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# How (Managed) Drainage Shapes Regional Hydrology: Model Based Insights for Flanders

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**Abstract.** Artificial drainage is widely used in agricultural landscapes to improve trafficability and prevent waterlogging, but comes at the expense of groundwater storage and regional drought resilience. Through model scenarios, this study evaluates how large-scale drain-level adjustments influence groundwater dynamics, water balances, and streamflow extremes across different regions in Flanders, Belgium. A physically based, spatially distributed hydrological model coupling land-surface and groundwater processes was adapted to represent controlled drainage through adjustable weirs, by modifying drain levels and incorporating temporary water storage within drainage ditches behind control structures. Permanently raising drain levels from 1 m to 0.5 m below the surface increased average groundwater levels by 15 cm across Flanders, with increases exceeding 30 cm in actively drained areas. Higher groundwater availability generally resulted in modest increases in evapotranspiration, particularly in flat sandy regions. Simulations showed that raising drain levels shortly after winter (April) was more effective than implementing measures only during summer (June onward), when groundwater tables had often already fallen below the drainage depth. Drainage management also altered streamflow extremes. Under a permanent drain-level increase, low flows increased by 12.8%. In contrast, summer-only management reduced low flows by up to 10.1% in some drainage-dominated catchments, highlighting a trade-off between local water retention and downstream water availability. The effects on flood peaks were spatially variable. Peak discharges increased by up to 11.3% in saturation-prone areas due to reduced unsaturated soil storage, whereas temporary storage behind control structures reduced peak flows by up to 26.5% in regions dominated by infiltration-excess runoff. The results demonstrate that drainage management can be an effective tool for increasing groundwater storage and mitigating drought impact. Nevertheless, its impact on flood risk and downstream flow regimes needs to be assessed carefully, since it depends strongly on local hydrogeological conditions and management timing. Depending on the location, the effect can exacerbate or mitigate flooding risk due to peak flows. These findings highlight the need for spatially targeted and adaptive drainage-management strategies to support climate-resilient water management in heavily modified agricultural landscapes.

## 1 Introduction

Drainage systems are widely applied in agricultural landscapes to prevent wet soil conditions and to enhance land productivity. By lowering groundwater levels, drainage enables timely field traffic for agricultural operations and protects crops from water-

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logging stress (Skaggs et al., 1994). However, this comes at the cost of reduced groundwater storage and increased vulnerability to drought stress during dry periods (Ritzema, 2006). Under changing climate conditions, optimizing agricultural water management has become increasingly important (Castellano et al., 2019). Managed drainage might have the potential to reconcile the competing objectives of avoidance of waterlogging, and sufficient water retention to limit drought impacts (Smedema et al., 2004). Despite their widespread use, knowledge of the cumulative effects of widespread drainage adjustments on water storage and hydrological extremes remains limited.

Previous research has examined the hydrological impacts of drainage at field and catchment scales, with a distinction between subsurface (tile) drainage through underground pipes, and surface drainage through open channels or ditches. Drainage lowers groundwater levels and modifies flow pathways, altering the timing and magnitude of streamflow. Ditches create faster routing and less surface storage in local depressions, thereby removing runoff and enhancing peak flows compared to natural conditions without drainage (Levavasseur et al., 2012; Rathore et al., 2024). On the other hand, drainage decreases the groundwater table, which results in more available pore space for the storage of infiltrating rainwater in the unsaturated soil layer. Since lateral waterflow through the soil towards ditches or pipes is generally slower than overland flow, intensifying drainage can also reduce peaks (Skaggs et al., 1994; Blann et al., 2009). By reducing soil saturation, drainage systems can thus shift part of the surface runoff to slower sub-surface pathways (Podzorski and Ryberg, 2025), a mechanism found to be more pronounced for soils with low infiltration rates (Zhou and Margenot, 2025). However, this effect might be limited during extreme rainfall events, when surface runoff tends to dominate the flow response (Sloan et al., 2017). Peak mitigation can also occur through temporary storage of runoff behind control structures in open ditches (Evans et al., 1995; Strock and Ranaivoson, 2024). Reported effects on baseflow, are not uniform across studies. While some studies indicate that drainage enhances baseflow by increasing subsurface contributions to streams (Rathore et al., 2025; Sloan et al., 2017; Podzorski and Ryberg, 2025), others report reduced baseflow due to lowered groundwater storage and its outflow to rivers, particularly during dry periods (Hendriks et al., 2014; Blann et al., 2009). A more detailed assessment is required to identify the local factors that drive these observed differences.

Rather than applying permanent modifications to drainage systems, drain levels can also be managed dynamically with the aim of both reducing peak discharges and limiting drought impacts (Ritzema and Stuyt, 2015). Studies on managed drainage have highlighted the importance of the timing of the drain level increase. For water availability during the growing season, the drain level should be increased as soon as possible during spring (Salo et al., 2021; Rozemeijer et al., 2016; Tähtikarhu et al., 2025). In summer, groundwater tables are often below the level of the drains (Rathore et al., 2024; Rodríguez-Lache et al., 2025), limiting the potential for effective management and drought reduction during this period. In some cases, controlled tile drainage at field-level was found to lead only to moderate increases in groundwater levels (GWL) as the water may still drain away beyond the field boundaries (Miller et al., 2022), especially when the field is close to an open channel (Rozemeijer et al., 2016). Salo et al. (2021) mention the impact of drainage control on groundwater was higher during wet years and diminishes during dry conditions. The impact on crop transpiration, however, was found to be larger during dry years (Isomäki et al., 2024), although this study might not have incorporated the impact of aeration stress on transpiration. On the other hand, Rodríguez-

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Lache et al. (2025) found a limited net impact of managed drainage on transpiration and often a decrease due to waterlogging stress.

For modeling the hydrological impacts of drainage interventions, it is essential to adequately represent interactions between surface water and groundwater, particularly in regions where groundwater contributes substantially to streamflow (Frederiksen and Molina-Navarro, 2021; Liu et al., 2020). Spatially distributed models that realistically represent both surface and subsurface processes are generally more robust for assessing the effects of drainage alterations, as they rely less on extensive calibration and can better capture system behavior under changing conditions (Rathore et al., 2024). Coupled surface–subsurface models, such as SWAT-MODFLOW or MIKE SHE, have been widely tested and have shown promise in improving the simulated flow dynamics in drainage-dominated catchments (Liu et al., 2020; Molina-Navarro et al., 2019; Hansen et al., 2013).

Existing research focuses mostly on field-scale or smaller catchments, and the impact of drainage systems on crop yields and nutrient losses, whereas the impact on larger-scale hydrology is scarce (Castellano et al., 2019). Especially studies evaluating the hydrological consequences of controlling ditch water levels using weirs or other control structures remain scarce (Paavonen et al., 2025). Upscaling drainage management into coarser resolution hydrological models (here, 250 m grid cells) offers an opportunity to assess the broader regional impacts of these practices and assess their environmental and agronomic effects. In this study, we advanced and validated a physically based, spatially distributed model that couples land surface and subsurface processes with groundwater flow. The model was then used to investigate the hydrological impact of controlled drainage, and to compare the geohydrological controls that influence its effectiveness. The overall aim of this work is to provide new insights into both the potential and the limitations of altering drainage practices, and to assess how drainage modifications influence regional water balances, river discharge dynamics, and extreme streamflow events. By quantifying these impacts at the regional scale, the findings can support policymakers and water managers in designing evidence based strategies for sustainable water management.

## 2 Materials and methods

### 2.1 SM-GW model

For this study, we adapted the coupled Soil Moisture Ground Water model (SM-GW) by Moustakas and Willems (2024). The model contains both a spatially distributed land surface model to simulate processes at the surface and in the upper soil layers, and a groundwater model to simulate horizontal ground water (GW) flows between the pixels. The SM-GW model was thoroughly described and validated by Moustakas (2023) and was run over the region of Flanders (13 760 km$^2$). The model runs at a daily timestep and at a spatial resolution of 250 m, a scale that enables flexible and computationally efficient simulations while still capturing the key spatial processes relevant for regional hydrological analysis.

Figure 1 illustrates the model structure and main processes. The surface and subsurface components of the model are based on Aquacrop (Raes et al., 2009). This empirical, water-driven crop growth model simulates processes occurring at the surface and in the upper soil layers, taking into account the first 150 cm of soil, divided into five sub layers. The model requires inputs of daily precipitation and potential evapotranspiration (ETo), along with temporally constant land surface properties

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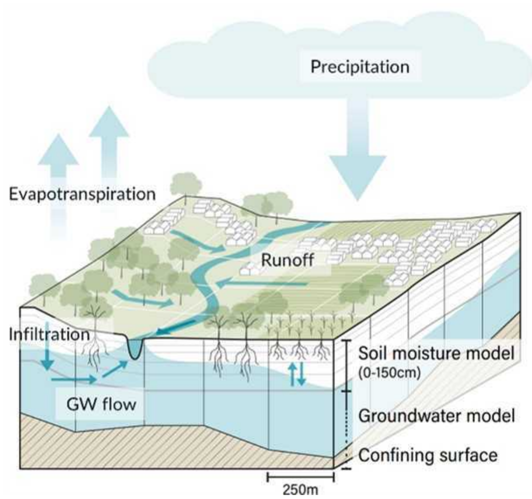


**Figure 1.** Schematic overview of the coupled SM-GW model.

such as the soil characteristics, topography and imperviousness. At each timestep the incoming precipitation is divided into runoff, evapotranspiration, storage into the upper soil layers, or percolation to the groundwater. The actual transpiration is calculated from ETo based on the plant-accessible water in the different soil layers and the dynamic rooting depth of the crops. Transpiration can be reduced by both drought stress and aeration stress under excessively wet conditions according to the Aquacrop principles from Raes et al. (2023). Capillary rise from the ground water to the unsaturated zone is also taken into account, and is calculated using an adapted form of the formulas provided by Raes et al. (2023), as explained in Moustakas and Willems (2024).

The ground water model simulates 2D horizontal GW flow to neighboring pixels based on the gradients in hydraulic head, based on the methodology of MODFLOW (Hughes, 2017). The properties of conductivity and specific yield were estimated from the main geological layers of Flanders as in Moustakas (2023), based on 3D hydrogeological data from Deckers et al. (2019). These properties were treated as uniform within each geological unit, which might introduce local discrepancies due to heterogeneity of the layers. The bottom boundary of the model is determined by the first impermeable layer. Groundwater abstractions were also included in the model using licensed pumping rates obtained from the Databank Ondergrond Vlaanderen (2022). Actual abstraction rates were assumed to correspond to 70% of the licensed volumes and were implemented as constant daily abstractions.

The model was run with a daily time step from 2000 until the end of 2025, discarding the first 5 years of model output as model spin-up. The meteorological inputs were based on station measurements (Waterinfo Vlaanderen, 2025). Using spatially variable interpolated values for precipitation (P) using inverse distance weighing, and a spatially uniform value for ETo based on the station average.

Apart from the drainage-related modifications introduced in this study (see below), the model setup largely follows Moustakas and Willems (2024). Several updates were nevertheless implemented to improve the representation of current conditions.

Land-use, imperviousness, and crop-type maps were updated to more recent datasets, and fruit orchards were added as a separate crop class. Waterlogging stress was incorporated in the crop-growth module following the AquaCrop methodology (Raes et al., 2023), with the corresponding crop parameters listed in Appendix A. In addition, the procedure used to derive saturated hydraulic conductivity ($K_{sat}$) values for the five surface model soil layers was revised. These values are based on the EU-SoilHydroGrids dataset of Tóth et al. (2017), whose soil depth intervals do not coincide with the model layers. Therefore, $K_{sat}$ values must be aggregated across depths. In the original model setup (Moustakas and Willems, 2024), this aggregation was performed using the trapezoidal rule. Here, a harmonic mean was used instead, as it better represents the influence of low-permeability layers on vertical water flow. To avoid unrealistically low conductivity values, $K_{sat}$ values were constrained to a minimum of 10 mm day$^{-1}$.

Overland flow generated by the land surface component is combined with subsurface contributions of drainage and baseflow from the groundwater module to form the total river discharge. To account for travel-time delays along the land surface, the overland flow is passed through a simple grid to grid routing until it reaches the river network. The overland flow velocity ($v_{OF}$) is derived from the surface slope (S) and Manning roughness (n), following the empirical relation (Tran et al., 2018): $v_{OF} = c/n^{0.6}$ where $c$ is a calibration coefficient that is uniform over the study region. The manning coefficient was estimated from the landuse based on the values in Asante et al. (2007). Note that in the used setup, the routing is not influenced by changes made to the drainage system.

The model is primarily parameterized using physically based datasets and requires only limited calibration. Calibration was restricted to two parameters: $v_{OF}$, described above, and the drain conductance parameter discussed in the next section. To avoid overfitting and maintain the model's applicability at the regional scale, calibration was not performed separately for individual stations. Instead, parameters were either assigned uniformly across the model domain or linked to spatially distributed landscape characteristics as in the case of $v_{OF}$. The set-up was evaluated through comparison of simulated and observed hydrograph recession behavior, cumulative discharge volumes, and extreme peak and low flow characteristics, complemented by performance metrics such as the Kling-Gupta Efficiency (KGE) and Nash-Sutcliffe Efficiency (NSE).

### 2.2 Controlled drainage representation in the model

The effect of drainage is represented within the groundwater module of the model. Because the spatial resolution is relatively coarse (250 m pixels), the influence of individual ditches or drainage pipes cannot be modeled explicitly. Instead, each pixel is assigned a conceptual 'drain level', which defines the groundwater elevation above which drainage occurs. This drain level can be interpreted as the effective depth of drainage features such as ditches or tile drains. In the baseline runs, the drain level was assumed to be 1 m below the surface elevation, where surface elevation is defined as the average elevation of the 250 m model cell derived from a higher resolution digital elevation model. In reality this depth would vary with soil type, land use and local drainage practices. Nevertheless, the adopted value of 1 m is the commonly used drainage depth in Flanders, and is consistent with previous modeling studies (Salo et al., 2021; Hansen et al., 2013). In the scenarios where the drain level is increased, the level was assumed to be 0.5 m below the surface.

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Flow towards rivers is modeled in a similar way as artificial drainage, but at different locations. River pixels in the model are defined as pixels that have more than 10 upstream pixels, or 62.5 ha draining towards them. The drain level of a river is determined by the minimum level of the river course derived from a 1 m resolution digital elevation model (DEM). Within a single pixel, two drainage pathways may thus operate simultaneously: shallow artificial drainage (DR), representing small-scale ditches or tile drains, implemented with a conceptual drain level set 1 m below the surface; and drainage towards rivers (baseflow, BF), representing groundwater outflow to the river system, using the DEM-derived river level as the drain level. An important simplification is that rivers and drains can only receive water, but cannot lose water back to the ground or aquifer. However, as described below, the presence of control structures such as weirs allows part of the locally generated surface runoff to be temporarily retained within ditch-storage reservoirs. In the used setup these reservoirs can only capture surface runoff generated within the same pixel. They do not intercept or store stream discharge that has already entered the routing network from upstream areas, which is a simplification of reality.

In the model, the drainage outflow ($Q_{\mathrm{drain}}$, m day$^{-1}$) for a given pixel and timestep is a function of the amount of water stored above the drain level ($S_{\mathrm{drain}}$, m) and is represented using a linear reservoir concept:

$$Q_{\mathrm{drain}} = S_{\mathrm{drain}} \left(1 - e^{-1/CK}\right) \tag{1}$$

where $CK$ (days) represents the residence time in the storage compartment. Following Moustakas (2023), this value is approximated by:

$$CK = \frac{A_{\mathrm{cell}}\, Sy_{\mathrm{drain}}}{K_{\mathrm{drain}}} \tag{2}$$

where $A_{\mathrm{cell}}$ (m$^2$) is the pixel area, $Sy_{\mathrm{drain}}$ (m$^3$ m$^{-3}$) is the specific yield of the drainable storage compartment, and $K_{\mathrm{drain}}$ (m$^2$ day$^{-1}$) is the drain conductance. The drainable water storage used in Eq. 1 depends on the groundwater head above the drain level and the specific yield. The drain conductance depends on the transmissivity and on the surface area of the drainage canals, following the approach used in the MODFLOW River Package (Hughes, 2017):

$$K_{\mathrm{drain}} = \frac{K_{\mathrm{bed}}\, L_{\mathrm{ditch}}\, W_{\mathrm{ditch}}}{d_{\mathrm{bed}}} \tag{3}$$

where $K_{\mathrm{bed}}$ is the conductivity of the channel bed, approximated as the saturated hydraulic conductivity ($K_{\mathrm{sat}}$) multiplied by a uniform calibration factor of 0.2. The ditch surface area ($L_{\mathrm{ditch}} \cdot W_{\mathrm{ditch}}$) was derived from the ditch map obtained from the University of Antwerp (UA, see Fig. 2d) and was limited to 5% of the pixel area. The channel-bed thickness $d_{\mathrm{bed}}$ was approximated as 0.1 m. It should be noted that parameters such as $K_{\mathrm{bed}}$ and $d_{\mathrm{bed}}$ are uncertain and depend on local conditions, including channel maintenance, vegetation, and sediment properties (Abimbola et al., 2020; Naganna et al., 2017). In this study, a generalized approach was adopted for estimating $K_{\mathrm{drain}}$. This supports a consistent regional-scale assessment while minimizing manual calibration. Although suitable for large-scale analysis, local conditions are not fully represented everywhere.

Raising the drain level alters the modeled water balance through two main mechanisms. First, a higher drain level reduces groundwater outflow by restricting drainage when the water table remains below the elevated outlet. Second, when combined

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with control structures such as weirs, ditches can function as temporary storage basins that retain surface runoff. This stored water can subsequently infiltrate and recharge the groundwater system, depending on soil permeability. Both reduced drainage losses and enhanced infiltration from ditch storage are explicitly represented in the model. The land-surface module was in this study adapted to allow runoff capture by ditches when the drain level is increased. As a simplification, only runoff generated within the pixel itself was captured until the ditch storage reservoirs overflow. The storage capacity of the infiltration basins formed by closing weirs was estimated using the 1 m resolution ditch map. For each 1 m ditch pixel, the additional storage created by raising the drain level and closing a weir was assumed to be 1 m long, 0.5 m wide, and 0.5 m deep. The resulting storage volumes were aggregated to the 250 m model grid. The storage capacity is reduced when the GWL lies above the bottom of the ditch. Infiltration from these basins is calculated in the same way as infiltration elsewhere in the pixel and is constrained by soil properties such as $K_{\mathrm{sat}}$ and saturated water content. The ditch map from UA was also used to determine which model pixels contain drainage channels.

Multiple scenarios of weir implementation were simulated. These scenarios assume centralized implementation and management of weirs. They are theoretical and are intended to assess the potential hydrological impacts of large-scale implementation:

- **Baseline**: Drainage operates without restrictions. The drain level is fixed at 1 m below the surface throughout the simulation period. This scenario does not necessarily represent the current situation, as drainage management already exists in some regions (e.g. the polders).
- **Uniformly increased levels**: Drainage is restricted in all drainage channels throughout the simulation. The drain level is raised to 0.5 m below the surface, representing continuous weir installation or year-round controlled drainage.
- **Managed drainage**: The drain level is raised during most of the year but temporarily lowered during periods of field access: February–March for soil preparation and sowing and August–September for harvesting. As a simplification, changes are applied simultaneously across the entire study area regardless of local conditions. Although in reality, for each field and crop, the exact timing of field operations is different.
- **Summer increase**: The drain level is raised only during the summer months (June–August). This scenario represents a reactive measure once drought stress becomes apparent rather than a preventive management strategy.

### 2.3 Study area

Much of Flanders is shaped by its low-relief terrain and shallow groundwater systems, which have prompted the development of an extensive artificial drainage network to enhance agricultural productivity and efficiently remove runoff. The landscape is largely flat, becoming more hilly toward the south (see Fig. 2). Soil types vary markedly across the region with heavy clay soils dominating the reclaimed polder areas in the northwest, sandy soils in the northern inland zones, and sandy-loam to loam soils prevalent in the southern part of Flanders. The region of Flanders is also characterized by intensive land use, with approximately 45% of the territory devoted to agriculture and about 15.7% covered by impervious surfaces such as buildings and paved areas (Statistiek Vlaanderen, 2025). The high share of built-up and agricultural land places substantial pressure on

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the hydrological system. To reduce the impact of drought conditions, policy is moving away from efficiently removing water towards a more balanced approach of storing water when possible, for instance by making adjustments to the drainage network.

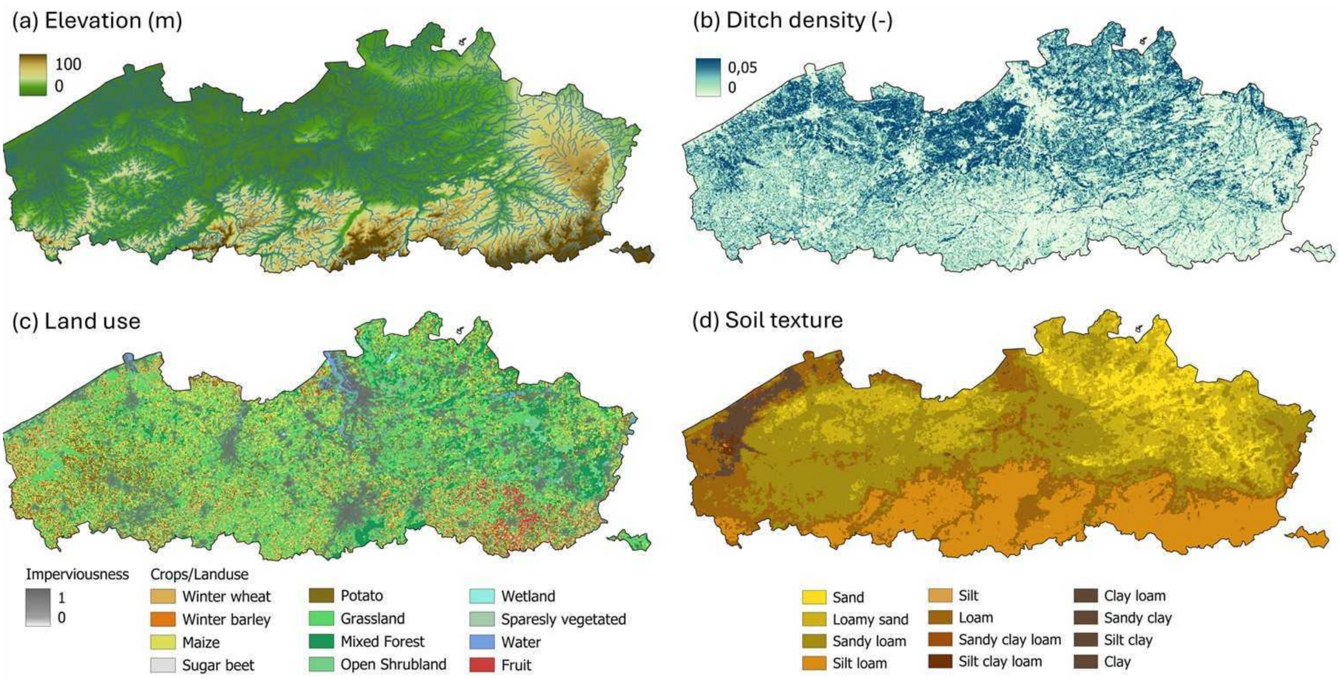


**Figure 2.** Vlaanderen. (a) elevation (m), (b) density of ditches (fraction of pixel), (c) land use, and (d) the soil texture.

## 3 Results and discussion

### 3.1 Model validation

The SM-GW model was validated against publicly available discharge records from Waterinfo Vlaanderen (2025) and GWL measurements from Databank Ondergrond Vlaanderen (2025). After quality screening to remove river discharge stations with substantial human influence (e.g. controlled canals) or insufficient data availability, 40 stations remained for model evaluation across Flanders (see Fig. 3 for locations). Since the land and water system in Flanders is intensively managed, it is not feasible to completely eliminate all human influence (i.e. abstractions, wastewater discharges), and some degree of anthropogenic impact on the records is still to be expected. Performance metrics for the baseline simulation were computed for the period 2005–2025 and are summarized as boxplots in Fig. 3. Across all stations, the median Kling-Gupta Efficiency (KGE) was 0.64, the median Nash-Sutcliffe Efficiency (NSE) was 0.54, and the median Pearson correlation reached 0.80. Taking into account the large spatial area covered and that the model was not calibrated station by station, these statistics show that the model reproduces the timing and variability of river discharge reasonably well. The map of KGE per station shows that the model

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performance is lowest in the western part of Flanders, where summer baseflow tends to be overestimated. Several stations in the hilly loam region in the southeast show lower NSE values due to an overestimation of peak discharges. Given the strong sensitivity of NSE to high runoff events (Gupta et al., 2009), the absence of explicit floodplain storage processes in the current model likely contributes to these deviations. Example time series for three stations from different hydrogeological regions are show in Fig. 3). The timeseries show that the model captures the contrast between wet and dry years, produces realistic recession behavior and captures the main geohydrological differences between the catchments. Since the SM-GW framework explicitly simulates baseflow, drainage, and surface runoff as separate components, the modeled hydrographs provide insight into the partitioning of flow generation processes.

Similarly the GWL was validated through measurements at 2089 available monitoring stations. Owing to the model's relatively coarse spatial resolution (250 m), the representativeness of individual wells can vary, particularly when wells are located close to rivers, drains, or strong hydraulic gradients. Figure 4c compares the average modeled GWL (m above sea level) of each 250 m pixel to the mean measured GWL of the wells located within that pixel. The spatial pattern shows a correlation of 0.99. This high value stems from the fact that the groundwater table partly follows the topography. When comparing the GWL relative to the soil surface, the correlation between the average modeled vs measured GWL decreases to $\sim$0.63. The MAE of 1.16 m reflects local deviations in absolute groundwater levels, although part of this can be attributed to the comparison of point measurements to coarse pixels. For stations with more than 50 observations ($n = 175$), timeseries metrics were calculated. Across all stations, median timeseries correlation was 0.80 and KGE 0.51. The spatial variability of the KGE for stations with sufficient observations is depicted in Fig. 4. The distribution shows variable results, with performance generally lower for the stations with deep GWL.

GWL timeseries for three monitoring sites are presented in Fig. 5, with Fig. 5b showing larger deviations between simulated and observed groundwater dynamics. These discrepancies may arise from uncertainties in soil hydraulic properties, i.e. soil water contents at saturation, field capacity, and wilting point, which were derived from Tóth et al. (2017), as well as from simplifications in the representation of drainage conductance and geology. Furthermore, Flanders is characterized by strong spatial heterogeneity and extensive anthropogenic modification. Such factors are difficult to represent fully in a regional-scale model and likely contribute to part of the remaining model error.

The modeled soil saturation was also validated for 19 available stations. The results were added in Appendix B and indicate realistic temporal dynamics (median KGE at depth of 10 cm = 0.51), but often slightly underestimating the degree of saturation.

Given these results on discharge, soil saturation and GWL we assume the dominant hydrological processes in Flanders are represented with sufficient realism to consider the model suitable for exploring the effects of drainage-system modifications on groundwater levels, streamflow dynamics, and hydrological extremes.

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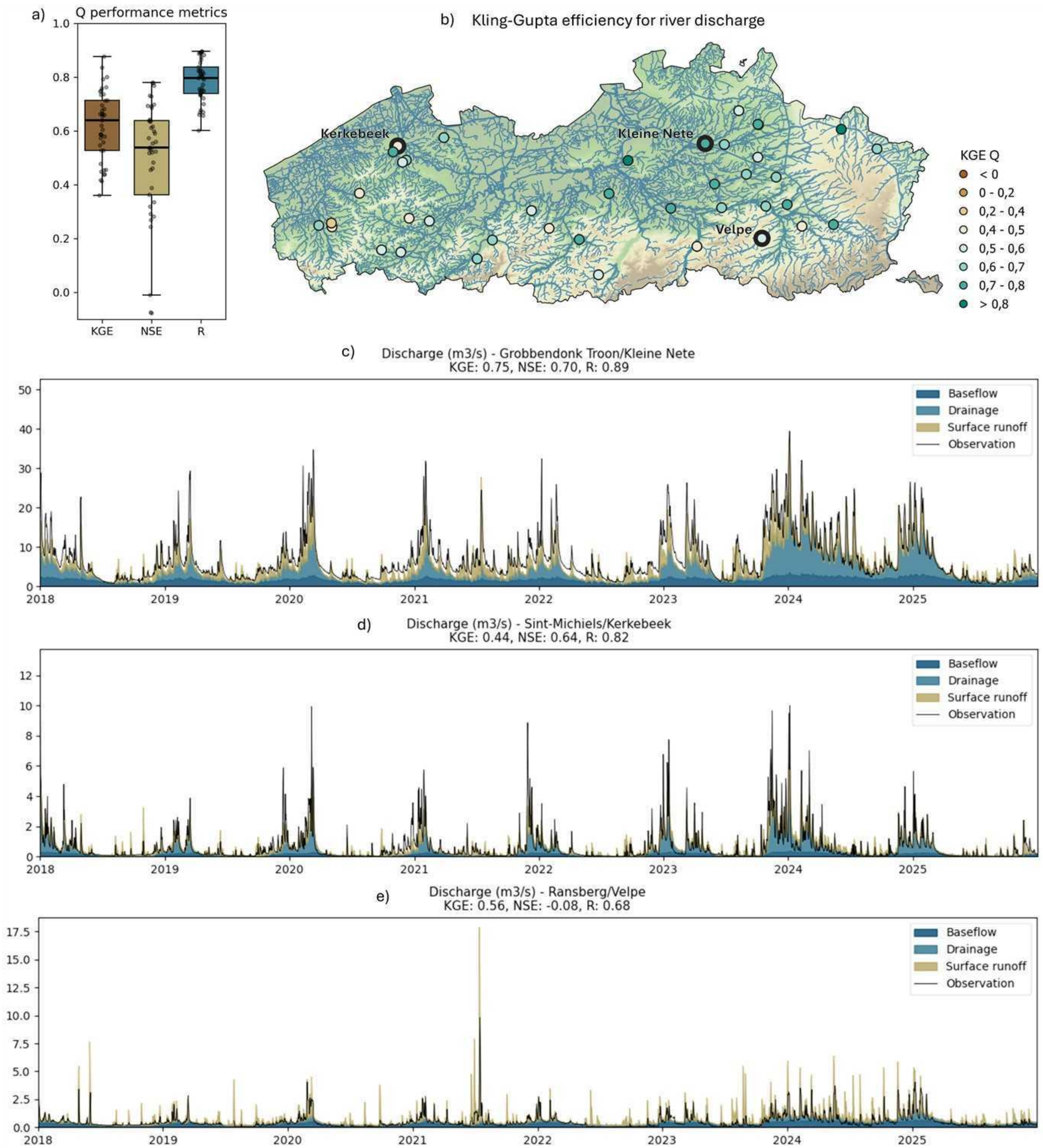


**Figure 3.** River discharge (Q) performance. (a) shows the distribution of metrics across all stations ($n = 40$) and (b) shows the spatial distribution of the KGE. Subplots c, d, and e show example timeseries representing a range of model performances and hydrogeological settings across Flanders, shown for the Kleine Nete at Grobbendonk, the Kerkebeek at Sint-Michiels, and the Velpe at Ransberg.

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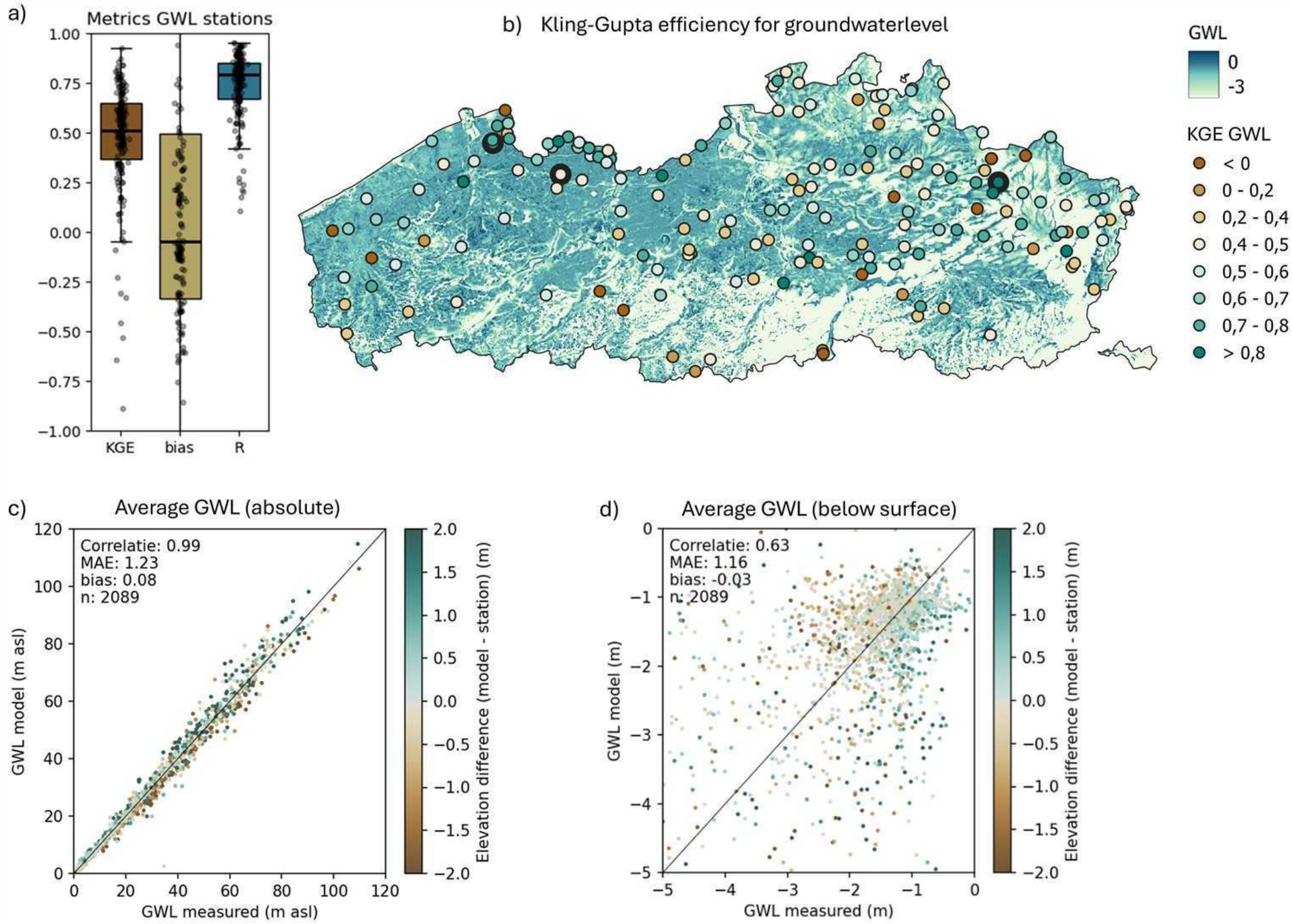


**Figure 4.** Model validation of GWL using station based measurements for Flanders. (a) shows the distribution of metrics across all stations with more than 50 observations ($n = 175$), (b) shows the spatial distribution of the KGE. The stations with the darker outline are presented in the timeseries in Fig. 5. (c) and (d) compares the average measured and modeled GWL (in m above sea level and below the soil surface, respectively).

### 3.2 Impact of drain level (management)

#### 3.2.1 GWL timeseries

Timeseries of GWL provide insight into how the timing of drain-level adjustments influence groundwater dynamics. Figure 5 shows GWLs for 2018–2025 at 3 locations across Flanders. The difference between the baseline scenario and the scenario with a permanently raised drain level illustrates the maximum attainable effect of increasing the drain level from 1 to 0.5 m below the soil surface. Averaged across the study area and over time, groundwater levels increased by approximately 15 cm. The effect was considerably larger in actively drained regions, where average GWL increases reached 30 cm for pixels with

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baseline drainage rates exceeding 10 mm/year. Due to ET and the draining effect of natural streams, the intended water table of 0.5 m below the soil surface can never be fully reached. In regions with active drainage, during the wet winter months, the GWL typically lies near the drain level. As a result, the wet winter GWL in the raised-drain scenario closely reflects the imposed +0.5 m increase. Groundwater levels can temporarily exceed the drain level as the drainage water is released only gradually. During the dry summer months, the GWL in both scenarios converge as evapotranspiration and capillary rise lower the groundwater table. This leaves a larger volume of water between the winter and summer levels available to plants in the increased drain level case. Averaged over the entire region, permanently rising the drain level leads to an ET increase of ~5 mm/year.

The managed drainage scenario demonstrates the importance of retaining groundwater throughout the year. Temporarily lowering the drain level to facilitate field operations in February–March and August–September substantially reduces the potential groundwater gains. Across the study area, the average GWL increase under managed drainage was 6.5 cm. However, the impact differs from year to year. If spring conditions remain wet, part of the lost groundwater can be 'refilled' after drainage levels are raised again, as is visible during wet years such as 2023 or 2024. In other years, e.g. 2020, the drain level increase happens as the GWL is already near or below the baseline level of 1 m depth. When the GWL drops below this point there is no more opportunity to retain it. Nevertheless, the GWL can still replenish through infiltration during rainy periods, or through a reduction in drainage in connected lower lying pixels. This is in line with Salo et al. (2021), who mentioned that controlled drainage has a higher impact on GWL during wet years.

The results also indicate that drain levels should be raised as early as possible to maximize groundwater storage before the growing season. This is especially visible in the summer-management scenario, where drain levels are only raised in June. In most years, the GWL is already below the drain level by that time, making the intervention too late to have a meaningful effect. As a result, summer management generally has a negligible effect on GWLs, except during unusually wet summers such as 2024. Other exceptions may occur in areas receiving sustained groundwater seepage, where drains can continue to convey groundwater to the stream network during dry periods.

A special case is the clay-rich polder region, where frequent surface runoff is simulated by the model. This allows for more infiltration opportunities in the ditches when weirs are installed. As a result Fig. 5a shows modest rises in the GWL also in the summer increase scenario. For the sandy regions, however, surface runoff is less frequent and the impact of additional infiltration by the ditches seems to be more limited.

Finally, Fig. 5c illustrates that groundwater levels can increase even at locations where the local water table remains below the drainage level and no direct interaction with drains occurs. This is especially the case in regions with highly transmissive aquifers such as the Campine region in northeast Belgium.

Overall, the results show that the effectiveness of drain-level management is controlled by the timing of the intervention, but also by subsequent meteorological conditions and the groundwater table dynamics at that specific location. These findings are consistent with previous studies showing that control structures should be raised early in spring, before drainage discharge naturally ceases (Rozemeijer et al., 2016). Once the groundwater table has fallen below the drain level, increasing the control level has little effect on GWLs (Rathore et al., 2024). When groundwater reserves have been lost through spring drainage,

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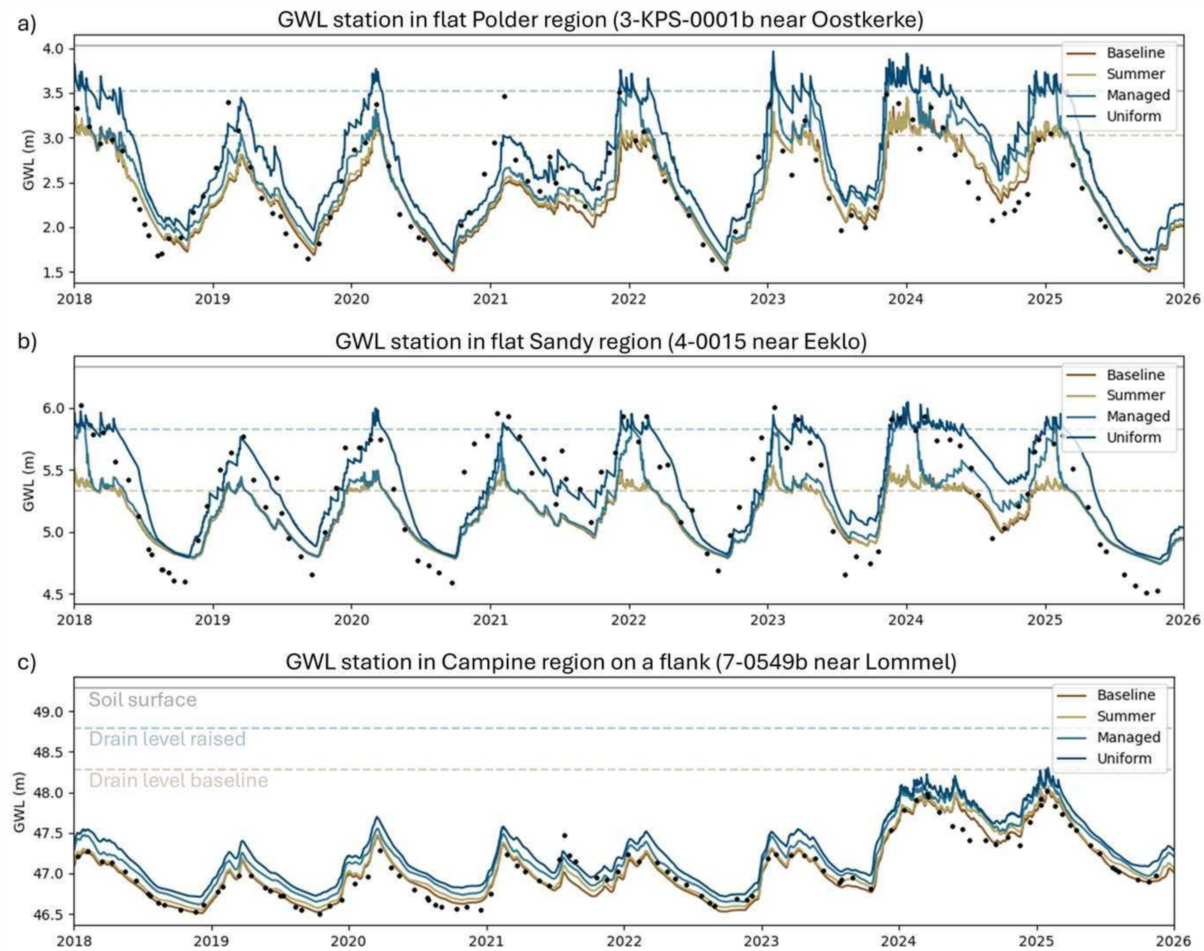


**Figure 5.** Timeseries of GWL under different drain level management scenarios at three different sites. The black dots represent GWL measurements at the site. The locations of the sites is show in Fig. 4, and are ordered a–b–c from west to east.

opportunities for recovery during the growing season are limited, as ET generally exceeds precipitation and other inflows during this time (Tähtikarhu et al., 2025; Salo et al., 2021).

### 3.2.2 Water balance

Figure 6 presents the spatial patterns of the yearly averaged water balance components under the baseline scenario, and the modeled changes under a uniformly increased drain level. As expected, increasing the drain level leads to a clear rise in **groundwater levels** (GWL). This effect is strongest in areas where baseline GWLs were already high and drainage was active, as the raised drain outlet directly restricts groundwater outflow. On the other hand, the effect of additional infiltration by the ditches is most apparent in regions with high baseline surface runoff. For instance in the clayey polders and the hilly south-eastern region baseline runoff from open areas was relatively high. Here the closure of ditches creates additional infiltration

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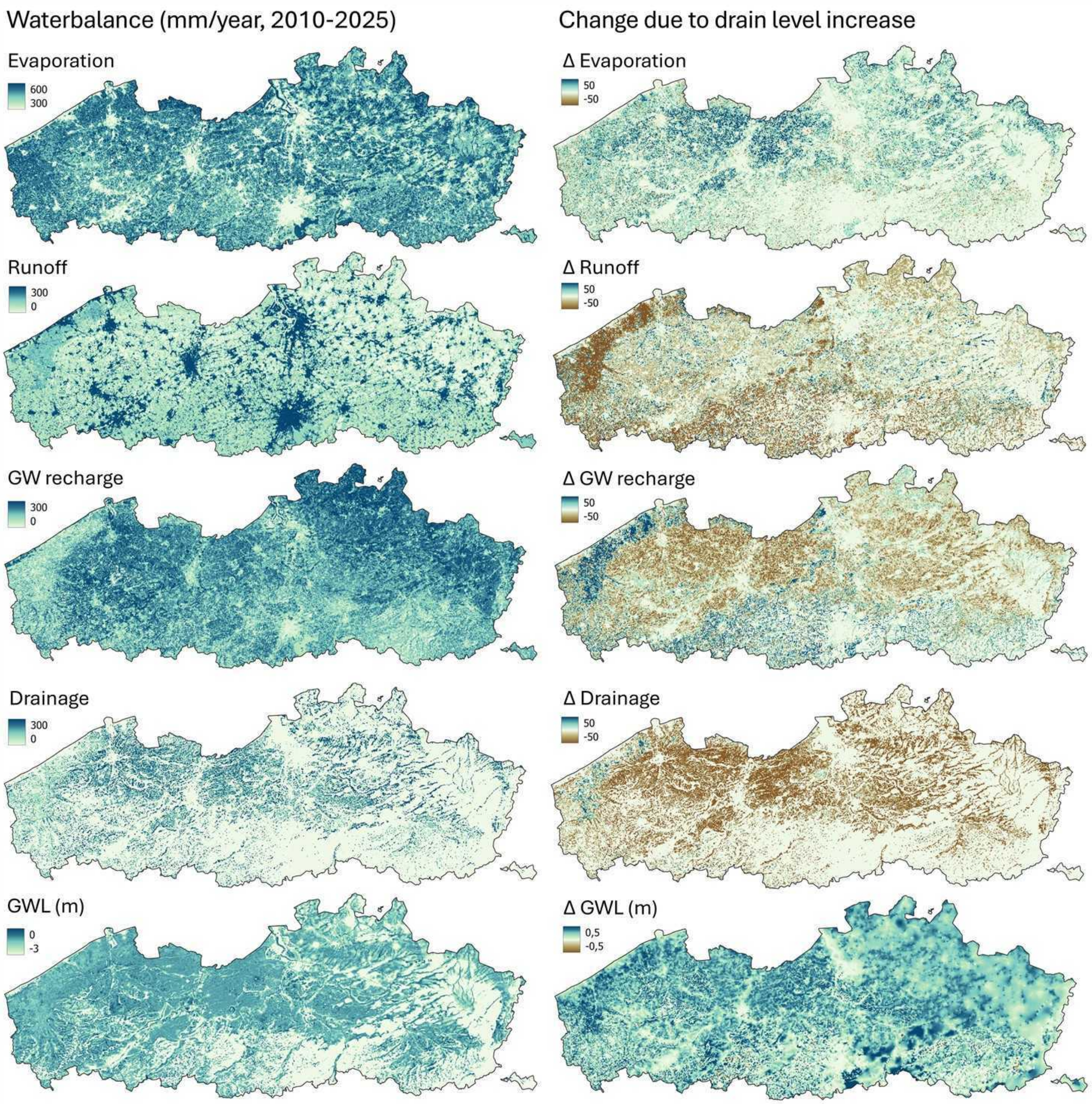


**Figure 6.** Water balance variables and the modeled change due to a uniform drain level increase.

305 opportunities, further contributing to groundwater rise. In highly permeable and thick aquifer systems, such as the Campine region in the northeast, the high transmissivity allows these groundwater changes to propagate more broadly, resulting in a more spatially diffuse GWL response.

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Higher GWLs translate into increased availability of water for **evapotranspiration** (ET). Accordingly, ET generally increases, driven by both enhanced plant transpiration under reduced drought stress and greater soil evaporation from surface layers. Exceptions for this are found in persistently wet areas where waterlogging limits transpiration. The magnitude of the ET response to the drain level increase depends on local conditions such as soil type and slope. Fig. 6 shows the largest increase in the flattest regions, and a slightly smaller increase in the clay-rich polder regions than for the sandy regions.

The **surface runoff** was found to either increase or decrease depending on regional characteristics. Specifically the runoff change is influenced by two counteracting mechanisms. Firstly, increasing the drain level leads to shallower GWLs. The hereby reduced unsaturated storage leads to less temporary buffering capacity in the soil during rainfall and thus higher runoff generation. Secondly, the assumed storage capacity created by control structures within the ditches leads to capturing of a part of the overland flow. The resulting infiltration effect is most pronounced in areas where overland flow is common even during modest rainfall events, such as the hillier southern part of Flanders and the impermeable clay polder areas in the northwest. It should be noted that the current representation of ditch storage does not explicitly account for slopes or the exact placement of weirs. As a result, storage and infiltration opportunities may be overestimated in strongly sloping areas, where substantial water retention would in reality require a denser network of control structures. The balance between these two mechanisms determines the net runoff response. The net yearly surface runoff appears to increase where baseline GWLs were already high. Presumably, in these regions, runoff generation due to saturation excess will become more common, mostly during wet periods where GWLs are high and infiltration storage in ditches is unavailable. For less permeable soils where runoff is usually caused by infiltration excess rather than saturation, the average yearly runoff was found to decrease due to the capturing of runoff in the ditches.

The **net GW recharge** is controlled by local soil permeability, leading to the highest values in sandy soils. In the water balance, this represents the portion of incoming water that is not lost through evapotranspiration or surface runoff. Following an increase in the drain level, net GW recharge rises in areas where surface runoff is captured in the ditch storage, and it declines in regions where higher groundwater levels allow for greater evapotranspiration. In the model, the infiltration to the groundwater will leave the cell through GW flow, GW abstractions or drainage to ditches and rivers. If the GWL increase is caused by a reduction in drainage, this is thus not considered as increased GW recharge here.

The changes for the managed and summer drain level increase were added in Appendix B and show similar spatial patterns, but much less pronounced. The limited impact on ET and GWL in regions with shallow groundwater for these scenarios show that the temporarily lowering of drain levels leads to a substantial loss in groundwater reserves near the rootzone compared to a uniform drain level increase. In the scenario where the drain level is increased only from June until August, the drainage reduction is almost only visible in the Campine region in the northeast of Flanders that contains deep aquifers.

Finally, the baseline water balance maps of runoff and infiltration also highlight differences in hydrological regimes across Flanders: regions dominated by rapid rainfall-runoff processes contrast with areas where infiltration and thus groundwater contributions to rivers and drains play a more prominent role. Understanding these regional contrasts is useful for interpreting the differences in river discharge dynamics and the effects of drain-level adjustments on river discharge and flow extremes, as explored further in the next section.

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### 3.2.3 River discharge extremes

To assess how drainage management influences hydrological extremes, we analyzed changes in the peak flows and low flows. These extreme flows were extracted from the daily discharge timeseries (2005–2025) using the WETSPRO tool (Water Engineering Time Series PROcessing tool, by Willems (2009)). An illustration of the peak and low flows versus the empirical return period is shown in Fig. 7 for the Kleine Nete catchment. We extracted the 4 most extreme independent events of our timeseries, or the events with an estimated return period of 5 years (T5) or higher, and calculated the relative change in those peak flows and low flow values.

We found that uniformly increasing the drain level consistently raised **dry-season river flows** across the domain. Over all gauged catchments, median low flows increased by 12.8% relative to the baseline. When drains were temporarily lowered for field access, a median increase of 6.2% remained. However, not all scenarios showed increased low flows. When the drain level was raised only during summer months, several catchments exhibited reduced low flows, in some cases by up to -10.1% (see Fig. 7). This occurred in catchments where, even under drought conditions, drainage constitutes a non-negligible fraction of streamflow. Halting drainage in these systems retains water locally, presumably alleviating field-scale drought symptoms, but withholds water from the river network, thereby reducing flows downstream. The implication is that seasonally targeted measures might be beneficial on fields but detrimental at the catchment outlet if drainage is an important contribution to the flow.

Studies report contrasting effects of drainage on baseflow and low flows. In line with the present results, Hendriks et al. (2014) found that anthropogenic drainage reduced baseflow by 25–40 % in Dutch sandy catchments, indicating that limiting drainage has the potential to restore groundwater storage and streamflow during dry periods. Similarly, Blann et al. (2009) noted that drainage can exacerbate late-season water shortages by lowering groundwater levels in valley bottoms. In contrast, a few studies focusing on subsurface tile drainage have reported increased low flows following drainage installation. For instance Rathore et al. (2025) and Sloan et al. (2017) both reported that tile drainage increased streamflow during low-flow periods. Podzorski and Ryberg (2025) highlighted that subsurface drainage can convert rapid surface runoff into slower subsurface flow pathways, thereby enhancing baseflow. Possibly the definition of 'baseflow' compared to extreme low flow (>T5) events used in this study explains the difference with that result.

The impact of raising the drain level on **high-flow events** can either be positive of negative and is controlled by the dominant runoff-generation mechanisms within each catchment. In areas where GWL rises close to the surface, the reduced unsaturated storage causes soils to saturate more quickly during rainfall events. This enhances saturation-excess runoff, leading to higher peak flows of up to 11.3%. This mechanism was also reported in other studies (i.e., Skaggs et al., 1994; Blann et al., 2009; Yimer et al., 2023; Podzorski and Ryberg, 2025). In contrast, in catchments where high runoff peaks are typically governed by infiltration-excess runoff, such as regions with heavier soil and steeper terrain, control structures can promote temporary storage in ditches. The additional storage delays and reduces surface runoff, allowing some of it to infiltrate, which results in attenuated and delayed peak flows (peak flow decrease up to -26.5%). Only few previous studies have explicitly taken into account infiltration by ditches. Evans et al. (1995) found that flashboard risers generally reduced flood peaks through additional storage, although the effectiveness diminished under wetter conditions when peaks occasionally increased. These findings suggest that the net effect of drainage control on flood peaks results from the balance between increased soil saturation and the additional storage provided by controlled drainage structures. Under the managed drainage scenario, the results show strongly increased peaks for some stations. The runoff flow timeseries revealed that these higher peaks originate after uniformly lowering the drain level over the entire area, creating a sudden outflow of groundwater to the river system. When this artificial release coincides with rainfall events, the resulting discharge peaks can become considerably larger than under the baseline conditions. In reality, however, the opening of drainage structures would be applied more gradually over an entire region, and would be adapted to local conditions and weather forecasts. As such, the weirs can even become a way to mitigate floods by pre-emptying a part of the saturated zone before a storm and as such providing more storage space in the soil. The risk of high drain discharge after releasing the drainage control was also mentioned by Salo et al. (2021).

## 4 Implications for water management

The model results demonstrate that the hydrological effects of raising drain levels are spatially and temporally variable and controlled by local soil and landscape characteristics. The results of this study give indications of which characteristics lead to higher potential for drainage management.

From an agricultural perspective, drainage is performed to (amongst others) 1) allow timely access to the field for soil preparation and sowing in spring, 2) increase the soil temperature faster in spring and 3) avoid oxygen stress due to saturated conditions in the root zone. However, too much drainage can result in lack of water in the root zone in the dryer part of the growing season. The simulations show that ET gains due to avoided crop stress with a raised drainage base are rather small and mainly present in the flat sandy regions. Increases are much more limited in the hilly loam belt. ET also decreases in some wet areas due to aeration stress. The relatively limited ET gains found in this study are consistent with previous modeling studies (Rodríguez-Lache et al., 2025; Ritzema and Stuyt, 2015). As for timely access to the field: we did not investigate this in detail here, but the timeseries indicate that if the weirs are only opened a few days before field operations and closed immediately after, it should be possible to briefly lower the water table for field operations. This should not happen too late in the growing season so that the water table can still rise after closure of the weirs. If groundwater levels have already fallen below the baseline drain depth at the moment of intervention, the ability to retain groundwater is partly lost; in such cases, only substantial rainfall can restore groundwater levels, limiting the usefulness of late season adjustments. This is especially evident in the summer management scenario, where raising the drain level in June typically had no effect because groundwater tables were already too deep to retain it. If weirs are considered as a water retention measure in a region, it is therefore crucial to pay attention to the timely implementation of the raised drainage base in spring. Only in a relatively small area with high seepage, GWLs could benefit from summer only management, although this was found to have a negative effect on the river baseflow. In this case, a mismatch exists between weir management aimed at maximizing local gains and the management strategies needed to optimize benefits across the entire catchment. The operational weir management from a user perspective (e.g. farmers) may thus not always align with the objectives from the water managers.

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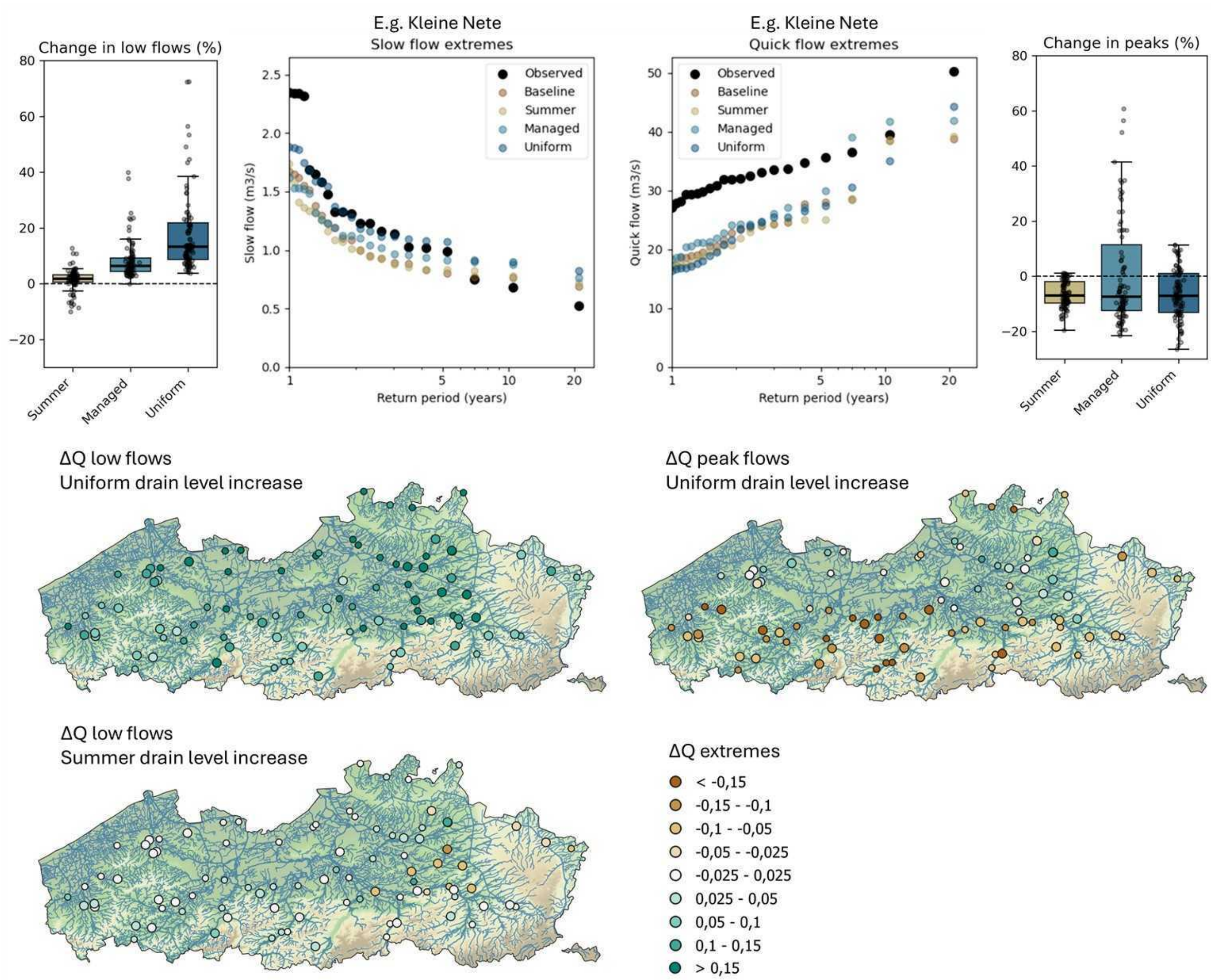


**Figure 7.** Change in peak flows and low flow extremes for the drain level increase scenarios compared to the baseline. The larger dots on the maps show the stations that were validated against measurements. The smaller dots were outlets added to further extend the coverage.

The results also reveal trade offs related to flood risk. Permanently raising the drain level can increase the risk of high flows in some areas. The results indicate this is mostly the case for regions prone to saturation excess runoff, where shallow groundwater leaves little unsaturated storage. At the same time, the temporary storage provided by closed ditches may reduce peak flows by retaining part of the surface runoff from the stream network. These findings suggest that adjustable weirs could be deployed dynamically, storing water during dry months while being opened temporarily during high GWL periods to avoid excessive soil saturation and mitigate flood risk. Notably, under the summer management scenario, ditch storage reduced peak flows across all studied catchments, indicating that this kind of short term, targeted use of drainage infrastructure has potential

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as a flexible flood mitigation measure. Nevertheless, this requires timely and coordinated reaction to weather forecasts, which is not always evident in rural areas.

Overall, the results underline that large scale modifications to drainage systems can offer meaningful opportunities for both drought alleviation and flood mitigation, but that their success largely depends on the spatial placement and seasonal or ad-hoc operation of weirs, as well as on local soil properties, topographic conditions, and typical groundwater dynamics. Model based scenario exploration therefore provides a valuable decision support tool to guide policymakers and water managers in designing targeted and effective drainage management strategies.

## 5 Conclusions

This study applied a physically based, spatially distributed hydrological model to assess how large-scale drainage management influences groundwater levels, water-balance components, and streamflow extremes across Flanders. The results confirm that raising drain levels has a substantial influence on the hydrology, including peak and low flow extremes, although the magnitude and even the direction of the response vary with local hydrogeological conditions.

If coherently implemented in a region, increasing the drain level leads to higher groundwater tables and, consequently, increased evapotranspiration and reduced drought stress in many agricultural areas, but increased waterlogging stress in other areas. The potential for ET increase is strongest in flat and sandy regions. Infiltration by storage in ditches can enhance groundwater recharge, particularly in areas with frequent surface runoff, such as regions with steeper slopes and less permeable soils. The time-series analysis further showed that the timing of drainage management is crucial. Raising drain levels shortly after winter proved more effective than implementing measures only during summer, when groundwater levels have often already fallen below the drainage level.

Drainage adjustments also alter river discharge extremes. Under uniformly raised drain levels, low flows increase across nearly all catchments, with a median rise of around 13%. A notable exception occurs when rising drain levels only in summer; in that case withholding drainage water may aggravate downstream drought in some catchments. The impact on flood peaks is bidirectional. In saturation prone areas, peak flows were found to increase because of reduced unsaturated soil storage, whereas the added ditch storage also reduces and delays peak discharge.

The objective of the present study was to identify large-scale patterns and regional differences in hydrological responses to drainage management rather than to reproduce local conditions in detail. For site-specific applications, higher-resolution models and more extensive calibration of parameters such as drain conductance would improve the representation of local drainage behavior and increase the accuracy of impact assessments. Although the model includes several simplifications, the hydrological responses are physically realistic and consistent with findings from previous studies. Future work should combine validation from field experiments with higher resolution modeling to refine these insights, and explore how dynamic, spatially targeted drainage management strategies can best support climate adaptation, agricultural productivity, and sustainable water governance.

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Future model development could focus on refining the representation of both groundwater and surface-water processes. Potential improvements include a more detailed river routing scheme that explicitly accounts for floodplain storage, river-aquifer interactions, as well as an improved representation of geological and soil hydraulic properties.

Despite the model simplifications, this study advances our understanding of the regional-scale hydrological consequences of drainage management. The results show that increasing water retention through drainage control has considerable potential to reduce drought impacts, but that benefits are dependent on local conditions and may be accompanied by unintended effects on flood peaks or downstream flows. These findings emphasize the need for spatially targeted and adaptive drainage management strategies that balance agricultural production with broader water-management objectives.

*Data availability.* Model output will be made available through an online repository (i.e. Zenodo) upon acceptance of the paper. The output will consist of discharge timeseries and water balance maps for the scenarios presented in this manuscript.

*Author contributions.* IB developed and adapted the model and performed the simulations. JS contributed to the preparation of the drainage ditch maps needed for the simulations. IB and PW contributed to the study design and analysis. All authors contributed to the interpretation of the results, the writing and revision of the manuscript.

*Competing interests.* The authors declare that they have no conflict of interest.

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https://doi.org/10.5194/egusphere-2026-4557
Preprint. Discussion started: 6 August 2026


## References

Abimbola, O. P., Mittelstet, A. R., Gilmore, T. E., and Korus, J. T.: Influence of watershed characteristics on streambed hydraulic conductivity across multiple stream orders, Scientific Reports, 10, https://doi.org/10.1038/s41598-020-60658-3, 2020.

Asante, K. O., Artan, G. A., Pervez, S., Bandaragoda, C., and Verdin, J. P.: Technical Manual for the Geospatial Stream Flow Model (GeoSFM), Tech. rep., US Geological Survey, http://www.usgs.gov/pubprod, 2007.

Blann, K. L., Anderson, J. L., Sands, G. R., and Vondracek, B.: Effects of agricultural drainage on aquatic ecosystems: A review, Critical Reviews in Environmental Science and Technology, 39, 909–1001, https://doi.org/10.1080/10643380801977966, 2009.

Castellano, M. J., Archontoulis, S. V., Helmers, M. J., Poffenbarger, H. J., and Six, J.: Sustainable intensification of agricultural drainage, Nature Sustainability, 2, 914–921, https://doi.org/10.1038/s41893-019-0393-0, 2019.

Databank Ondergrond Vlaanderen: Grondwatervergunningen, https://www.dov.vlaanderen.be/geonetwork/srv/eng/catalog.search#/metadata/397d5188-50a0-45f4-9ce2-f7baf7d77422, 2022.

Databank Ondergrond Vlaanderen: Grondwatermeetnet, https://www.dov.vlaanderen.be, 2025.

Deckers, J., De Koninck, R., Bos, S., Broothaers, M., Dirix, K., Hambsch, L., Lagrou, D., Lanckacker, T., Matthijs, J., Rombaut, B., Van Baelen, K., and Van Haren, T.: Geologisch (G3Dv3) en hydrogeologisch (H3D) 3D-lagenmodel van Vlaanderen, Tech. rep., VITO, 2019.

Evans, R. O., Skaggs, R. W., and Gilliam, J. W.: Controlled versus Conventional Drainage Effects on Water Quality, Journal of Irrigation and Drainage Engineering, 121, 271–276, 1995.

Frederiksen, R. and Molina-Navarro, E.: The importance of subsurface drainage on model performance and water balance in an agricultural catchment using SWAT and SWAT-MODFLOW, Agricultural Water Management, 255, https://doi.org/10.1016/j.agwat.2021.107058, 2021.

Gupta, H. V., Kling, H., Yilmaz, K. K., and Martinez, G. F.: Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling, Journal of Hydrology, 377, 80–91, https://doi.org/10.1016/j.jhydrol.2009.08.003, 2009.

Hansen, A. L., Refsgaard, J. C., Christensen, B. S. B., and Jensen, K. H.: Importance of including small-scale tile drain discharge in the calibration of a coupled groundwater-surface water catchment model, Water Resources Research, 49, 585–603, https://doi.org/10.1029/2011WR011783, 2013.

Hendriks, D. M. D., Kuijper, M. J. M., and van Ek, R.: Groundwater impact on environmental flow needs of streams in sandy catchments in the Netherlands, Hydrological Sciences Journal, 59, 562–577, https://doi.org/10.1080/02626667.2014.892601, 2014.

Hughes, J. D.: Documentation for the MODFLOW 6 Groundwater Flow Model, Tech. rep., US Geological Survey, 2017.

Isomäki, K., Salla, A., Salo, H., and Koivusalo, H.: Hydrological effects of open ditch damming and controlled subsurface drainage in a Nordic agricultural field, Hydrology Research, 55, 112–127, https://doi.org/10.2166/nh.2024.053, 2024.

Levavasseur, F., Bailly, J. S., Lagacherie, P., Colin, F., and Rabotin, M.: Simulating the effects of spatial configurations of agricultural ditch drainage networks on surface runoff from agricultural catchments, Hydrological Processes, 26, 3393–3404, https://doi.org/10.1002/hyp.8422, 2012.

Liu, W., Park, S., Bailey, R. T., Molina-Navarro, E., Andersen, H. E., et al.: Quantifying the streamflow response to groundwater abstractions for irrigation or drinking water at catchment scale using SWAT and SWAT–MODFLOW, Environmental Sciences Europe, 32, https://doi.org/10.1186/s12302-020-00395-6, 2020.

Miller, S. A., Witter, J. D., and Lyon, S. W.: The impact of automated drainage water management on groundwater, soil moisture, and tile outlet discharge following storm events, Agricultural Water Management, 272, https://doi.org/10.1016/j.agwat.2022.107828, 2022.

https://doi.org/10.5194/egusphere-2026-4557
Preprint. Discussion started: 6 August 2026


Molina-Navarro, E., Bailey, R. T., Andersen, H. E., et al.: Comparison of abstraction scenarios simulated by SWAT and SWAT-MODFLOW, Hydrological Sciences Journal, 64, 434–454, https://doi.org/10.1080/02626667.2019.1590583, 2019.

Moustakas, S.: Investigation of computationally efficient methodologies for spatially distributed hydrological modelling, Ph.D. thesis, KU Leuven, 2023.

Moustakas, S. and Willems, P.: Simplified spatially distributed, coupled soil moisture–groundwater model, evaluated for Flanders (Belgium), Journal of Hydrology: Regional Studies, 56, 102 006, https://doi.org/10.1016/j.ejrh.2024.102006, 2024.

Naganna, S. R., Deka, P. C., Ch, S., and Hansen, W. F.: Factors influencing streambed hydraulic conductivity and their implications on stream–aquifer interaction: a conceptual review, Environmental Science and Pollution Research, 24, 24 765–24 789, https://doi.org/10.1007/s11356-017-0393-4, 2017.

Paavonen, E., Salo, H., Salla, A., and Koivusalo, H.: Modelling the Spatio-Temporal Effects of Water Level Control in an Agricultural Collector Ditch Network, Irrigation and Drainage, https://doi.org/10.1002/ird.3091, 2025.

Podzorski, H. L. and Ryberg, K. R.: A Framework for Understanding the Effects of Subsurface Agricultural Drainage on Downstream Flows, Tech. rep., US Geological Survey, 2025.

Raes, D., Steduto, P., Hsiao, T. C., and Fereres, E.: AquaCrop—The FAO crop model to simulate yield response to water: II. Main algorithms and software description, Agronomy Journal, 101, 438–447, https://doi.org/10.2134/agronj2008.0140s, 2009.

Raes, D., Steduto, P., Hsiao, T. C., and Fereres, E.: Chapter 3 Calculation procedures AquaCrop Reference manual, Tech. rep., FAO, 2023.

Rathore, S. S., Svyatsky, D. S., Coon, E. T., Son, K., and Painter, S. L.: Modeling the Effects of Artificial Drainage on Agriculture-Dominated Watersheds Using a Fully Distributed Integrated Hydrology Model, Water Resources Research, 60, https://doi.org/10.1029/2023WR035993, 2024.

Rathore, S. S., Sloan, B., and Painter, S. L.: Hydrologic response of artificially drained agricultural watersheds: insights from high-resolution integrated surface/subsurface simulations, Environmental Research Letters, 20, https://doi.org/10.1088/1748-9326/adf240, 2025.

Ritzema, H. P.: Drainage Principles and Applications, vol. 16, ILRI Publications, ISBN 9070754339, 2006.

Ritzema, H. P. and Stuyt, L. C.: Land drainage strategies to cope with climate change in the Netherlands, Acta Agriculturae Scandinavica Section B: Soil and Plant Science, 65, 80–92, https://doi.org/10.1080/09064710.2014.994557, 2015.

Rodríguez-Lache, E., Blanchy, G., Mehmandoostkotlar, A., and Garré, S.: Performance of controlled drainage in tile-drained agricultural fields: An exploratory scenario analysis with the soil-plant model SWAP, Agricultural Water Management, 322, 109 973, https://doi.org/10.1016/j.agwat.2025.109973, 2025.

Rozemeijer, J. C., Visser, A., Borren, W., et al.: High-frequency monitoring of water fluxes and nutrient loads to assess the effects of controlled drainage on water storage and nutrient transport, Hydrology and Earth System Sciences, 20, 347–358, https://doi.org/10.5194/hess-20-347-2016, 2016.

Salo, H., Salla, A., and Koivusalo, H.: Seasonal effects of controlled drainage on field water balance and groundwater levels, Hydrology Research, 52, 1633–1647, https://doi.org/10.2166/NH.2021.056, 2021.

Skaggs, R. W., Brevé, M. A., and Gilliam, J. W.: Hydrologic and Water Quality Impacts of Agricultural Drainage, Critical Reviews in Environmental Science and Technology, 24, 1–32, https://doi.org/10.1080/10643389409388459, 1994.

Sloan, B. P., Mantilla, R., Fonley, M., and Basu, N. B.: Hydrologic impacts of subsurface drainage from the field to watershed scale, Hydrological Processes, 31, 3017–3028, https://doi.org/10.1002/hyp.11218, 2017.

Smedema, L. K., Vlotman, W. F., and Rycroft, D.: Modern Land Drainage, Taylor & Francis, 2004.

Statistiek Vlaanderen: Landbouwareaal, 2025.

Strock, J. S. and Ranaivoson, A. Z.: Ditch management using low-grade weirs: an opportunity for mitigating water quality and quantity impacts, Frontiers in Environmental Science, 12, https://doi.org/10.3389/fenvs.2024.1488925, 2024.

Tähtikarhu, M., Räsänen, T. A., Hyväluoma, J., Piayda, A., and Myllys, M.: Analysing hydrological impacts of controlled drainage, peat thickness and groundwater fluxes in cultivated peat soils, Acta Agriculturae Scandinavica Section B: Soil and Plant Science, 75, https://doi.org/10.1080/09064710.2025.2454388, 2025.

Tóth, B., Weynants, M., Pásztor, L., and Hengl, T.: 3D soil hydraulic database of Europe at 250 m resolution, Hydrological Processes, 31, 2662–2666, https://doi.org/10.1002/hyp.11203, 2017.

Tran, Q. Q., De Niel, J., and Willems, P.: Spatially Distributed Conceptual Hydrological Model Building: A Generic Top-Down Approach Starting From Lumped Models, Water Resources Research, 54, 8064–8085, https://doi.org/10.1029/2018WR023566, 2018.

Van Gaelen, H., Vanuytrecht, E., Willems, P., Diels, J., and Raes, D.: Bridging rigorous assessment of water availability from field to catchment scale with a parsimonious agro-hydrological model, Environmental Modelling and Software, 94, 140–156, https://doi.org/10.1016/j.envsoft.2017.02.014, 2017.

Waterinfo Vlaanderen: Meetreeksen, https://waterinfo.vlaanderen.be/Meetreeksen, 2025.

Willems, P.: A time series tool to support the multi-criteria performance evaluation of rainfall-runoff models, Environmental Modelling and Software, 24, 311–321, https://doi.org/10.1016/j.envsoft.2008.09.005, 2009.

Yimer, E. A., Riakhi, F. E., Bailey, R. T., Nossent, J., and van Griensven, A.: The impact of extensive agricultural water drainage on the hydrology of the Kleine Nete watershed, Belgium, Science of the Total Environment, 885, https://doi.org/10.1016/j.scitotenv.2023.163903, 2023.

Zhou, S. and Margenot, A. J.: The double-edged sword of agricultural tile drainage effects on stream flashiness: A meta-analysis, Journal of Hydrology, 651, https://doi.org/10.1016/j.jhydrol.2024.132500, 2025.

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## Appendix A: Crop parameters

Below the crop parameters used in the model are listed. These were originally set up by Moustakas and Willems (2024) based on Van Gaelen et al. (2017). The root extraction parameters of forests were adjusted in this study to more appropriately simulate 565 forest transpiration.

**Table A1.** Description of crop parameters used in the model.

| Parameter | Description | Units |
|---|---|---|
| PD | Planting date | – |
| eme | Period after planting to emergence | days |
| sen | Period after planting to start senescence | days |
| mat | Period after planting to maturity | days |
| KcTr,x | Coefficient for maximum crop transpiration | – |
| Kyield | Crop yield response factor | – |
| flogging | Fraction of saturation at which logging stress occurs | % |
| psto | Fraction of TAW below which water stress for crop transition is induced | – |
| rtexup | Maximum water extraction rate in the top quarter of the root zone | $m^3$ water/($m^3$ soil $\times$ day) |
| rtexlw | Maximum water extraction rate in the bottom quarter of the root zone | $m^3$ water/($m^3$ soil $\times$ day) |
| CC0 | Initial canopy cover | % |
| CCx | Maximum canopy cover | % |
| CGC | Increase in canopy cover | $day^{-1}$ |
| CDC | Decrease in canopy cover | $day^{-1}$ |
| Zn | Minimum effective rooting depth | m |
| Zx | Maximum effective rooting depth | m |
| tx | Period after planting to the maximum rooting depth | days |
| arD | Root distribution parameter (Equation 3.12) | $m^{-1}$ |
| brD | Root distribution parameter (Equation 3.12) | $m^{-1}$ |

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**Table A2.** Crop parameters that were used in the model (part 1). Units are given in Table A1

| Class | rtexup | rtexlw | arD | brD | PD | eme | sen | mat | tx |
|---|---|---|---|---|---|---|---|---|---|
| Winter wheat | 0.028 | 0.008 | 5.558 | 2.614 | 25 Oct | 13 | 242 | 263 | 214 |
| Winter barley | 0.019 | 0.006 | 5.558 | 2.614 | 1 Oct | 9 | 219 | 247 | 179 |
| Maize | 0.021 | 0.007 | 5.558 | 2.614 | 25 Apr | 8 | 133 | 144 | 144 |
| Sugar beet | 0.025 | 0.006 | 5.558 | 2.614 | 15 Apr | 4 | 133 | 168 | 62 |
| Potato | 0.088 | 0.022 | 5.558 | 2.614 | 25 Apr | 12 | 112 | 130 | 49 |
| Fruit | 0.100 | 0.050 | 7.5965 | 2.1195 | 1 Apr | 1 | 160 | 190 | – |
| Grassland | 0.040 | 0.010 | 10.740 | 2.608 | – | – | – | – | – |
| Mixed forest | 0.100 | 0.050 | 4.453 | 1.631 | – | – | – | – | – |
| Open Shrublands | 0.040 | 0.010 | 7.718 | 1.262 | – | – | – | – | – |
| Permanent Wetlands | 0.040 | 0.010 | 10.740 | 2.608 | – | – | – | – | – |
| Barren or Sparsely Vegetated | 0.040 | 0.010 | 4.372 | 0.978 | – | – | – | – | – |

**Table A3.** Crop parameters that were used in the model (part 2). Units are given in Table A1

| Class | KcTr,x | Kyield | flogging | psto | CC0 | CCx | CGC | CDC | Zn | Zx |
|---|---|---|---|---|---|---|---|---|---|---|
| Winter wheat | 1.10 | 1.05 | 95 | 0.65 | 1.5 | 92 | 0.037 | 0.133 | 0.30 | 1.50 |
| Winter barley | 1.10 | 1.00 | 85 | 0.60 | 1.5 | 92 | 0.054 | 0.097 | 0.30 | 1.30 |
| Maize | 1.05 | 1.25 | 95 | 0.69 | 0.5 | 87 | 0.093 | 0.091 | 0.30 | 1.10 |
| Sugar beet | 1.10 | 1.00 | 95 | 0.65 | 0.1 | 98 | 0.126 | 0.046 | 0.30 | 1.00 |
| Potato | 1.10 | 1.10 | 95 | 0.55 | 0.6 | 100 | 0.127 | 0.120 | 0.30 | 0.60 |
| Fruit | 0.90 | 1.33 | 95 | 0.55 | 5 | 90 | 0.039 | 0.076 | 1.50 | 1.50 |
| Grassland | 0.85 | 0.80 | 97 | 0.55 | 90 | 90 | – | – | 0.60 | 0.60 |
| Mixed forest | 0.95 | – | 97 | 0.50 | 90 | 90 | – | – | 1.50 | 1.50 |
| Open Shrublands | 0.85 | – | 97 | 0.55 | 80 | 80 | – | – | 0.80 | 0.80 |
| Permanent Wetlands | 0.85 | – | 100 | 0.55 | 80 | 80 | – | – | 0.50 | 0.50 |
| Barren or Sparsely Vegetated | 0.85 | – | 97 | 0.55 | 5 | 5 | – | – | 0.50 | 0.50 |

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## Appendix B: Model validation – Soil saturation

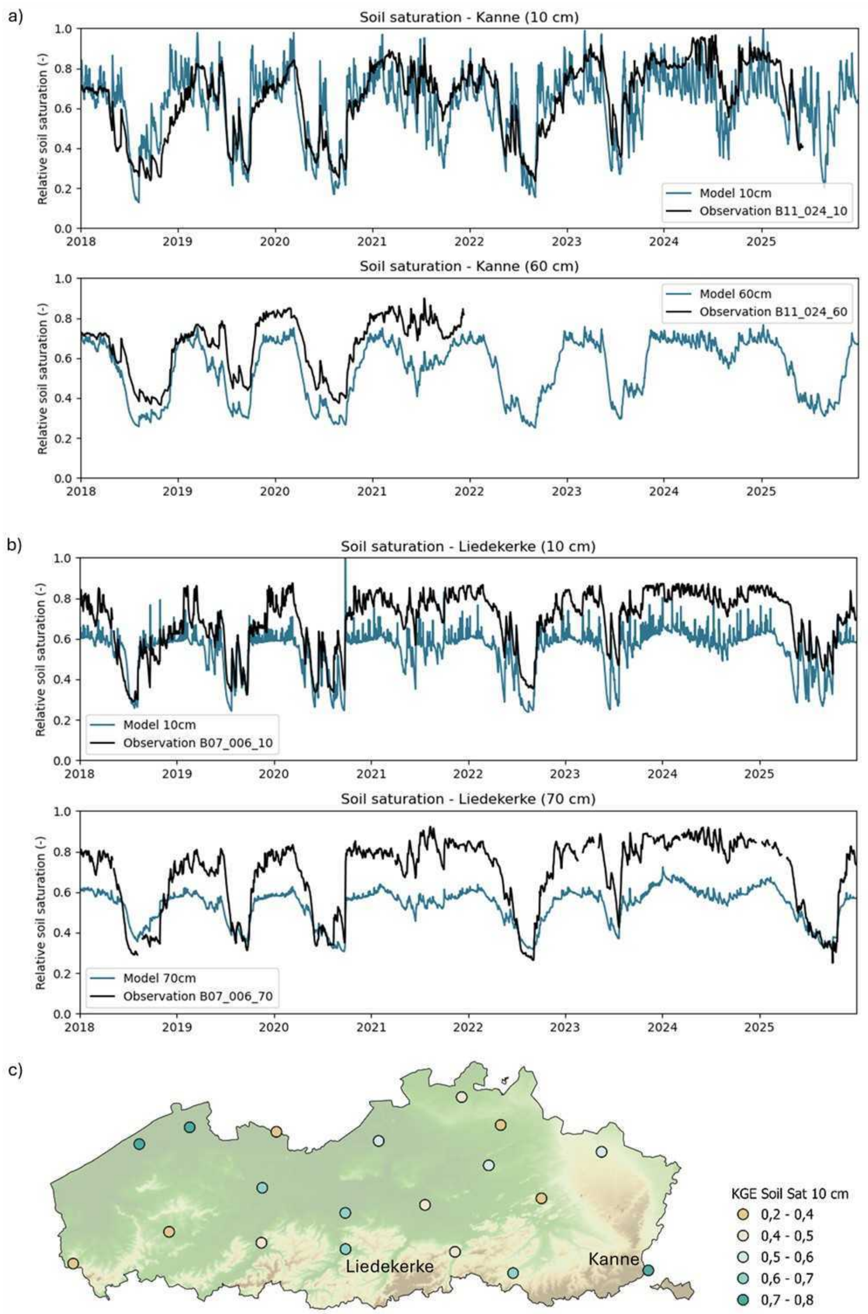


**Figure A1.** Soil saturation validation. Timeseries at 10 and 60/70 cm depth for two stations. Spatial variability of KGE at 10 cm depth.

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## Appendix B: Water balance change – management scenarios

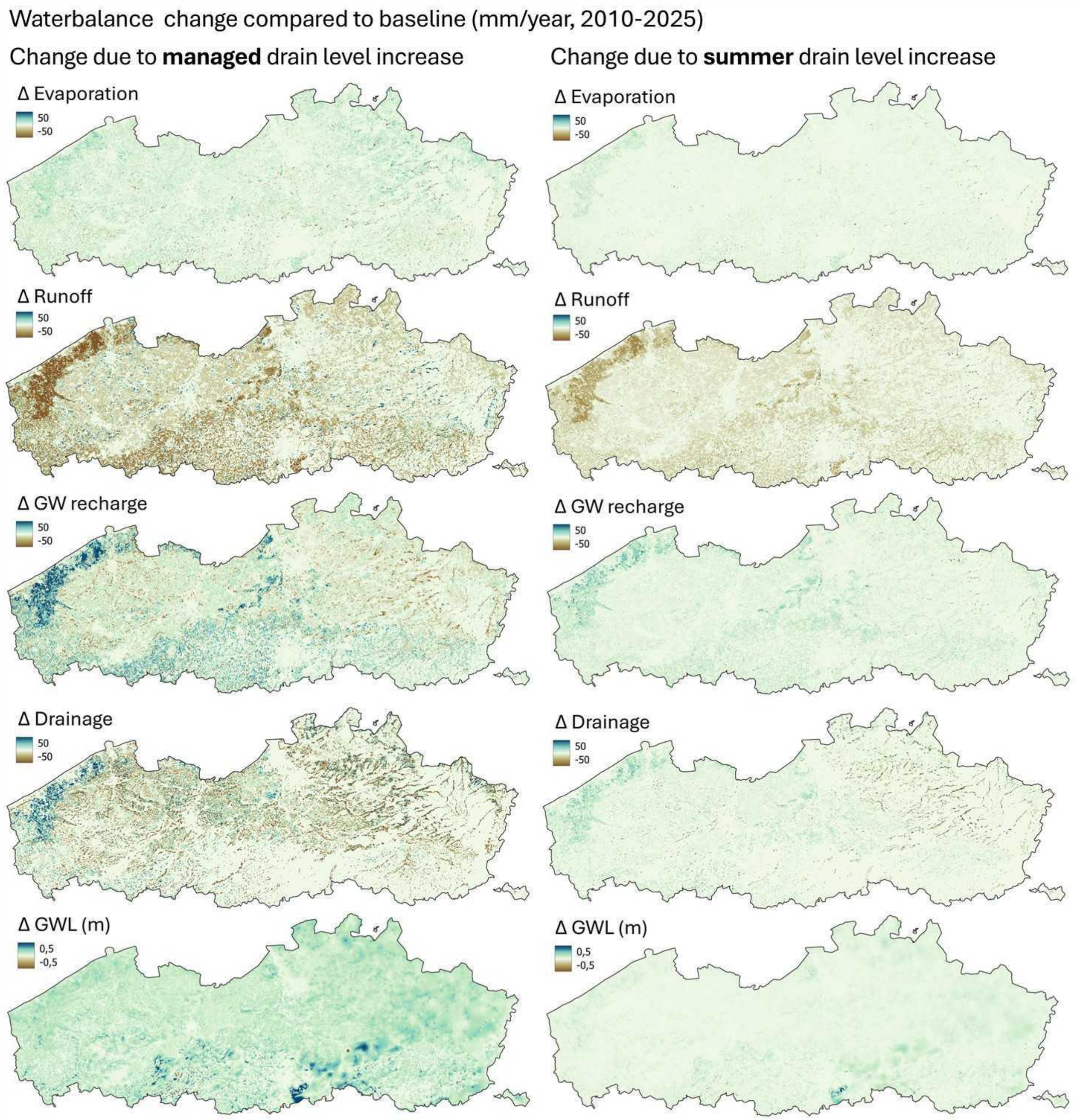


**Figure B1.** Water balance variables and their modeled change for the scenarios of managed drain level increase (left) and summer drain level increase (right). In addition to Fig. 6.