Forestation can mitigate extreme floods in the Meuse basin

by

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Abstract

In Northwestern Europe, including the Meuse basin, extreme flood discharge has increased. In July 2021, an extreme flood caused extensive losses within the Meuse basin. Forestation is a potential measure to mitigate such extreme floods by increases certain mechanisms important for assessing its effect on reducing peak discharge of the flood in 2021 in the Meuse basin, namely: evapotranspiration rates, percolation (which transports water from soil to deeper layers) and total water storage in the soil, and the delay of runoff. However, previous hydrological modelling research did not adequately represent these mechanisms, leading to an incomplete assessment of the effect of forestation on peak discharge. In this research, I improve the hydrological simulation of the Geographical, Environmental, and Behavioural model (GEB) by adding a runoff delay function and incorporating in-situ measurements for evapotranspiration rates and the van Genuchten parameters (determining percolation and total water storage), and adding a runoff delay. I used the improved hydrological simulation to more accurately assess the effect of forestation on peak discharge. Here I show that foresting the entire Meuse catchment reduced modelled peak discharge of the 2021 flood event by 14.3% (410 m^3/s). The most significant contributors to peak discharge reduction were the effects of increased percolation and evapotranspiration across the catchment. These processes mainly decreased pre-event soil saturation which allowed more water to infiltrate during the flood event, reducing the amount of runoff. This research demonstrates that forestation can be an effective measure to reduce future extreme flood discharge.

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1. Introduction

Flood extremes and climate change

Globally, riverine floods are estimated to impact 58 million people (Dottori et al., 2018) and cause US$ 104 billion in damage annually (Blöschl et al., 2019). Flood risk is likely to increase steeply in the future (Alfieri et al., 2017; Arnell & Gosling, 2016; Winsemius et al., 2016), driven by rising populations, economic growth and climate change (Kundzewicz et al., 2014; Ward & Winsemius, 2018). Recently, nature-based solutions, in this research applied through forestation, were proposed to mitigate flood risk trends (The World Bank, 2017).

Flood hazard does not exhibit any ubiquitous trends such as a global increase in flood frequency but displays varying regional trends (IPCC, 2023; Kundzewicz & Licznar, 2021; Sharma et al., 2018). Regional flood hazard trends exist because of spatial differences in the effects of the intensification of the water cycle (Blöschl et al., 2019; Huntington, 2006) and land use and land cover change (IPCC, 2023; Seneviratne et al., 2021). The intensification of the water cycle entails changes in important drivers of flood generation, namely precipitation, soil moisture and snowmelt (Huntington, 2006; Sivapalan et al., 2005).

In Northwestern Europe, including the Meuse basin, observed extreme flood discharge has increased over the past few decades, indicating an increase in extreme flood magnitude (Blöschl et al., 2019). The increase in observed flood discharge is driven by an increase in soil moisture and winter precipitation (Blöschl et al., 2019). These factors align with the main drivers of floods in Northwestern Europe which are the combined effects of high soil moisture and precipitation in winter (leading to saturation excess runoff), rather than extreme precipitation alone (Berghuijs et al., 2019).

Meuse basin 2021 flood events

In July 2021 extreme discharges caused extensive floods in the Belgian and Dutch parts of the Meuse basin (Dewals, 2021; Journée et al., 2023; Kok et al., 2023). Thousands of buildings were destroyed or damaged and tens of people died or were injured, of which most impacts occurred in Belgium (Dewals, 2021; Kok et al., 2023). At Eijsden (near the Belgium-Netherlands border), discharge reached record levels (Slager, 2021).

The floods were caused by exceptional multi-day precipitation, combined with presumably high soil moisture levels due to a preceding wet period (Asselman et al., 2022; Dewals, 2021; Journée et al., 2023). The hourly intensity of the precipitation was moderate, however, it rained steadily for 48 hours resulting in an extremely large 48-hour total (Asselman et al., 2022). The substantial amount of precipitation, along with (presumably) high soil moisture levels, rapidly saturated the soil, making all subsequent precipitation turn into runoff (Asselman et al., 2022;Boon & Kaspersma, 2023).`

Nature-based solutions

Nature-based solutions are a low-cost approach which can potentially mitigate flood hazard (Nature-Based Solutions to Address Global Societal Challenges, 2016; Ruangpan et al., 2020; The World Bank, 2017) while providing additional co-benefits such as carbon sequestration, erosion reduction and improved water quality (Jones et al., 2012; Raymond & Centre for Ecology and Hydrology (Great Britain), n.d.). Forestation, a commonly proposed nature-based solution, can reduce and delay runoff, which in turn reduces peak flood discharge through increasing 5 factors, further referred to as runoff-reducing mechanisms: 1) evapotranspiration, 2) infiltration, 3) percolation 4) total water storage, and 5) runoff delay (Beschta et al., 2000; Mcguinness & Harrold, 1971; Robinson et al., 2009). In the following sections (where the section numbers correspond to the number of the runoff-reducing mechanism) I discuss how forestation increases these runoff-reducing mechanisms, and how they mainly contribute to reducing runoff of flood-inducing precipitation events. This is also visualised in Figure 1.

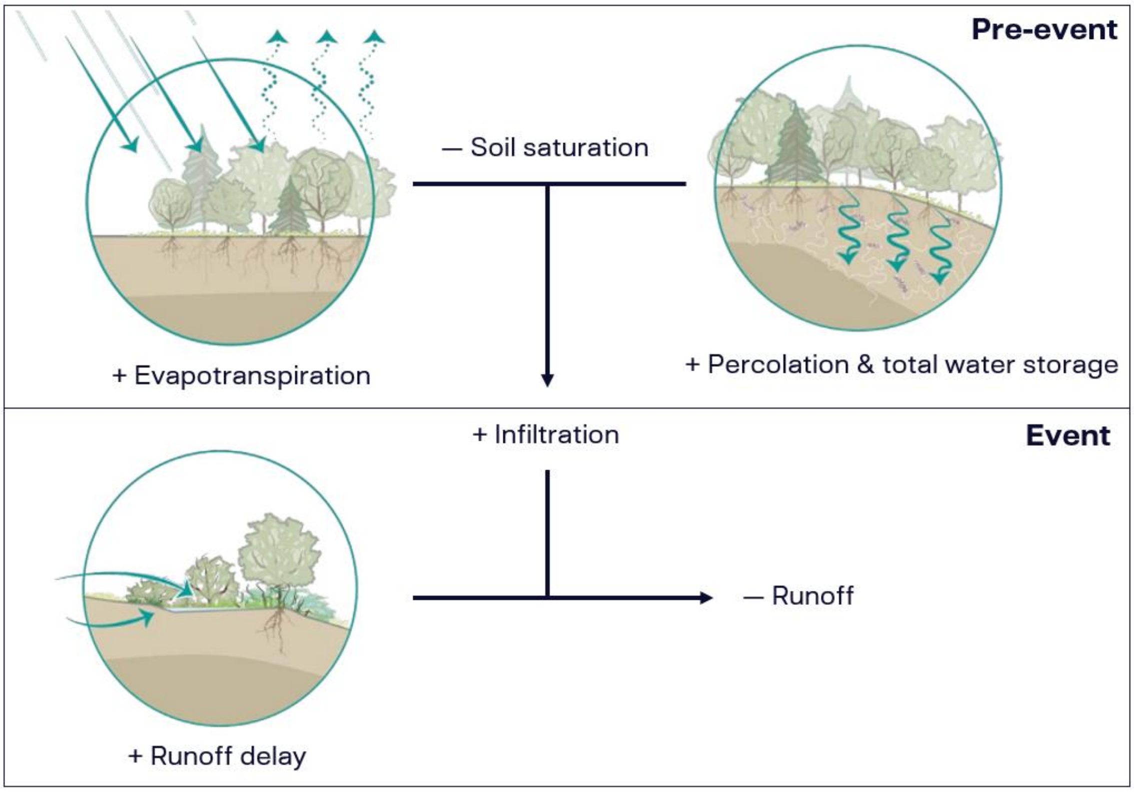

Figure 1. Illustration of how forestation increases runoff-reducing mechanisms—evapotranspiration, infiltration, percolation, total water storage, and runoff delay—both before (pre-event) and during (event) a flood-inducing precipitation event. The effect of the runoff-reducing mechanisms on key variables during floods, namely soil saturation (which in turn affects infiltration) and runoff, is also illustrated. The effects of forestation on each runoff-reducing mechanism, soil saturation and runoff are depicted as + (increase) and – (decrease).

1. Evapotranspiration is higher in forests (Bonan, 2008; Breil et al., 2021; Bright et al., 2017), which reduces soil saturation, especially in the upper zone of the soil. This reduction in saturation increases available water storage, which increases the infiltration of precipitation, thereby reducing the amount of saturation excess runoff.

2 & 3. Forests can increase infiltration and percolation by increasing hydraulic conductivity (Archer et al., 2013; Gonzalez-Sosa et al., 2010; Marshall et al., 2009; Mongil-Manso et al., 2021). Forests increase hydraulic conductivity by increasing the porosity of the soil, particularly macroporosity, by improving soil structure and increasing organic matter content. Improved soil structure results from increased root density and depth (Alaoui et al., 2011; Beven & Germann, 1982; Canadell et al., 1996; Jackson et al., 1996), organic matter content (Covington, 1981; Riestra et al., 2012), and macrofauna activity (Angers & Caron, 1998; Coleman et al., 1999; Vieira et al., 2012). Macrofauna decompose organic

matter and improve the incorporation of organic matter (deeper) into the soil, thereby increasing organic matter content (deeper) in the soil and improving soil structure.

Higher infiltration rates reduce runoff by decreasing infiltration excess runoff (Alaoui et al., 2011; Marshall et al., 2009). Furthermore, higher percolation transports more water from upper soil layers to deeper layers, less permeable layers. This results in lower saturation in the upper layer, allowing for more infiltration during a flood-inducing precipitation event.

4. Improved porosity, especially microporosity, as a result of improved soil structure and more organic matter, results in higher water storage capacity (Marshall et al., 2009; Nath, 2014). This allows for more water stored during flood-inducing precipitation events.

5. Tree trunks and understory vegetation slows runoff (Nisbet, 2022; Thomas & Nisbet, 2007) by functioning as a physical barrier. The slowing of runoff, thereby delaying runoff, results in a lower discharge peak.

In-situ evaluation of forestation on flood discharge

In-situ studies of catchment forestation have been used to evaluate the effectiveness of forestation in reducing floods, but have not addressed extreme floods and have several limitations. One limitation is that conducting catchment forestation requires extensive spatial and temporal research (Beschta et al., 2000; Mcguinness & Harrold, 1971; Robinson et al., 2009). Furthermore, the effectiveness of forestation varies between catchments due to differences in precipitation-runoff characteristics because of differences in size, climate, landscape features and management practices. Consequently, the results of catchment forestation research cannot directly be upscaled to other catchments.

Hydrological models

In contrast, hydrological models can be used to rapidly assess the effect of catchment forestation on flood discharge efficiently in both temporal and spatial context. However, current hydrological modelling research did not accurately determine the effect of forestation in reducing peak discharge because these runoff-reducing mechanisms were not adequately represented. Firstly, current research does not account for all runoff-reducing mechanisms of forests (Ellis Penning et al., 2024; Guido et al., 2023; Johnen et al., 2022; Lama et al., 2021; Natuurkracht, 2023; Thomas & Nisbet, 2007). Additionally, how models represent runoff-reducing processes, through choices made in parameterisation, is often unclear and not substantiated or parameterised and validated with in-situ measurements.

Aim and research question

Therefore, this study aims to extend knowledge and reduce uncertainties regarding the effectiveness of forestation in reducing extreme flood discharge by:

1. **Improving hydrological simulations:** I improve the Geographical, Environmental, and Behavioural (GEB) model (Burek et al., 2020; De Bruijn et al., 2023) by validating evapotranspiration rates and parameterizing soil hydraulic parameters (crucial for percolation and total water storage) per natural land cover type in GEB (i.e. forest, agricultural land and grassland) with in-situ measurements, and adding a runoff delay function to the model. This ensures that the model parameters and processes align more with reality, allowing a more precise simulation of the hydrological system.

2. **Evaluating the effectiveness of forestation in reducing peak flood discharge:** Using the improved hydrological model, I can more accurately assess the effect of forestation on peak discharge. This includes evaluating the contribution of each runoff-reducing mechanism to improve understanding of how forestation mitigates peak discharge.

The following research question is addressed: how effective is forestation in the upper and middle catchment area of the Meuse basin in reducing peak discharge of extreme flood events? I address this research question by examining the impact of various forestation scenarios on peak discharge of the 2021 extreme flood event in the Meuse basin.

General overview GEB & Meuse

GEB is a coupled agent-based human adaptation and hydrological model, known as CWatM (Burek et al., 2020) and implemented in Python 3. The agent-based model simulates agents such as individual farmers, interacting bidirectionally with CWatM on a daily timestep (De Bruijn et al., 2023). This allows GEB to simulate farmer irrigation (by extracting groundwater and reapplying it to the topsoil) in conjunction with the water cycle.

GEB calculates the water balance and river routing daily for each grid cell at 30 arcseconds (~1 km^2 at the equator). Within each grid cell, smaller sub-grid units, known as Hydrological Response Units (HRU's), represent various land cover classes and individual farmer fields. These HRU's vary in size, with a minimum of 30 x 30 meters. Each HRU allows calculations on evapotranspiration, soil processes (infiltration, percolation, capillary rise, interflow, runoff), and irrigation. The HRU's have different calculations and parameters for each land cover class in GEB, which are forest (FRS), grassland (GRS), agriculture (AGR), water covered and sealed areas. The outflow components of the water balance–surface runoff, interflow (lateral water flow) and groundwater recharge–are determined for each HRU and then aggregated to the larger grid cell, taking into account the relative size of the HRU. Subsequently, runoff, interflow and groundwater flow (i.e. baseflow) from each grid cell are directed, based on the runoff direction, to a grid cell with a water area. Thereafter, river routing is computed per grid cell by applying the kinematic wave approximation of the Saint-Venant equation (Chow et al., 1998).

Study area

The Meuse catchment was modelled upstream from Roermond (the Netherlands) for this study. The catchment spans approximately 33,000 km^2 across regions of France, Luxembourg, Belgium, Germany and the Netherlands (Figure 1). The catchment within France, Luxembourg, Belgium, and Germany was considered as the upper and middle catchment area. The Meuse River has a total length of about 950 km (Strijker et al., 2023). Elevations range from around 50 to 750 m, with steeper slopes in France and Belgium and flatter terrain in the Netherlands (Strijker et al., 2023).

The climate within the Meuse basin is classified as a temperate maritime climate (Beck et al., 2018). The mean annual precipitation across the basin is 950 mm (Fenicia et al., 2009; Ward et al., 2007), ranging from approximately 750 mm in the Netherlands to 1100 mm in the Ardennes (de Wit et al., 2007; Frijns, 2022; Torfs & Uijlenhoet, 2001). Precipitation shows little seasonal variation (de Wit et al., 2007; Ward et al., 2007). The mean annual temperature across the basin is 9.4 °C and shows significant seasonal variation with higher temperatures in summer half-year (Ward et al., 2007). Mean potential evapotranspiration is substantially larger in summer (76%) than in winter (24%) (Ashagrie et al., 2006). The basin consists of about 42% forest, 28% grassland, 20% agricultural land, 4% urban area and 6% water area (Figure 1).

Meuse discharge regime

The Meuse is an almost purely rain-fed river, leading to large annual and seasonal variations in discharge due to varying precipitation (De Wit et al., 2001; Frijns, 1993; Strijker et al., 2023; Ward et al., 2007). The mean summer discharge of the Meuse is about one-quarter of the average winter discharge, primarily due to the large seasonal variation in evapotranspiration (de Wit et al., 2007). The river's discharge responds rapidly to precipitation, mainly because of the fast response in the Ardennes (de Wit & Buishand, 2007; Strijker et al., 2023). The fast response makes high discharges likely to occur during large or extreme precipitation events (Strijker et al., 2023).

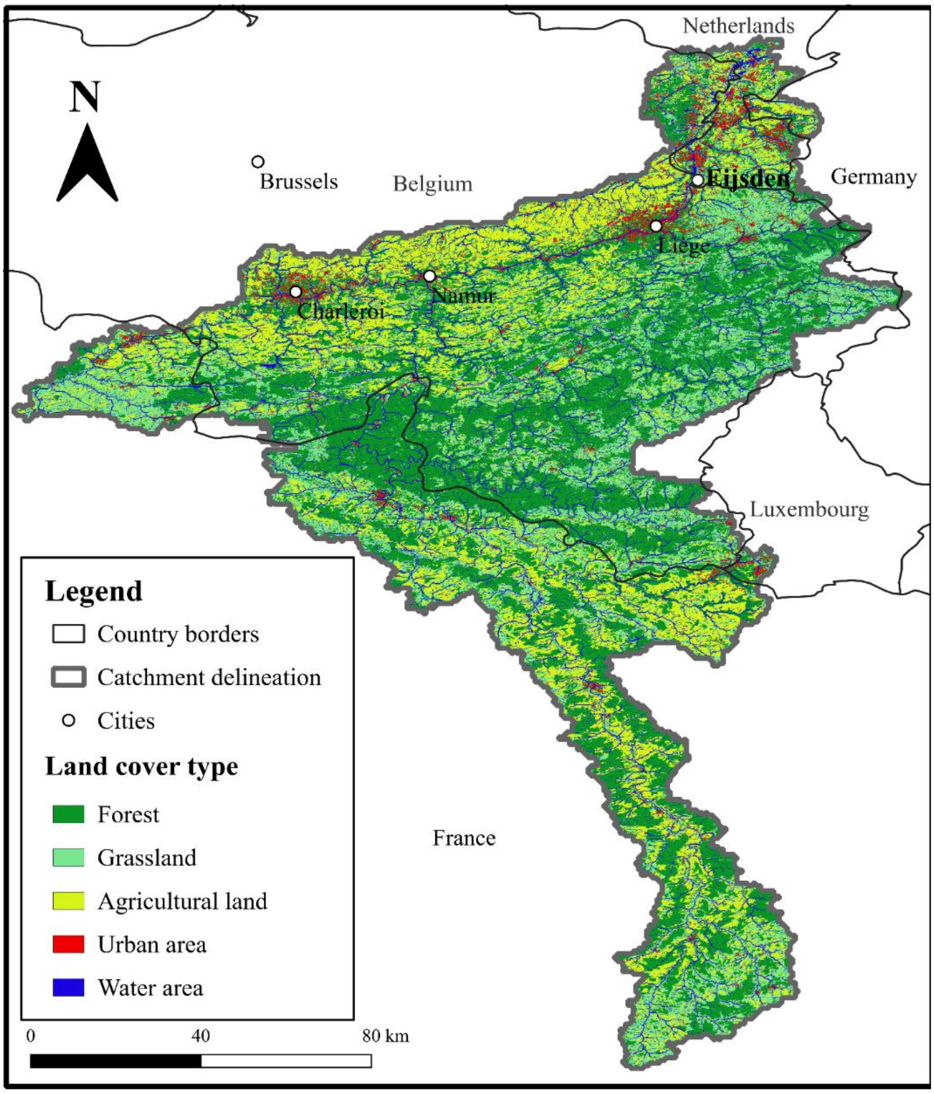

Figure 2. Land cover type distribution across the Meuse basin. The southern region of the basin is characterized by a mix of forest, agriculture and grassland, the middle region (mainly the Ardennes) is dominated by forest and grassland, and the northern region is predominantly agriculture. Eijsden is highlighted as discharge was modelled and evaluated here.

2. Methodology

This chapter outlines the methodology used to study the impact of forestation on reducing flood discharge in the Meuse basin. To accurately represent the effects of forestation on the runoff-reducing mechanisms in GEB, a literature review was conducted on in-situ measurements of some runoff-reducing mechanisms and their parameters (see Sect. 2.2.2 for details) in forests, agricultural land and grasslands; these in-situ measurements were incorporated into GEB through different approaches (see Sect. 2.3 and Sect 2.5). Subsequently, different forestation scenarios were created (see Sect. 2.7.1 for details), of which the results were analysed (see Sect 2.7.2 for details on how the results were analysed). The following paragraphs elaborate on these steps, the reasoning behind them, and provide theoretical information to explain and substantiate the reasons. The workflow of these steps is also schematised in Figure 3.

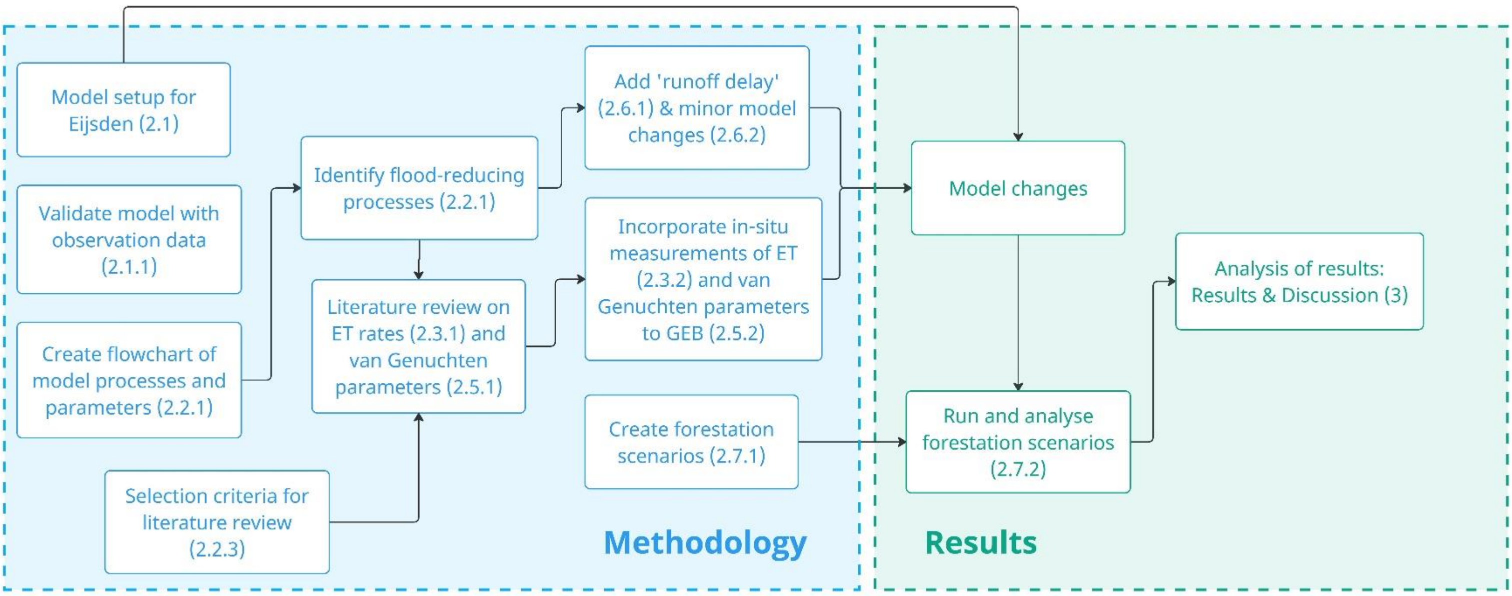

Figure 3. Workflow of methodology and how these steps generated results

2.1 Model setup for Eijsden

The GEB model was configured for the Meuse basin using ERA5 climate data, a high-resolution land use map, a Digital Elevation Model (DEM), and standard CWatM input maps (Table A1). General model parameter settings (in Figure 4 the parameters corresponding to 'Parameter, set value') were sourced from a previously calibrated GEB model (De Bruijn et al., 2023). The period from July 1, 2020, to July 1, 2021, was used as the spin-up period and July 2021 was used as the study period. The one-year spin-up period was short in comparison to other GEB or CWatM runs (Burek et al., 2020), but was used to minimise computation time. Discharge was modelled and evaluated at Eijsden.

2.1.1 Model validation with observed discharge

Discharge data was collected for Eijsden from Rijkswaterstaat. Hourly data were converted to daily data by computing the mean discharge (m^3/s) of the 24-hour sum. This data was used to validate the simulated peak discharge by the model. The magnitude of the first peak was simulated reasonably accurately (Observed: Figure, Appendix, Modelled: Figure, Appendix), therefore, I assumed the model to be suitable for comparing the effect of forestation on the extreme flood event, despite being uncalibrated.

2.2 General literature review overview

2.2.1 Identification of which runoff-reducing mechanisms and parameters can be incorporated in GEB

A flowchart was created detailing the processes and parameters used in GEB to calculate the water balance of a grid cell (Figure 3). The flowchart was created to 1) identify if all runoff-reducing mechanisms were incorporated in GEB, 2) identify which parameters (concerning the runoff-reducing mechanisms) were based on datasets (Figure 3, 'Parameter Based on data'), 3) identify which parameters (concerning the runoff-reducing mechanisms) were a manually set value (Figure 3, 'Parameter Set value'). The following sections describe the effects of identifying these different runoff-reducing mechanisms and their corresponding parameters:

1) Evapotranspiration, infiltration, percolation and soil water storage (related to total water storage) were incorporated into the model. However, runoff delay was missing from the model, therefore this process was added to the model (see Sect 2.6.1 for details).
2) Datasets contain spatially different values for parameters, which in turn can create spatial differences in model processes (e.g. evapotranspiration rates through spatial differences in crop coefficient parameter). Thus, datasets can create differences in parameters or model processes between land cover types. Spatial differences or differences between land cover types can be validated with in-situ measurements from literature.
3) In contrast, a set value parameter does not vary spatially or across land cover types and therefore cannot be validated with in-situ measurements. In GEB, the amount of infiltration occurring during a timestep (infiltration factor in Figure 3) is calculated by such a set value parameter, combined with soil saturation and the amount of water available for infiltration. Thus, infiltration rates in GEB are not influenced by spatially varying landscape features such as land cover, topography, soil properties, and management practices, which affect infiltration rates (Beschta et al., 2000; Covington, 1981; Robinson et al., 2009). This limitation prevents validation of infiltration rates with in-situ measurements. Therefore, the potential effects of land cover type (e.g. forests) on infiltration rates could not be incorporated in this research, potentially introducing uncertainty to the research outcomes. However, given that the flood in 2021 was likely caused by saturation excess, I presume the effect of improved infiltration rates through forestation to be small for this event.

A preliminary literature review was conducted to identify which runoff-reducing mechanisms (except for runoff delay and infiltration) and corresponding parameters (based on datasets) were sufficiently described with in-situ measurements to validate GEB with. This literature review was conducted using certain criteria described in Sect. 2.3.2. In-situ measurements on evapotranspiration, interception and transpiration rates for forests, as well as the soil hydraulic parameters of the model (Figure 3: $\alpha, \lambda, K\mathrm{s}, \theta\mathrm{r}, \theta\mathrm{s}$), known as the van Genuchten parameters (see Sect. 2.4.1 for a detailed description on these parameters), were sufficiently described in literature. These studies were collected and used to validate and parameterize GEB to in-situ measurements. This was done through different methodologies: modelled evapotranspiration rates (including interception and transpiration rates) were calibrated to in-situ measurements (see Sect. 2.3.2 for details) and in-situ measurements were incorporated into the van Genuchten parameter dataset used in GEB (Table A1) (see Sect. 2.5.2 for details).

Other parameters important for evapotranspiration and percolation (i.e. see Figure 3: crop coefficients, root density, root depth, storage depth and interception capacity), and evapotranspiration, interception and transpiration rates for agricultural land and grassland were insufficiently described in literature. Thus, not all parameters could be validated in-situ measurements in literature, which is a limitation of this research. However, global findings on crop coefficients (Liu et al., 2017), root density (Jackson et al., 1996) and depth (Canadell et al., 1996) across land cover types aligned with mean values across the Meuse catchment in GEB (Table G2) and thus partially validated GEB. For example, each parameter was higher in forests compared to agricultural land and grasslands. Furthermore, grasslands were on average higher in root density and depth than agricultural land.

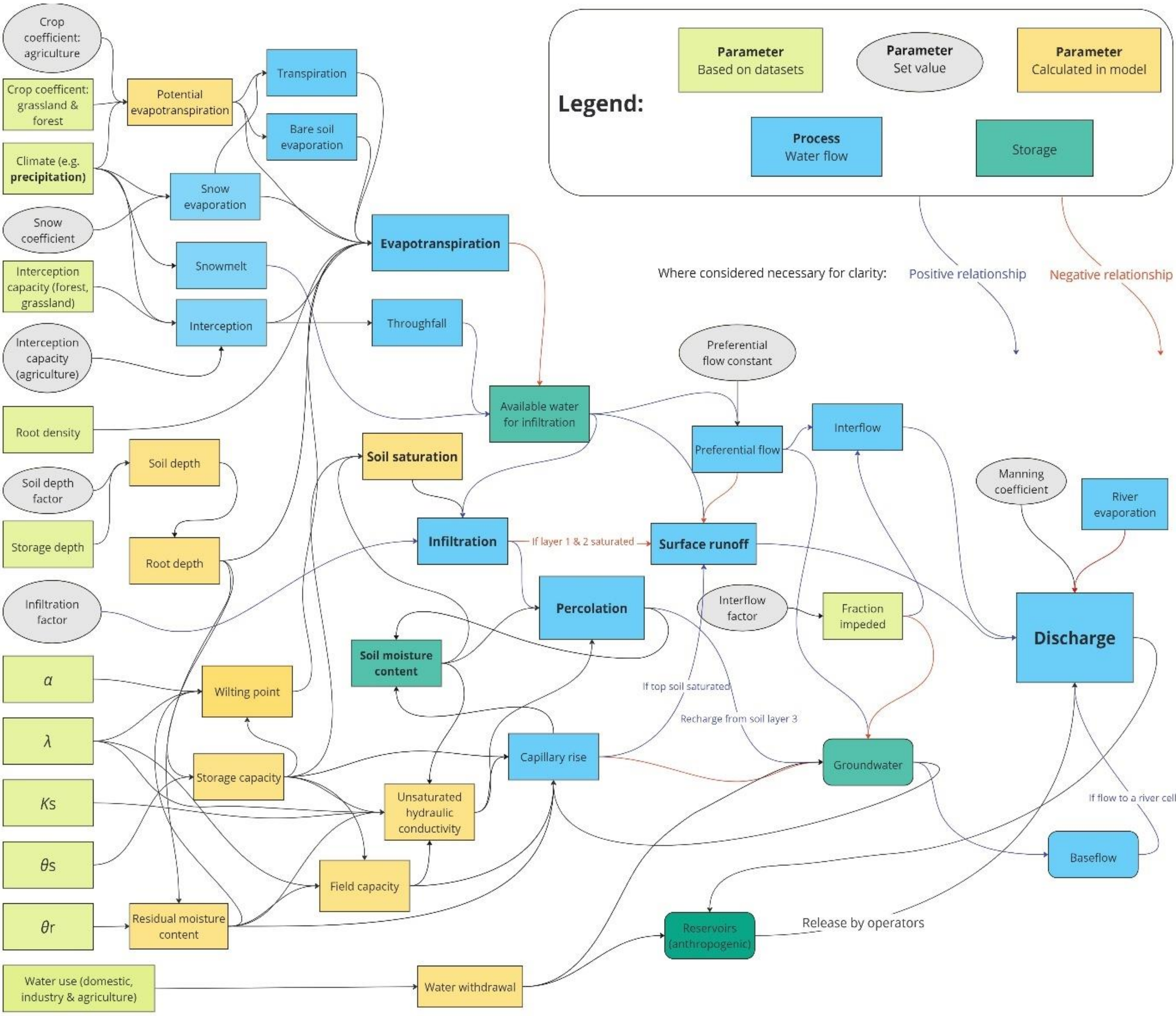

Figure 3. Flowchart showing the processes and parameters used in GEB to calculate the water balance of a grid cell during a timestep, and how runoff is turned into discharge in a nearby river cell. It shows the conversion of precipitation into discharge in GEB through the various parameters, processes and storages involved.

2.2.3 Literature selection criteria

Studies for the literature review were selected if the research locations had environmental conditions similar to those of the Meuse. By only selecting studies with a similar environment, the evapotranspiration rates and van Genuchten parameters from the literature review, although studied in different regions, are more comparable to the Meuse basin. The studies were selected on a similar climate (see Sect. "Study Area" for the environmental conditions in the Meuse), with similar mean annual precipitation (± 100 mm: 850-1050 mm), mean annual temperature (± 1°C: 8.4-10.4°C), elevation (<800m), and slope (gentle: <10°). Precipitation and temperature influence evapotranspiration rates and soil hydraulic properties by affecting organic matter decomposition (Kirschbaum, 1995; Meentemeyer, 1978; Várallyay, 2010) and soil fauna activity (Tan et al., 2021; Wall et al., 2008). Moreover, precipitation, particularly in sloped regions, can induce topsoil erosion, leading to the removal of soil components such as organic matter. Also, elevation influences humidity, wind and incoming solar radiation (Körner, 2007), affecting evapotranspiration rates. Furthermore, primarily European studies were selected to ensure that tree and plant species and compositions roughly match that of the Meuse basin. Different forest types have varying evapotranspiration rates (e.g. Teuling, 2018). Furthermore, different species compositions (in forests, agricultural lands and grasslands) can affect soil hydraulic properties by influencing soil structure through variations in root depth and density (Canadell et al., 1996; Jackson et al., 1996; Jevon et al., 2023; Gutmann & Small, 2007) and organic matter content, decomposition and integration into the soil (which in turn affects soil structure) through differences in litter production, quality and soil fauna activity (Bradford et al., 2016; Edwards & Arancon, 2022 Jarvis et al., 2013; Vereecken et al., 2010).

2.3 Incorporating in-situ forest evapotranspiration measurements to GEB

2.3.1 Literature-derived mean values for evapotranspiration rates.

Studies documenting forest evapotranspiration, interception and transpiration rates (mm/d) were only collected if they measured these processes for a complete year, to eliminate seasonal variation. The mean rates (mm/d) of a complete year were reported (Table B1, Table B2, Table B3). From the collected rates from all acquired literature, mean evapotranspiration, interception and transpiration rates were calculated (Table B4). Interception rates were calculated separately for different forest types—deciduous broadleaved forest (DBF), deciduous needle-leaf forest (DNF) and mixed forest (MF)—because sufficient data was acquired to make these distinctions. The interception rate for MF was determined by averaging the interception rates of DBF and DNF. For evapotranspiration and transpiration rates no distinction was made between forest types, and hence these rates were represented by a single mean value for each forest type.

2.3.2 Applying in-situ evapotranspiration rates to GEB

The evapotranspiration, interception and transpiration rates in GEB were adjusted to the calculated literature-derived mean rates (described in Sect. 2.3.1). This was done by calculating the mean evapotranspiration, interception and transpiration rates across the catchment from the spin-up period in GEB (July 2020 - July 2021) and calibrating these rates to the literature-derived mean rates. To calibrate, various multiplication factors were added to variables affecting evapotranspiration, interception and transpiration rates in GEB, namely: potential evapotranspiration, transpiration, bare soil evaporation, interception capacity (the maximum water storage of vegetation) and interception evaporation (water evaporating from leaves) (these parameters are shown in Figure 3). For interception capacity and interception evaporation the multiplication factors were calibrated per forest type, by first implementing a spatial map containing these forest types to the Meuse in GEB (see Sect. 2.3.3), until the mean interception rates per forest type in GEB across the catchment were equal to the literature-derived mean interception rates.

2.3.3 Forest-type map

To apply forest types to the Meuse catchment in GEB and have spatially different interception rates, a forest-type map containing spatial raster data of DBF, DNF and MF at a 100 m resolution (Copernicus 2018) was implemented in GEB. The interception rates in GEB were adjusted per forest type. According to this map, the Meuse basin contains 69.7% DBF, 17.0% DNF and 13.3% MF. The map was upscaled to a resolution of 1 km to match the grid cell resolution in GEB, allowing for application to GEB. When the forest-type map was integrated into GEB, the HRU's within a specific grid cell of the land use map in GEB were all assigned the forest type of the corresponding grid cell of the forest-type map. The raster was resampled with mode, which ensures that the most frequently occurring forest type within each larger grid cell is represented, thereby preserving the most dominant land cover. However, resampling led to an overrepresentation of deciduous forest (79.6%) and an underrepresentation of coniferous (16.6%) and mixed forest (3.8%). However, because evapotranspiration rates between forest types were kept equal, the effect on results was negligible. The forest-type map was 3 years older than the land use map used in GEB. Therefore, some forest areas within GEB lacked classification. These unclassified forests were randomly assigned while maintaining the same percentage of forest types as in the original dataset (Copernicus, 2018).

2.4 Evaluation of van Genuchten parameters

2.4.1 Van Genuchten parameters description

The van Genuchten parameters consist of the saturated hydraulic conductivity (Ks), saturated moisture content (θs), residual moisture content (θr) and 2 shape parameters, also termed water release parameters, of the Soil Water Retention Curve (SWRC): pore-size distribution index (λ), and the inverse of the air entry suction (α) (Tian et al., 2018). The SWRC determines how water is retained and released within the soil, influencing percolation and water storage in GEB.

Ks, λ and α determine water transport within the soil, which in the model is most important for percolation. Ks is the measure of the soil's ability to transmit water under saturated conditions (Klute & Dirksen, 2018). Moreover, Ks positively affects unsaturated conductivity. Soils with many large pores, but especially macropores, have high saturated conductivity (Jarvis et al., 2013). λ and α determine how much water is stored and released in the soil with decreasing suctions. λ is a measure of the soil pore-size distribution. α determines the pressure at which air starts to enter the soil pores. λ is important for hydraulic conductivity at every water content while α is important for hydraulic conductivity at higher water contents (Hodnett & Tomasella, 2002). Higher values of both shape parameters indicate that water is released more easily. Soils with many large pores, especially macropores, generally have higher values of λ and α. Conversely, soils with many small pores have low values of λ and α.

θs and θr are respectively the maximum and minimum amount of water in the soil (Fu et al., 2024). θs is the water content at full saturation. Thus, θs determines the maximum amount of water the soil can store. Soils with many large pores, especially macropores, can store more water. θr is the water content where water is retained within the smallest pores, by strong adhesive forces (Fu et al., 2024). Water below this level can hardly be removed, by either plants or evaporation and therefore hydraulic conductivity is practically 0 at θr. Soils with many small pores, especially micropores, lead to higher θr. The difference between θs and θr (i.e. θs – θr) is the total amount of water which can be stored in the soil.

2.4.2 Evaluation of van Genuchten parameter datasets vs in-situ measurements

Soil hydraulic parameters datasets (such as van Genunchten parameters datasets) can only partly capture, unlike in-situ measurements, the effects of soil structure and the effects of land cover type (i.e. if land cover type is forest, agricultural land or grassland) on soil structure and organic matter. Soil structure affects the distribution of pore sizes which affects soil hydraulics (e.g. hydraulic conductivity and water storage). Van Genuchten parameters datasets, such as the one usually used in GEB (Table, Appendix) or from European Commission, 2017 or Simons et al., 2020, are derived through pedotransfer functions (e.g. Zhang & Schaap, 2017 for the dataset used in GEB). These functions estimate the van Genuchten parameters based on datasets of standard soil properties (soil texture, porosity, organic matter, and bulk density). These standard soil properties can partly account for the effects of soil structure (through porosity and bulk density), but the effect of variations in pore size distributions (e.g. the distribution and subsequent effects of macropores and micropores) cannot be accounted for. Also, these standard soil properties maps are generally low-resolution which therefore cannot account for local field variability in soil structure and organic matter caused by land cover types. Furthermore, the pedotransfer functions are derived from laboratory measurements of soils with a small sample size while soil structure is highly variable and affects soil hydraulics. As a result, the transfer of soil properties to soil hydraulic parameters (i.e. a pedotransfer) has performed poorly in the past compared to in-situ measurements (Jarvis et al., 2013; Pachepsky & Rawls, 2003). Datasets of the van Genuchten parameters within the Meuse basin (European Commission, 2017; Simons et al., 2020; Table, Appendix) also did not seem to perform well. For example, they did not show substantial differences in the van Genuchten parameters across the catchment or between land cover types (e.g. G2). The lack of variation in the van Genuchten parameters does not reflect the expected heterogeneity in soil properties and the potential effects of land cover on soil properties. Moreover, the dataset by Simons et al (2020) indicated very low saturated conductivity values across the catchment across all soil depths, which is highly improbable. Conversely, literature on the van Genuchten parameters are derived through in-situ measurements (which fully incorporates the effects of soil structure), and have a large sample size across a region (which more accurately computes soil hydraulic parameters for an area because it takes into account many variations in soil structure and organic matter).

2.5 Incorporating in-situ measurements of van Genuchten parameters to GEB

2.5.1 Data collection of van Genuchten parameters

The literature review collected data on van Genuchten parameters per natural land cover type used in GEB (forest, agricultural land and grassland). The van Genuchten parameters of each study were reported along with literature references, details about the country of research, the soil depths examined, USDA soil textural classes (classification of clay, silt and sand %) and soil type (Table C1, Table C2, Table C3). If the studies did not classify soil textures according to USDA standards, but provided the percentages of clay, silt and sand, these percentages were classified using the USDA textural triangle (United States Department of Agriculture, 2017). These studies, including the values of the van Genuchten parameters, classify soil textures according to USDA standards but provided the percentages of clay, silt and sand, I classified these percentages by the Food and Agriculture Organization of the United Nations [FAO]. Additionally, in one article (Puhlmann & Von Wilpert, 2012) soil classifications were provided in a German soil classification system. These were converted to USDA classifications. This conversion process resulted in German classifications overlapping with multiple USDA soil textures. Consequently, van Genuchten parameters were documented for each corresponding USDA soil texture category.

2.5.2 Methodology for incorporating in-situ measurements to GEB

The van Genuchten parameters data collected with the literature review were transformed into spatial maps of each van Genuchten parameter across the Meuse basin, per land cover type (for example, for saturated hydraulic conductivity you would have a map for each land cover type). This was done by integrating the parameters into a high-resolution (1 km) soil map (see panel D in Figure 4) by the Food and Agriculture Organization of the United Nations [FAO]. This section describes the methodology of incorporating these parameters into the soil map and how these were then incorporated in GEB. First, I will give a short overview of the contents of the paragraphs in this section to improve understanding of each paragraph:

1. In the first paragraph of this section, I will describe the contents of the FAO soil map and what its connected database consists of (see Sect. “FAO soil map and database”).

2. In the next paragraph (see Sect. “Classifying soil layers”) I will describe how the van Genuchten parameters reported in the literature were classified into the soil layers of GEB and how these could subsequently be classified into the soil layers of the FAO database.

3. In the next paragraph (see Sect. “Adding van Genuchten parameters to FAO database and GEB”) I will describe how the van Genuchten parameters reported in the literature were incorporated into the soil database, and how the soil map (which is linked to the database) was incorporated into GEB.

4. In the next paragraph, to clarify these previous steps, I will provide an example of how one study describing the van Genuchten parameters was incorporated into the FAO soil map and subsequently into GEB (see section “Example study” and Figure 4).

5. In the last two paragraphs of this section I substantiate certain steps taken during this methodology and how I handled missing data.

FAO soil map and database

The soil map contains polygons (see panel D in Figure 4). Each polygon had a certain ID linked to an FAO soil database (see box ‘FAO soil database’ in Figure 4) which includes extensive data on soil properties (most importantly USDA soil textural classes and soil types) for 7 soil layers (0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, 80–100 cm, 100–150 cm and 150–200 cm). Each polygon consists of a certain soil type and texture.

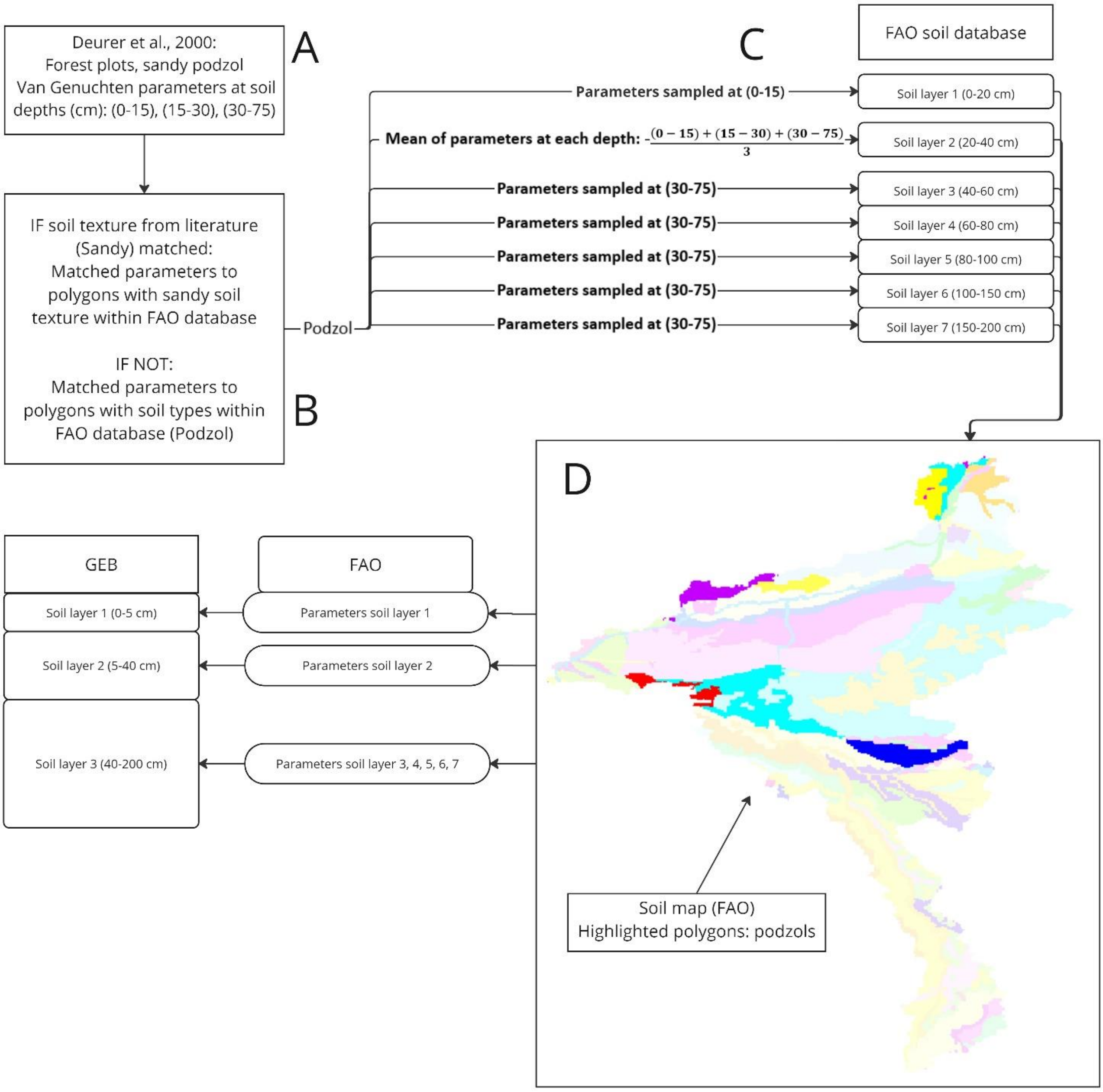

Figure 4. An example of how one study describing the van Genuchten parameters was incorporated into the FAO soil map and subsequently into GEB.

Classifying soil layers

The soil depths of the van Genuchten parameters described in literature were classified to the soil depths of GEB. GEB contains 3 soil layers: 1) 0-5 cm, 2) 5-40 cm, and 3) 40-200 cm (see Figure 4: box GEB). Thus, if a study investigated van Genuchten parameters at a depth of 10-20 cm then these values would be classified within the 5-40 cm soil layer within GEB**.** GEB's three soil layers were matched to FAO's layers as follows: layer 1 GEB: layer 1 FAO (0-20 cm), layer 2 GEB: layer 2 FAO (20-40 cm), layer 3 GEB: layer 3, 4, 5, 6 and 7 FAO (40-200 cm) (see Figure 4: box FAO and box GEB). In this way, the van Genuchten parameters which were classified into soil layers in GEB could then be classified into the soil layers of the FAO database.

Adding van Genuchten parameters to FAO database and GEB

Three van Genuchten parameter maps were created, each corresponding to a certain land cover type (forest, agricultural land and grassland. Each van Genuchten parameter reported in literature, for a certain land cover type and soil depth, was added to the FAO soil database. In the first instance, the parameters were added to the polygons in the database with matching soil texture classification (meaning that the soil textural class of the sampled parameter in literature was added to every polygon with matching soil textural class in the FAO database). However, if no polygon matched the soil texture from the research, the parameters were added to polygons matched by soil type. If a study provided van Genuchten parameters data for a soil depth that overlapped two soil depths in GEB, the parameter was applied to both soil depths. Similarly, if data from multiple depths in a study overlapped a single soil depth in GEB, the mean value of those parameters was used. If polygons contained data from multiple studies, because these studies had documented van Genuchten parameters for the same soil texture or type, the mean of the values reported in these studies was taken. After all van Genuchten parameters reported in literature were incorporated into the database, the database was linked to the soil map in QGIS. Subsequently, the maps for each van Genuchten parameter were integrated into GEB and used for the respective land cover type.

Example study

The study by Deurer et al., 2001 examined forest plots and described the van Genuchten parameters across multiple depths (0-15, 15-30, 30-75 cm) of sandy podzols (see panel A in Figure 4). I processed the van Genuchten parameters of this study by adding them to the FAO database for polygons with podzol as soil type (Figure 4, panel B), with the value of each parameter at a certain depth of the study added to the matching depth in the database (see arrows, text in arrows and the soil depths of the FAO soil database these arrows are connected to, near panel C in Figure 4). Here, soil depths 0-15 cm and 30-75 cm studied in Deurer et al., 2001 were respectively classified to soil layer 1 (0-5 cm) and 3 (40-200) in GEB, and thus added to soil layers (0-20 cm) and (40-200 cm) in the FAO soil database (see panel C in Figure 4). Furthermore, all soil depths in Deurer et al., 2001 overlapped the depths of soil layer 2 in GEB (5-40 cm) so the mean was taken of these parameters to calculate the van Genuchten parameter values for soil layer 2 in the FAO database (see panel C in Figure 4). Initially, these parameters would be added to the polygons with soil texture 'sandy'; however, because no polygon within the basin contained this soil texture, the van Genuchten parameters were added to polygons with 'podzol' soil type (see panel B in Figure 4). Thus, all polygons within the Meuse basin classified as podzols would adopt the van Genuchten parameters from Deurer et al., 2000.

In the previous step, described in the previous paragraph, soil textural class was chosen first to match van Genuchten parameters from literature to polygons of the FAO soil map because of its strong correlation with the van Genuchten parameters (Fang et al., 2023; Fu et al., 2024; Hodnett & Tomasella, 2002; Tian et al., 2018); soil texture highly affects porosity, soil structure and organic matter content (Fundamentals of Soil Physics - Daniel Hillel - Google Books, n.d.; García-Gutiérrez et al., 2018; Prasad & Power, 1997; Reichert et al., 2009; Wösten et al., 1990). Soil type was matched second because although it also relates to soil properties such as soil texture and porosity, its relationship to these properties is less strong compared to soil texture but is less strongly related to these properties than soil texture (Hristov, 2013; Soil Survey Staff, 1999). Additionally, other factors of influence on soil hydraulic properties, soil structure and organic matter content (Bockheim et al.,

2014) such as climate and land cover were accounted for by selecting literature in a similar climate and topography.

Handling missing data

Not all polygons were filled with data because not every soil texture or soil type within the FAO soil map was described through in-situ measurements in literature. To address missing data of van Genuchten parameters within polygons of the FAO soil map, varying steps were taken. Within soil maps of forest and agricultural land, in 2 polygons which lacked texture data and did not match through soil type, the values of van Genuchten parameters within polygons were filled with the mean from all collected studies (Table C4, Table C5). Within soil layer 3 in GEB, for forests, a substantial amount of polygons was missing data, therefore studies which were already matched to a polygon through soil texture were also matched through soil type. As a result, all polygons in the van Genuchten parameters map for forests contained data (filled manually), and thus the original van Genuchten parameters dataset of GEB for forests did not have to be used for further model runs in this research. Due to a limited amount of van Genuchten parameter data for grassland and agricultural land, only some FAO polygons could directly be applied in GEB. Hence, data from the original datasets was used for large parts of the basin.

2.6 Additional model changes

2.6.1 Runoff delay

I have added a runoff delay function to the model. This function computes a minimum amount of expected delay per land cover type based on friction coefficients used in other runoff delay methods (Fang et al., 2007; Woodward et al., 2008). Through this function, 5%, 2% and 2% of the runoff from respectively forests, grassland and agricultural land, is delayed until the next timestep (i.e. a day) through a 'runoff delay factor'. Within these runoff delay methods, forests usually have more than double the friction of agricultural land and grassland, sometimes even reaching a difference of 400% (Fang et al., 2007; Woodward et al., 2008). The exact effect of these friction values on discharge delay is unknown but provides a rough indication of the eventual runoff delay. Runoff delay methods such as the triangular-weighting method (Woodward et al., 2008) or the velocity method (Fang et al., 2007) have also been evaluated for use within GEB. However, due to the relatively high grid cell resolution compared to the large timestep, all runoff exits a grid cell within a single timestep, making the use of such methods ineffective.

2.6.2 Minor model changes

Values of some important variables in GEB, interception capacity and crop coefficient, were not in line with the literature. These values were subsequently adjusted for all future runs as follows. Daily interception capacity values of forests and grassland are calculated from a vegetation cover dataset (Hanse et al., 2013). As a result, the interception capacity of forests during November and December was computed as 0 and consequently, interception rates were computed as 0 during these months. However, literature indicates that interception does not drop to 0 during leafless periods because of interception via tree trunks (Gerrits et al., 2010; Rutter et al., 1975; Staelens et al., 2008). Therefore, the minimum interception capacity for forests was adjusted to the lowest mean interception capacity observed in forests within GEB, which was 0.186 mm in January. Furthermore, the interception capacity for agriculture was at first set to 1.0 year-round, a value higher than any interception capacity value of forests across the year and nearly twice that of grassland, observations which are not in line with literature on interception capacity in models (e.g. Rutter et al., 1975) and interception rates (Table B2). Because of this large discrepancy, the interception capacity value for agriculture across the catchment was changed to the mean value for grassland.

2.7 Forestation analysis

2.7.1 Forestation scenarios description

Various forestation scenarios were designed to assess the effects of afforestation on discharge. In a scenario, termed 'Full Forestation', all grassland and agricultural land within Belgium and France was converted to forest. In this scenario, any conversion of land cover in the Netherlands was not considered because the location where discharge is evaluated is not affected by land cover changes in the Netherlands. A scenario was created which could be more realistic in being applied for forestation in the future, termed 'Restoration Opportunities' (see Figure 5 for which areas were forested in this scenario). This scenario was based on a map which identified areas with potential for future forestation (Laestadius et al., 2011). This map determined locations suitable for forest growth based on soil and climate conditions while excluding areas unsuitable for forestation such as densely populated areas (>100 people/km^2), urban regions or intensively managed agricultural lands. Four additional scenarios were used: in France and Belgium, grassland and agricultural land were each separately per land cover type and country converted into forest.

2.7.2 Analysis of forestation scenarios

A baseline model run of peak discharge at Eijsden was compared and analysed to model runs of the different forestation scenarios (see Sect. 3.3.2). The 'Baseline' and forestation scenarios results (see Sect. 3.1 and Sect. 3.3.1) included the adjustments to evapotranspiration, transpiration and interception rates (see Sect. 2.3), the incorporation of in-situ measurements to the van Genuchten parameter datasets (see Sect 2.5), the addition of the runoff delay and the minor model changes (see section). The contribution of the runoff-reducing mechanisms (i.e. the increases in evapotranspiration, percolation and water storage, and runoff delay because of forestation) in reducing peak discharge of the 'Full forestation' run compared to 'Baseline' was estimated. This was achieved by running the model with complete forestation and applying the effects of forestation individually to evapotranspiration rates, the van Genuchten parameters (for percolation : $K\mathrm{s}, \lambda, \alpha$ and for water storage: $\theta\mathrm{r}, \theta\mathrm{s}$), and runoff delay. Here, the results on the individual contribution of percolation and water storage were more uncertain because these factors influence each other; water storage influences soil saturation, which subsequently affects percolation rates, while percolation rates affect the amount of water stored in the soil (Shackelford, 2003).

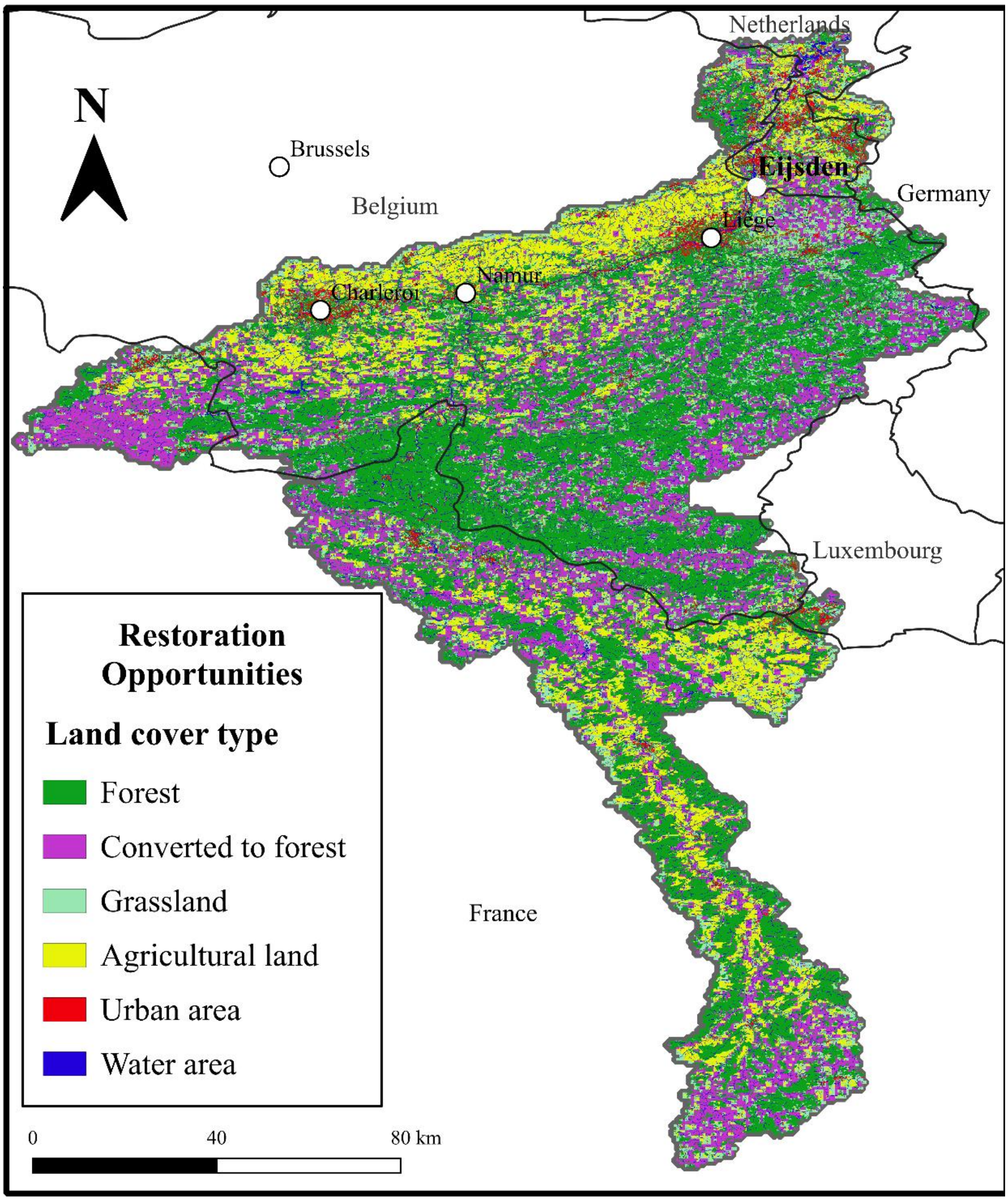

Figure 5. Map of 'Restoration Opportunities' forestation scenario applied in GEB. The dataset this map is based on (Laestadius et al., 2011) identified areas which are suitable to convert to forest. Areas which were converted to forest in GEB are shown in purple.

3. Results & Discussion

In this chapter, the results of this study will be shown, interpreted and discussed.

- In Sect. 3.1 I discuss the effects of modelling forestation in the entire catchment on peak discharge and how the runoff-reducing mechanisms contribute to this reduction.
- In Sect. 3.2 I show how saturation excess was the main driver of runoff in the model.
- In Sect. 3.3 I evaluate the representativeness of my modelling results for future flood hazard reduction, including a section on insights derived from the various forestation scenarios.
- In Sect 3.4 I address model uncertainties concerning modelled soil saturation across the basin.
- In Sect 3.5 I discuss the effects of the van Genuchten parameters on model processes and insights from discrepancies in van Genuchten parameters between the used dataset and in-situ measurements.
- In Sect. 3.6 is a short section where I validate modelled evapotranspiration rates with literature findings.
- In Sect. 3.7 I provide recommendations for future research based on the limitations and uncertainties identified in this study.

3.1 Understanding the effect of full forestation on peak discharge

Foresting the entire catchment reduced modelled peak discharge (July 15) at Eijsden by 410 m^3/s (14.3%), from 2876 to 2466 m^3/s (Figure 5, 'Baseline' vs 'Full Forestation' scenario). The peak discharge reduction indicates the potential of forestation in mitigating extreme floods in the Meuse basin. Foresting the entire catchment changed ~43% to forest, which was more than double the current amount of forest in the catchment (~42%). Hence, a substantial amount of land must be converted to forest to realize this change.

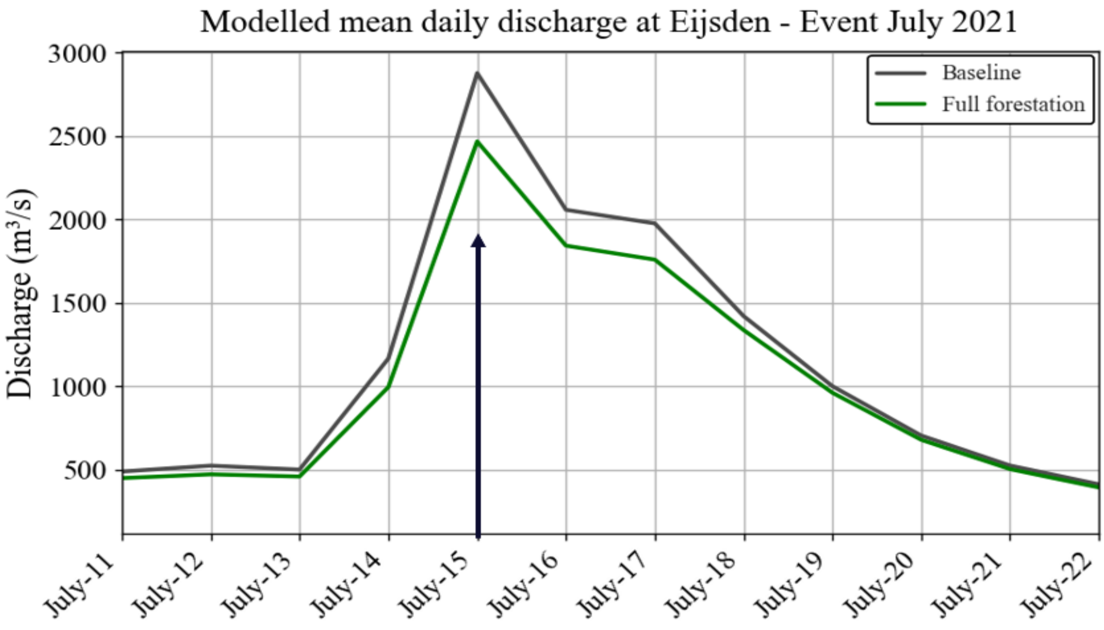

Figure 6. Modelled mean daily discharge at Eijsden during the flood event of July 2021 of the 'Baseline' and 'Full Forestation' scenarios. Peak discharge during the event (Figure D1, Figure D2), and in the model, occurred on July 15, indicated with an arrow. Peak discharge decreased during the 'Full Forestation' scenario compared to the 'Baseline' scenario.

Runoff was the main contributor to peak discharge within the model. Overall, the entire forestation of the catchment increased mean evapotranspiration, infiltration, percolation, total water storage (see Table 1 and Table 2) and the delay in runoff across the catchment. Each runoff-reducing mechanism contributed to the 14.3% reduction in peak discharge in the 'Full Forestation' scenario as follows:

- Percolation: ~6%
- Evapotranspiration (ET): ~5%
- Total water storage: ~2%
- Runoff delay: ~1%

The largest contributors to reducing peak discharge in the 'Full Forestation' scenario were the effects of increased percolation and evapotranspiration. The increase in total water storage and runoff delay had a relatively minor effect on reducing peak discharge compared to the effects of percolation and evapotranspiration. Percolation and evapotranspiration decreased mean pre-event soil saturation across the catchment in the 'Full Forestation' scenario compared to the 'Baseline' scenario (see column 'Pre-event soil saturation' in Table 2, and Figure 7). The reduced soil saturation subsequently decreased runoff of precipitation during the event because more water could infiltrate and be stored in the soil (Table 2). In the 'Full Forestation' scenario percolation transported more water from the soil to deeper layers and evapotranspiration intercepted (entering the soil) or evaporated and transpired (removed from the soil) more water (columns Percolation and ET in Table 1 and Table 2). Although mean evapotranspiration across the catchment percentage-wise increased substantially during the event (see 'Relative change', column ET in Table 2), the amount of water removed during the event (see 'Absolute change', column ET in Table 2) was minor relative to the amount of water removed by evapotranspiration during the year before the event (see 'Absolute change' column ET in Table 1). Thus, the increase in evapotranspiration before the event has a substantially larger effect on reducing peak discharge than evapotranspiration during the event.

Table 1. *Mean change in evapotranspiration (ET), percolation and soil saturation from 'Baseline' to 'Full Forestation' scenario across the catchment, summed over the year of the spin-up period (July 2020-July 2021).*

Change from 'Baseline' to 'Full Forestation' scenario	ET [mm]	Percolation [mm]	Soil saturation [%]
Absolute change	+51.1	+69.4	-6
Relative change [%]	+10.9	+4.2	-9.0

Table 2. *Mean change in pre-event soil saturation (July 14), processes during the event (July 15) and the general change in total water storage from 'Baseline' to 'Full Forestation' scenario across the catchment.*

	Pre-event (July 14)	Event (July 15)				General
Change from 'Baseline' to 'Full Forestation' scenario	Soil saturation [%]	ET [mm]	Infiltration [mm]	Runoff [mm]	Percolation [mm]	Total water storage [mm]
Absolute change	-6	+0.17	**+3.9**	**-2.2**	+2.3	**+27**
Relative change (%)	-7.5	+36.2	**+21.9**	**-15.6**	+14.3	+3.2

3.2 Saturation excess as the main driver of runoff in the Meuse

Saturation excess was the primary driver of runoff during the modelled event. Forestation reduced mean pre-event soil saturation (visually compare the right figure to the left figure in Figure 7) across the catchment which reduced runoff (Table 2 and Figure 8). Modelled pre-event soil saturation was high across large parts of the basin in both the 'Baseline' (Figure 7, map on the left) and the 'Full Forestation' scenario (Figure 7, map on the right). During the event, precipitation turned into surface runoff in areas with high pre-event saturation levels (Figure 8), showing that saturation excess was widespread during the modelled event. Higher pre-event saturation levels led to higher amounts of runoff (Figure 8). Runoff mainly occurred in the very high saturated areas (>98% saturation); here, minimum amounts of precipitation could be stored in the soil, making the precipitation turn into runoff. Previous analyses also suggest that saturation excess, rather than infiltration excess or subsurface flow, was the main runoff process for this event in the Meuse, thereby increasing the models' validity in computing runoff for this event (Asselman et al., 2022; Boon & Kaspersma, 2023).

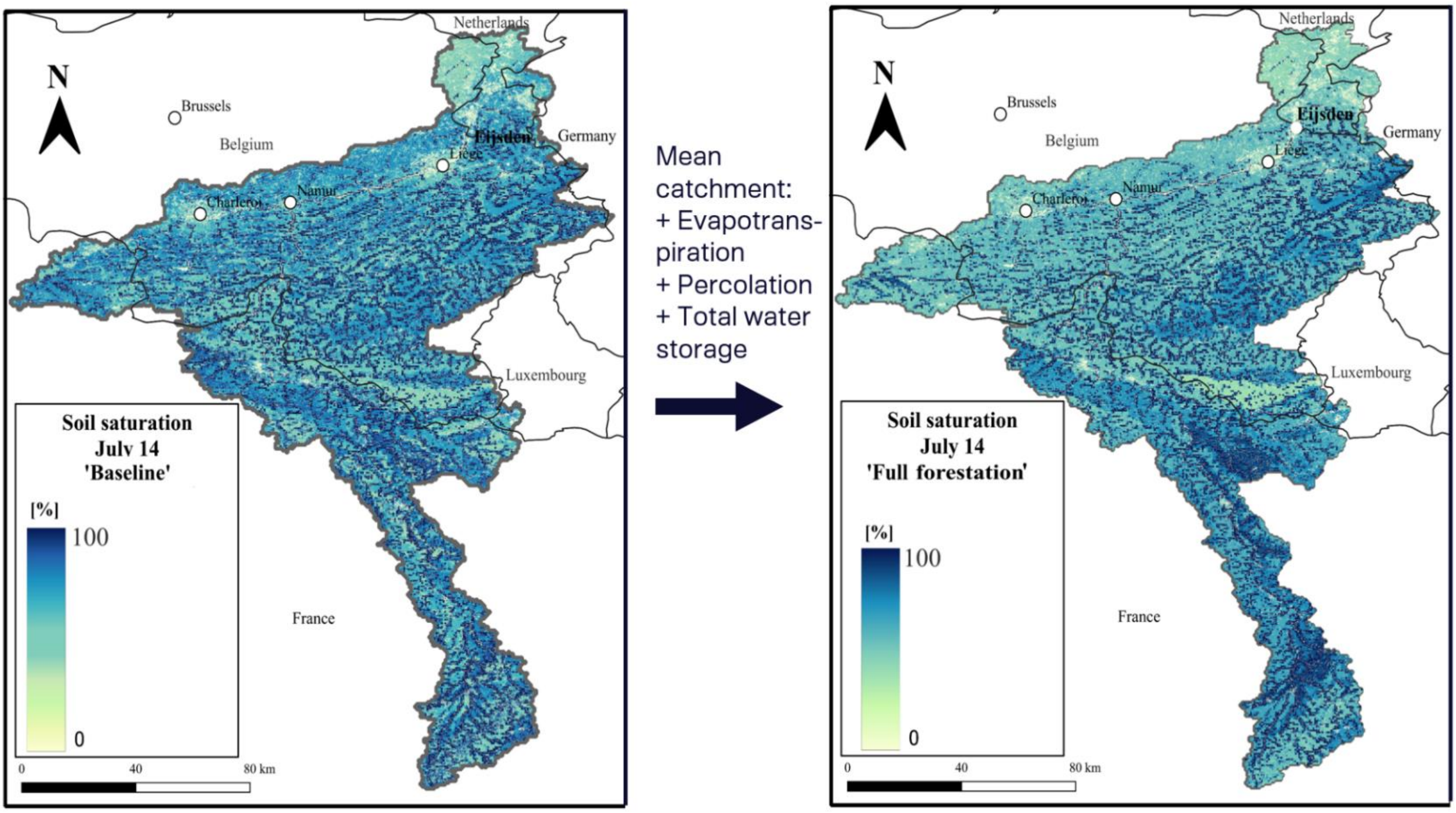

Figure 7. Modelled pre-event soil saturation (July 14) in the 'Baseline' (map on the left) and 'Full Forestation' scenario (map on the right). The colour bar depicting soil saturation has linear discrete scaling except for the first and last colours (pastel white and dark blue), these are respectively classified as 0-2% and 98-100%. Thus, the blue 'spots' on the map are highly saturated areas (>98% saturation).

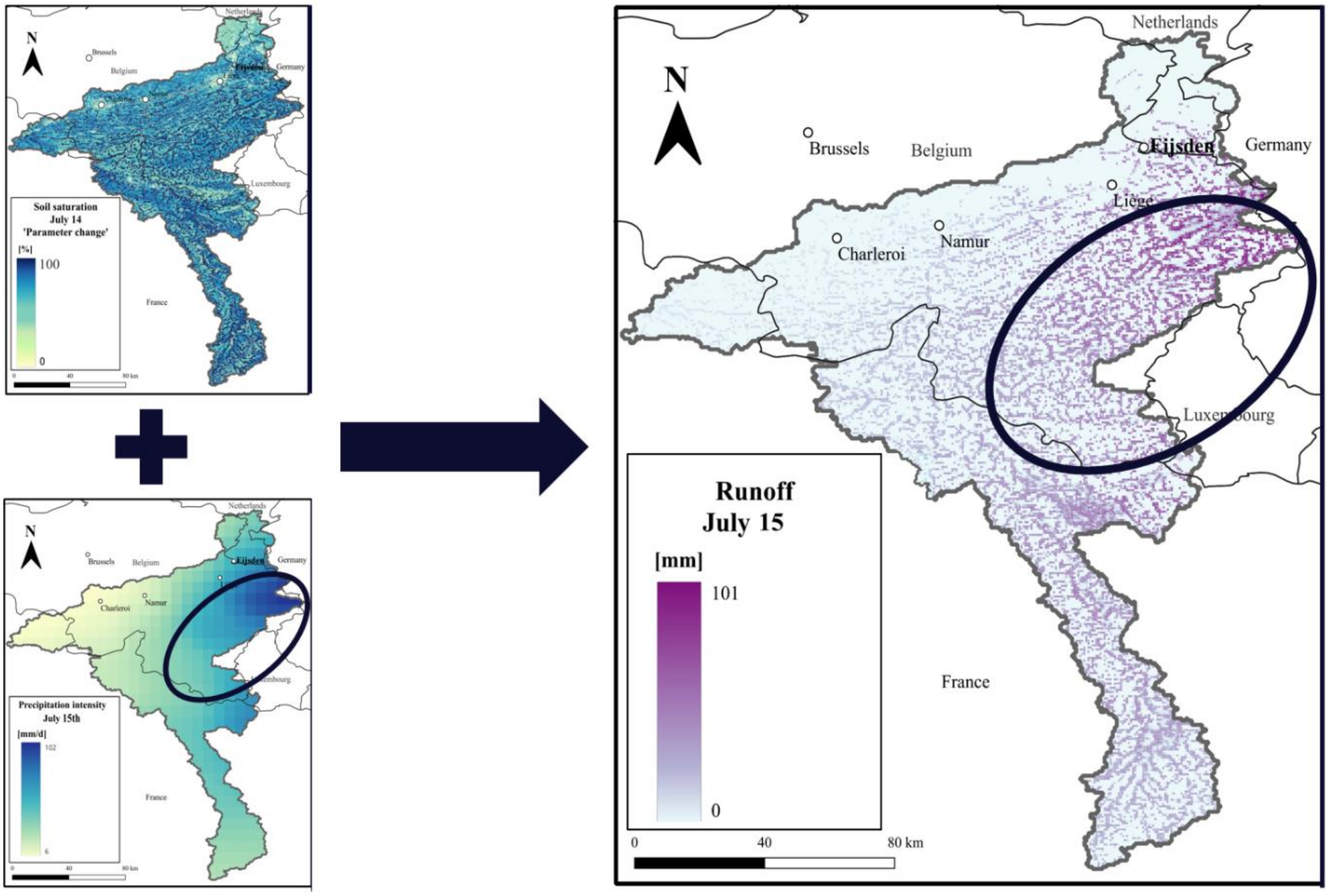

Figure 8. Spatial overview of how saturation excess runoff was modelled. The top left figure is the soil saturation map in the 'Baseline' scenario. The bottom left figure is the precipitation intensity on the day of the event (July 15) (visible on a larger scale in Figure F1) with darker blue colours indicating higher precipitation intensities. The map on the right is runoff during the event, where runoff mainly occurs at locations of high soil saturation . Also, the black circles highlight the Belgian Ardennes, where most precipitation fell, causing the relatively highest amount of runoff in the catchment.

3.3 Forestation for reducing future flood hazard in the Meuse

The modelled results of peak discharge reduction in the 'Full Forestation' scenario indicate that forestation could be a measure to mitigate future peak discharges in the Meuse. The observed peak discharges in 2021 were similar to discharges during previous extreme discharge events in 1993 and 1995, which also caused floods (Frijns, 2022; Heylen, 1997; KNMI, 2020). Analyses indicate that previous extreme discharge events in the Meuse, such as in 1993 and 1995, were primarily caused by large multi-day precipitation events, similar to those in 2021 (Tu et al., 2006). Furthermore, the days and weeks before these events occurred were very wet which likely led to high pre-event soil saturation, similar to 2021 (Frijns, 2022; Heylen, 1997; KNMI, 2020; Tu, 2006). These observations align with previous analyses indicating that saturation excess runoff has been the main driver of floods in the Meuse. Thus, in the future, similar conditions (high pre-event soil saturation in combination with large multi-day precipitation) may recur and cause peak discharges again. Forestation can reduce such peak discharge events, as shown by the modelling results. Moreover, forests may increase infiltration rates according to literature, which can reduce infiltration excess runoff. This suggests that forestation in the Meuse basin could mitigate future extreme discharge events.

The modelled reduction in peak discharge from foresting the entire catchment suggests a decrease in extreme flood hazard. Discharge is typically related to water height, so a reduction in peak discharge implies lower peak water heights within the river. Lower peak water heights can prevent floods in certain areas. Additionally, the reduction in peak discharge indicates that the daily water volume reaching and passing Eijsden was reduced, potentially decreasing flood depth and extent which occurred before and after Eijsden. For example, Johnen et al. (2022) showed that a reduction in peak discharge leads to a reduction in flood extent. They modelled the effect of forestation on both peak discharge and flood depth and extent through hydrologic and hydrodynamic modelling. In that study, foresting the entire catchment peak flow was reduced by 10% (although for a non-extreme flood event) while flood extent was reduced by 25%.

Forestation in the Meuse may be more effective in mitigating lower return period floods. For example, Johnen et al. (2022) examined the effect of forestation on precipitation intensities across different flood return periods and found that forestation was more effective in reducing peak discharge for lower return-period flood events. Lower-return period flood events generally occur through lower amounts of precipitation. Because forests reduce pre-event soil saturation, relatively more precipitation can infiltrate during precipitation events of lower return-period floods. Consequently, relatively more runoff is reduced through forestation during these events, leading to a greater reduction in peak discharge.

3.3.1 Insights from evaluating forestation scenarios

Converting Grassland in Belgium most effective

During the event, GEB simulated the highest runoff within the Belgian Ardennes, located in the east of Belgium (area within the black circle in Figure 8). Precipitation intensity during the event was greatest around the Belgian Ardennes (Figure F1), which caused the large amount of runoff in this area (Figure 8). The high amount of runoff in the Belgian Ardennes corresponds with observed data from the event, where peak discharge was exceptionally high in the Ardennes tributaries (Dewals, 2021).

Modelled forestation was most effective in reducing peak discharge when converting grassland within Belgium (scenario ‘Grassland – Belgium’ in Figure 9) compared to the other forestation scenarios; in this scenario, the peak discharge reduction was highest per percentage of land converted to forest. Grassland in Belgium is mainly located in the Belgian Ardennes (Figure 2). Forestation in this scenario also reduced soil saturation (Table H1). Because daily precipitation intensities were highest in this region (Figure F1), more of the extra available water storage (because of reduced soil saturation) could be filled with precipitation compared to other scenarios, where precipitation intensities were lower. Therefore, in this scenario, relatively the most amount of runoff was reduced per percentage of land converted to forest compared to other scenarios (Table H2).

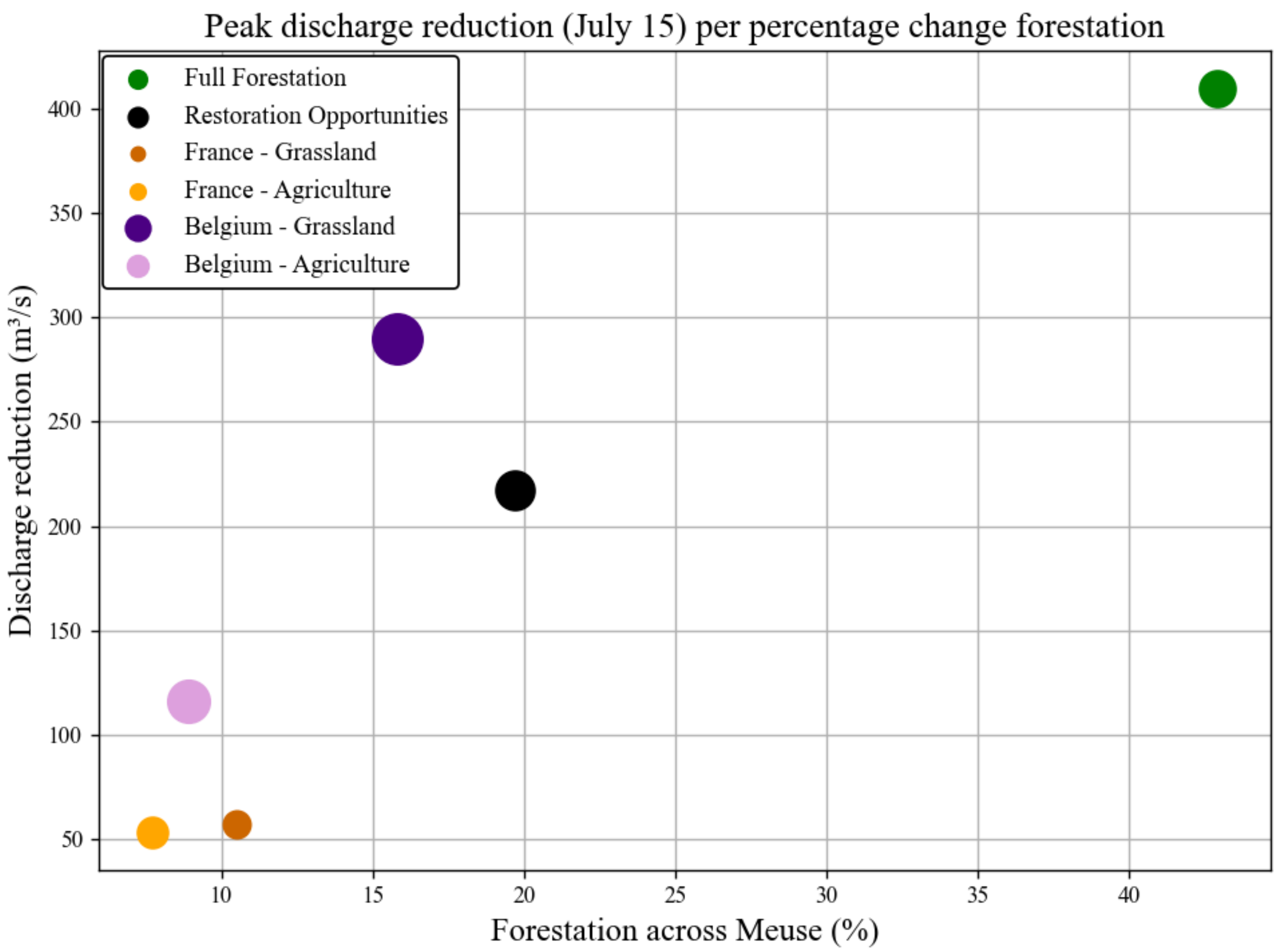

Figure 9. Modelled peak discharge reduction (July 15) for various forestation scenarios. The y-axis represents peak discharge reduction, while the x-axis represents the percentage of land converted to forest across the Meuse basin. The size of the markers indicates the effectiveness (discharge reduction per percentage of land converted to forest) of a forestation scenario. The Belgium - Grassland scenario shows the highest effectiveness, represented by the largest marker.

Foresting agricultural areas could be more effective in reducing peak discharge in reality than modelled in this research (Figure 9). Tillage in agricultural lands negatively affects soil structure, reduces organic matter and increases compaction, all of which decreases percolation and total water storage (Kay & Van den Bygaart, 2002; Pires et al., 2017). These negative effects of tillage on soils have not been sufficiently incorporated due to the lack of in-situ measurements of van Genuchten parameters in agricultural land and the van Genuchten parameters dataset used in GEB, which does not account for the effect of management practices such as tillage. Consequently, the model may have overestimated percolation and total water storage in agricultural lands.

Forestation in the Ardennes: reducing future extreme discharge

Foresting wet areas, such as the Ardennes, could be the most effective strategy for mitigating future peak discharges. The Ardennes is the wettest region within the Meuse basin, receiving the highest annual precipitation (de Wit et al., 2007; Frijns, 2022; Torfs & Uijlenhoet, 2001). This suggests that soil saturation is generally higher in the Ardennes compared to other regions in the basin. Therefore, saturation excess runoff is more likely to occur, and in larger quantities (because the soil is saturated faster causing subsequent precipitation to turn into runoff) than in drier regions in the Meuse basin. Thus, reducing soil saturation by foresting regions in the Ardennes could decrease the likelihood and quantity of saturation excess runoff during heavy or extreme precipitation events. Furthermore, data from extreme discharge events in 1993, 1995 and 2021 show that the largest amounts of precipitation consistently fell within the Ardennes (Frijns, 2022; Heylen, 1997; KNMI, 2020; Tu, 2006), suggesting that the Ardennes is prone to such events. Foresting wet areas in other catchments where floods are primarily caused by saturation excess runoff may also prove effective in reducing peak discharge.

Suitability of forestation scenarios

In this research, some areas included in the forestation scenarios may be unsuitable for forestation. Local knowledge is necessary to determine which areas are suitable for forestation. The dataset (Laestadius et al., 2011) used for the 'Restoration Opportunities' scenario (Figure 5) specifies areas that are suitable to convert to forests. The dataset identified mainly grasslands suitable to convert to forest, suggesting that much of the agricultural land within the Meuse basin is unsuitable for conversion to forests. However, certain grassland areas (potentially not accounted for by the dataset) might also not be suitable for forestation. For example, the Upper Ardennes contains raised bogs with grassland vegetation (Frankard et al., 1998). Raised bogs typically have high water tables, occasionally extending above the soil, and nutrient-poor soils, only supporting flora adapted to such conditions (Frankard et al., 1998). Naturally foresting these areas without draining the soils, might not be possible because of the poor conditions for forest growth. Furthermore, some of these wetlands are protected nature reserves (Frankard et al., 1998). Thus, integrating local knowledge is necessary to determine which areas, among those used in forestation scenario in this research, are actually suitable.

3.4 Uncertainties in modelled soil saturation

3.4.1 Evaluation of the accuracy of spatial soil moisture content within GEB

In some regions, the pre-event simulated soil saturation (Figure 7) was very high (>98% saturation), which may not accurately reflect the real-world situation. This high saturation was driven by a high amount of capillary rise from groundwater (Figure 10). These areas are typically adjacent to rivers and situated in low-elevated grid cells relative to their surroundings (see DEM in appendix). The excessive capillary rise in these locations occurred due to high groundwater storage in elevated regions, causing significant groundwater flow to lower-elevated areas. The large influx of groundwater fills the groundwater storage in low-elevated areas, but the excess water causes capillary rise. Consequently, capillary rise from groundwater to the soil saturates the soil or results in runoff if the soil is already saturated (Burek et al., 2020). The high groundwater levels are the result of GEB initiating the groundwater level at 2 m below the surface, which levels out over time while decreasing more under highly elevated areas. A longer spin-up time could prevent the excessive capillary rise. Therefore, I recommend future research with the GEB model to use a longer spin-up time.

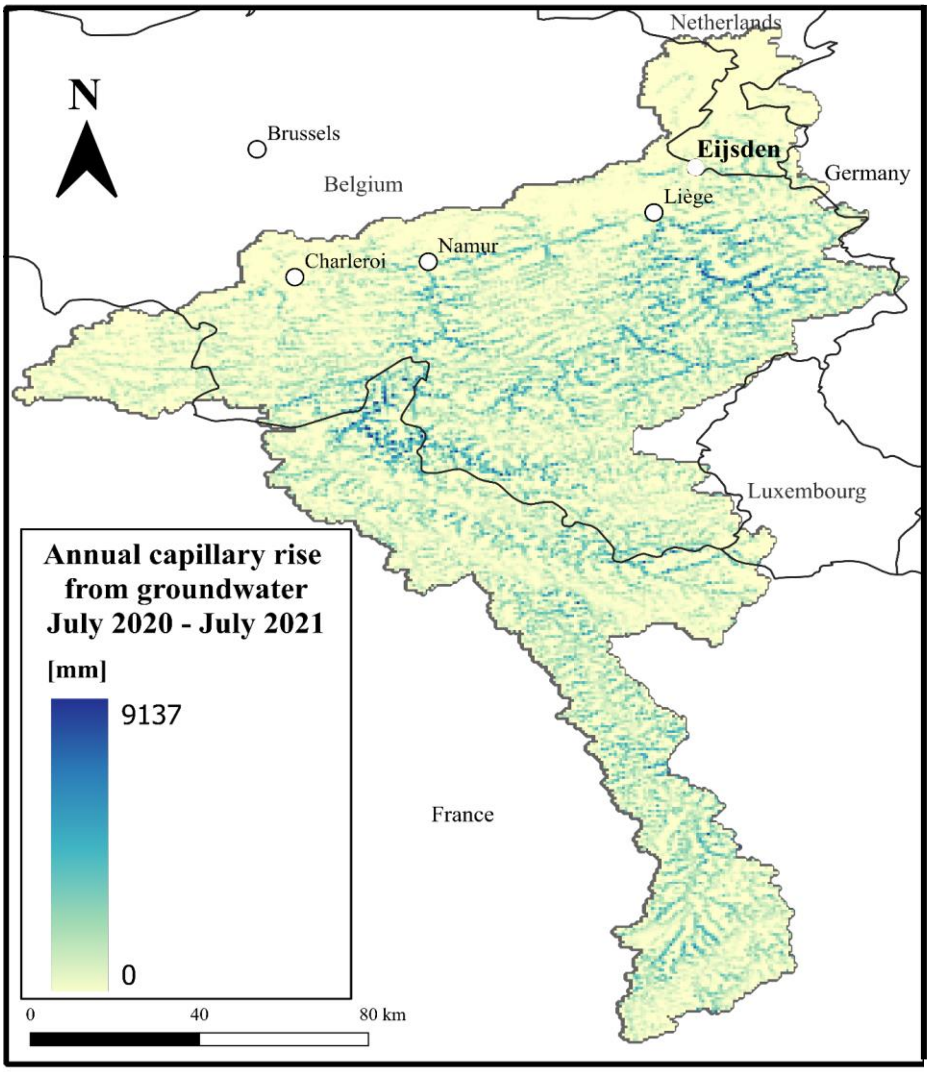

Figure 10. Total capillary rise from groundwater from July 2020- July 2021. Capillary rise occurred widespread across the basin and was in exceptionally large in quantity (maximum 9137 mm).

The modelled effect of forestation (in the 'Full Forestation' scenario') on reducing peak discharge may be underestimated due to these highly saturated regions (>98% saturation). Forestation generally did not reduce saturation in the very high saturated regions (see Figure 7). Forestation likely increased water loss from the soil through increased evapotranspiration, percolation and total water storage. However, excessive capillary rise kept the soil saturated, leading to similar runoff levels at the >98% saturated regions as in the 'Baseline' scenario. If the model did not compute capillary rise excessively, forestation could potentially have reduced more pre-event soil saturation, thereby reducing more runoff during the event.

Modelled pre-event soil saturation was higher in some areas after forestation (Figure 7), indicating an uncertainty caused by the applied methodology. In the model, forestation always increases evapotranspiration, implying a substantial decrease in percolation or total water storage in these areas. However, forestation should positively affect porosity, soil structure, and organic matter content, which should increase percolation and total water storage. To reduce uncertainties in computing the effects of forestation on these factors, future research could apply a methodology that consistently computes higher percolation and total water storage for forests compared to agricultural land or grassland.

3.5 Impact of van Genuchten parameters on soil hydrology

The increased percolation and total water storage modelled in the Meuse basin when foresting the entire catchment were caused by changes in the van Genuchten parameters. These changes can be validated by current knowledge and in-situ measurements from literature. The increased percolation resulted from increased hydraulic conductivity caused by increases in Ks, λ and α. (Table 3). Additionally, total water storage increased due to a rise in θs (Table met kleurtjes), which resulted in a higher maximum water storage capacity. Part of the increase in total water storage was offset by a rise in θr which reduced the total amount of water that can be stored within the soil (Table 3). Forests are known to increase hydraulic conductivity (indicated by the increases in Ks, λ and α) and total water storage (θs) by improving porosity and soil structure, and increasing organic matter content. Additionally, the increase in θr may result from forests increasing the abundance of smaller pores, particularly micropores. Furthermore, literature which compared van Genuchten parameters of forests to agricultural land or grassland within the same area (i.e. Alaoui, 2023; Archer et al., 2013; Chandler et al., 2018; Gonzalez-Sosa et al., 2010) found substantially higher Ks (research count=4) and θs (research count=1), highlighting the increasing effect of forests on percolation and total water storage

Table 3. *Mean relative change of the van Genuchten parameters across the Meuse basin when converting the entire catchment to forest. Most parameters increased in value, which generally increased percolation and total water storage.*

	Relative change from 'Baseline' to 'Full Forestation' scenario (%)
Ks1	+178.0
Ks2	+168
Ks3	−79
θs1	−1.53
θs2	+8.5
θs3	+3.8
θr1	+22.6
θr2	+29.4
θr3	−2.8
α1	+88.4
α2	+ 145
α3	+40.7

Legend	
Very large increase (+100 - 250%)	
Large increase (+50-100%)	
Moderate increase (+25-50%)	
Slight increase (+2.5-25%)	
Roughly equal (2.5% difference)	
Slight decrease (–2.5-25%)	

Table continues on next page

$\lambda 1$	+94.1
$\lambda 2$	+19.4
$\lambda 3$	−21.3

3.5.1 Van Genuchten parameters dataset compared to in-situ measurements

There were large variations between the van Genuchten parameters datasets and in-situ measurements (Table, Appendix), suggesting a need for better consideration of the effect of soil structure (through in-situ measurements) in hydrologic models. The initial van Genuchten parameter dataset used in GEB (so without incorporating in-situ measurements) might have underestimated true parameter values; values in the initial van Genuchten parameter dataset were generally much lower than the dataset with in-situ measurements incorporated (Table G1). This underestimation may result from the dataset not being able to capture soil heterogeneity caused by land cover types.

The modelled forestation scenarios might have overestimated peak discharge reduction due to the potential underestimation of the van Genuchten parameters datasets (particularly for agricultural land and grassland). Few in-situ measurements could be incorporated into the van Genuchten parameters datasets for agricultural land and grasslands because of limited literature (Table.. Appendix). Consequently, the van Genuchten parameters for agricultural land and grassland used in the model might have been underestimated. As a result, modelled forestation of agricultural lands and grasslands might have led to a larger increase in van Genuchten parameters than would be accurate for the actual catchment. The potentially larger increase of most van Genuchten parameters (Ks, λ, α, and θs) might have led to increased percolation and total water storage, resulting in a larger peak discharge reduction.

The mean of van Genuchten parameters across the Meuse in the 'Baseline' and 'Full Forestation' scenarios showed a decrease in Ks and λ with depth (Table 3, Appendix). The changes in Ks and λ with depth might be due to a larger relative abundance of smaller pores in deeper soil layers which has been found in various studies (Emerson & McGarry, 2003; Eynard et al., 2004; Ko Enková & Urík, 2012). Deeper soil layers are typically more compacted due to increased pressure from the soil above, have finer soil textures (e.g. more clay content) and have reduced organic matter content (Emerson & McGarry, 2003; Jarvis et al., 2013). These factors all reduce pore sizes. In smaller pores water is retained more tightly due to adhesive forces, resulting in lower hydraulic conductivity and lower λ values.

3.7 Validating modelled evapotranspiration rates

Modelled mean daily evapotranspiration rates from the spin-up period (July 2020 – July 2021) across the catchment were highest in forests, followed by grassland, and lowest in agricultural land. Forests have higher evapotranspiration rates than agricultural land and grassland, which aligns with findings in the literature, making modelled evapotranspiration, and its effect on discharge reduction with forestation more credible. Global comparisons (Farley et al., 2005; Varcoe & Sterling, 2016) and studies within the Netherlands and Belgium (Teuling, 2018; Verstraeten et al., 2005) show temperate forests (which is the forest type in the Meuse basin) have higher mean daily evapotranspiration rates than agricultural land or grassland. Moreover, analyses of discharge following large-scale in-situ forestation found substantially lower discharges in subsequent years, attributed to increased evapotranspiration (Bosch & Hewlett, 1982; Hibbert, 1962). However, no literature was acquired reporting differences in evapotranspiration rates between agricultural land and grassland. Thus, the higher modelled evapotranspiration rates for agricultural lands compared to grassland could not be validated by in-situ measurements from literature.

3.8 Recommendations

In this section, I will discuss limitations and uncertainties encountered in this research, to subsequently give recommendations for future research. These recommendations can improve hydrological simulations and improve flood hazard and risk assessments.

- In Sect. 3.8.1 I discuss the potential effects of microclimates on evapotranspiration in forests and how these affect future flood discharge modelling.
- In Sect. 3.8.2 I address how forest type and age can influence flood discharge reduction, to discuss the effectiveness of forestation on peak discharge over time.
- In Sect. 3.8.3 I address the uncertainties in using van Genuchten parameters for future research on flood discharge reduction with modelling.
- In Sect. 3.8.4 I provide additional future research ideas that could enhance our understanding of the exact effects of forestation on reducing peak discharge.

3.8.1 Forest microclimates

In temperate climates, forests typically create a cooling effect and increase humidity within their interiors, compared to the surrounding area outside of the forest. (Alkama & Cescatti, 2016; Brooks & Kyker-Snowman, 2008; Chen et al., n.d.; Chen’ et al., 1993; Matlack, 1993; Morecroft et al., 1998; Verbiest et al., 2023; Young & Mitchell, 1994). Such localised climatic conditions is known as a microclimate. The changes in temperature and relative humidity relative to adjacent areas might affect the evapotranspiration of forests. These microclimates can influence evapotranspiration calculations in models since climate data, usually measured above the forest canopy, cannot account for forest interior effects. The primary characteristic of forest microclimates is reduced temperature and increased humidity during summer days compared to adjacent agricultural lands or grasslands (Chen’ et al., 1993; Matlack, 1993; Morecroft et al., 1998; Schultz et al., 2017; Young & Mitchell, 1994). However, microclimates can also increase temperature during summer nights and winter days, although these effects are less substantial (Chen et al., n.d.; Schultz et al., 2017; Young & Mitchell, 1994). Also, the effects are not uniformly constant throughout the forest. Closer to the forest edge, temperature and humidity are more similar to those of the surrounding area outside of the forest. These effects are known as edge effects and can extend to up to 150 m in the forest (Davies-Colley, 2000; Young & Mitchell, 1994).

The effect of microclimates within forests could not be incorporated into the model of this research. However, the effect of microclimates has been somewhat accounted for by calibrating the evapotranspiration, transpiration and interception rates of the model to in-situ measured rates within forests. The effects of microclimates could not be incorporated in this research due to insufficient research in climates similar to the Meuse, and the difficulty in quantifying and modelling edge effects. Moreover, most studies on microclimates did not account for these edge effects or showed variability in how far these edge effects influence the forest interior. In addition, studies often report changes for specific periods rather than monthly variations throughout the year. Thus, the exact effects could not be accurately quantified for each calendar month.

Future research could account for the effects of microclimates to develop more robust hydrological models. Current evapotranspiration calculations in models would decrease in forests based on the typical cooling effect and increase in humidity within the forests. Incorporating these effects on evapotranspiration, through for example taking in-situ measurements within and outside of the forest in the catchment area, can improve hydrological models and the exact effect of forestation on flood discharge reduction.

3.8.2 Forest age

Forests may become more effective over time in reducing peak discharge. The literature on forest age mainly indicates higher evapotranspiration rates in young forests (although differences are relatively small), because of increased forest growth at young ages (Andréassian, 2004; Farley et al., 2005; Skubel et al., 2015; Varcoe & Sterling, 2016). Based on knowledge from the literature, the van Genuchten parameters should improve with age of the forest due to increases in organic matter content in the soil, higher root depth and density, and more soil fauna activity (basically forests have had a longer time to exert their positive effects on soils). All in all, forestation seems to improve soil structure over time while forest evapotranspiration rates are higher at younger ages. Given that percolation and total water storage in this research are more impactful in reducing peak discharge than evapotranspiration, I hypothesize that forests will reduce flood discharge more effectively over time.

The effects of forest type and age could not be incorporated in this research. Literature found substantial differences in evapotranspiration, interception, transpiration, and the van Genuchten parameters between young and mature forests at similar locations (for the literature, see Table B1. Table B2. Table B3). However, insufficient data on these differences prevented accurate model quantification. The effects of forest type and age have not been incorporated in hydrologic flood modelling research yet. Future research could measure, quantify and model the differences in soil hydraulic parameters between different forest age stands to generate a more representative hydrological simulation and a more accurate effect of forestation on discharge reduction.

3.8.3 Reduce uncertainty in the Van Genuchten parameters

In this research, the van Genuchten parameters incorporated in the datasets through in-situ measurements are uncertain because of insufficient data and the non-scientific methodology used to incorporate these parameters. As a result, the modelled effects of percolation and water storage capacity are somewhat uncertain. Future research could conduct in-situ measurements within the catchment to increase the amount of in-situ data incorporated in the datasets and to incorporate more representative data (because the measurements are conducted within the catchment). Furthermore, future research could apply various van Genuchten datasets (or other soil hydraulics parameter datasets) or parameters combined with methodologies to derive how forests affect these parameters for each soil type. This is done, for example, by varying organic matter content and applying a function which translates these changes in organic matter content to the van Genuchten parameters. The effect of different forest ages could be simulated by varying the effect on the van Genuchten parameters over time. The effect of different datasets and forest ages would derive various outcomes of forestation. These outcomes can generate an uncertain range of the actual impact of forestation on reducing discharge. This approach will provide more reliable information on the effects of forestation, allowing policymakers to make more informed decisions.

3.8.4 Additional ideas for future research

Future research could also examine different flood-return periods caused by different precipitation intensities, to provide more robust results about the exact effect of forestation on flood discharge. This approach would inform policymakers about the impacts on both high-return period floods and low-return period floods. This creates a comprehensive overview of the effectiveness of forestation in reducing floods, which aids the decision-making of policymakers. Incorporating the flood extent, depth and the corresponding expected damage of these floods could clearly demonstrate the exact effect on floods and damage reduction (when investing in solutions such as forestation) for society, further aiding decision-making.

In addition, future research could investigate the effects of forestation across multiple catchments using a consistent model, methodology, and flood event(s), such as comparing the Meuse and Geul catchments, and other catchments affected by July 2021 floods. This would provide a more accurate assessment of how catchment characteristics (e.g. size) influence peak discharge. This information would help us better understand and draw more definitive conclusions about the impact of forestation on flood discharge. Such results could potentially be scaled up, enabling forestation to be implemented as a flood mitigation measure by multiple municipalities or governments.

4. Conclusion

This study aimed to investigate the effectiveness of forestation in reducing extreme flood discharge in the Meuse basin. I modelled the effect of various forestation scenarios on peak discharge of the July 2021 extreme flood event. Discharge was modelled at Eijsden. I incorporated in-situ measurements of evapotranspiration rates and the van Genuchten parameters into the GEB model and added a runoff delay to improve the hydrological simulation. With the improved hydrological model the effectiveness of forestation in reducing flood discharge could be determined with more certainty.

Foresting the entire catchment reduced modelled peak discharge at Eijsden by 410 m^3/s (14.3%). The modelled results and analyses demonstrated that forestation can function as a measure to reduce peak discharges within the Meuse catchment. The reduction in peak discharge suggests a reduction in extreme flood hazard.

Saturation excess was the dominant driver of runoff in the model, and according to previous analyses. Forests mainly reduce runoff contributing to peak discharge by reducing pre-event soil saturation and reducing saturation excess during the event. Increased percolation and evapotranspiration were the most important mechanisms in reducing peak discharge.

Foresting the grasslands in Belgium was the most effective scenario (the peak discharge reduction per percentage forested area was highest). This area experienced the highest daily precipitation intensity. Therefore, a greater portion of the available water storage in the soil (which was reduced in saturation due to forestation) could absorb the precipitation compared to other scenarios with lower precipitation intensities during the event. Therefore forestation reduced relatively more runoff compared to other scenarios.

Forestation in wet areas of other catchments might be most effective in reducing peak discharges compared to foresting other regions. These areas are more likely to have higher pre-event soil saturation levels. Consequently, during heavy or extreme precipitation events, soils are more likely to saturate, and saturate more quickly, turning relatively more precipitation into runoff than in drier regions.

This research highlighted the importance of including the effects of forestation on percolation and total water storage; as a result of incorporating in-situ measurements of the van Genuchten parameters, forestation increased percolation and total water storage, substantially affecting the reduction in peak discharge. However, it is important to acknowledge that the methodology used to incorporate these in-situ measurements contains uncertainties, affecting the certainty concerning the exact effects of percolation and total water storage. For future research, improving such methodologies and conducting in-situ measurements within a catchment improves hydrological simulations on the effects of forestation, consequently reducing uncertainties of drafted results.

In Northwestern Europe, including the Meuse, extreme flood discharges have increased in magnitude. This research has shown the potential of forestation in mitigating (extreme) flood discharge. Furthermore, as global flood risk is expected to increase in the future, effective policymaking becomes increasingly crucial. Therefore, I recommend to enhance the assessment of the effects of forestation on floods by further improving hydrological simulations and understanding the impact on flood hazards and risks.

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Appendix A: GEB model input layers data

Table A1. *Input layers used in the GEB model in this research, including the respective sources and resolutions.*

Layer type	Source	Resolution
Climate variables: - Precipitation [m] - Maximum, minimum and mean temperature [K] - Relative humidity [-] - Surface pressure [Pa] - Short wave and long wave radiation [W/m] - Windspeed [m/s]	ERA5 re-analysis data (Hersbach et al., 2023)	~10km
Land cover	Copernicus, 2021	10 m
Forest type	Copernicus 2018	100 m
Digital Elevation Model (DEM)	Yamazaki et al., 2019	100 m
Mask for catchment area	Derived from DEM, outflow point as personal choice	1 km
River topography (channel dimensions, slope)	Derived from DEM	1 km
River routing	Yamazaki et al., 2019	1 km
Lakes and reservoirs	Lehner et al., 2011	Minimum lake or reservoir size of 100 ha
Vegetation cover forest and grassland; used for interception capacity	Hanse et al., 2013	1 km
Crop coefficient	Portmann et al., 2010	1 km
Root depth & fraction	Burek et al., 2020	1 km
van Genuchten parameters	Pedotransfer function Rosetta Zhang & Schaap, 2017of Harmonized World Soil database FAO et al., 2012	10 km
Agents (farmers, households)	De Bruijn et al., 2023	-
Water consumption quantity of households, industry, livestock and farmers	Wada et al., 2016	5 min, downscaled to relevant land uses

Appendix B: Literature review evapotranspiration rates

Table B1. *Mean evapotranspiration rates of yearly periods of each study found during the literature review.*

Mean annual evapotranspiration per forest type [mm/day]	Research	Country (ISO codes)
DNF: 1.68 DBF: 1.37	Teuling, 2018	NED
DBF: 0.96	Granier et al., 2000	FRA
DNF: 1.09	Jarosz et al., 2008	FRA
DBF & DNF: 1.9	Soubie et al., 2016	BEL
DBF: 1.9	Herbst & Kappen, 1998	GER

Table B2. *Mean interception rates of yearly periods of each study found during the literature review.*

Deciduous/needleleaf-forest interception [mm/day]	Research	Country (ISO codes)
DBF: 0.56 DNF: 0.68	Dolman & Moors, 1993	NED
DBF: 0.38 DNF: 0.84	Soubie et al., 2016	BEL
DBF: 0.42	Staelens et al., 2008	BEL
DBF: 0.51	Loustau et al., 1992	FRA
DBF: 0.80	Ringgaard et al., 2014	DEN
DBF: 0.39 DNF: 0.70	Rutter et al., 1975	ENG
DBF: 0.54	Herbst et al., 2008	ENG
DBF: 0.45 DNF: 0.34	Bryant et al., 2005	USA

Table B3. *Mean transpiration rates of yearly periods of each study found during the literature review.*

Transpiration (mm/d)	Research	Country (ISO codes)
DBF: 0.74 DNF: 0.79 Mean: 0.77	Dolman & Moors, 1993	NED
DBF: 1.08	Schipka et al., 2004	GER
DBF: 0.6	Vincke et al., 2005	BEL
DBF: 0.66	Granier et al., 2000	FRA
DBF: 1.27	Herbst & Kappen, 1998	GER
DNF: 0.67	Jarosz et al., 2008	FRA

Table B4. *Mean evapotranspiration, interception and transpiration rates of all researches of the literature review described in Table B1, Table B2 and Table B3. These values were used to calibrate the GEB model with.*

	Mean of literature review	Research count	Data
Evapotranspiration total (DBF & DNF)	1.42	5	Table B1
Interception (varying values per forest type)	DBF: 0.44 DNF: 0.66 MF: 0.55	DBF: 6 DNF: 6	Table B2
Transpiration (DBF & DNF)	0.84	6	Table B3

Appendix C: Literature review Van Genuchten parameters

Table C1. Background information of literature found during the literature review concerning the van Genuchten parameters (further described in Table C2 and C3).

Country	Land cover type	Soil depth research: layer in GEB	Soil texture/type researched,	Research
GER	DBF	10-34: 2	Loam, sandy loam, sandy clay loam Silty loam Sandy loam Silty clay loam Sandy loam, loamy sand Silty loam Clay, loam, silty loam Silty loam Clay, clay loam	Puhlmann & Von Wilpert, 2012
GER	DNF[1]	0-15: 1, 2 15-30: 2 30- >75: 2, 3	Sandy podzol	Deurer et al., 2001
GER	DBF[2]	0-10: 1 0-40: 2 40-100: 3	1, 2: Silt loam luvisol 3: Silt clay loam luvisol	Bittner et al., 2010
SWI	FRS AGR	0-5: 1	FRS: Silty loam AGR: Loam	Alaoui, 2023
GER	DBF	0-5: 1	DNF, DBF: Sandy Cambisol	Bens et al., 2007
FRA	DBF DNF AGR	Topsoil: 1	DBF, DNF: Sandy loam, sandy clay AGR: Loamy sand	Gonzalez-Sosa et al., 2010
SCO	DBF DNF AGR	Topsoil: 1	DBF, DNF, AGR: Podzol, cambisol	Chandler et al., 2018
SCO	DBF[2] DNF[1] GRS	Topsoil: 1 5-25: 2		Archer et al., 2013

Table continues on next page

BEL	DBF DNF[2]	Topsoil & 0-10: 1 0-40: 2 40-80: 3	A1, 2, 3: loamy sand, podzol B1, 2, 3: Arenosol C1, 2, 3: Sandy loam, umbrisol D1, 2: Silty loam, planosol D3: Clay, planosol E1, 2: Retisol E3: silty loam, retisol	De Vos et al., 2021
BEL	AGR	0-5: 1 5-135: 2, 3	Podzol, cambisol	Rezaei et al., 2016

Table C2. *Van Genuchten parameter values of researches studying temperate forests. The link of the parameter values of a certain research to the FAO soil map is described within the column 'applied polygons FAO' through either texture or soil type. Numbers within this column or before a parameter represent the soil layer the parameters have been applied to. If a single soil layer number is described in the 'applied polygons FAO' column, the van Genuchten parameter values do not have a number in their columns, meaning that the values of that research are applied to only that respective soil layer value.Furthermore, capital letters within the 'applied polygons FAO' represent a link for the van Genuchten parameters to an applied soil type or soil texture plot, meaning that the respective research has studied multiple forest soils.*

Forest: Applied in FAO soil map	K_s [cm/d]	$\boldsymbol{\theta}_s$ [cm^3/cm^3]	$\boldsymbol{\theta}_r$ [cm^3/cm^3]	$\boldsymbol{\lambda}$ [-]	$\boldsymbol{\alpha}$ [1/cm]	Research
2: A: loam, sandy loam, sandy clay loam B: Silty loam C: Sandy loam D: Silty clay loam E: Sandy loam, loamy sand F: Silty loam G: Clay, loam, silty loam H: Silty loam I: Clay, clay loam	2: A: 72.86 B: 69.11 C: 67.78 D: 35.36 E: 3651.8 F: 24.86 G: 26.21 H: 12.96 I: 0.28	2: A: 0.471 B: 0.503 C: 0.489 D: 0.467 E: 0.548 F: 0.486 G: 0.457 H: 0.469 I: 0.463	2: A: 0.102 B: 0.079 C: 0.084 D: 0.051 E: 0.009 F: 0.045 G: 0.033 H: 0.141 I: 0.311	2: A: 0.561 B: 0.294 C: 0.304 D: 0.180 E: 0.249 F: 0.273 G: 0.189 H: 0.167 I: 0.203	2: A: 0.060 B: 0.118 C: 0.089 D: 0.086 E: 0.161 F: 0.03 G: 0.039 H: 0.181 I: 0.134	Puhlmann & Von Wilpert, 2012
1, 2, 3: Podzol	1. 1.584 2: 3.064 3: 6.144	1: 0.353 2: 0.29 3: 0.27	1: 0.139 2: 0.104 3: 0.033	1: 0.64 2: 0.80 3: 0.9	1: 0.044 2: 0.048 3: 0.047	Deurer et al., 2000, 2001
1, 2: Silt loam 3: Silty clay loam & luvisol	1: 78.84 2: 52.92 3: 6.90	1: 0.527 2: 0.457 3: 0.409	1: 0.07 2: 0.08 3: 0.11	1: 0.341 2: 0.302 3: 0.236	1: 0.024 2: 0.052 3: 0.043	Bittner et al., 2010
1: Silty loam	1: 899.053	X	X	X	X	Alaoui, 2023
1: Cambisol	1: 724.5	X	X	X	X	Bens et al., 2007
1: Sandy loam	1: 704.16	1: 0.49	X	X	X	Gonzalez-Sosa et al., 2010
1: Podzol & cambisol	1: 196.32	X	X	X	X	Chandler et al., 2018

A1: Cambisol A2: Sandy loam B2: Loam	A1: 976.8 A2: 537.6 B2: 249.6	X	X	X	X	Archer et al., 2013
A1, 2: Loamy sand A3: loamy sand, podzol B1, 2, 3: Arenosol C1, 2: Sandy loam C3: sandy loam, umbrisol D1, 2: Silty loam D3: Clay, planosol E1, 2: Retisol E3: silty loam, retisol	X	A 1: 0.606 2: 0.42 3: 0.387 B 1: 0.524 2: 0.434 3: 0.341 C 1: 0.612 2: 0.509 3: 0.37 D 1: 0.645 2: 0.477 3: 0.593 E 1: 0.520 2: 0.422 3: 0.404	A 1: 0.165 2: 0.079 3: 0.031 B 1: 0.061 2: 0.049 3: 0.005 C 1: 0.12 2: 0.047 3: 0.001 D 1: 0.150 2: 0.100 3: 0.077 E 1: 0.103 2: 0.094 3: 0.045	A 1: 0.849 2: 1.270 3: 1.305 B 1: 0.289 2: 0.398 3: 0.367 C 1: 0.297 2: 0.345 3: 0.377 D 1: 0.123 2: 0.282 3: 0.105 E 1: 0.229 2: 0.379 3: 0.175	A 1: 0.127 2: 0.030 3: 0.027 B 1: 0.089 2: 0.057 3: 0.025 C 1: 0.086 2: 0.017 3: 0.012 D 1: 0.105 2: 0.046 3: 0.016 E 1: 0.0057 2: 0.0037 3: 0.009	De Vos et al., 2021

Table C3. Van Genuchten parameter values of researches studying agricultural lands and grasslands. linked to the soil map through texture or soil type described within 'applied polygons FAO'. Numbers within this column or before a parameter represent the soil layer the parameters have been applied to. If a single soil layer number is described in the 'applied polygons FAO' column, the van Genuchten parameter values do not have a number in their columns, meaning that the values of that research are applied to only that respective soil layer value. Furthermore, capital letters within the 'applied polygons FAO' represent a link for the van Genuchten parameters to an applied soil type or soil texture, meaning that the respective research has studied multiple forest soils.

Land use	Applied in FAO	Ksat [cm/d]	θs [-]	θr [-]	λ [-]	α [cm^{-1}]	Research
AGR	1: Loam	138.24	X	X	X	X	Alaoui, 2023
AGR	1: Loamy sand	233.28	0.43	X	X	X	Gonzalez-Sosa et al., 2010
AGR	1: Podzol, cambisol	7.68	X	X	X	X	Chandler et al., 2018
AGR	1, 2, 3: Podzol, cambisol	1: 230.16 2, 3: 113.76	1: 0.39 2, 3: 0.31	1: 0.09 2 & 3: 0.03	1: 0.72 2, 3: 0.34	1: 0.017 2, 3: 0.021	Rezaei et al., 2016
GRS	A2: Cambisol B2: Luvisol	A2: 10.32 B2: 8.04	X	X	X	X	Archer et al., 2013

Table C4. Mean of all van Genuchten parameters of forests found during the literature review (Table C2).

FRS	K_s [cm/d]	$\boldsymbol{\theta}_s$ [cm^3/cm^3]	$\boldsymbol{\theta}_r$ [cm^3/cm^3]	$\boldsymbol{\lambda}$ [-]	$\boldsymbol{\alpha}$ [1/cm]
0-5 Mean (research count)	556.27 (7)	0.52 (4)	0.12 (3)	0.40 (3)	0.069 (3)
5-40 Mean (research count)	179.45 (4)	0.57 (4)	0.094 (4)	0.51 (4)	0.035 (4)
40-190 Mean (research count)	6.5 (2)	0.40 (3)	0.043 (3)	0.50 (3)	0.026 (3

Table C5.Mean of all van Genuchten parameters of agricultural land and grassland found during the literature review (Table C3).

AGR & GRS	K_s [cm/d]
0-5 Mean (research count)	152.34 (4)
5-40 Mean (research count)	44.04 (2)
25-max Mean (research count)	113.76 (1)

Appendix D: Observed discharge and precipitation

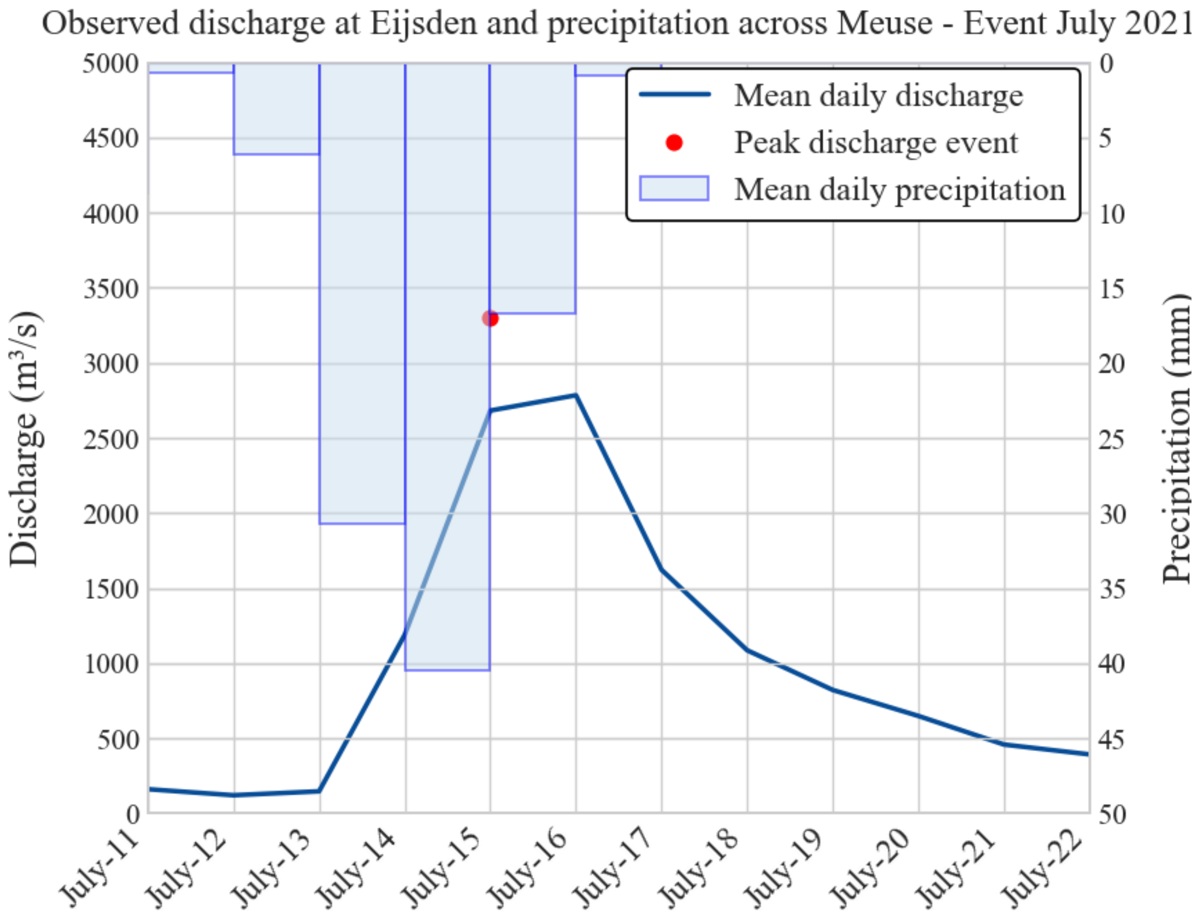

Figure D1. Mean daily observed discharge at Eijsden and mean precipitation across the Meuse catchment, around the flood event time period.

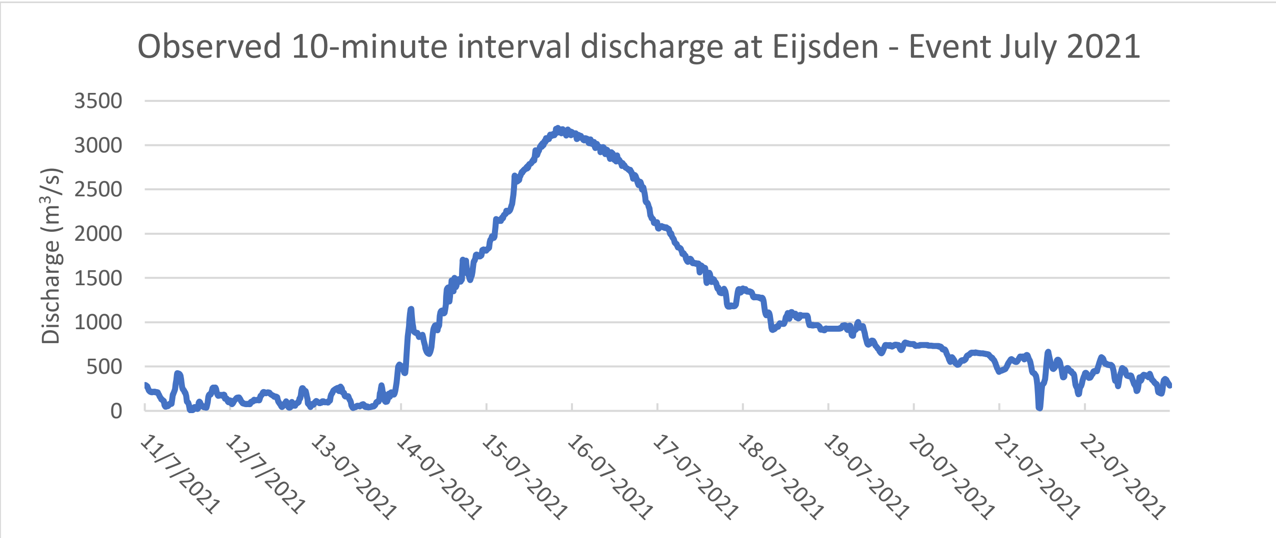

Figure D2. Observed 10-minute interval discharge at Eijsden around the flood event time period

Appendix E: Model processes

Table E1. *Model processes across the catchment in the 'Baseline' and 'Full Forestation' scenario during the spin-up (summed over this period) and during the event.*

	Soil saturation [%]	Actual ET [mm]	Infiltration [mm]	Runoff [mm]	Percolation [mm]	Interflow [mm]	Total water storage [mm]
Spin-up							
July 2020-July 2021							
Baseline [mm]	67	470.85	624.15	299.30	1642.50	94.90	815
Full forestation [mm]	61	521.95	700.80	281.05	1711.85	80.30	842

	July 14		July 15				General
	Pre-event soil saturation [%]	Actual ET [mm]	Infiltration [mm]	Runoff [mm]	Percolation [mm]	Interflow [mm]	Total water storage [mm]
Event							
July 15, 2021							
Baseline - Parameter change	80	0.47	**17.79**	**13.94**	**16.29**	1.39	815
Full forestation – Parameter change	74	0.64	**21.69**	**11.76**	**18.62**	1.22	842

Appendix F: Precipitation intensity map

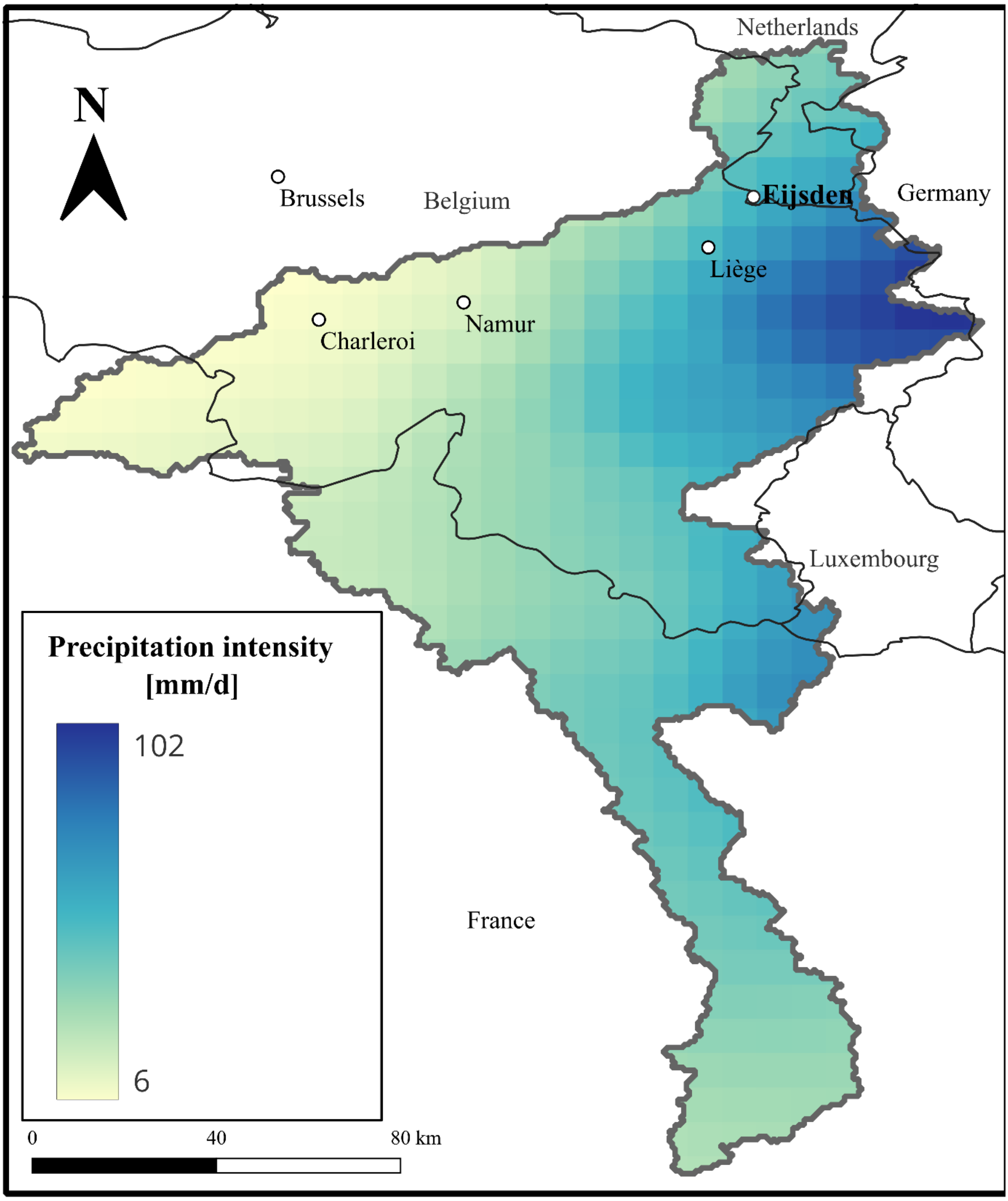

Figure F1. Precipitation intensity map (mm/d) during the event (July 15) across the catchment.

Appendix G: Van Genuchten parameters

Table G1. *Change in mean van Genuchten parameter values across the catchment, between the initial dataset and the initial dataset with in-situ measurements incorporated.*

Legend	
Extreme increase (+250%)	
Very large increase (+100-250%)	
Large increase (+50-100%)	
Moderate increase (+25-50%)	
Slight increase (+5-25%)	
Roughly equal (5% difference)	
Slight decrease (–5-25%)	
Moderate decrease (–25-50%)	
Large decrease (–50-75%)	
No difference	

Ks1	+1100.8%	+111.1%		+546.1%
*K*s2	+558.2%	+82.3%	-25.7%	+200.1%
*K*s3	-74.71%	+82.2%		-17.0%
θs1	-5.03%	-5.8%		-5.4%
θs2	+6.55%	-7.6%		+1.1%
θs3	+2.49%	-6.7%		-1.0%
θr1	+31.7%	+1.4%		+14.4%
θr2	+67.5%	-19.7%		+29.1%
θr3	-15.6%	-19.0%		-13.0%
λ1	+32.7%	+28.3%		+30.9%
λ2	+30.1%	-1.1%		+13.8%
λ3	-25.3%	+0.3%		-11.3%
α1	+196.2%	+1.4%		+78.7%
α2	+369.9%	+9.7%		+192.5%
α3	+61.6%	+5.5%		+28.6%

Table G2. *Difference in van Genuchten parameters between land cover types (indicated percentages are the differences with forest) in the initial dataset.*

Initial dataset	Forest	vs grassland	vs agriculture	Mean land cover
Ks1	32.295	32.140 (-0.48%)	31.293 (-3.1%)	31.71
Ks2	28.062	27.932 (-0.46%)	26.431 (-5.81%)	27.18
Ks3	26.975	26.819 (-0.58%)	26.537 (-1.62%)	26.69
$\boldsymbol{\theta}$s1	0.477	0.481 (+0.76%)	0.482 (+1.10%)	0.480
$\boldsymbol{\theta}$s2	0.443	0.446 (+0.64%)	0.447 (+0.89%)	0.445
$\boldsymbol{\theta}$s3	0.402	0.409 (+1.71%)	0.418 (+2.43%)	0.407
$\boldsymbol{\theta}$r1	0.079	0.0784 (-0.82%)	0.0781 (-1.18%)	0.0787
$\boldsymbol{\theta}$r2	0.080	0.0793 (-0.84%)	0.0791 (-1.18%)	0.0798
$\boldsymbol{\theta}$r3	0.082	0.0814 (-0.81%)	0.0811 (-1.13%)	0.0814
$\boldsymbol{\lambda}$1	0.370	0.368 (-0.57%)	0.367 (-0.91%)	0.368
$\boldsymbol{\lambda}$2	0.373	0.371 (-0.61%)	0.369 (-0.94%)	0.371
$\boldsymbol{\lambda}$3	0.380	0.383 (+0.82%)	0.383 (+1.15%)	0.382
$\boldsymbol{\alpha}$1	0.0133	0.0134 (-4.47%)	0.0144 (-5.88%)	0.0136
$\boldsymbol{\alpha}$2	0.0156	0.0146 (-3.61%)	0.0144 (-4.65%)	0.0147
$\boldsymbol{\alpha}$3	0.0172	0.0166 (-3.75%)	0.0163 (-5.05%)	0.0168
Root depth	2.361 meter	2.358	2.2661	
Root fraction	0.829	0.674	0.690	
Soil depth	0 = 0.05m	1 = 0.05-0.4m	2 = 0.4-1.9m	

Table G3. *Mean van Genuchten parameters across the Meuse basin in the Baseline scenario and Full Forestation scenario, Table 3 in the report is based on this data.*

	Baseline	Full Forestation	Absolute difference
Ks1	139.5	387.8	+178.0
Ks2	68.0	182.0	+168
Ks3	32.6	6.83	-79

$\boldsymbol{\theta}$s1	0.458	0.451	-1.53
$\boldsymbol{\theta}$s2	0.435	0.472	+8.5
$\boldsymbol{\theta}$s3	0.397	0.412	+3.8
$\boldsymbol{\theta}$r1	0.0848	0.104	+22.6
$\boldsymbol{\theta}$r2	0.0852	0.135	+58.5
$\boldsymbol{\theta}$r3	0.0705	0.069	-2.1
$\boldsymbol{\lambda}$1	0.0207	0.039	+88.9
$\boldsymbol{\lambda}$2	0.0302	0.074	+144.0
$\boldsymbol{\lambda}$3	0.0199	0.028	+40.7
$\boldsymbol{\alpha}$1	0.68	1.32	+94.1
$\boldsymbol{\alpha}$2	0.402	0.48	+19.4
$\boldsymbol{\alpha}$3	0.356	0.28	-21.35

Appendix H: Forestation scenarios

Table H1. *Hydrologic variables affected by the various forestation scenarios.*

Parameter change	Peak discharge (15th)	Forest cover change (%)	Peak discharge reduction per percentage land cover change	Mean pre-event soil saturation
Baseline: parameter change	2870	X	X	80
100%	2466	42.9	8.43	72
Restoration opportunities	2659	19.74	10.69	77
Grassland Belgium	2586	15.83	17.94	**76**
Agriculture Belgium	2760	8.91	12.34	76
Grassland France	2819	10.49	4.86	77
Agriculture France	2823	7.65	6.14	77

Table 2. *Model processes affected by the various forestation scenarios.*

Mean catchment (bio area (excluding urban))	Act ET	Potential Infiltration	Infiltration	Runoff	Percolation	Relative S
July 2020– July 2021						
Parameter change	1.29	92.55	1.71	0.824	4.5	67
100 afforestation	1.43	130.275	1.79	0.772	4.67	61
Restoration opportunities	1.34	107.59	1.75	0.795	4.65	64
Belgium Grassland	1.35	105.63	1.74	0.798	4.59	65
Belgium Agriculture	1.34	102.41	1.73	0.814	4.61	65
France Grassland	1.32	99.3	1.74	0.81	4.53	66

France Agriculture	1.33	96.1	1.71	0.82	4.57	67
Event (14th – 16th July 2021)						
Parameter change	0.60	43.01	13.87	9.27	16.68	80
100 afforestation	0.79	69.41	16.49	8.03	17.75	74
Restoration opportunities	0.69	52.97	15.00	8.65	17.11	77
Belgium grassland	0.67	51.98	15.12	**8.57**	17.00	78
Belgium agriculture	0.64	50.65	14.65	8.91	16.96	78
France grassland	0.65	48.23	14.47	8.96	16.96	78
France Agriculture	0.64	45.93	14.16	0.91	16.58	79