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Model-based design of drought-related climate adaptation strategies using nature-based solutions: case study of the Aa of Weerijs catchment in the Netherlands

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ABSTRACT

This article presents a methodology for designing and assessing drought-related Nature-Based Solutions (NBS) adaptation strategies on a catchment scale using an integrated hydrological model that simultaneously provides surface water and groundwater results. The Aa of Weerijs catchment, shared between Belgium and the Netherlands, was used for demonstrating the methodology. The model was developed with the MIKE SHE modelling system, using a combination of globally available and local data. Different types of NBS (ditch blocking, infiltration ponds, wetland restoration and heathland restoration) were combined spatially to develop two adaptation strategies with different spatial extents. Their design was based on drought-related Key Performance Indicators (KPIs) linked with water management actions by key stakeholders (bans on water extraction), both on the surface and groundwater. The KPI values were obtained by model simulations under current and future climate conditions, and with the implementation of the two adaptation strategies. The results show that the strategy with a larger spatial extent gives better KPI values, almost eliminating days with no groundwater availability in the downstream part of the catchment, reaching the goal of increased infiltration and groundwater recharge. Additionally, our results show that there is significant accumulation of positive effects from upstream to downstream.

1. Introduction

Hydrological extremes, such as floods and droughts, are expected to increase in frequency and intensity under projected climate change [1–3]. In the Netherlands, a low-lying country located in Northwestern Europe, flooding has for centuries been a key water management issue, resulting in highly developed flood management policies and practices, supported by sophisticated physical infrastructure. Over the last couple of decades, however, drought conditions and water shortages during summers have started to occur, already partly attributed to the altered climate [4]. Such conditions are expected to exacerbate under further climate change, and adaptation measures and strategies need to be planned and implemented. In general, rather than de-watering and extensive drainage, aimed at fast evacuation of excess water, dealing with droughts requires increasing water storage and slowing down of surface and sub-surface flows. Some of these actions have been recognized as beneficial for flood management as well [5], but they may be critically important for droughts. To achieve these goals, Nature-Based Solutions (NBS) have recently been researched, promoted and implemented, as measures that can complement and partly replace engineering solutions (grey infrastructure) [6–8]. It should be noted that the term “NBS” is used here to encompass similar, more conventional “green” practices (e.g. green infrastructure, conservation agriculture, landscape management approaches incorporating stormwater best management practices, etc). Although there may be differences between these traditional interventions and the more modern NBS (in design objectives and actual implementations), the modelling approaches introduced here, which are the main focus of this article, are applicable to both. Herein it is assumed that the all "green" interventions applied will be developed, implemented and managed in accordance with the IUCN Global Standard for Nature-Based Solutions [9] and thus the term "NBS" is used to describe all actions. The arguments in support of NBS

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implementation are their multiple benefits, such as improved management of hydrological extremes, better water quality, enhanced soil health, support for biodiversity, restoration / creation of nature areas for recreation, and overall improvement of land use planning and management [10–12].

Research regarding NBS is very active, but there are still a number of challenges and open questions. For example, while much attention has been paid to the contributions of NBS to improved management of floods and flood adaptation (e.g. [13–16]), very little has been explored in the field of drought management. Indeed, as a recent literature review pointed out, in only 6 % of case studies in Europe NBS were focused on drought management and adaptation, while this percentage grows up to 14 % at the global scale [6]. Furthermore, research on the effects of NBS in urban areas is more developed, compared to their application on larger, catchment scales and rural areas [6,17]. Additionally, while effects from single type NBS may be known, designing solutions where different NBS types need to be spatially combined is still challenging [18], due to the multiple goals that NBS need to achieve, and to the numerous issues that can potentially determine their combination. The lack of proper modelling approaches to simulate the diverse NBS effects for drought adaptation at a catchment scale [19] is yet another gap in the understanding of the potential offered by such measures, especially because analysis of catchment-wide NBS for drought adaptation require integrated modelling of surface and sub-surface hydrology [6]. Such integrated modelling is required for assessing both the effectiveness of such solutions, and because surface water and groundwater resources need to be jointly considered in drought management. This is especially true when planning NBS in rather flat areas, where the key goal of such measures is to enable increased water storage in the sub-surface during wet periods, for sufficient groundwater and surface water availability during dry periods. Specifically, integrated models are required that *simultaneously* provide results in terms of observable variables such as river discharge and groundwater levels, together with water balance variations associated with the interactions between surface and sub-surface. To the best of our knowledge, past research with integrated modelling approaches have predominantly assessed surface water, together with variations in groundwater recharge, without providing data on the actual groundwater levels (e.g. [20–22]).

The lack of comprehensive simulated results and proper quantitative assessment tools contributes to a lack of evidence of success in the application of NBS, which is in turn perceived as an obstacle to the implementation and maintenance of such measures by citizens [23], together with potential citizens' unwillingness to give up private land for NBS development [24]. Engaging stakeholders, such as private land owners (e.g. farmers), water and land managers, and local and regional authorities, to participate in the design and implementation of NBS adaptation strategies is a challenge, due to their diverse interests and attitudes, and adequate tools for this purpose are still in development [25]. While scientific research argues for adopting more *generic* Key Performance Indicators (KPIs) to enable comparisons across cases and catchments [12], stakeholders, including both water managers and private land owners, may require more *specific* KPIs that relate to observable variables (groundwater levels, river water levels and/or discharges) and address actual water management actions.

This research addresses some of the abovementioned gaps, presenting a methodology to design catchment-wide NBS adaptation strategies for hydrological drought management. More specifically, we demonstrate: i) how the effects of different types of NBS for drought adaptation at a catchment scale can be simulated with an integrated hydrological model, simultaneously providing surface water and groundwater levels information; ii) how to select meaningful KPIs directly related to observations in close collaboration with key stakeholders, their computation and usage for assessing the effectiveness of NBS; iii) how NBS performance regarding groundwater availability can be used to design adaptation strategies consisting of spatially combined NBS. To this aim, we use the case study of the Aa of Weerijs catchment, shared between Belgium and the Netherlands, as our test-bed. To perform our analysis we developed an integrated hydrological model of the study area based on the MIKE SHE modelling system [26], which is used to assess NBS effects on drought adaptation both in the current conditions and under future climate change projections. The obtained results and insights may be applicable to other similar areas where drought-related NBS are being considered.

After this introduction, the paper details the methodology applied to answer the research questions, followed by Results and Discussion. The last section on Conclusions summarises the main findings and possible future directions of research.

2. Methods

2.1. Case study area

The Aa of Weerijs catchment has a total area of 346 km^2, divided into an upstream area of 199 km^2 in Belgium and a downstream area of 147 km^2 in the Netherlands. Agriculture is the predominant land use (73 %), which includes a tree nurseries sector of high commercial export value (Fig. 1B, on the right). The remaining land use consists of nature area (14 %) and urbanized areas (13 %). The river of Aa of Weerijs and its smaller tributaries flow on the eastern part of the catchment through a gentle sloping area from about 30m height above mean sea level (amsl) in the most upstream part of the catchment to about -3m amsl at the catchment outlet located in the city of Breda. On the western side of the catchment, there are two larger brooks, Bijloop and Turfvaart, which join Aa of Weerijs close to the city of Breda. Flood protection and agriculture have been the main water management objectives in the past, leading to the creation of a network of drainage canals, river canalisation and straightening. A number of weirs have also been introduced for maintaining target water levels during winter and summer seasons. This catchment has recently experienced summer droughts, particularly severe in 2018, when so called bans, regulatory restrictions on water extractions had to be introduced by the key stakeholders of the area, the Province of Noord Brabant (PNB - the regional government body charged with spatial planning) and the Water Board Brabantse Delta (WBD – the regional government body charged with managing water). More specifically, bans are introduced to either limit water extraction for irrigation, prioritizing irrigation for specific crops, or completely forbid water abstraction for irrigation, according to the current surface water availability (lower surface discharge corresponds to higher limitations in water abstraction). While this system of bans is aimed at saving water resources in the area and ensuring environmental flow during dry periods, its application can damage crop and tree nursery production, leading to economic losses for the producers. Because of these recent drought-related issues, the PNB and WBD have selected this catchment as a pilot for introducing climate adaptation strategies composed of NBS. Fig. 1A presents on the left the catchment boundary and the main river network, together with the spatially distributed (and numbered) discharge (Q) and groundwater level (GWL) measuring sites used in this research.

2.2. Methodological framework

The main methodological steps followed in this research are presented in Fig. 2. An integrated, spatially distributed MIKE SHE hydrological model that captures the interactions between surface and subsurface waters within Aa of Weerijs catchment has been developed, to simulate the current and future hydrological conditions. This was in fact the main tool used for the design of the NBS adaptation strategies. In consultation with the main stakeholders (Water Board Brabantse Delta and Province of Noord Brabant), a set of KPIs was selected and agreed upon, related to observable hydrological variables, to be used for evaluating the performance of the NBS strategies. For assessing hydrological conditions and KPI values under future climate change, four projections

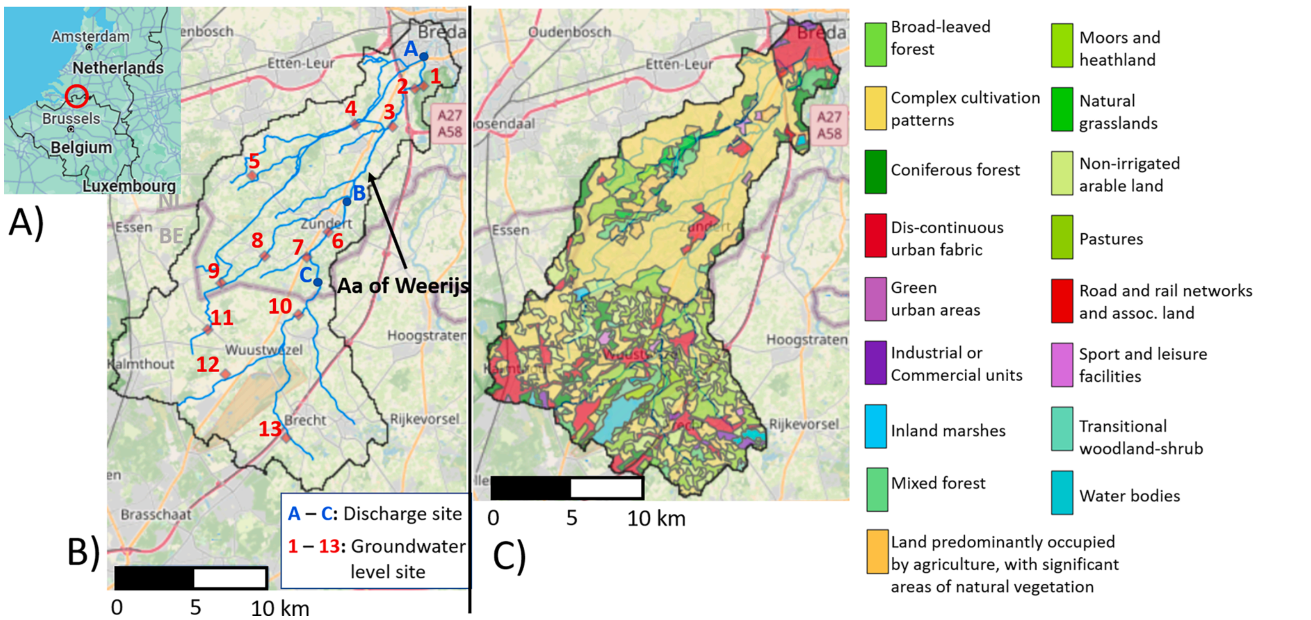


Fig. 1. A) Location map of the Aa of Weeris catchment, indicated on a background map from Google maps (n.d.); B) Aa of Weerijs catchment boundary and main river network, together with discharge and groundwater level observation sites used in this study; C) Land-use map of the catchment; background maps for B) and C) are from [27].

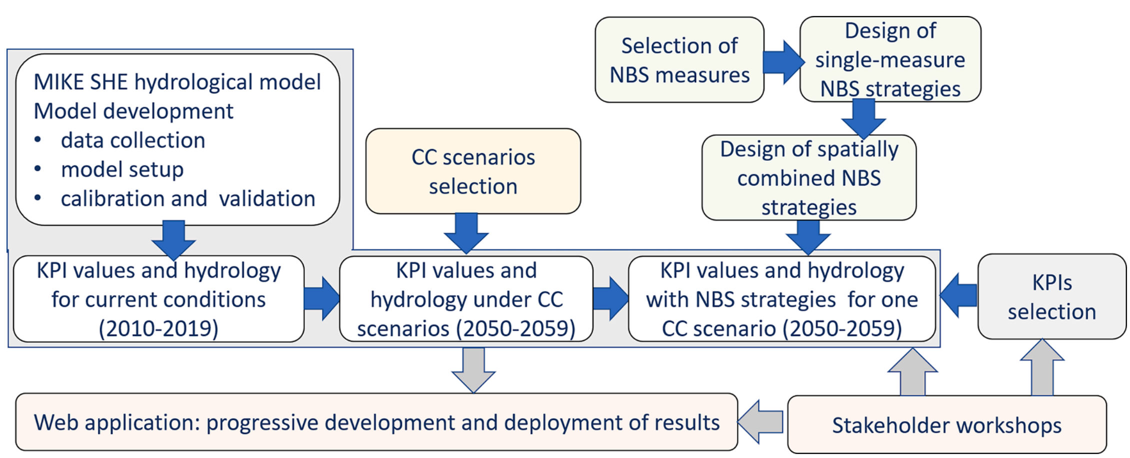


Fig. 2. Methodological steps for design and evaluation of the drought-related NBS adaptation strategies in the Aa of Weerijs catchment. (The web-application development will not be discussed here, as it is out of the scope of this article).

scenarios developed by the Royal Netherlands Meteorological Institute (KNMI, [28]) have been considered. The design of the NBS adaptation strategies included testing different types of single NBS, together with selection of appropriate approaches for their modelling, as well as testing spatial combinations of different types of NBS. The performance of the strategies in terms of KPIs was analysed for one of these four climate change scenarios, specifically the one characterised by high CO_2 emissions and a drying climate, which is expected to result in the most prolonged periods of droughts.

The design of the NBS strategies and the KPIs to assess their performance was done in consultation with the local stakeholders, through dedicated meetings. Additionally, a web-app was also developed in consultation with these stakeholders, to provide them with transparent and accessible information, allowing for improved informed decision making and stakeholders engagement in NBS design. This web application has been made publicly available to support further discussions and planning of adaptation strategies with wider groups of stakeholders. Although it is not the main focus of this article, the reader is referred to the following link for its exploration: https://eiffel.un-ihe.org/EIFFEL-prod/.

Each of the methodological steps is briefly elaborated in the following sub-sections.

2.2.1. MIKE SHE hydrological model of the Aa of Weerijs catchment

MIKE SHE is a software tool designed for integrated catchment hydrological modelling developed by the Danish Hydraulic Institute (DHI), enabling development of physically-based distributed hydrological models. It was chosen as the modelling tool in this study both because of its ability to capture the complex interactions between surface water and groundwater (Refsgaard et al. 2010), and due to the possibility to provide, among others, water balance assessment results. Additionally, it proved to be superior to alternative software tools for integrated modelling (e.g. SWAT), especially for flat areas with dense river networks or where groundwater is dominant [29], as in the case of Aa of Weerijs. MIKE SHE-based modelling has recently been applied for NBS analysis [20,21], although focusing mainly on streamflow only or in combination with groundwater recharge, rather than analysing groundwater levels and surface water together.

The setup of the MIKE SHE model is presented in Fig. 3. The main grid of the model is with 500m x 500m resolution, used for simulating 2D horizontal overland flow and groundwater flow in the saturated zone (SZ). These two components are connected with a 1D vertical unsaturated zone (UZ) model for each grid cell, and the top UZ part, representing the vegetation root zone, is connected to the evapotranspiration component. The river network is represented in the MIKE 11 river model of DHI (which is fully integrated in MIKE SHE), with all hydraulic structures and weirs. The smaller drainage network (not represented in MIKE 11) is captured by introducing spatially distributed conceptual drains with spatially varying elevations and drainage time constants. For further information regarding the MIKE SHE modelling system, see [26].

As this work was part of the EIFFEL project ([30]) on joint use of local and globally available GEOSS data (Global Earth Observation System of Systems) for climate-related applications, this research also used such combination of data sets, as depicted in Fig. 3.

Main hydrological forcings for this model were Precipitation (P) and Potential Evapotranspiration (PET). Precipitation data from three stations was used and represented spatially over the model grid using Thiessen polygons. The data from the two stations in the Netherlands (Ginneken and Zundert) was obtained from KNMI website [31], while the data for the third station situated in Belgium (Leonhout) was sourced from the Flemish Environment Agency website [32]. The PET data from one nearby meteorological station in the Netherlands (Gilze-Rijen) was used and also sourced from KNMI website [31]. In-situ discharge data was provided by the Water Board Brabantse Delta. Groundwater levels for the wells in Netherlands were obtained from Water Board Brabantse Delta and Data and Information on the Dutch Sub-surface website [33], while the data for the wells in Belgium was sourced from Databank Ondergrond Vlaanderen website [34].

The model was calibrated for the period 2009-2016, and validated for the very dry period of 2017-2019 using daily data. The model setup and input are elaborated in detail in [35], and here we will give only a brief summary.

As this is a physically-based spatially distributed model, which provides outputs in terms of multiple observable variables, a multi-site and multi-variable manual calibration approach was adopted. Given the large number of parameters, automatic calibration was infeasible, and manual calibration has shown to be effective in other MIKE SHE models (e.g. [36,37]) and it is sometimes preferred [38]. The manual calibration values selected were informed by independent sources and existing literature. This followed a sensitivity analysis of few uncertain and more conceptual parameters (see for the detailed procedure [35]). In fact, this calibration was mainly limited to parameters in the saturated zone (drainage time constant), using as target variables Q and GWL (at sites depicted in Fig. 1), as well as satellite-observed Actual Evapotranspiration (AET) data (SATDATA 3.0, [39]) at 13 additional sites with different vegetation cover. Each site with its associated variable was used in the manual calibration, using as calibration target a weighted mean of correlation coefficient (MR) and Nash-Sutcliffe Efficiency coefficient (MNSE) of the three variables (Q, GWL and AET) across all sites. Equal weights were used for the three different variables (see again [35] for the detail model setup, inputs, as well as for the locations of the additional AET calibration sites).

2.2.2. *Key Performance Indicators for assessing drought-related NBS strategies*

Although hydrological drought characterization using indicators is well established (see for a recent overview [40]), there is no general agreement on universal usage of such indicators [41,42] and the selection of the appropriate indicators depends on the intended *use* of water, which can be very diverse. The challenge of selecting the proper indicator is extended also to impact assessment of drought adaptation and management measures, such as those based on NBS. Indeed, actual implementation of NBS critically depends on stakeholders' recognition of their benefits, and use of specific KPIs that relate to their immediate concerns and water usage may be more useful. We computed several drought-related indicators, including some that are commonly used in practice (Soil Moisture Index, Groundwater Dynamics parameters, Localized Model Outputs). This study presents only two newly developed KPIs which link percentiles of long-term observations of streamflow and groundwater levels (typically used for conventional

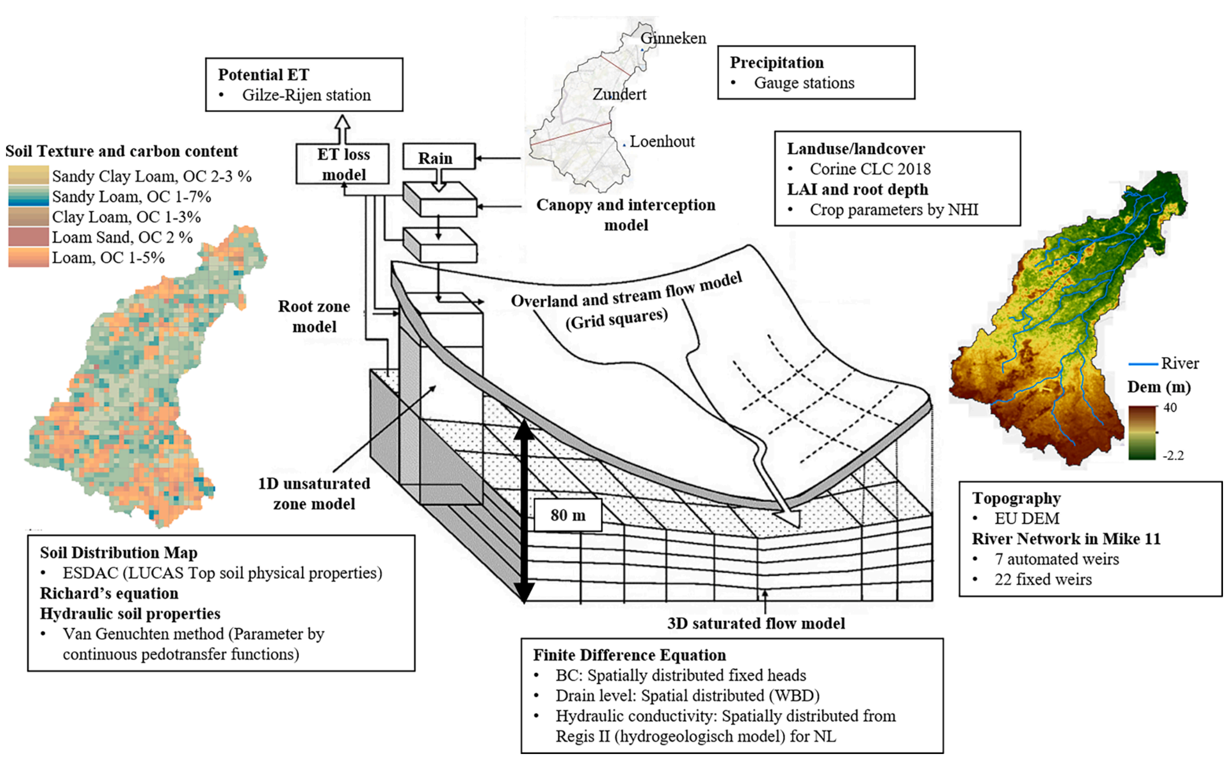


Fig. 3. Schematic representation of the MIKE SHE model for Aa of Weerijs.

hydrological drought indicators) to actions taken by the Water Board Brabantse Delta to manage drought. Indeed, the Water Board constantly monitors groundwater levels and discharge in several locations across Aa of Weerijs and can decide to ban water extraction in case water levels and/or discharge are lower than the pre-defined percentile-based thresholds. The bans can be partial or total, i.e. being applied to only certain water usages or to all, and can be applied to both surface and groundwater. Taking inspiration from this withdrawal bans system, and in consultation with the Water Board, two KPIs were developed, named Surface Water Availability (SWA) and Groundwater Availability (GWA). They are defined as *number of days* with *sufficient* (surface/ground) water availability, *limited* availability and *no* availability. These KPIs are computed for each monitoring location by comparing the simulated discharge (or groundwater level) to the percentile-based thresholds of the same variable for the specific location. The availability conditions and corresponding thresholds are summarised in Table 1 and are defined as follows: if discharge (or groundwater level) falls below the 10^{th} percentile, then a total withdrawal ban is introduced and status of water is defined as 'not available'; if discharge (or groundwater level) falls between the 10^{th} and the 40^{th} percentile, then a partial ban is introduced and water is said to have 'limited availability'; if discharge (or groundwater level) is above the 40^{th} percentile, no ban is introduced and water has 'sufficient availability' for any human usage. Note that the bans are actually introduced to ensure environmental flow, i.e. sufficient water availability for aquatic ecosystems. Recommendations for types of bans in relations to different brook / river ecosystem conditions have been developed and are regularly revised and updated by the Water Board. The 10^{th} and 40^{th} percentile thresholds are computed on a seasonal basis (winter, spring, summer, autumn) using simulated discharge (or groundwater level) for the period 2010-2019, which represents current conditions. Simulated variables are preferred to observed ones for two main reasons: i) to account for biases in the hydrological model, ensuring that KPIs are computed in the same procedure both in current and future conditions, with or without NBS; ii) to compute the KPIs for locations where in-situ observations are not available, but model outputs are. Once the seasonal thresholds are computed, the lowest value (usually in summer) is taken as the reference for the KPIs computation. Although it is possible to calculate such KPIs in every season of the year, this article shows the results for summer only (June, July, August), as it is the period of the year mostly affected by drought events for the case study.

These indicator values are calculated for the summer seasons under current conditions (2010-2019), under climate change scenarios for the period 2050-2059, and with NBS adaptation strategies for the same future period. Furthermore, the number of days with a specific availability class are the cumulation over the entire reference period (e.g. from 2050 to 2059 for future climate change studies).

2.2.3. Climate change scenarios

To assess drought conditions in the future, the latest climate change scenarios developed for the Netherlands were used, as provided by KNMI in October 2023 [28], referred to as KNMI'23. These are based on the projections of IPCC presented in the 6^{th} Assessment report [43], obtained by the so-called Coupled Model Intercomparison Project (CMIP6) model suite of Global Circulation Models (GCMs), with which simulations have been performed for scenarios of future emissions of greenhouse gasses (and land use change), known as Shared Socioeconomic Pathways (SSPs). KNMI'23 climate scenarios have been developed based on 33 CMIP6 model simulations under three emission scenarios, denoted as 'H' (High - increase at the same rate until 2080 and then levelling off, resulting in global warming of 4.9°C by year 2100, compared to pre-industrial era), 'L' (Low - in line with the Paris Agreement to limit global warming to well below 2°C, resulting in global warming of 1.7°C by year 2100), and 'M'(Moderate – emissions increase until 2050, after which they start declining, resulting in 2.7°C of global warming by 2100). These 33 CMIP6 model simulations were then divided in three sets of 11, for developing two storylines in terms of wetness in future climate. The first set leads to wet conditions (denoted as 'N', from 'nat', meaning 'wet' in Dutch language) with much wetter winters and slightly drier summers, and the second set leads to dry conditions (denoted as 'D'), with much drier summers and slightly wetter winters. The combined six climate change scenarios, denoted as HD, HN, LD, LN, MD and MN, were simulated by ensemble simulations (16 members) performed by the KNMI EC-Earth3 GCM [44], coupled with the KNMI regional climate model RAMCO [45], which reproduced the variability of the CMIP6 sets of simulations and provided downscaled climate variables at 12×12 km spatial resolution. KNMI has prepared the scenarios for two different 30-year periods in the future, centred around years 2050 (period 2036-2065) and 2100 (period 2086-2115). For analysing hydrological conditions and KPIs under climate change, this research focused on the High and Low scenarios only (HD, LD, HN, LN), as they represent the best and worst case, respectively, in terms of drought evolution in the future. Precipitation and potential evapotranspiration from these four scenarios were used as forcings to the Aa of Weerijs MIKE SHE hydrological model for the relatively nearby decade of 2050-2059. KPIs are computed for all the four scenarios mentioned above, to analyse the effects of climate change on the hydrological behaviour of the catchment. However, here we present only the results for HD scenario (the driest), as this was used as basis for assessing the performance of the NBS adaptation strategies.

Table 1
Summary of the thresholds, (water) availability class and bans on water extraction used to compute the Surface Water Availability (SWA) and Groundwater Availability (GWA).

Discharge or Groundwater level (x)	*Availability class*	*Ban on water extraction*
$x < 10^{th}$ *percentile*	No availability	Total ban
$10^{th} \leq x \leq 40^{th}$ *percentile*	Limited availability	Partial ban
$x > 40^{th}$ *percentile*	Sufficient availability	No ban

2.2.4. NBS types and modelling in Aa of Weerijs

Climate change impacts within the Netherlands are brought together and presented to stakeholders via different channels, one of which is the climate atlas portal [46]. Guided by such information, provinces and municipalities in the country are developing local climate effect analyses and adaptation strategy plans. Within the Province of Noord Brabant these plans are led by the Province itself and the Water Board Brabantse Delta, especially when it comes to water-related aspects of climate adaptation to floods and droughts. The Province maintains a climate adaptation platform [47], with information about planned and implemented adaptation measures, where NBS are prominent. The Water Board also has NBS as primary target in climate-adaptive water management. Their current strategy for the period 2022-2027 [48] states that the approach for integral water and land management is 'nature-based solutions where possible, technical solutions where necessary'. Within the Aa of Weerijs catchment, some local measures have already been implemented around the town of Zundert, in collaboration with local stakeholders, aimed at rainwater capture for nature in residential areas and increased water storage in the sub-surface.

The recent European research project named *Co-adapt* [49] (which also introduced one of the pilots around Zundert), contributed to the first assessment of types and spatial distribution of potential NBS *on a scale of the whole Province of Noord Brabant*, which included the Dutch part of the Aa of Weerijs catchment. Using information regarding the water system, landscape characteristics, land use and land cover, together with data on NBS from existing projects and plans, a set of NBS types was proposed. For each NBS type a so-called 'opportunity map' was created, covering all possible areas where that NBS type can potentially be implemented. These maps have been provided by the Province for this research, and served as the basis for the design of the

NBS-based adaptation strategy. An example of the opportunity maps is presented in Fig. 4.

The design of our adaptation strategies started by modelling single-type NBS (*single-measure strategy*) within the developed hydrological model, using the opportunity maps as inputs. Six different types of NBS - Ditch Blocking, Tree Planting, Wetlands Restoration, Heathlands Restoration, Infiltration Ponds, Brook Bed Barriers - were pre-selected based on their potential beneficial effects for drought adaptation shown in literature [21,50,51] and on the *Co-adapt* project outcomes. Ditch Blocking consists in blocking the flow from small channels to larger streams, causing the water to slow down and allowing it to infiltrate in the sub-surface. From a modelling perspective, ditches in our MIKE SHE model are modelled through conceptual sub-surface drainage in the saturated zone. Ditch Blocking is hence reproduced in the model by reducing the parameter “drain time constant” by two-thirds with respect to initial values (range 1.50 exp^{-7} - 4.5 exp^{-7} 1/s - corresponding to 77 days - 26 days) in the cells where the block is applied. The initial values (without NBS) have been obtained after calibration, using ranges reported in literature [52–54]. Brook Bed Barriers are NBS where the natural barriers (wooden logs or stones) are used in small streams to increase flow resistance, reducing downstream flow velocity, and enhancing water retention in upstream sections [55,56]. These inline features are modelled in the MIKE 11 river network by weirs as in [18,57,58]. Wetland Restoration aims to store water and increase its retention in the application area. In our hydrological model, this NBS is introduced by changing the parameters representing the existing vegetation type to values characteristic of wetland plant species and grass commonly found in the Netherlands. To model these vegetation types we used Leaf Area Index (LAI) of 2.5 and Root Depth (RD) of 450 mm, as suggested in [59] and [60]. Additionally, the Strickler roughness coefficient value is set to 15 $m^{1/3}$ s^{-1} in areas where wetlands are restored [61,62]. The overland flow detention storage is set at 0.15 m to represent the typical shallow ponding and temporary water retention characteristic of wetlands [63,64]. Wetlands store more organic matter compared to crop areas, which would alter the soil hydraulic properties in the area where wetlands are restored. The changes in the soil properties are incorporated in the model by recalculating the soil hydraulic properties based on the potential changes in the soil organic content as studied by [65,66] and using equations of continuous pedotransfer functions from [67]. Infiltration Ponds are areas with highly permeable material that allows water to infiltrate into the sub-surface. As such, they are introduced in our MIKE SHE model by providing the top 30 cm layer of soil as sandy soil to facilitate infiltration [68,69] and corresponding soil hydraulic parameters are again calculated using equations of pedotransfer functions from [67]. Strickler roughness coefficient is set at 40 $m^{1/3}s^{-1}$ [70] and the overland detention storage is set at 0.15 m to represent the temporary surface ponding as suggested in [69]. Heathlands Restoration aims at reducing transpiration and interception from plants with large canopy cover. For this reason, they are represented in our hydrological model by reducing the LAI and RD parameters,

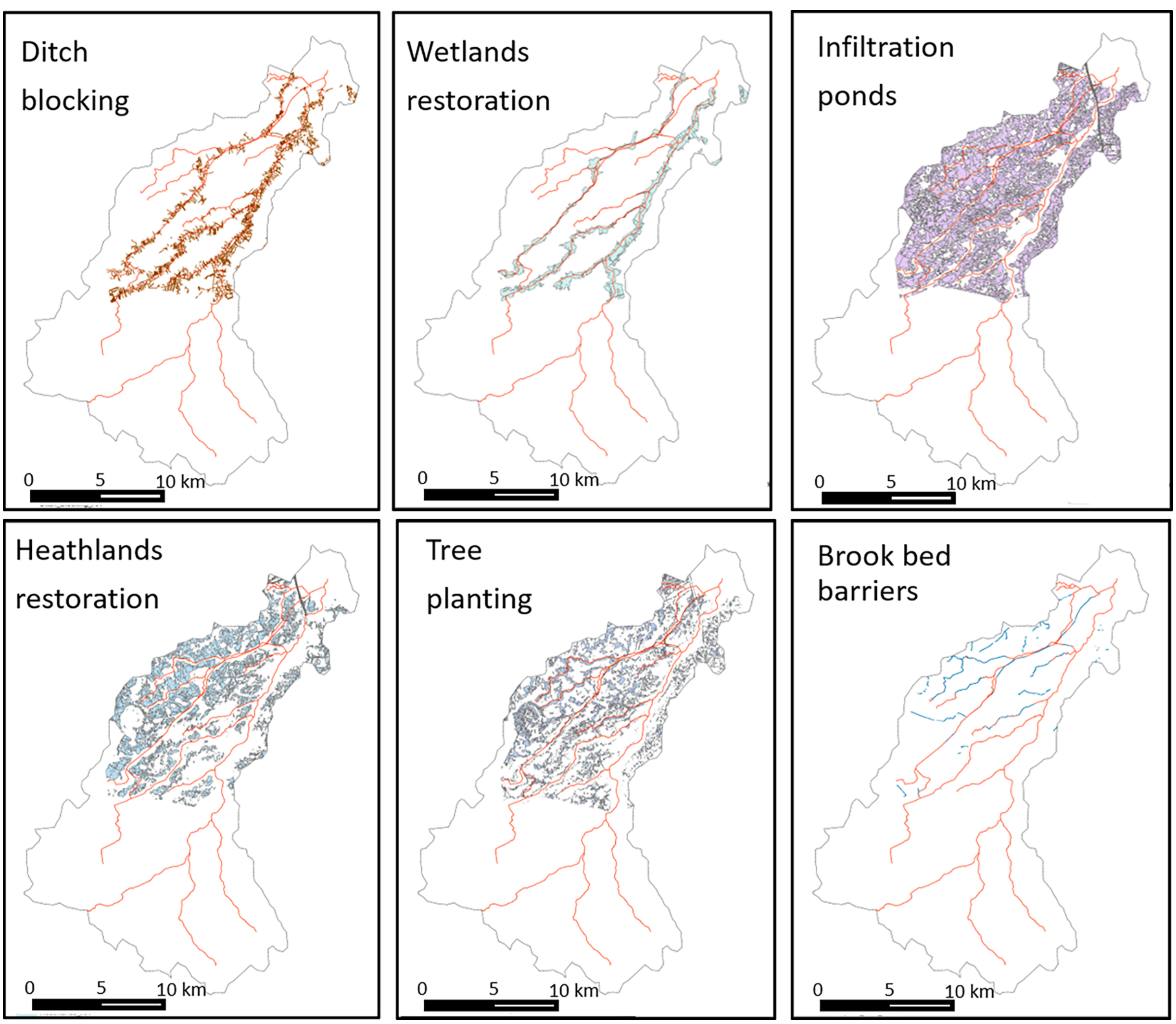


Fig. 4. Opportunity maps for potential implementation of different types of NBS within the Dutch part of the Aa of Weerijs catchment.

according to the values suggested by [59] for heathlands. Further, Strickler roughness coefficient is set at 20 $m^{1/3}$ s^{-1} in these areas [71], same as in the base model for heathlands. Tree planting can play a dual role in hydrology. Trees function as 'pumps' through enhanced ET [72] and as 'sponges' by improving soil infiltration [73]. The overall hydrological effects of tree planting within a specific catchment are therefore dependent upon the complex interplay between these two fundamental processes. They are modelled by modifying LAI, RD, Strickler coefficient and soil hydraulic properties to capture the influence of roots in the infiltration process. The values of LAI and RD are kept same as used in base model for the forest areas and these values were taken from [59]. Strickler roughness coefficient is set at 10 $m^{1/3}$ s^{-1} [71,74]. Similar to wetlands, trees also increase organic content in the soil leading to enhanced water holding capacity. This process is incorporated in the modelling by calculating the soil hydraulic parameters using equations of continuous pedotransfer functions from [67], considering the potential percentage changes in soil organic content values based on [66].

Table 2 gives an overview of the pre-selected NBS and a brief explanation of the modelling approach used to represent them in the MIKE SHE model.

Each of the NBS described was modelled independently within MIKE SHE in current conditions (2010-2019). Both KPIs, i.e. GWA and SWA, were computed for each of the single-measures, and the NBS types that did not provide improvement in terms of surface and groundwater availability were excluded from further analysis, which resulted in the exclusion of Tree Planting and Brook Bed barriers from the next step of the analysis. More detailed results regarding performance of these single-measure strategies in terms of the selected KPIs are available in the developed web application [30].

2.2.5. NBS-based adaptation strategies design

With the remaining four NBS types (Ditch Blocking, Wetland Restoration, Infiltration Ponds, and Heathland Restoration) the design of spatially *combined adaptation strategies* was undertaken. Two combined adaptation strategies were designed (S1 and S2), by restricting the implementation of the above described NBS selection procedure to two different spatial domains (Fig. 5). For S1, the area proposed by the existing "Nature Management Plan" (NMP) was used, developed already in the 1990s. For S2, this area was expanded with the recently developed "Green Blue Mantel" (GBM) area, which represents a buffer zone surrounding the nature network of Brabant and is identified to be used for climate-proofing and making the water system more resilient, as well as nature and landscape enhancement. With this final step, the proposed NBS adaptation strategies are embedded in the existing water and land management plans of Nature Management Plan, regarding climate adaptation and nature development.

Both NBS strategies were developed using their performance with respect to groundwater conditions improvement as the main criterion. Given that the main objective for drought adaptation is to enhance storage of water in the sub-surface, the guiding criterion to select or exclude each of the single NBS types from a specific location was based on its positive effect on groundwater availability, which also results into positive effects on baseflow and hence on surface water. Indeed, locations where the individual NBS had a negative impact on GWA were excluded from the strategy. The final location for a particular NBS type was determined by comparing the magnitude of positive impacts that each individual NBS type provided. In cases of conflicting locations, priority was given to the single measure that provided larger positive impact. It should be noted, however, that Ditch blocking always provided positive effects on GWA, so it was combined with other individual measures on some locations.

The performance of strategies S1 and S2 was then analysed in terms of the chosen KPIs, using the most severe climate change scenario for droughts, namely HD. This scenario is not the most likely, but it was selected in order to best reveal the potential impact of implementing NBS adaptation strategies. In this article, the results in terms of SWA and GWA values at all sites are presented, together with the decadal and seasonal water balances of the whole catchment, which provide supporting information regarding the modifications of the hydrological conditions that the two strategies bring, as they provide the positive drought-related effects.

Table 2
NBS types considered in the Aa of Weerijs catchment and approaches taken for their modelling in the MIKE SHE hydrological model.

NBS type	*Main drought-related function*	*Modelling approach*
Ditch blocking	Slowing down drain flow and allowing more infiltration upstream	Conceptual drain time constant reduced by 2/3 of the initial values [52–54]
Wetlands restoration	Water storage and retention	Modified vegetation parameters: LAI = 2.5, RD = 450 mm [59, 60]; Flow detention storage introduced (0.15m) [63,64]; Modified Strickler roughness coefficient = 15 $m^{1/3}$/s [61,62]; Modified soil hydraulic properties [60,65,66]
Infiltration ponds	Increase of infiltration into the sub-surface	Sandy soil in the top 30 cm [68, 69]; Flow detention storage introduced (0.15m) [69]; Modified Strickler roughness coefficient = 40 $m^{1/3}$/s [70] and soil hydraulic properties [67]
Heathlands restoration	Reduce interception and transpiration from currently forested areas	Reduced LAI and RD according to [59]; Modified Strickler roughness coefficient [71]
Tree planting	Increased infiltration and soil water retention; enhanced flow resistance	Modified LAI and RD values [59]; Modified Strickler roughness coefficient [71,75]; Modified soil hydraulic properties in trees' root zone [66,67]
Brook bed barriers	Slowing down upstream river flow and allowing more infiltration	Using weirs in Mike 11 river model to represent barriers [18, 57,58]

3. Results and discussion

3.1. MIKE SHE hydrological model calibration and validation

The multi-site, multi-variable model calibration resulted in values of MR=0.80 and MNSE of 0.45. There are no clear guidelines in literature regarding MNSE values. Some authors suggest a single-variable NSE value above 0.5 as an indication of a satisfactory model performance [76], but others argue against using fixed thresholds [77,78]. In our case, except for a couple of groundwater level and actual evapotranspiration sites with poor validation performance, overall, most sites showed good validation results with single-variable NSE above 0.7 and with average correlation (R) values across all locations of 0.76, 0.84 and 0.77 for river discharge, groundwater levels and actual evapotranspiration, respectively. Fig. 6 presents selected time series results (calibration and validation) for river discharge and groundwater levels.

The obtained results demonstrated that the developed model is of sufficient quality to be used as a tool for designing drought-related NBS adaptation strategies, especially regarding results of river discharge and groundwater levels, since these observable variables were used in defining the two most important KPIs, SWA and GWA.

3.2. KPI results and water balance for current conditions (2010-2019)

The results for the current conditions, obtained from simulation for the decade 2010-2019 are summarized in Fig. 7.

The left part of Fig. 7 (part A) shows the values of SWA and GWA under current conditions across all investigated sites. We point out that since these two KPIs are defined based on historical percentiles specific

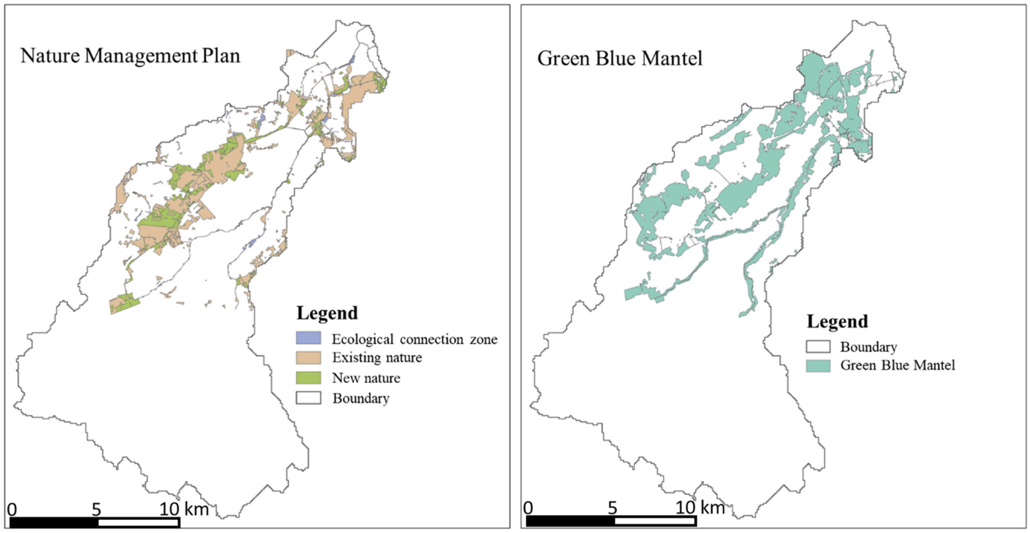


Fig. 5. Spatial domains used for designing strategies S1 and S2.

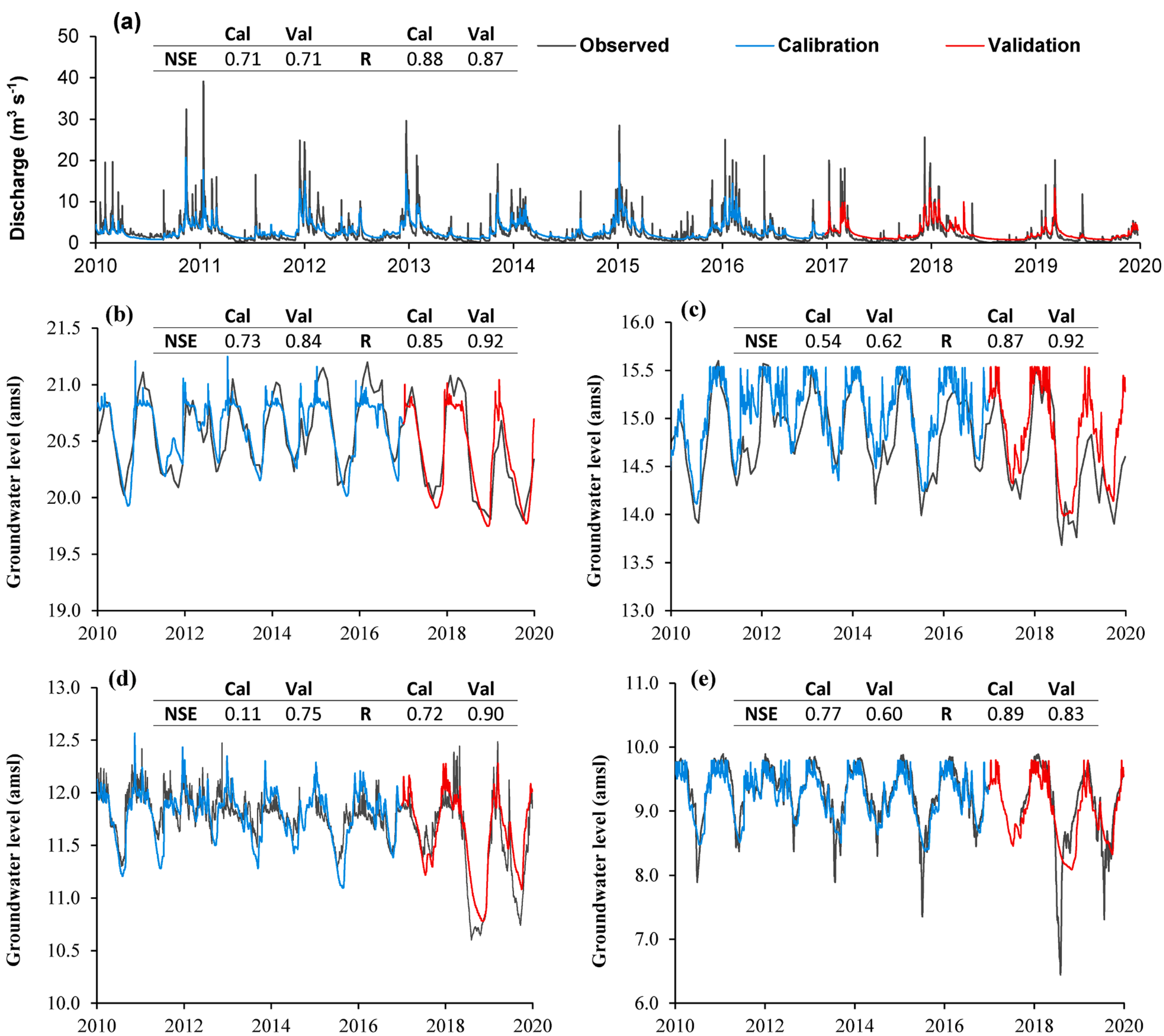


Fig. 6. Selected time series of variables used as targets in calibration (Cal) and validation (Val), along with values of Nash-Sutcliffe Efficiency coefficient (NSE) and correlation coefficient (R): a) River discharge at site A; b), c), d) and e) Groundwater heads at sites 13, 11, 9 and 7, respectively (numbering according to Fig. 1).

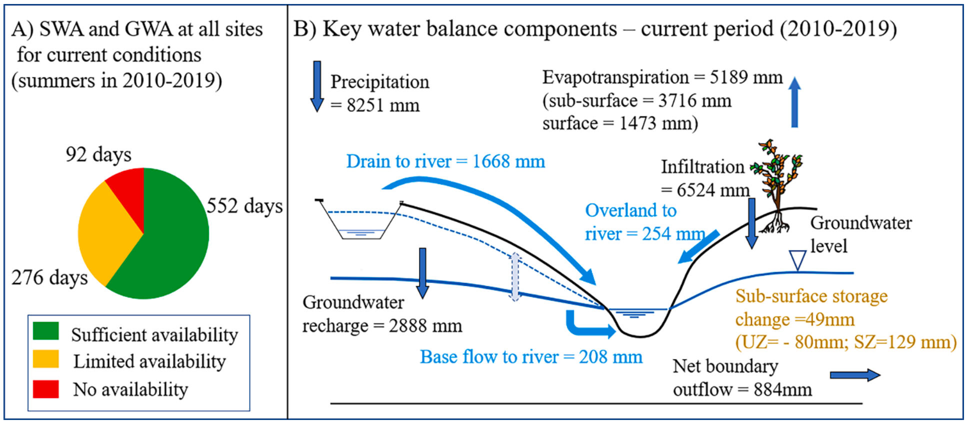


Fig. 7. Results for current conditions (2010-2019): A) Surface Water Availability (SWA) and Groundwater Availability (GWA) at all sites indicated in Fig. 1; B) Conceptual representation of key water balance components, accumulated over the decade 2010 – 2019.

for each location, under the current conditions the SWA and GWA have the same values independently from the site considered. For example, the 'no availability' class for both surface water and groundwater is defined as the number of days when discharge or groundwater level is below 10th percentile, which by definition of the 10th percentile is 10 % of the total number of days considered (i.e. 92 days with 'no availability', that are 10 % of the 920 total days, equal to a total number of days in 10 summers considered). It should be noted that the associated bans with the 'no availability' and 'limited availability' conditions do not necessarily coincide with actual bans that the Water Board introduced, as such decisions depend on multiple factors (e.g. decisions may vary across extraction sites, surface water extraction ban is always introduced first, etc.). For purposes of analysing KPI values under climate change and with NBS strategies these were the guidelines agreed in discussion with the Water Board.

Summarized total accumulated water balance for the whole catchment, as simulated for the decade 2010-2019, is presented on the right of Fig. 7 (part B). The main water balance components (in mm over 10 years, rounded off at integer values) are presented on a conceptual cross-section to indicate their position within the surface or sub-surface. It should be noted that the surface part of the evapotranspiration consists of evaporation of intercepted water together with open water evaporation (including ponded water on the surface), while sub-surface part of evapotranspiration consists of transpiration and soil evaporation. The infiltrated water into the sub-surface is available in the unsaturated zone for sub-surface evapotranspiration processes and for groundwater recharge. The saturated zone contributes significantly to the river runoff, while also significant part of it is lost as downstream groundwater outflow via the model boundaries. This presentation of the water balance allows to develop an understanding of the overall hydrological conditions, by looking at water balances of individual components, as presented in Table 3.

The obtained results from our model conform to what has been reported in literature [79], where it is reported that the average annual evapotranspiration in the Netherlands is around 550 mm, with values closer to 500 in areas further from the coast. Also, the zone of Aa of Weerijs catchment is reported in [79] to have average annual groundwater recharge between 200 and 300 mm (with large spatial variability), which also conforms with our results. A modelling study of a catchment in near vicinity in Belgium [80], with similar characteristics, reported annual water balance results for the year 2000 that included average annual precipitation of 832 mm, average annual evapotranspiration of about 462 mm, groundwater recharge of 292 mm, and small surface runoff (overland flow) of only 93 mm. All these water balance results are very similar to what we have obtained for Aa of Weerijs. Our results show that in this rather flat catchment, with relatively permeable soils, a significant amount of water infiltrates into the sub-surface, and a very small amount of direct runoff as overland flow is generated (only 254 mm). The largest portion of river runoff comes from the drainage network via the saturated zone when the groundwater level is above the drainage levels (1668 mm). The remaining part of river runoff comes from direct interaction between the aquifer and the river as baseflow (208 mm). It should be noted that this presentation of water balance is a summary and that there are also smaller details that can be analysed from the model results. For example, the identified processes may vary spatially, or, in the downstream part there would be moments when the whole sub-surface is saturated (no unsaturated zone), resulting in ponding of water on the surface (which can evaporate or infiltrate again). However, for this analysis on a catchment scale, we will focus on the main water balance components, as presented in Fig. 7, so that we can compare them under climate change conditions and with NBS strategies.

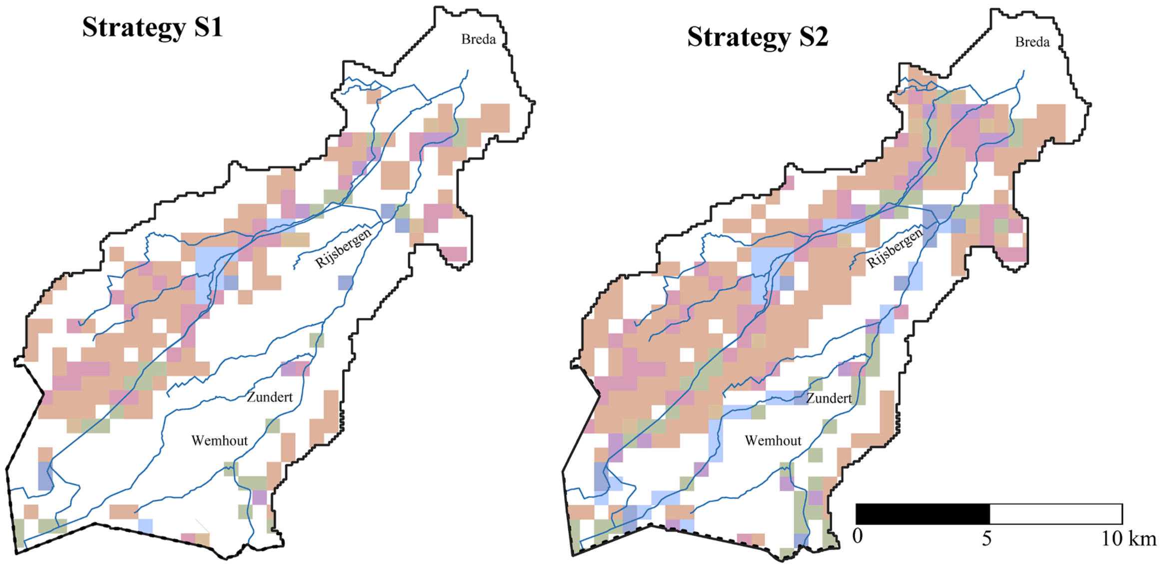
Table 3
Water balance (WB) calculations per component of the Aa of Weerijs catchment, as obtained from the simulation for current conditions (2010-2019).

WB component	*WB calculation*	*WB result (mm)*
Surface	Infiltration = Precipitation -Evapotranspiration (surface) - Overland flow	6524 = 8251 – 1473 - 254
Unsaturated zone (UZ)	UZ storage change = Infiltration – Evapotranspiration (sub-surface) – Groundwater recharge	-80 = 6524 – 3716 - 2888
Saturated zone (SZ)	SZ storage change = Groundwater recharge – Drain to river – Baseflow to river – Net boundary outflow	129 = 2888 – 1668 – 208 - 884

3.3. NBS adaptation strategies and their KPIs and water balance results

Following the procedure described in the methodology, the design of S1 and S2 strategies with combined NBS types was proposed as presented in Fig. 8.

Clearly, S1 covers a smaller spatial area compared to S2. Also, following the current land use map and the two nature development plans, the opportunities for NBS implementation seem to be more on the western side of the catchment. There are already more natural areas in the west currently, and these strategies are mainly proposing that the expansion with NBS take place on that side of the catchment. On the eastern side, in S2 there seem to be some opportunities, but only close to the Aa of Weerijs river. In the following lines we present the effects of both S1 and S2 only in terms of the selected KPIs, which are calculated using simulated time series of river discharge and groundwater levels. The reader can access these time series either through the web application, where they are presented as an additional KPI named 'localized



	NBS Measure	Strategy S1		Strategy S2	
		Km^2	% of catchment size	Km^2	% of catchment size
	Ditch Blocking (DB)	6.25	1.8	12.5	3.6
	Heathland restoration	9.75	2.8	14.0	4.0
	Heathland restoration and DB	1.75	0.5	4.48	1.3
	Infiltration ponds	30.0	8.7	47.2	13.6
	Infiltration ponds and DB	1.50	0.4	2.05	0.6
	Wetland restoration	2.75	0.8	7.28	2.1
	Wetland restoration and DB	1.50	0.4	3.20	0.9

Fig. 8. Spatial design of S1 (left panel) and S2 (right panel) NBS adaptation strategies.

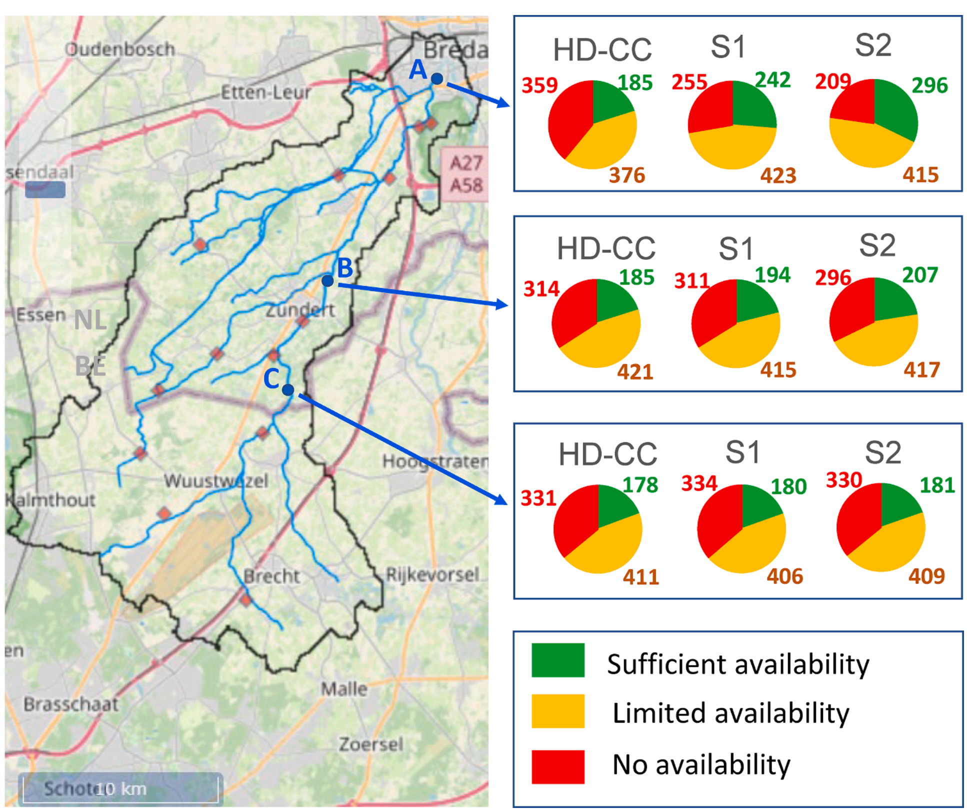


Fig. 9. Surface Water Availability (SWA) results for climate change scenario HD (HD-CC) and nature-based solutions adaptation strategies S1 and S2.

model outputs', or in the Zenodo repository [81], where they are provided as separate datasets.

The spatial distribution of the NBS in S1 and S2 has implications for the results in terms of the obtained KPI values under climate change scenario HD (also referred as to HD-CC from now on). Fig. 9 presents the results in terms of SWA, compared to current conditions. Clearly, under HD projections the situation would be much worse, with expansion of 'no availability' and significant reduction of 'sufficient availability conditions'. The conditions would be similar for all three discharge monitoring sites (A, B and C), which are all located on the eastern part of the catchment along the main Aa of Weerijs river. With strategies S1 and S2 there would be some significant improvements in SWA, higher for S2 than for S1, but they are more pronounced in the most downstream point A. As NBS implementations are rather limited in the east, the effects on SWA are significant only after the eastern tributaries that flow through areas with more NBS implementation join the main Aa of Weerijs river.

Such variations in KPI values depending on spatial distribution of NBS implementations in strategies S1 and S2 are even more noticeable when analysing GWA results, as presented in Fig. 10. Even when looking only at HD scenario, points located in the west (e.g. 4, 5) have less severe impact from those in the east (e.g. 2, 3 6), due to the already existing natural areas in the west. With strategies S1 and S2 most significant improvements are in downstream points (1,2,3 and 4), with S2 basically eliminating 'no availability' conditions in these points. Similar conditions occur in the most western point 5, which is more upstream, but located in a zone surrounded by many NBS implementations. As we move further upstream, in points 6, 7 and 8, because of limited number of NBS, strategy S1 hardly provides any improvements, and only strategy S2, with more NBS in that area brings significant improvements. In the points located in Belgium, without NBS there are no noticeable improvements from strategies S1 or S2. From these results, it can be concluded that next to the positive effects in local areas where NBS are implemented, there is also a cumulative accumulation of positive effects from NBS from upstream to downstream, for both groundwater and surface water. These results are conforming to other literature that investigated spatially distributed NBS strategies [50].

In order to further analyse the changes in hydrological conditions brought about with the NBS strategies we present in Table 4 the same water balance components as in Fig. 7, but now for HD projections, strategies S1 and S2, for the period 2050-2059. As HD is a dry scenario,

Table 4
Total accumulated water balances for HD scenario (HD-CC), S1 and S2 strategies, 2050-2059.

Water balance component	Values for each Case (all values are expressed in mm		
	HC-CC	S1	S2
Precipitation	8060	8060	8060
Total Evapotranspiration	5939	5816	5752
- From Sub-surface	3051	3201	3290
- From Surface	2887	2617	2462
Infiltration	5062	5336	5493
Groundwater recharge	2089	2211	2277
River runoff	1379	1462	1496
- From drain flow	1094	1171	1201
- From base flow	174	182	191
- From overland flow	111	109	104
Sub-surface storage change	44	56	63
- From unsaturated zone	-78	-75	-74
- From saturated zone	122	131	137
Boundary outflow	699	727	749

the most significant change compared to current conditions is the increase in evapotranspiration by about 14 %. The precipitation is also somewhat reduced, by about 2 %, but it is the enhanced evapotranspiration that drives the negative effects under this climate change scenario. Under strategies S1 and S2 this increase of evapotranspiration is reduced, and the key components that are increased are infiltration and groundwater recharge, resulting also in increased river runoff.

To further analyse the way in which these strategies bring about these results, Fig. 11 shows the seasonal variations of these key components for scenario HD, strategies S1 and S2, represented as average seasonal values over the 10-year simulation period. The results presented in Fig. 11 show that the already-mentioned effects from the NBS strategies S1 and S2 in terms of decreased evapotranspiration and increased infiltration occur in any season, but that they are more pronounced during spring and summer. For example, average actual evapotranspiration during summer is reduced from 261 mm/season (under HD-CC) to 251 mm/season (with strategy S2), and infiltration is increased from 82 mm/season (under HD-CC) to 98 mm/season (with strategy S2). Note that groundwater recharge is actually negative in the summer (groundwater losing water due to evapotranspiration), but that this negative recharge is reduced with strategies S1 and S2. This

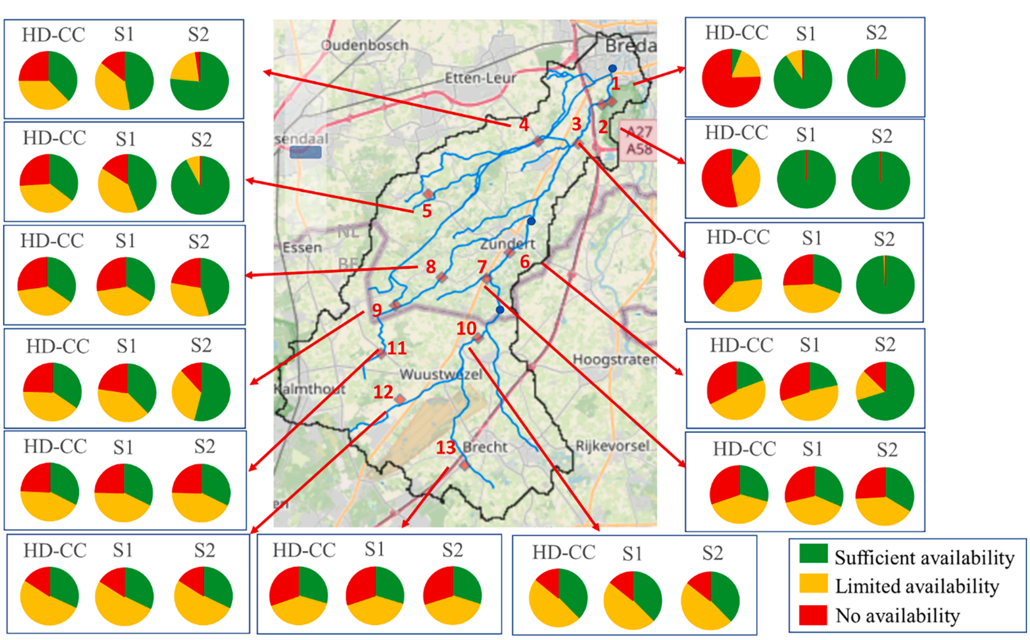


Fig. 10. Groundwater Availability (GWA) results for climate change scenario HD (HD-CC) and nature-based solutions adaptation strategies S1 and S2.

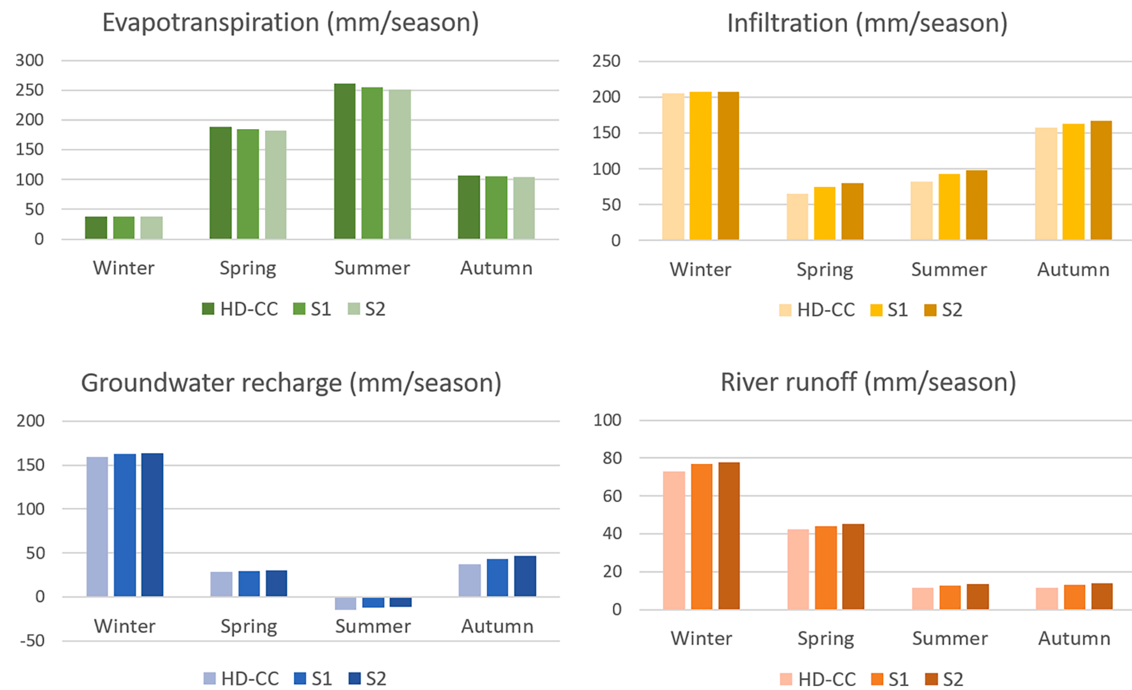


Fig. 11. Seasonal variation of key water balance components, represented as average seasonal values over the 10-year simulation period, under HD climate change scenario (HD-CC), and nature-based solutions adaptation strategies S1 and S2.

indicates that the main goals of NBS strategies to store more water in the sub-surface are achieved, but that considerable positive effects come from implementation of NBS in large spatial domains.

When focusing further on the obtained results for actual evapotranspiration, and we consider both those presented in Fig. 11 and Table 4, we can conclude that the NBS strategies lead to overall decrease of evapotranspiration, primarily because they enable more water to infiltrate into the sub-surface, leaving less water on the surface to evaporate. It can be seen from Table 4 that the actual evapotranspiration components from the sub-surface actually increase under the two NBS strategies, but the surface-related evapotranspiration components decrease. Multiple, combined effects from the NBS measures are causing this, such as change of vegetation parameters (with wetlands and heartland restoration), direct enhancing of infiltration (with infiltration ponds) and slowing of the flow (with ditch blocking), which is of more significance in cold and wet periods, when there is less evapotranspiration and more groundwater recharge. These combined effects lead to overall higher groundwater levels (thus, increased GWA) as well as increased river discharge (increasing SWA), especially in the summer. Similar effects have been reported in literature that studied NBS effects on droughts, such as [20–22]. It needs to be mentioned, however, that the catchments and the NBS measures considered in these studies were somewhat different, e.g. [20] addressed very small catchment (1 km^2) in the UK, with Runoff Attenuation Features (RAFs - consisting of leaky stream barriers), [21] considered two mountainous catchments (78 km^2 and 46 km^2) in South Africa with Invasive Alien Trees (IAT) clearing and [22] studied a 928 km^2 catchment in South Africa with In-Field Rainwater Harvesting (IFRH) with field basins. These results show the potential of different NBS adaptation strategies across different scales and climates, as long as they are oriented towards runoff slowdown and enhanced infiltration. Our contribution with this research is providing further evidence about these effects from an integrated model that simulates the interactions of groundwater and surface water under NBS strategies.

While our proposed methodology improves drought adaptation by reducing the (negative) impacts of hydrological drought on a catchment, identified as the number of days with withdrawal bans for irrigation, we believe that the increased water availability determined by the application of NBS strategies could be beneficial in reducing drought intensity as well. Hydrological drought intensity (or severity) is usually quantified with standardised indices, such as Standardised Groundwater level Index- SGI [82] and Standardised Runoff Index-SRI [83], according to which drought intensity is expressed in terms of number of standard deviations from the mean [84]. Taking the SRI as an example, the increased surface water availability generated over summer by the application of NBS in the catchment would produce an overall increased runoff, which in turn could change the value of SRI (number of standard deviations from the mean) for the same period of time. We acknowledge, however, that such analysis has not been yet done in this research and could be investigated in the future.

Our results also show that the proposed NBS strategies in Aa of Weerijs catchment lead to higher river discharges in winter seasons, driven primarily by increased drain flow and base flow (both components originating from the saturated zone, see again Table 4), due to increased infiltration and groundwater recharge. This is undesirable, of course, although for this particular catchment it is not of main concern, as strong flood protection measures have already been implemented and are continuously being updated and expanded. Nevertheless, there is a general concern that drought-oriented NBS measures may lead to increased floods and vice versa [12]. On a small scale, as reported in [20], it is possible to obtain positive effects on both floods and droughts, but for larger, catchment-scale studies, this issue is subject of ongoing research [85,86]. Our own research for the Aa of Weerijs catchment is currently being extended to identify more balanced combinations of NBS measures (in terms of types and their spatial distribution) that will have positive effects on both droughts and floods.

It should be noted that all these results are still specific to the Aa of Weerijs catchment. In terms of generalization to other catchments, it can be expected that other similar studies may provide different findings for NBS performance, depending on catchment characteristics, especially regarding land use, soils and overall sub-surface conditions. It should be expected, however, that allocating larger areas for NBS implementation would lead to overall better results (as in our case, when comparing S2 and S1 strategies). Most important general contribution of this study is in the proposed and implemented methodology, with clear and interconnected steps for designing, selecting and evaluating NBS strategies for droughts, based on an integrated hydrological model that simulates surface and sub-surface conditions simultaneously. One key aspect of this methodology is the identification of relevant KPIs, which needs to be done in close consultation with the relevant stakeholders, so that they are associated with stakeholders needs for assessment and decision making. The actual individual NBS measures considered for implementation may be different in different cases, depending on the objectives, prior knowledge and experience, as well as opportunities provided by a particular landscape. Our methodological steps for model-based testing of individual NBS measures and the subsequent spatially distributed strategies would still be applicable, even if the model parameters to be modified would be different for other NBS measures.

3.4. Research limitations

Our research also has some limitations that need to be recognized. First, the MIKE SHE hydrological model, which is the main tool used in this for designing and assessing the drought-relate NBS strategies, can still be improved (e.g. finer spatial resolution, more detailed river network that would reduce the need for working with conceptual drains, etc). Such improvements would enable NBS representation on a smaller scale, closer to field implementations (at least for some NBS measures) that could be locally tested and validated. This would eventually provide higher confidence in the aggregated effects on catchment scale. Secondly, the ways in which different NBS measures have been implemented in the model can also be further improved. Additional sensitivity analysis could be performed of the parameters used for representing the individual NBS considered, especially for those associated with more conceptual parameters (e.g. drain time constant to represent ditch blocking). Thirdly, as mentioned earlier, the primary objective of this research has been NBS-based climate adaptation to droughts, and the performance of the proposed strategies during flooding conditions has not been tested. (Our results do indicate that the proposed strategies may lead to some increase of river runoff during wet periods). From a research methodology point of view this is clearly needed, as recognized in literature [12,85], and it is part of our ongoing research in this catchment. Finally, our research lacks some additional analysis of criteria that may be critical for actual implementation of NBS strategies, most importantly - costs and feasibility from the point of view of land ownership. These two criteria are in fact connected, because the main costs of implementing these strategies are associated with land use transformation to which landowners need to agree, or, transfer of land ownership (e.g. from private agricultural land to public nature area). Such issues are still very much in discussion among stakeholders within Aa of Weerijs catchment. Through these discussions, costs and feasibility will eventually be assessed on a catchment scale. Our present research contributes to these discussions by bringing transparency and clarity regarding the effects of the NBS strategies proposed.

4. Conclusions

The most significant contribution of this research is the methodology for catchment-scale assessment of performance of NBS adaptation strategies, using indicators that are close to stakeholders needs and practices. Our proposed methodology is based on the development of an integrated, distributed hydrological model based on MIKE SHE software, which was able to represent the current groundwater and surface water conditions of the catchment. The same hydrological model has been employed to simulate the behaviour of the catchment after the implementation of single type NBS, under climate change projections and combined NBS adaptation strategies. While the hydrological model was calibrated and validated using traditional relevant metrics (MNSE, MR), the effects of climate change scenario and NBS (single and combined in strategies) on the catchment conditions are evaluated using two newly introduced KPIs (SWA and GWA), developed together with the water managers of the case study. The two KPIs were developed to express surface and groundwater availability status, linking traditional thresholds with actions on water withdrawal taken by the managers. Both strategies based on combination of NBS resulted in a reduction of evapotranspiration, together with increased infiltration and groundwater recharge (which led also to increased river discharge), which was the main purpose for their application in the first place. Among the two strategies tested, the one with higher spatial extension (S2) had more positive impacts on surface and groundwater, almost eliminating days with no availability of water for withdrawal. Furthermore, in both strategies, it emerged that positive impacts of NBS solutions accumulate from upstream to downstream, as the area with NBS measures also increases in the same direction.

This assessment was focused on drought adaptation, and there is a clear need to extend the analysis for flood adaptation and flood-related KPIs, which is an ongoing research in Aa of Weerijs catchment. We believe that the methodology presented in this research can be applied not only for flood adaptation studies in the same catchment, but also in other case studies, once specific KPIs are identified with the local stakeholders.

Our modelling results also revealed some important general issues regarding NBS design, namely that some NBS measures might not function as expected. Tree planting, for example, did not bring the expected benefits, because of increased evapotranspiration. Further research is needed regarding types of trees and plants (e.g. in the wetlands), with varying leaves and roots characteristics, to be used within different NBS. Future models should also consider smaller spatial representation, closer to field implementation sizes of NBS. This would also allow for more detailed, physically-based representation of the river network (decreasing the need to model smaller drains conceptually). Furthermore, such improved models could be then used for joint operation of NBS and existing engineering infrastructure, under weather / hydrological forecasts, in order to maximise the intended benefits. Overall, our results support the conclusion that NBS can be designed for river basin scale with positive effects. Successful replication of such analysis, however, should primarily be informed by our methodology, with awareness that actual NBS design and implementation would depend on the posed objectives, and the characteristics of a particular landscape.

NBS impacts and implication

Environment: this paper proposes Nature-Based Solutions for drought adaptation in rural catchments, contributing to improved resilience to climate change of such areas.

Economy: thanks to the positive effect on groundwater and surface water provided by the proposed NBS strategies, less water withdrawal bans are expected. This implies that irrigation activities can continue normally also in case droughts occur, reducing crop and consequent economic losses due to limited crops watering.

Social: by reducing water withdrawal bans and consequent water usage prioritization during summer and drought events, the NBS adaptation strategies are expected to reduce conflicts between water managers and water users (e.g. farmers).

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Data availability statement

Datasets for KPI results presented in this research are available in the main web application at https://eiffel.un-ihe.org/EIFFEL-prod/. This application also lists all publicly available data used in this research.

Additional results in terms of groundwater levels and discharges are available from: https://zenodo.org/records/11082998.

The MIKE SHE modelling system is available from DHI Denmark at: https://www.dhigroup.com/technologies/mikepoweredbydhi/mike-she.

Local data and actual MIKE SHE model setups are available on request under conditions.

Ethics statement

N.A.

CRediT authorship contribution statement

A. Jonoski: Writing – original draft, Visualization, Supervision, Methodology, Funding acquisition, Conceptualization. **M.H. Ali:** Writing – review & editing, Visualization, Methodology, Investigation, Data curation, Conceptualization. **C. Bertini:** Writing – review & editing, Formal analysis, Data curation. **I. Popescu:** Writing – review & editing, Supervision, Conceptualization. **S.J. van Andel:** Writing – review & editing, Methodology. **A. Lansu:** Writing – review & editing, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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