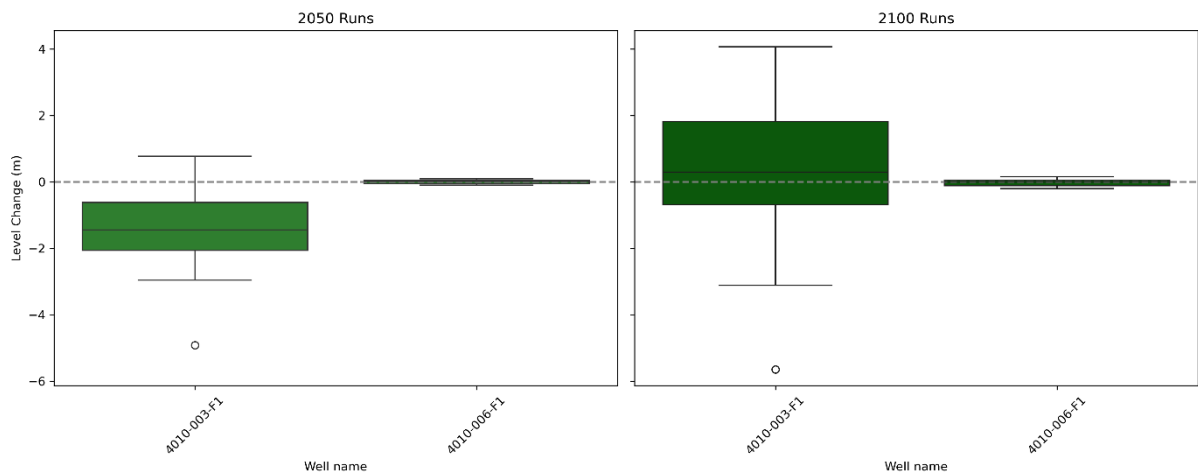
Change in Groundwater Levels for zemst_spelt Wells



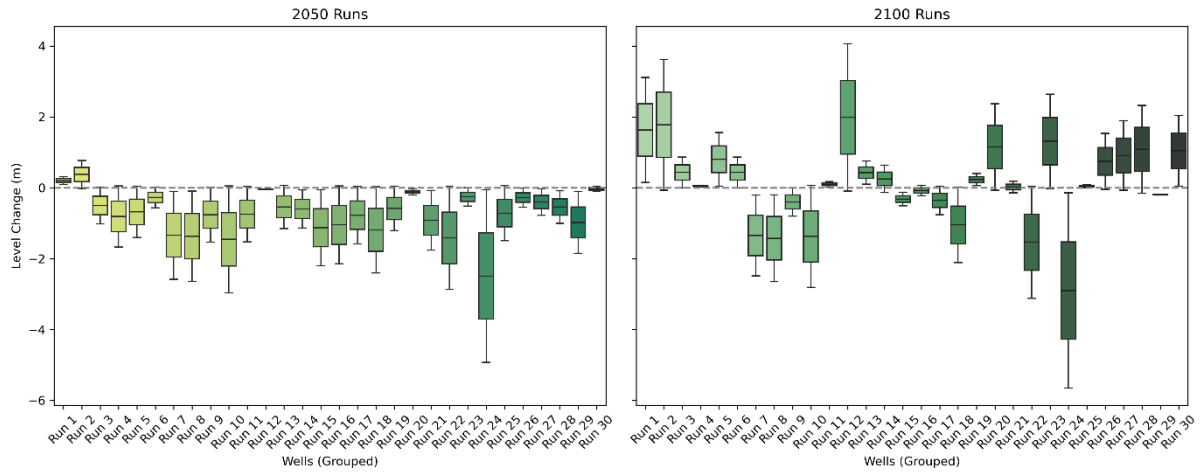
Change in Groundwater Levels for zemst_spelt



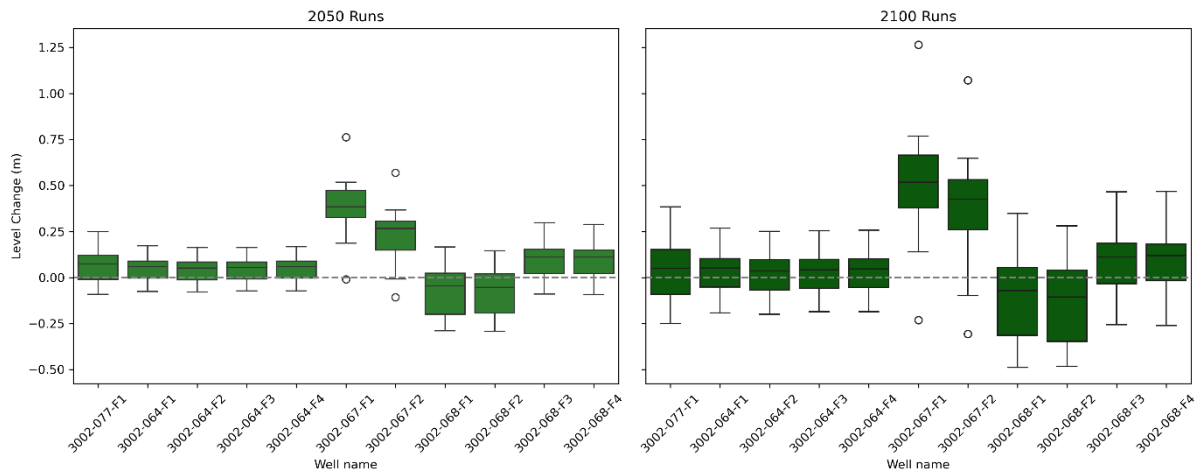
Change in Groundwater Levels for zepperen Wells



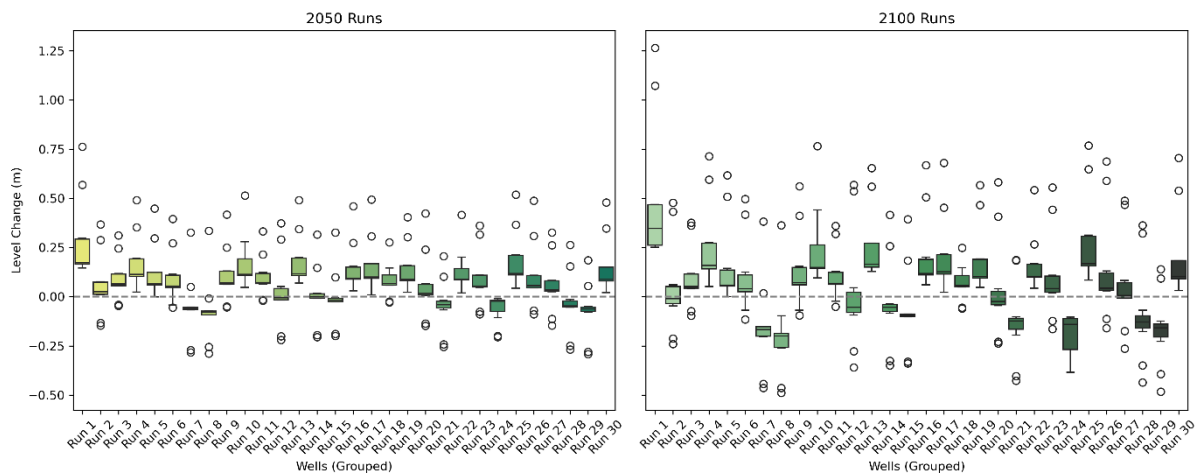
Change in Groundwater Levels for zepperen



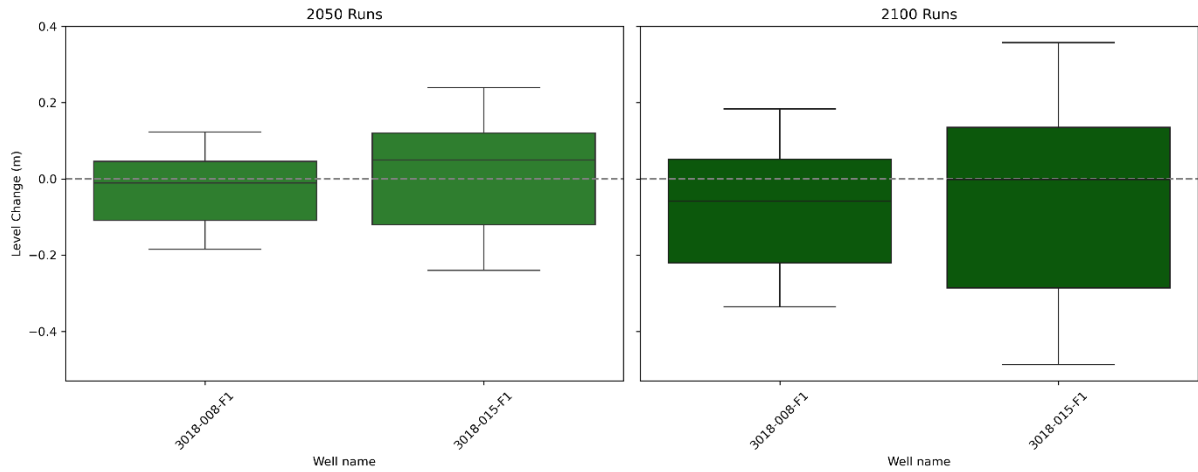
Change in Groundwater Levels for zichem_vinkenberg Wells



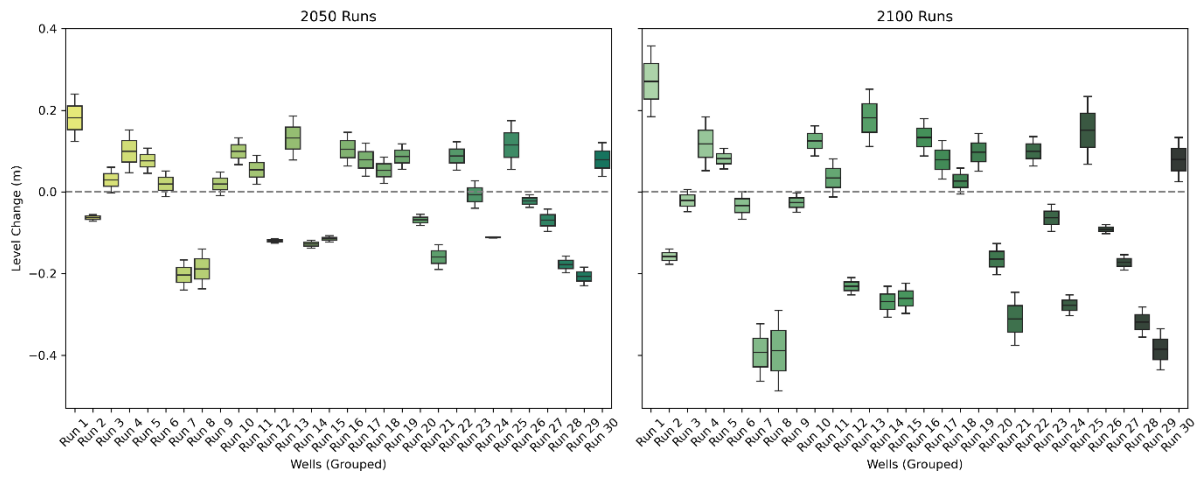
Change in Groundwater Levels for zichem_vinkenberg



Change in Groundwater Levels for zoutleeuw Wells



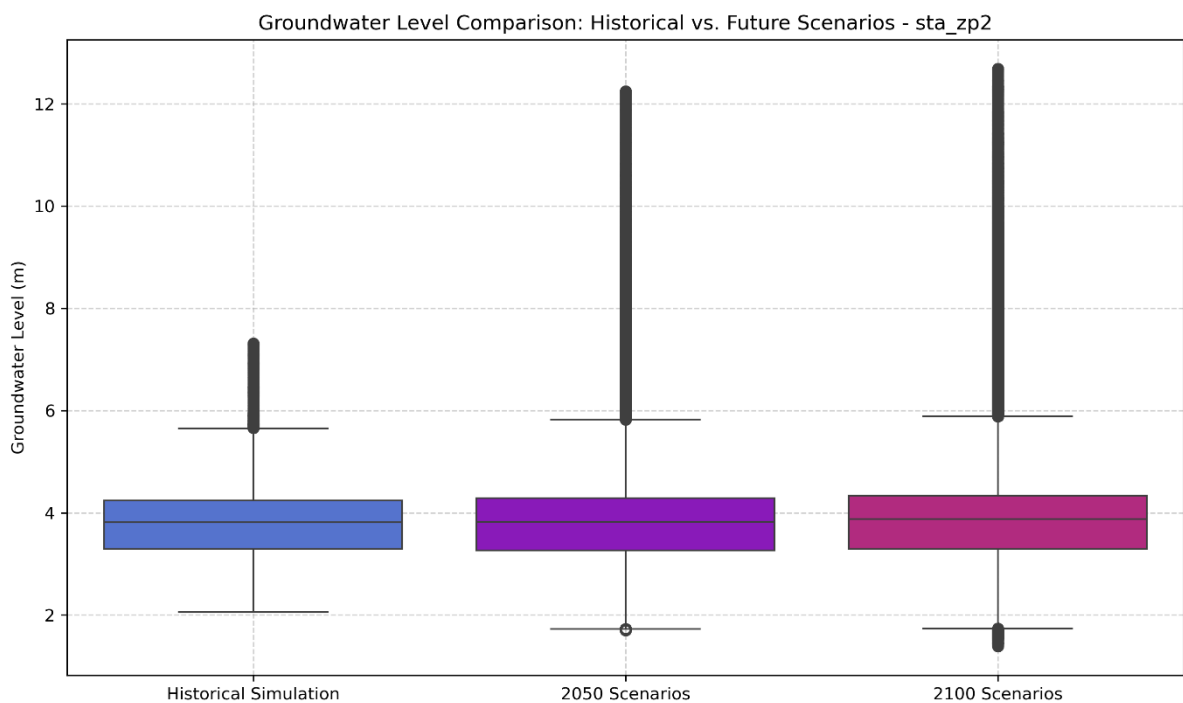
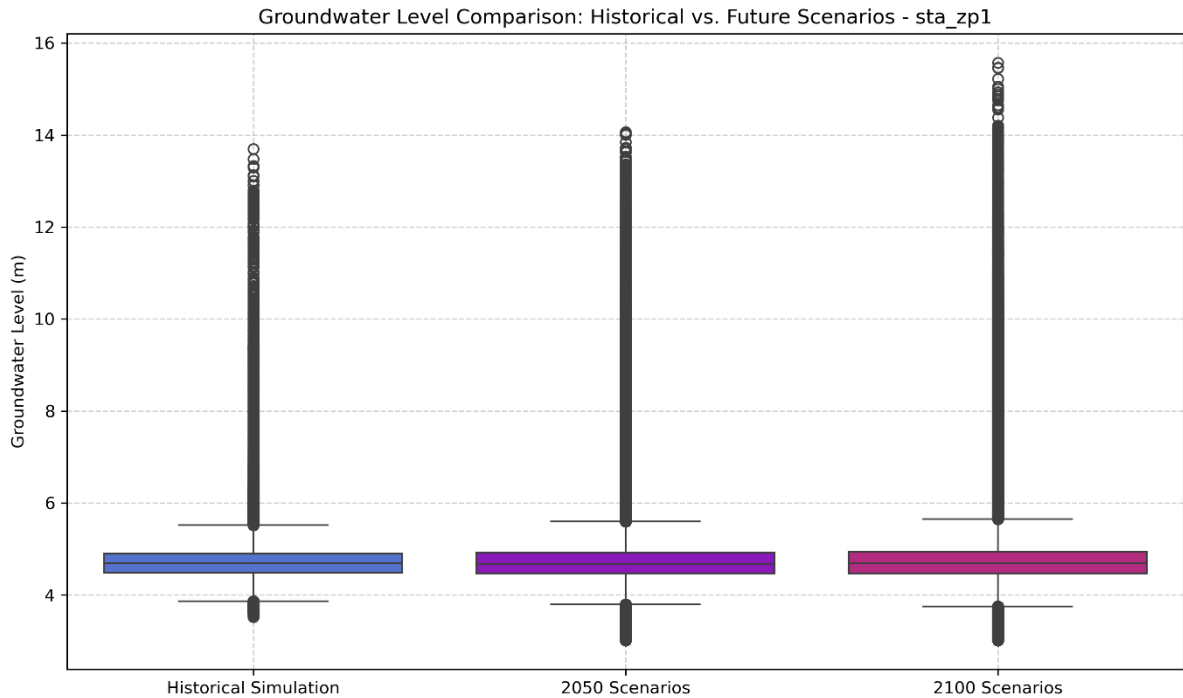
Change in Groundwater Levels for zoutleeuw

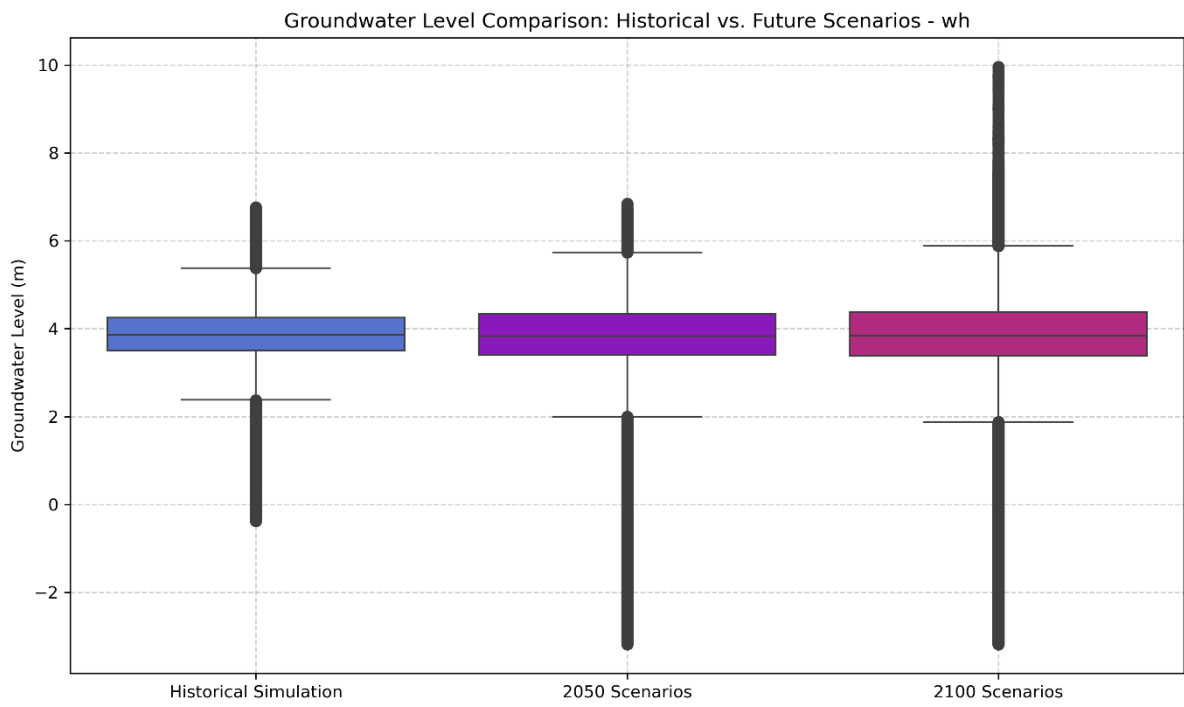


10.3 Appendix C: Aquaduin results

10.3.1 C.1 Aquaduin Groundwater Level comparison

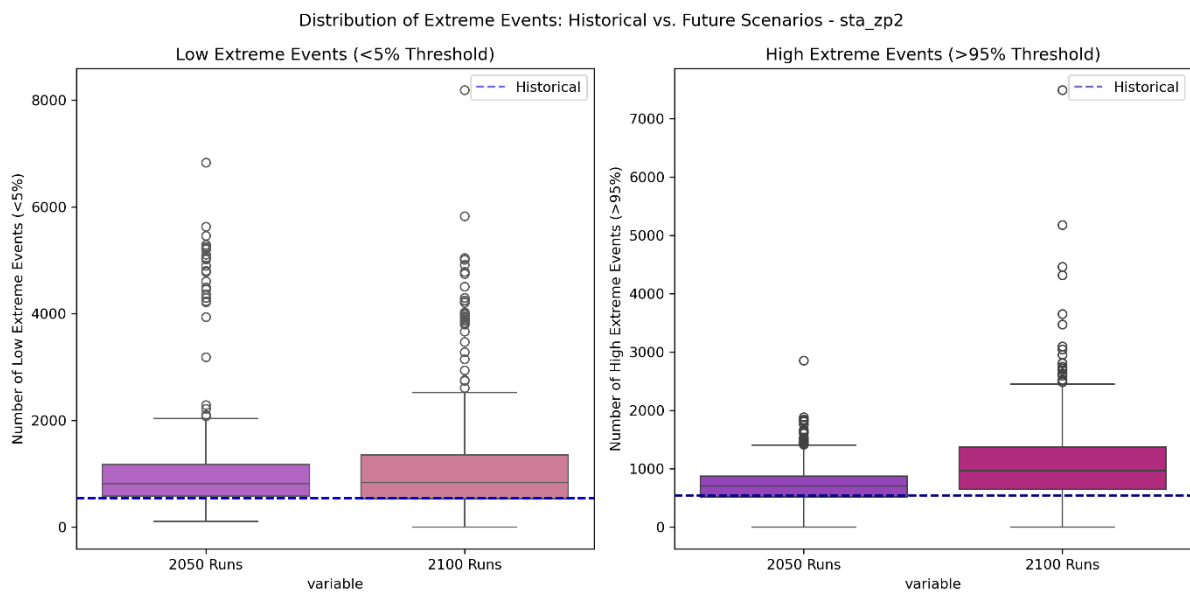
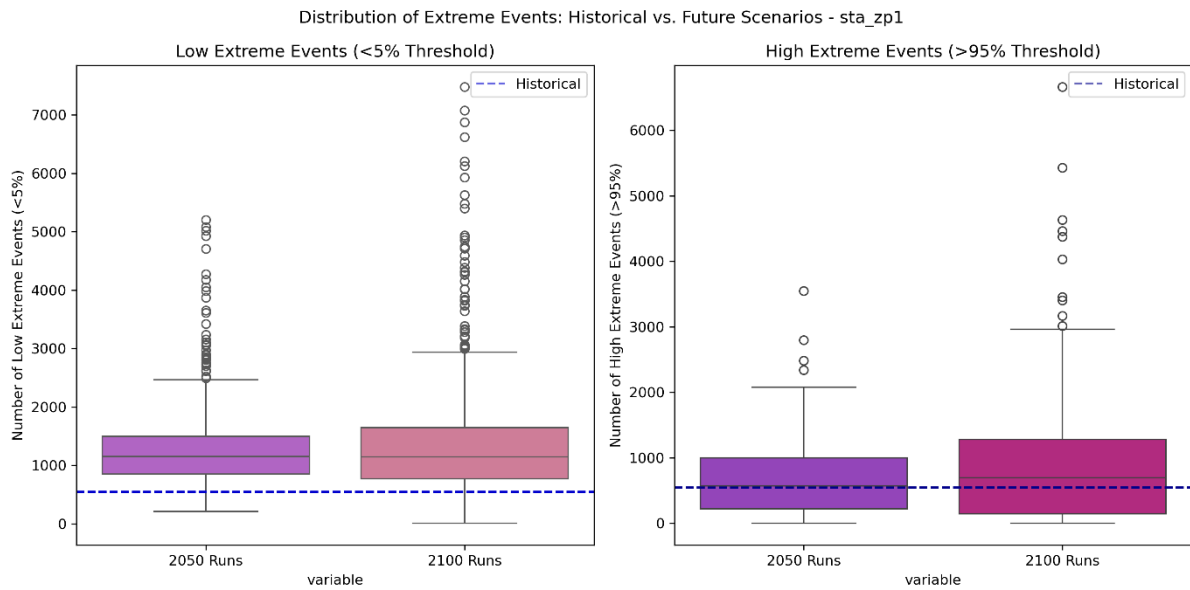
Comparison of simulated groundwater levels under historical and future climate scenarios for three examples of group of wells.



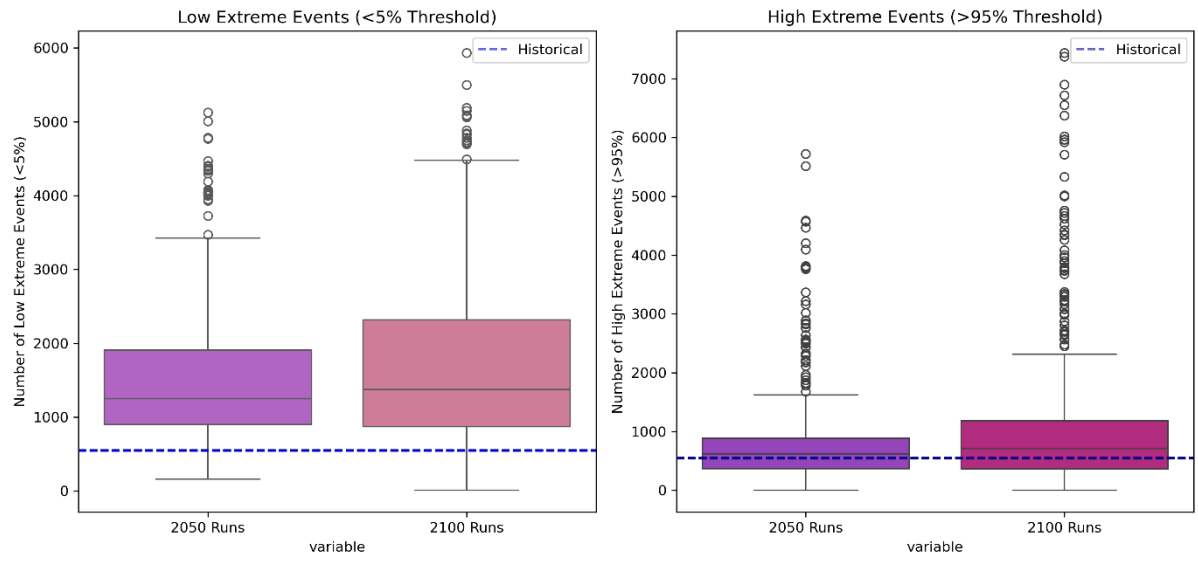


10.3.2 C.2 Aquaduin Distribution of Extreme Events

Distribution of extreme groundwater level events under future scenarios for the Hoogstraten group of wells.

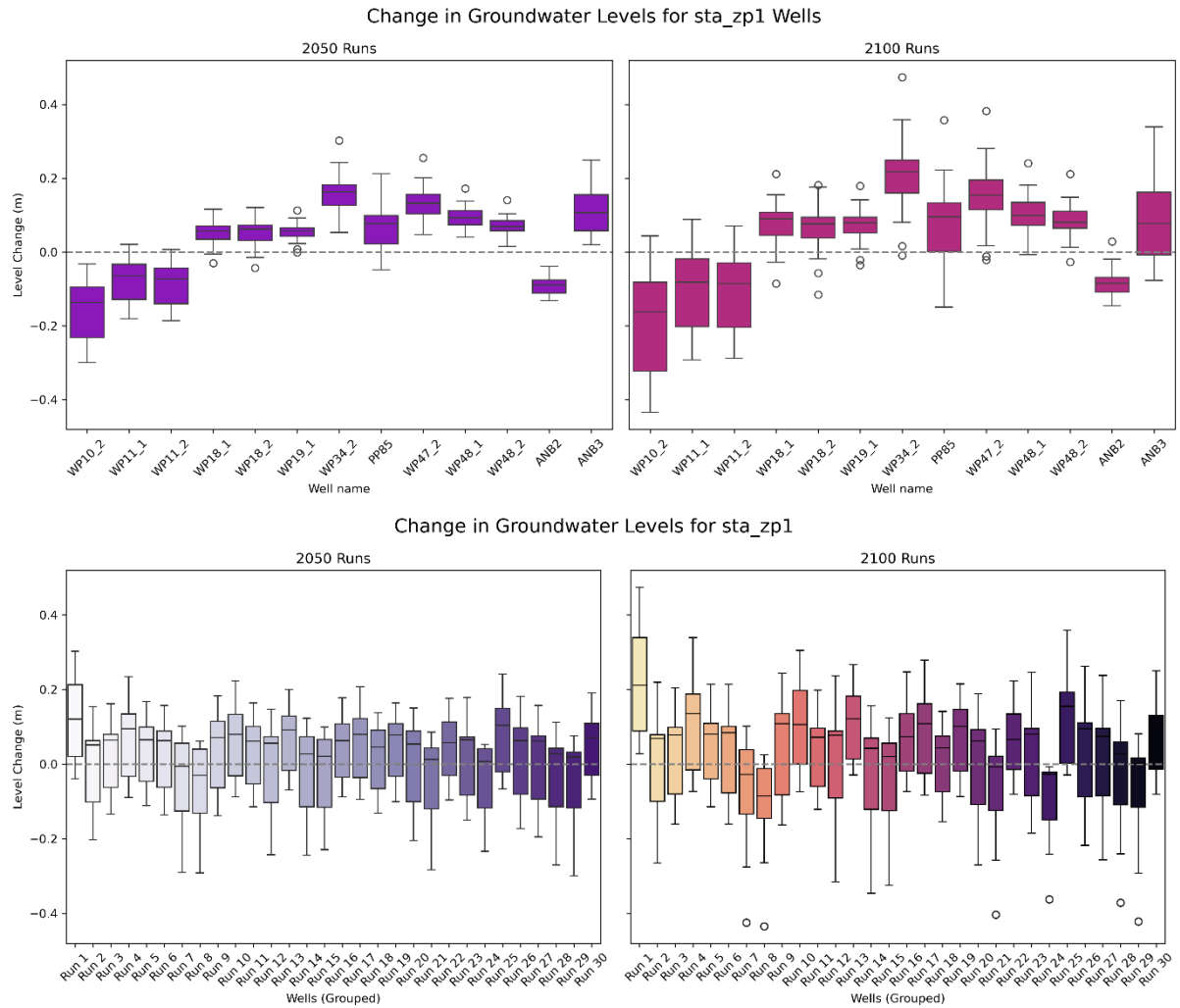


Distribution of Extreme Events: Historical vs. Future Scenarios - wh

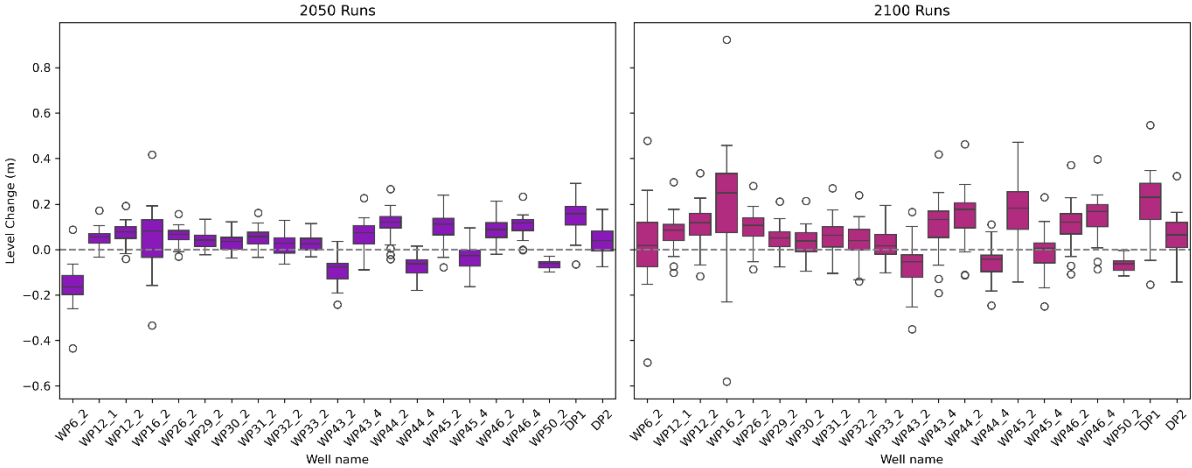


10.3.3 C.3 Aquaduin Projected change in groundwater levels

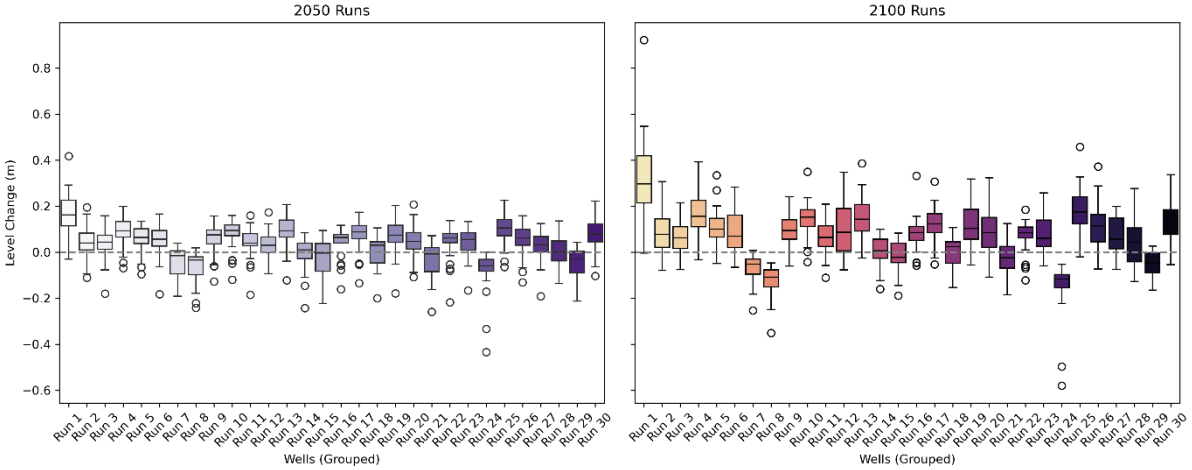
Projected change in groundwater levels across a) individual wells for aggregated simulation runs (2050 and 2100).



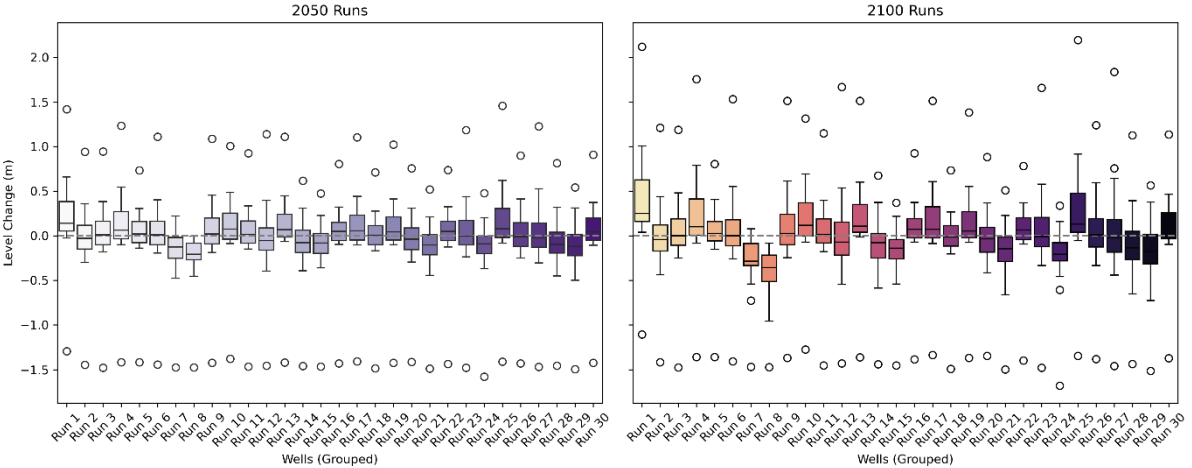
Change in Groundwater Levels for sta_zp2 Wells



Change in Groundwater Levels for sta_zp2



Change in Groundwater Levels for wh



Change in Groundwater Levels for wh Wells

