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Drought Mitigation Through Nature-based Solutions for Climate Adaptation in Headwater Catchments
Best Practices Compared with Scientific Knowledge

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Drought Mitigation Through Nature-based Solutions for Climate Adaptation in Headwater Catchments- Best Practices Compared with Scientific Knowledge

REPORT

InCompany Milieuadvies

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RESEARCH COMMISSIONED BY PROVINCIE NOORD-BRABANT, NL.
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Project information

Titel (nl)	**Droogte mitigatie door Nature-based Solutions voor klimaatadaptatie in beekstroomgebieden: best practices vergeleken met wetenschappelijke kennis**
Title (in English)	**Drought Mitigation Through Nature-based Solutions for Climate Adaptation in Headwater Catchments- Best Practices Compared with Scientific Knowledge**
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Omschrijving opdracht (nl)	Effectiviteit van Nature-based Solutions (NbS) evalueren naar aanleiding van het Co-Adapt project en op basis hiervan advies formuleren voor toekomstige beekstroomprojecten omtrent klimaatadaptatie.
Description of the order (in English)	Assessment of Nature-based Solutions (NbS) in the Co-Adapt project and advice on suitability of the NbS for future use in climate adaptation projects in water management of headwater catchments.
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Preface

In front of you is my undergraduate thesis on drought and Nature-based Solutions in brook catchments. Given recent dry summers as well as flooding, this is a hot topic. Society is increasingly seeking natural measures for this, as opposed to grey solutions like canalisation and draining the water as fast as possible. This is what I have been researching for the Province of North Brabant over the past few months to complete the Bachelor of Environmental Sciences at the Open University.

While pursuing this undergraduate degree, I found out that I am particularly interested in the ecological side of environmental sciences. Therefore, the choice of this subject was quickly made. It gave me satisfaction to deal with a practical subject that emerged from a problem in society (both drought in agriculture and floods in grey areas). I got to gain experience as a project leader, which I found exciting at first but ended up really enjoying doing. I also had the opportunity to give an online webinar in English to international water professionals. An extraordinary, exciting, but certainly enriching experience.

I would like to thank my supervisor, dr. ir. Angelique Lansu, for the vlaai, supervision and input during our weekly meetings. I am grateful for your knowledge, insights and relaxed way you guided me. You can certainly make me happy on Friday mornings with a homemade snowman. I would also like to thank our client Frank van Lamoen for his guidance and feedback. You gave me great insight into the link between science and practice and were always willing to think along with me. I am grateful to the water professionals in the Co-Adapt project for their input and cooperation in data collection.

Finally, I would like to thank Tobias, Olivier and Linne for all the hugs and understanding during my research process. Thanks to your support, I managed to get through most of it with a smile!

Hope you enjoy reading,

Charlotte Wieles-Rietveld

Delft, March 24, 2023

Summary

Drought is a topical issue, given extreme drought records in the Netherlands over the past five years and the IPCC's 2021 pronouncements on drought. Drought is a consequence of disruptions in the water cycle in response to climate change and can manifest itself in shortages of soil, surface or underground water. If these shortages have ecological and socio-economic consequences, we speak of drought as a climate effect. Society designs and implements solutions to these climate effects. In this study, we look at solutions based on natural processes, Nature-based Solutions (NbS), designed in co-creation with that society. In this study, we look at whether NbS designed for flooding in headwater catchments are also effective against drought impacts.

This research is conducted within eight river basins and is part of the European project Co-Adapt: Climate adaptation through co-creation (2019-2023). We conducted a document analysis, a Concensus Decision Process (CDP) and a Systematic Literature Review (SLR) to collect data. This CDP consisted of a questionnaire and a brainstorming and consensus phase in an interactive webinar. The data on NbS was analyzed using the definition according to Keesstra et al. Based on the concept of evidence-based practice (EBP), we combined field expertise with scientific knowledge to arrive at best practices of NbS with a mitigating effect on drought. We tested these results using a document analysis in one of the Co-Adapt catchments, Aa of Weerijs (NL), to understand the expected effects on drought in the catchment.

The document analysis showed that in seven of the eight river basins, drought was taken into account in the design of the NbS. The CDP indicated that from field expertise, water sinks, runoff pathways and soil processes were the three most effective parameters or processes to influence drought. Synthesis with scientific knowledge from the SLR confirmed this effectiveness. A document analysis combined with the results found earlier provided an overview of NbS, processes involved and parameters in the Aa of Weerijs catchment. The four designed NbS work through geomorphological processes by increasing water sinks, thereby reducing drought.

In this study, EBP shows that influencing water sinks, runoff pathways and soil processes is most effective to mitigate drought. What is challenging when implementing NbS is not to work with only one ecological aspect at one location, but to aim at restoring the entire watershed system. To facilitate this, we have developed a tool to select effective NbS based on different problems and locations.
The variety of NbS shows that their design is clearly strictly tied to the society from which the design originates and the local environment for which it is a solution. This makes the co-creation process iterative, always paying attention to the developing situation (other stakeholders, goals and spatial coverage). Thereby, it is interesting, for example, whether NbS for flooding are also effective for drought, given the differences in location of implementation and spatial coverage.
To ensure good cooperation between different stakeholders from multiple backgrounds, it is necessary to use the same terminology. Thereby, the classification by process function of Keesstra et al. (2018) provides good guidance to bring practice and science together and avoid misunderstandings.

The conclusion based on sub-question 1 is that drought was often one of the targets of implemented flood mitigation measures in the catchments studied. Sub-question 2 shows which processes and parameters influence drought according to EBP. Concluding based on sub-question 3, we argue that the water storage capacity in the Aa of Weerijs catchment will increase, which will reduce drought. Conclusion of the study is that if the underlying processes (geomorphological, soil, surface and chemical) are included in the design of flood measures, it is expected that after implementation of NbS in brook catchments, water storage capacity will increase and ecological and socio-economic drought will decrease.

Abstract

Drought is a topical issue, give extreme drought records in the Netherlands over the past five years and the IPCC’s 2021 pronouncements on drought. Drought is a consequence of disruptions in the hydrological cycle in response to climate change and can have social-economic impacts as a climate effect. To reduce vulnerability to climate effects, Nature-based Solutions (NbS) are being designed and implemented in co-creation with society. In this study, we look at whether NbS designed for flood mitigation in headwater catchments are also effective against the impacts of drought. This research is conducted within eight catchments involved in the European project Co-Adapt. We conducted a document analysis, a Concensus Decision Process (CDP) with 40 water professionals and an SLR to collect data. NbS were analyzed on involved processes and parameters using the definition from Keesstra et al. (2018). Based on the concept of evidence-based practice (EBP), we combined field expertise with scientific knowledge to arrive at best practices of NbS with a mitigating effect on drought. This is tested in one of the involved catchments. The results showed that drought was a primary or secondary motive for designing NbS. According to EBP, water sinks, runoff pathways and soil processes are the most effective parameters to influence for mitigation of drought. Therewith we predicted that drought will be mitigated in the sample catchment area by enhancing water sinks. We conclude that if the underlying processes (geomorphological, soil, surface and chemical) are included in the design of flood measures, it is expected that after implementation of NbS in headwater catchments, water storage capacity will increase and ecological and socio-economic drought will decrease.

Résumé

La sécheresse est un sujet d'actualité, étant donné les records de sécheresse extrême enregistrés aux Pays-Bas au cours des cinq dernières années et les déclarations du GIEC sur la sécheresse en 2021. La sécheresse est une conséquence des perturbations du cycle hydrologique en réponse au changement climatique et peut avoir des impacts socio-économiques en tant qu'effet du climat. Afin de réduire la vulnérabilité aux effets du climat, des solutions basées sur la nature (Nature-based Solutions, NbS) sont conçues et mises en œuvre en co-création avec la société. Dans cette étude, nous examinons si les NbS conçues pour atténuer les inondations dans les bassins versants sont également efficaces contre les impacts de la sécheresse. Cette recherche est menée dans huit bassins versants impliqués dans le projet européen Co-Adapt. Nous avons mené une analyse documentaire, un processus de décision par consensus (Concencus Decision Process, CDP) avec 40 professionnels de l'eau et un SLR pour collecter des données. Les NbS ont été analysés sur les processus et paramètres impliqués en utilisant la définition de Keesstra et al. (2018). Sur la base du concept de pratique fondée sur des preuves (evidence-based practice, EBP), nous avons combiné l'expertise de terrain avec les connaissances scientifiques pour arriver aux meilleures pratiques de NbS ayant un effet atténuant sur la sécheresse. Ceci est testé dans l'un des bassins versants impliqués. Les résultats ont montré que la sécheresse était un motif primaire ou secondaire pour la conception de NbS. Selon l'EBP, les puits d'eau, les voies de ruissellement et les processus du sol sont les paramètres les plus efficaces à influencer pour atténuer la sécheresse. Par conséquent, nous avons prédit que la sécheresse sera atténuée dans le bassin versant de l'échantillon en améliorant les puits d'eau. Nous concluons que si les processus sous-jacents (géomorphologiques, pédologiques, de surface et chimiques) sont inclus dans la conception des mesures d'inondation, on s'attend à ce qu'après la mise en œuvre de NbS dans les bassins versants d'amont, la capacité de stockage de l'eau augmente et la sécheresse écologique et socio-économique diminue.

1. Problem analysis

1.1. Climate change and meteorologic effects

The United Nations (UN)(2022) expressed concern about the current situation around climate change at the COP26 in Glasgow 2021. They uttered "alarm and utmost concern that human activities have caused around 1.1 °C of warming to date, that impacts are already being felt in every region" (United Nations, 2021). According to the International Panel on Climate Change (IPCC)(2021), this climate change is driving changes in the water cycle globally and regionally. According to Klimaat.be (2019), these changes include an increased likelihood of extreme precipitation events, longer droughts and sea level rise. Consequences include a higher risk of flooding, a decrease in water quality and quantity, and risk of coastal flooding and erosion. For the impact on the global water cycle, the Panel (2022) predicts that flood risks and societal damages will increase as global warming increases. In Europe, at 3°C warming, damage costs and the number of people affected by precipitation and river flooding could double. Regionally, for this study in north-western Europe, the Royal Netherlands Meteorological Institute (Koninklijk Nederlands Meteorologisch Instituur, KNMI)(2021) expects inland springs and summers to become drier, while heavy summer showers will become more extreme, which could lead to water-induced damage and flooding. This makes the search for climate-adaptive solutions against the effects of changes in the water cycle, such as flooding and drought, urgent and relevant.

Solutions are needed at local, regional and global levels. One of the tools developed for this globally following a request from the United Nations is the 'HELP Guiding Principles for Drought Risk Management under a Changing Climate' report by Deltares (2022). This report formulated 12 principles that require special attention in drought management, including:

- Principle 9: Mitigate the impact of drought and water scarcity on ecosystems and biodiversity
- Principle 10: Invest in nature-based and hybrid infrastructure

This research focuses on drought management using nature-based measures, thus contributing to the application of the aforementioned principles.

Effects in headwater catchments
Changes in the water cycle due to climate change have an impact on headwater catchments. Therefore, adaptive solutions to flooding are needed here. In these areas, society has worked in recent years to design and implement climate-adaptive solutions aimed at preventing flooding due to climate change. The climate effect ‘flooding’ is especially relevant in the area right next to the stream. However, catchment areas are more than just the stream: "an area from which all surface running water flows through a series of streams, rivers and possibly lakes through a single estuary or delta, into the sea", according to the Helpdesk Water (2014). This definition is relevant for the difference between floods and droughts. Whereas the geographical impact of a flood is limited to the stream and its immediate surroundings, drought affects the entire catchment. As KNMI (2023) pointed out, there are regional differences between inland and coastal areas in disruption of the water cycle due to climate change. For this study in stream catchments, mostly in inland sandy areas, we concur with KNMI (2023) that the impact of drought is increasing. Adequate solutions to mitigate drought are thus increasingly important. Floods occur quickly and are highly visible, prompting work on climate-adaptive solutions from within society. In contrast, drought as a climate effect develops more slowly and unobtrusively, according to Van Loon (2015). Therefore, we ask whether NbS targeting flooding, and thus spatially the stream and its immediate surroundings, also affect drought in the rest of the catchment.

The increasing impact of drought in a river basin affects different stakeholders (such as farmers, citizens, government) with a variety of interests and perspectives on this climate effect. This makes drought a socio-economic issue.

1.2. Drought

Drought as a socioeconomic problem manifests itself globally, regionally, and locally.

Globally, the effects of drought are mainly felt in the agricultural sector and drinking water supply in those areas prone to drought (inland, sandy soils)(Lesk et al., 2016; Sweet et al., 2017). Furthermore, drought affects the health of a society by causing food shortages and thus famines, migration and mortality (Grolle, 2015; WMO, 2016). Drought can also cause problems for urban water supply, hydropower production and industrial needs (Jerez et al., 2013). Dai (2011) indicates that, based on a review of droughts around the world in the last millennium, droughts can persist for a wide variety of periods and often cover a larger area spatially than other natural phenomena.

In Europe, Böhnisch et al (2021) show that the impact of climate change on drought results in increasing duration, frequency and intensity of droughts. In this study, the focus is on north-western Europe (southern England, northern France, Flanders, southern Netherlands).

Locally, expected consequences of drought have been formulated for each country in north-western Europe. For the Netherlands, KNMI (2021) expects summer precipitation to remain unchanged (under a low emission scenario) or to decrease (under a high emission scenario). Potential evaporation will increase due to both higher temperatures and decreasing cloud cover. KNMI sees clear regional differences for the Netherlands: it has been shown that there is a clear trend towards more such droughts in inland areas of the Netherlands, caused by climate change. However, no such change has been demonstrated for the coastal region (KNMI, 2023). For Flanders, the Flemish Environment Agency (Vlaamse Milieumaatschappij, VMM)(n.b.) expects the agricultural area vulnerable to drought to increase from 2% (current) to 9% (in 2050). For the United Kingdom, Hanlon et al (2021) indicate in the United Kingdom climate projections (UKCP) that the severity of a 12-month drought changes by -3 to +19% in the 21st century.

Drought can be considered in several ways. First, we consider drought as a climate problem after which, based on the water cycle, we determine which aspect of drought we focus on in this study. Drought as a climate problem is defined by the IPCC (2012) as: "a period of abnormally dry weather, long enough to cause serious hydrological imbalance". According to the World Meteorological Organisation (WMO)(2006), drought is an extreme climate phenomenon that occurs in terrestrial areas and can damage nature, agriculture and societies. Eertwegh et al. (2021b) indicate that drought manifests itself in different compartments of the water cycle and Das et al. (2022) thereby define meteorological drought, soil moisture drought, hydrological drought and socio-economic drought (table 1).

These four types of drought manifest in the order listed in table 1, but with increasing delays. Recovery from drought proceeds in the reverse order and takes longer the further the drought has developed (Van Loon, 2015). This delayed recovery highlights the importance of preventing drought development to subsequent stages. The consequences of socio-economic drought also underline the fact that it should be prevented as much as possible. In this research, we therefore focus on reducing soil moisture and hydrological drought so that socio-economic drought can develop less or be avoided. The way these types of droughts are related is elaborated in a conceptual model (figure 1). We do not focus on meteorological drought because according to Potopová et al. (2016), it has less influence on socio-economic drought than the other types. Where 'drought' is mentioned below, drought is meant as expressed in the grey shaded box in the conceptual model.

Table 1

Drought classification and definitions, explanation, impacts, indicators, and sources.

Type of drought	Definition	Notes, implications	Indicator	Source
1. Meteorological drought	Precipitation deficit combined with increased evapotranspiration in a given region for a period of time.	This type occurs first and precedes other types of droughts.	• SPI-1 • SPI-3	(Le et al., 2019; Weijers et al., 2020)
2. Soil moisture drought	Decrease in amount of soil moisture (mainly in the root zone), resulting in water stress on plants and reduced biomass.	Leads to loss of crops, damage to infrastructure and nature. Evapotranspiration greatly affects it. Also called "agricultural drought", but since it affects more than agriculture, we use the term soil moisture drought.	• SPI-1 • SPI-3 • Soil moisture content • NDVI • EVI	(Raksapatcharawong & Veerakachen, 2021; Van Loon, 2015; Leng, 2021; Weijers et al., 2020)
3. Hydrological drought	Lack of surface and subsurface water for the usual purposes of a water system.	Expressed as lowering of groundwater levels, lowering of water tables and reduced surface water runoff. Has consequences for drinking water supply, irrigation, transportation, electricity generation and recreation. Causes loss of biodiversity and food web complexity in aquatic systems.	• Groundwater levels • Stream discharge	(Harishnaika et al., 2022; Malik et al., 2021; Van Loon, 2015; Weijers et al., 2020)
4. Socio-economic drought	Insufficient water supply to meet socioeconomic demand, resulting in negative impacts on society, economy, and environment.	May lead to poverty, human migration, disease, and possible death.	• Disease rates • Migration rates • Water supply	(Lee et al., 2022; Van Loon, 2015; Weijers et al., 2020)

Climate adaptation and co-creation

As a society, we can mitigate the negative impacts of climate change on drought by taking certain measures (IPCC, 2022b). This process is called climate adaptation, defined by the IPCC (2012) as: "the process of adapting to current or expected climate change and its associated impacts." Climate adaptation achieved through co-creation has a high chance of success (IPCC, 2022a). Somerset County Council (2018) defines co-creation as a process in which there is active participation from stakeholders at different stages: as initiator, co-designer or co-executor. DeLosRíos-White et al (2020) mapped the process of co-creation in climate adaptation (Life Cycle Co-creation Process (LCCCP)) and described the different stages (figure 2). In our research, we use these stages of climate adaptation to analyze the processes in the case studies.

Figure 1

Conceptual model of relationships between different types of drought and compartments in the water cycle.

Note: The red boxes are indicators that determine the different classifications of drought; the yellow boxes are intermediate steps; the green boxes are the classifications of drought; the blue box is the trigger of drought; the purple box is human influence. The gray shaded section is what we focus on in this study. Adapted from:(Kim & Jehanzaib, 2020).

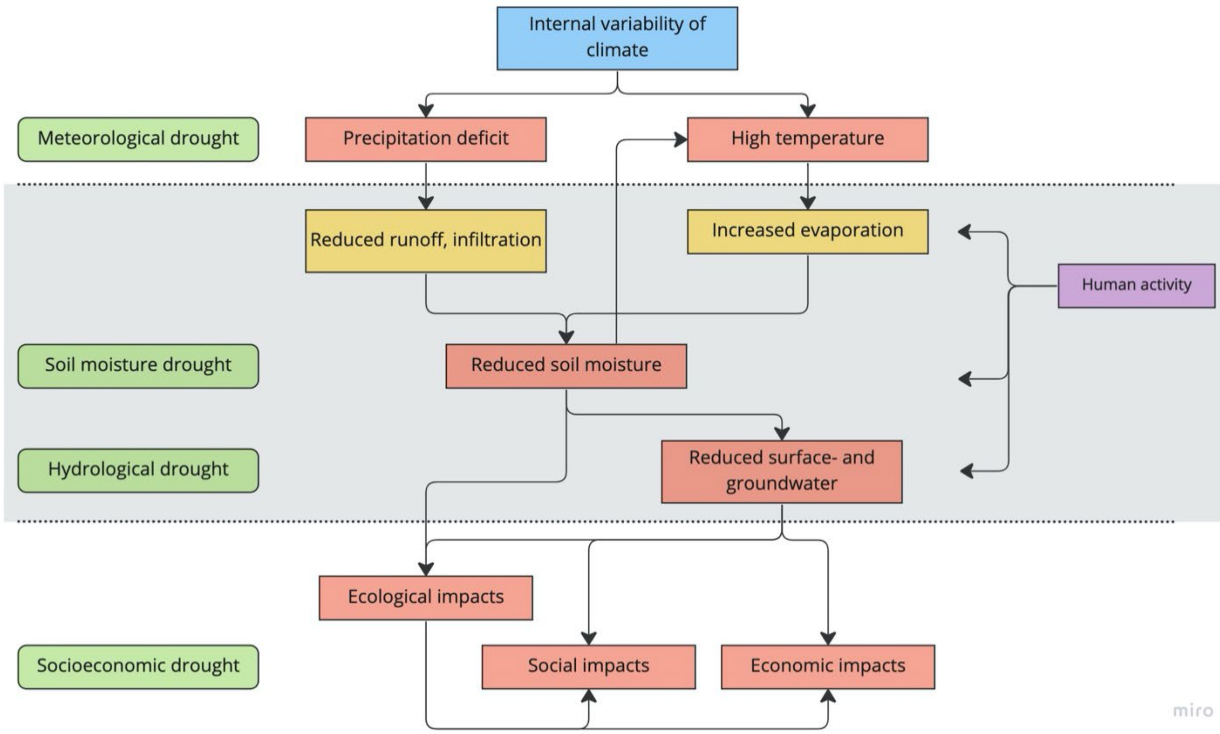
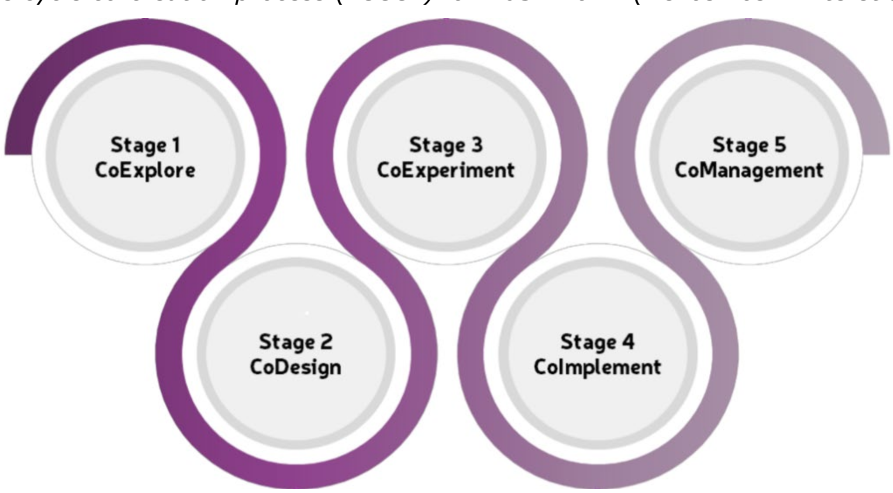


Figure 1

Life cycle co-creation process (LCCCP) for NbS. From: (DeLosRíos-White et al., 2020).



Nature-based Solutions

An example of measures that can be taken as a form of climate adaptation are Nature-based Solutions (NbS). NbS are also used as a measure against floods. For this study, we adopt the IUCN (2016) definition for NbS: "actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits." NbS use the power of healthy ecosystems to protect people, optimize infrastructure and ensure a stable and biodiverse future (IUCN, s.d.). NbS is a term that includes several solutions based on ecosystem functioning. Based on a literature review, Keesstra et al. (2018) classify NbS based on their working mechanisms (soil, surface, geomorphological and chemical processes), parameters and ecosystem services involved (table 2). They indicate that NbS can reduce drought by promoting infiltration, ponding, soil water retention and interception rather than discharge of water, contributing among others to the ecosystem services water provision, soil protection and flood regulation. We adopt the classification of Keesstra et al. for our study because it is broadly examined and creates a detailed framework to categorize the NbS involved in our study.

Table 2

Classification of NbS developed by Keesstra et al. (2018) from their review based on processes, parameters and ecosystem services involved.

NbS type	Parameters	Examples of involved ecosystem services, relevant to drought
NbS based on soil processes	Porosity Soil structure Aggregate stability Soil organic matter Water repellency Water holding capacity	Water provision Soil protection Flood regulation
NbS based on surface processes	Vegetation cover Mulch cover Surface roughness Shear strength Surface crusts Combustible fuel load	Water provision Soil protection Flood regulation
NbS based on geomorphological processes	Hillslope geomorphology Runoff pathways Topographic wetness Water and sediment sinks Connectivity	Water provision Flood regulation Water quality
NbS based on chemical processes	CEC Nutrien content Carbon content Solute transport and precipitation	-

1.3. Effectivity of NbS on drought

When weighing up the effectiveness of NbS, we see that many benefits are reported (Balzan et al., 2022). Souliotis & Voulvoulis (2022) indicate that NbS are effective to achieve targets around water quality in river basins. An economic analysis by Le Coent et al (2021) shows that NbS have higher cost-effectiveness than grey solutions, such as dykes. In contrast, evaluation of efficiency of NbS is little done, according to Kumar et al. (2021a). Telwala (2022) also states that the amount of scientific literature is limited in, for example, the effectiveness of agroforestry as NbS. In addition, monitoring methods of NbS are lacking in the current literature (Kumar et al., 2021b). A quantitative evaluation of climate adaptation has rarely been done, according to Holden et al. (2022). This indicates that there is little knowledge regarding evaluation of NbS. NbS often work systemically and sometimes give results only after a longer time (Gooden & Pritzlaff, 2021). Therefore, quantitative evaluation can be difficult and only possible after a long time.
Field expertise can contribute to knowledge around effectiveness of NbS. We define expertise according to Eraut (2005) as 'expert opinion or knowledge'. In this context, an expert is 'one whose special knowledge causes him to be a specialist'. We could not find any literature on the involvement of

expertise in the evaluation of effectiveness of NbS. Nor could we find any articles on the evaluation of NbS on drought specifically. Thus, the effectiveness of NbS on drought from the combination of field expertise and scientific evidence is still unknown. Despite its importance to efficiently anticipate the changing climate and thus reduce the adverse effects of drought.
The field expertise we use in this study is from water professionals currently in the field around the development and implementation of NbS in a stream catchment.

Evidence-based practice
How to evaluate the impact of NbS on drought from field expertise to scientific knowledge can be inspired by the medical world. There, according to Patelarou et al (2020), evidence-based practice (EBP) is a method of decision-making based on the latest scientific knowledge, as well as the expertise of professionals and patient's preferences. Miller et al. (2017) define EBP as "a systematic and structured process of identifying, collecting, assessing and applying knowledge to form and achieve best practice". EBP is increasingly applied outside the medical sciences (Kallaher et al., 2020). Knowledge exchange between scientists and all stakeholders involved is necessary for effective implementation of climate adaptation projects, for example. Greenhalgh & Wieringa (2011) argue that practical knowledge is as important as facts acquired with research. In this study, we leave out the patient part, in this case the stakeholders, and focus on combining scientific knowledge and practical knowledge. In the environmental sciences, we already see some examples where EBP is also used to combine field expertise with the best available literature to arrive at effective applications (e.g. Kano & Hayashi, 2021; Kallaher et al., 2020; Webb et al., 2011). Thus, in our research, we combine field expertise with scientific knowledge based on EBP.

Data collection of field expertise can be done using a Concensus Decision Process. This is described, for example, by the Kansas Coalition Against Sexual and Domestic Violence (2005). This process consists of an orientation, brainstorming and consensus phase. In the first phase, among other things, necessary information is collected, in the second phase possible options are gathered after which, in the third phase, a common outcome is determined. We will use this in our research to unify the field expertise of water professionals.

1.4. Scientific question

For this study, this is the main research question:

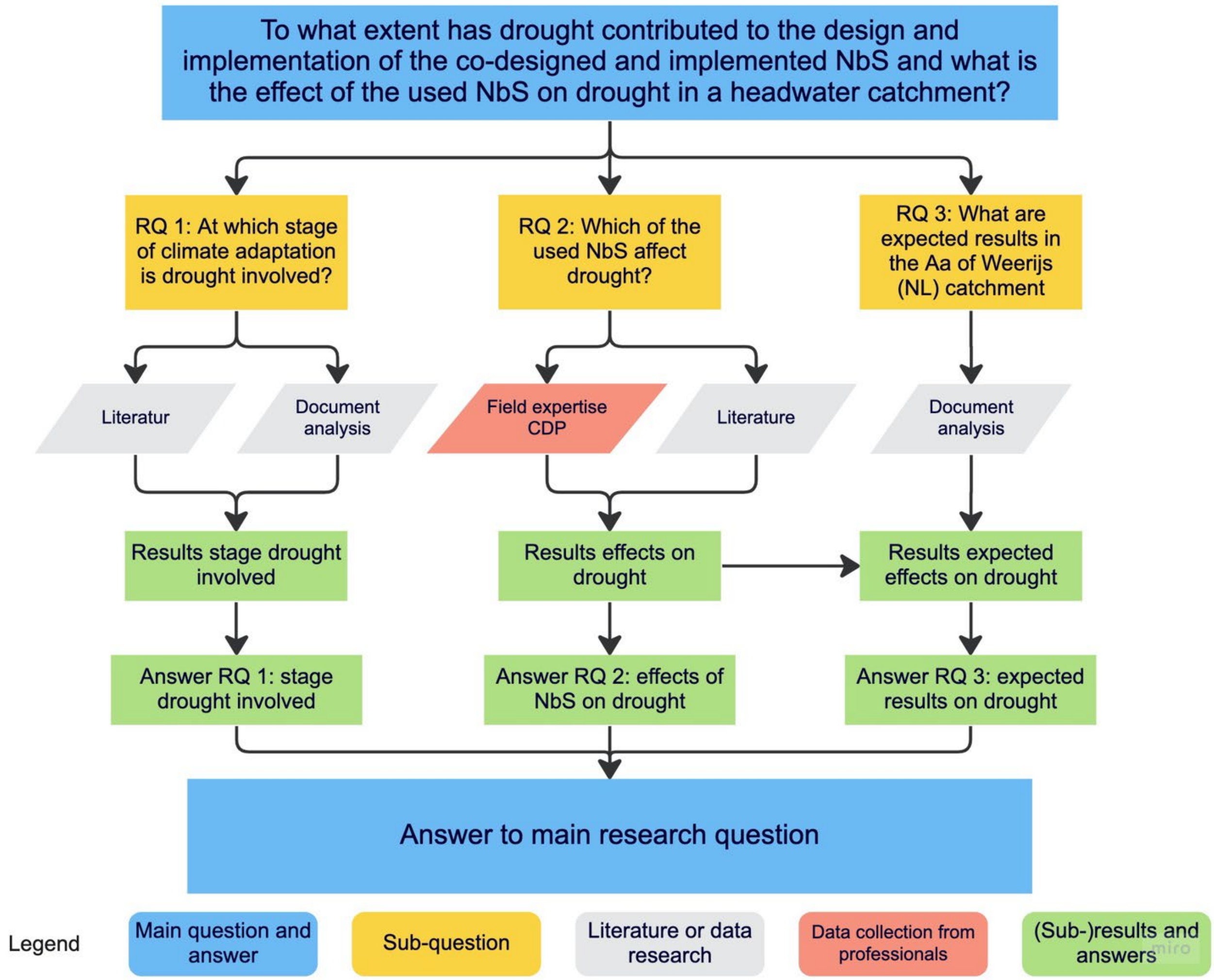
To what extent has drought contributed to the design and implementation of the co-designed and implemented NbS and what is the effect of the used NbS on drought in a headwater catchment?

This question is divided in three sub-questions (figure 3):

1. At which stage of climate adaptation is drought involved in the eight catchments of the Co-Adapt project?
2. Which of the used NbS in the eight catchments of the Co-Adapt project affect drought?
3. What are expected results of the implemented NbS on the state of drought in the Aa of Weerijs (NL) catchment?

Figure 3

Study design.



2. Method

2.1. Study area

The study areas are the brook catchments involved with the EU Interreg 2 Seas Program 'Co-Adapt: Climate adaptation through co-creation'. These are brook catchments in The Netherlands, Belgium, France and England who want to increase their resilience to water related impacts of climate change (figure 3, table 5). Through Co-Adapt, water professionals design and implement NbS in co-creation with different stakeholders from society (Somerset County Council, 2018).

Figure 2

Catchments involved with Co-Adapt. From: (Bogatinoska et al., 2022).

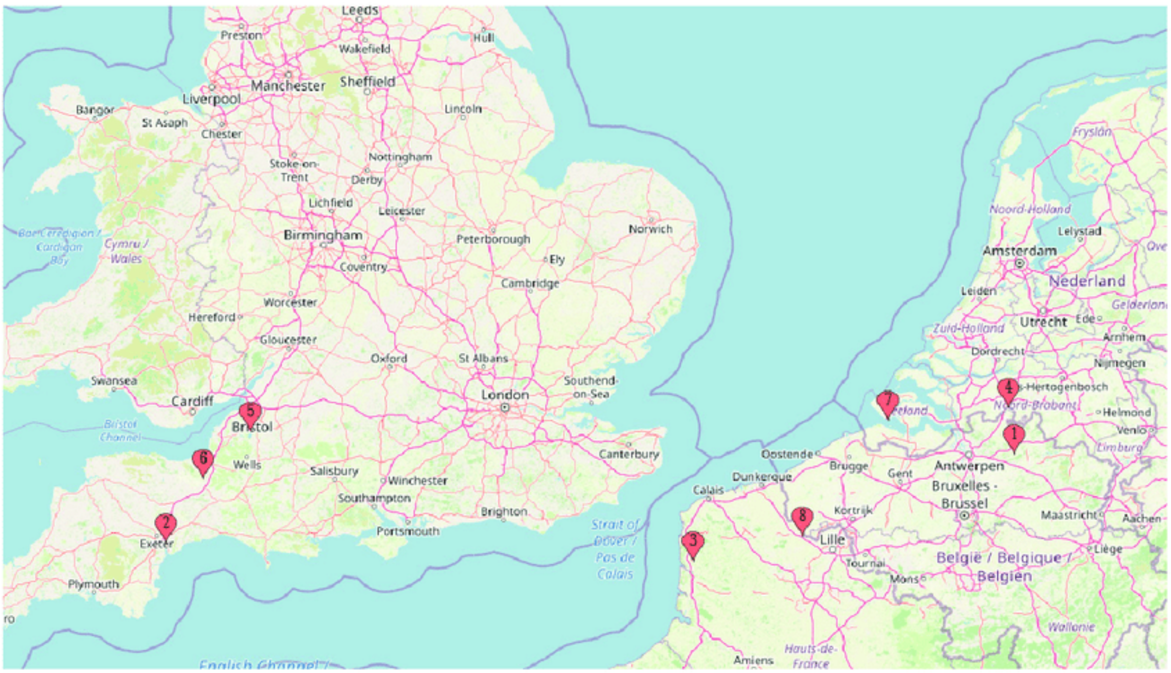


Table 3

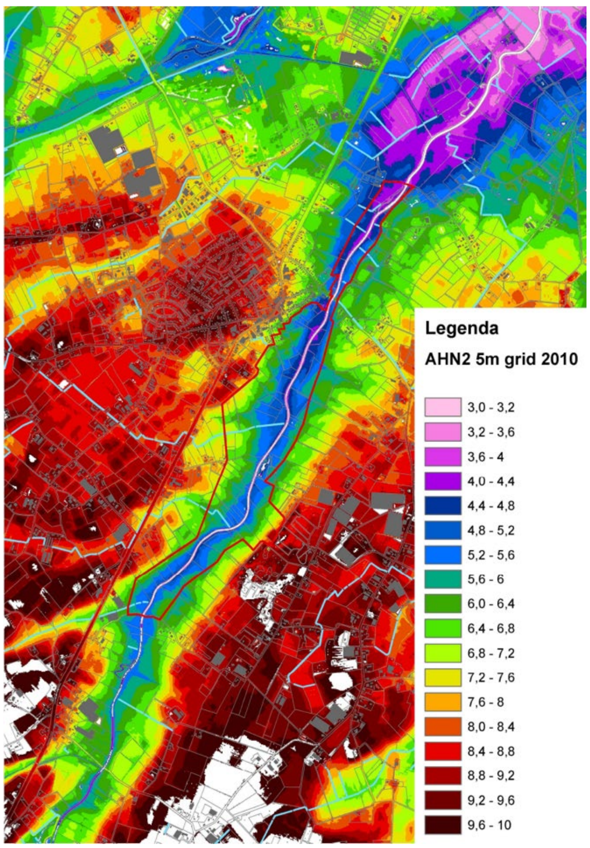
Catchments involved with Co-Adapt and key characteristics. Adjusted from: (Bogatinoska et al., 2022).

Nr.	Catchment	Land	Key characteristics
S1	Laakbeek	Belgium	Small brook passes through the semi-urban village with flooding history. Not much space for adaptation measures.
S2	The Culm	England	Brook passes a new 'green' development area and main railway. Flooding is the main water challenge causing deterioration in water quality.
S3	Liane	France	Brook passes a rural area with urbanized banks causing flooding and soil erosion.
S4	Aa of Weerijs	The Netherlands	Brook passes a rural area with a high density of tree nurseries for export. Main water challenge is drought due to high water demand and flooding in moments of peak flows.
S5	Porlock Vale	England	Brook passes a steep valley, creating a high risk of flooding in several villages.
S6	Somerset Levels and Moors	England	Flooding at lower reaches in several villages.
S7	Vlissingen	The Netherlands	Channelize brookds pass through the new 'green' development area. Flooding is the main water challenge.
S8	West-Flanders	Belgium	Four different brook catchments in Flanders: the Barbierbeek, Maarkebeek, Westhoek and the Gaverbeek. Lots of agriculture present. History of flooding.

Local: Aa of Weerijs (NL)
Locally we looked at the expected results on drought of the implemented NbS in the catchment of the Aa of Weerijs in The Netherlands. This is a 250 ha area of mainly sandy ground. Along the length of the stream, there is a small gradient of just 1 m in height differences over the 4 km around Zundert. Perpendicular to the stream, however, the ground level rises considerably in 300 m to a height of 3 m. The highest soils in the catchment are about 5 m above the stream (figure 5)(Waterschap Brabantse Delta, 2014). This height difference results in dryness in the higher areas in summer. In addition, the area around the stream suffers from flooding during peak discharge (Kortekaas, 2022).

Figure 3

Elevation map of the area around the Aa of Weerijs (NL). The blue strip is the stream, the red areas are the highest parts of the catchment. From: (Waterschap Brabantse Delta, 2014)



2.2. Drought in design and implementation of NbS

To analyse the extent to which drought played a role in design and implementation of NbS (research question 1.1), we first searched the literature for a process analysis of NbS development. We chose to use the Life Cycle Co-creation Process (LCCCP) analysis by DeLosRíos-White et al. (2020) because they analysed a similar process of co-creation for NbS (figure 3).

Document analysis
We conducted an analysis of eigth documents (table 4). The purpose of this was to analyse both the reason for designing and implementing the NbS and the stage at which drought was involved in the process. The questions we asked in this process are shown in table 5.

Table 4

Documents used for the analysis on drought involvement in process of desing and implementation of NbS: involved catchments and references.

Note: *Adjustment from original document: this incorrectly stated 'Province Antwerp'.

Nr.	Catchment	Reference
D1a. Appendix E: Interview, water management VLM*	S8	(Hensbergen et al., 2021)
D1b. Appendix F: Interview 2, Laakbeek-project	S1	(Hensbergen et al., 2021)
D1c. Appendix G: Interview Somerset Levels and Moors	S6	(Hensbergen et al., 2021)
D2	S4	(Werkgroep 'Groeien doe je samen', 2020)
D3	S4	(Kerngroep beekdal Aa of Weerijs, 2022)
D4	S4	(Waterschap Brabantse Delta, 2021a)
D5	S4	(Waterschap Brabantse Delta, 2021b)
D6	S4	(Waterschap Brabantse Delta, 2022)
D7	S1-8	(Kortekaas, 2022)
D8	S7	(Gemeente Vlissingen, z.d.)

Table 5

Questions used for the document analysis for the second research question.

Questions used for document analysis
Which catchment is involved?
What was the occasion to design and implement NbS?
In which phase of the LCCCP is drought involved?

2.3. Effects of NbS op droogte

We answered research questions 2 and 3 through an online Concensus Decision Process and a literature review. We then compared the data found from both. We first answered the question which of the implemented NbS are effective on drought, then we investigated the expected results of these NbS on drought. In doing so, we sought both qualitative and quantitative data.

Concensus Decision Process: data collection field expertise water professionals

We collected data on best practices through a Concensus Decision Process. We went through this process by means of a questionnaire (orientation phase) and an online webinar (brainstorming and consensus phase) using Mural as an online collaboration tool. Target audience for this webinar were water professionals involved in Co-Adapt, working with NbS. We ensured that each catchment was represented in the webinar. Beforehand, we sent out a questionnaire to survey the used NbS in the catchments. In the webinar, we asked the professionals to evaluate which of the submitted NbS affect drought. After a discussion, they then voted which of the chosen NbS was most effective for mitigating drought.

Literature review: data collection scientific knowledge

We conducted a literature review to assess the effectiveness from literature for the most effective NbS from the webinar. To do so, we first categorized the NbS based on the classification used by Keesstra et al. (2018), by processes involved in the NbS and by parameters affected by the NbS. We chose to explore the three most effective categories of NbS from the webinar in the literature review. We scored these categories of NbS as 'highly effective' (>25% improvement of a parameter), 'moderately effective' (10-25% improvement of a parameter) and 'little effective' (<10% improvement of a parameter), when quantitative information was found. The search terms we used were 'water sinks', 'runoff pathways' or 'soil processes', combined with 'nature-based solutions', 'effectivity' and 'drought' and their synonyms. Inclusion criteria were full availability online, journal or review article and top-25. We assessed the titles and abstracts of the results found for relevance to the topic. Of the useful articles, we noted which NbS were involved and what was described of their effectiveness on drought in quality or quantity.

Synthesis: comparison field expertise and scientific knowledge

We juxtaposed the information obtained from the webinar and the literature review for comparison on the criteria 'effectiveness' based on processes and parameters involved. We assessed specific NbS per parameter for effectiveness when information on this was available from both the literature and field expertise.

2.4. Expected results

By means of a document analysis and using the results from the synthesis, we analyzed what the expected results of the implemented NbS in the Aa of Weerijs catchment are. The documents used for this purpose were from the Waterschap Brabantse Delta and Somerset County Council (Tabel 6).

Table 6

Used documents for analysis on expected results for the catchment of Aa of Weerijs.

Document nr	Respective project	Reference
D9	Lodders	(Waterschap Brabantse Delta, 2021b)
D10	Hereijgers	(Waterschap Brabantse Delta, 2022)
D11	Boontuinen	(Somerset County Council, 2022; Waterschap Brabantse Delta, 2021a)
D12	Mortelbeek	(Somerset County Council, 2022; Waterschap Brabantse Delta, 2021a)

3. Results

3.1. Drought in design and implementation of NbS

Document analysis

The document analysis provided insights on NbS as drought measures for seven catchments (table 7); this information was missing for catchment S7 (Vlissingen). In all catchments, flooding was the trigger for design and implementation of NbS. In five catchments, drought was involved in phase 1 (co-explore) of design and implementation of NbS, in two catchments it was in phase 2 (co-design). Only from the Vlissingen catchment no information was found about drought involvement in the process.

Table 7

Results of document analysis: catchment areas, reasons for design and implementation of NbS and phase of LCCCP in which drought is involved.

Document nr.	Catchment	Ecological reason for NbS Flooding	Drought	Other, namely.	Social reason for NbS	Fase of LCCCP involving drought
D1a	Laakbeek	X	X			1. Co-explore
D1b	Laakbeek	X	X			1. Co-explore
D1c	Somerset Levels & Moors	X	X	Sea level rise		1. Co-explore
D2	Aa of Weerijs	X	X			1. Co-explore
D3	Aa of Weerijs		X			1. Co-explore
D4	Aa of Weerijs	X	X			1. Co-explore
D5	Aa of Weerijs				Expansion of business premises	2. Co-design
D6	Aa of Weerijs				Expansion of business premises	2. Co-design
D7	Rivier Culm	X		Erosion Decrease of water quality Soil compaction		2. Co-design
D7	Porlock Vale	X				2. Co-design
D7	Somerset Levels & Moors	X				2. Co-design
D7	Aa of Weerijs	X	X			1. Co-explore
D7	West-Flanders: Gaverbeek	X	X			1. Co-explore
D7	West-Flanders: Westhoek	X	X	Erosion		1. Co-explore
D7	Laakbeek	X				2. Co-design
D7	Boulonnais	X	X	Erosion		1. Co-explore
D8	Vlissingen	X				none

3.2. Effects of used NbS on drought

Concensus Decision Process: results field expertise water professionals

The questionnaire prior to the webinar was completed by five people. This gave us a list of 40 NbS implemented in the river basins. This list was simplified to 30 NbS so that it was clearer and more useful during the webinar (left column in table 18 (Appendix B)). Present at the webinar were 21 water professionals working with NbS, all involved in Co-Adapt. Each river basin was represented by at least one person (table 17 in Appendix B). During the webinar, 23 of 30 NbS were selected by the attendees in two break-out rooms that affect drought (table 18 in Appendix B). Subsequently, each attendee was able to cast three votes for the NbS they considered most effective. A total of 42 votes were cast. Improving infiltration, floodplain reconnection, water storage solutions and slow the flow measures were rated as most effective on mitigating drought by the water professionals (table 8).

Table 8

Selected NbS that are effective to mitigate drought, sorted by number of votes they received for highest effectiveness according to water professionals.

NbS with impact on drought	Number of votes
Improving infiltration	6
Floodplain reconnection	5
Water storage solutions, e.g. scrapes and bunds	5
Slow the flow measures	5
C-capture solutions, e.g. working straw or wood in the soil	4
Agroforestry	3
Soil aeration, e.g. sward lifting	2
Riverbank lowering	2
Testing new plants and cultures that are working on soil structure	2
Hedgerows	2
Gauge controlled drainage	1
Grassland management	1
Installing different Sustainable drainage solutions (SuDS)	1
Cross slope hedges	1
Disrupting flow pathways to make them more complex	1
Ploughing practices, e.g. rough ploughing margins of maize fields	1
Soil management trials	0
Debris dams	0
River reconnection	0
Tree planting	0
Riparian trees	0

Literature review: results scientific knowledge

The result of the literature review is an overview with effectiveness of NbS based on the literature (table 10). These NbS were assessed for influencing the three most relevant parameters to mitigate drought from the CDP. For this, we first made an overview of the NbS based on the classification of Keesstra et al. (2018), divided into processes in which the NbS work and parameters that the NbS influence (table 19 in Appendix B). We then assigned the votes cast in the webinar to the relevant categories (table 9).

Table 9

Implemented NbS sorted by number of votes in the webinar for effectiveness on drought.

Category of NbS based on Keesstra et al. (2018)	Votes	Parameter	Votes per parameter
Geomorphological processes	27	Water sinks	17
		Runoff pathways	9
		Otherwise	1
Soil processes	6	Otherwise	6
Surface processes	5	Vegetation cover	5
Chemical processes	4	Carbon content	4

We chose to examine the three parameters of which influence by NbS was found to be most effective from the webinar in the literature review: water sinks, runoff pathways and soil processes in general (table 9). The search terms and search strings used can be found in Appendix A: Literature review on effectiveness of NbS on drought. Twenty-five articles were found in the three SLRs, of which 8 were useful without duplicate results. In total we found information on effectiveness on drought on 16 NbS. Three NbS were found to be 'highly effective', two NbS to be 'moderately effective', one NbS to be 'little effective' and one NbS to be ineffective. No specification of effectiveness was given about nine NbS except that it was positive.

Table 10

Used articles and results of the literature review sorted by NbS. Where details were described, effectiveness was classified as 'little effective' (<10% improvement), 'moderately effective' (10-25% improvement) and 'highly effective' (>25% improvement).

Category NbS	Reference	Effect on drought	Clarification
Water sinks	(Spyrou et al., 2021)	Little effective	Storage for flooding
	(Keesstra et al., 2018)	Effective	Organic farming, wetland, and landscape restoration
	(Mukherjee et al., 2022)	Effective	Retention ponds in the city
	(Goyette et al., 2022)	Effective	At 20-150% increase in marsh more effective at reducing drought than at reducing flooding
Runoff pathways	(Keesstra et al., 2018)	Effective	Organic farming, wetland, and landscape restoration
	(Norbury et al., 2021)	Highly effective	Artificial willow logs congest the river (resembling a dam)
	(Hovis et al., 2021)	Moderatly effective	Restoring meander of stream, high time and costs investment
	(Hovis et al., 2021)	Effective	Dry dams, high cost-effectiveness
	(Gooden & Pritzlaff, 2021)	Effective	Stone dams increase water availability for vegetation
	(Acreman et al., 2021)	Ineffective	Upstream creation of forests and wetlands reduces water downstream
Soil processes	(Keesstra et al., 2018)	Effective	Processes affecting porosity, soil structure, water capacity, organic matter content
	(Hovis et al., 2021)	Highly effective	Ground cover to reduce runoff
	(Hovis et al., 2021)	Effective	Agriculture without ploughing
	(Hovis et al., 2021)	Effective	Breaking open hardened soil, effectiveness highly dependent on situation
	(Gooden & Pritzlaff, 2021)	Highly effective	Stone dams provide nutrient storage
	(Gooden & Pritzlaff, 2021)	Moderatly effective	Stone dams provide groundwater recharge

Synthesis: comparison field expertise and scientific knowledge
The comparison of the results in table 9 and 10 showed that NbS affecting water sinks, runoff pathways and soil processes are effective for drought mitigation from both field expertise and literature (table 11).

Table 11

Comparison between field expertise and scientific knowledge on effectiveness of studied NbS. Where information was available from both pillars, a more detailed comparison is made. Lines in bold are the main research terms, where possible these have been described in more detail in a row below.

Category NbS	Field expertise	Literatur	Comparison
Water sinks	**Highly effectivve(40% of votes)**	**Little effective - effective**	**Effective when primarily focused on drought**
Floodplain reconnection	12% of votes	Effective	Effective
Ponds, scrapes and bunds	12% of votes	Effective	Effective
Runoff pathways	**Highly effective (19% of votes)**	**Ineffective – highly effective**	**Effective to highly effective when forests and wetlands are not established upstreams**
Verschillende soorten dammen	0% of votes	Effective to highly effective	Effective, not voted on at the webinar because it fell under 'slow the flow measures'
Meander van beek herstellen	2% of votes	Moderatly effective	Moderatly effective, however low cost-effectiveness
Soil processes	**Higly effective (19% of votes)**	**Effective to highly effective**	**Effective to highly effective**
Ploegmethoden	2% of votes	Effective	Effective, highly depending on soil
Grasland- en bodembeheer	2% of votes	Highly effective	Highly effective, depending on environment
Bodembeluchting	5% of votes	Effective	Effective, depending on soil

3.3. Expected results

The results are two overviews showing (1) implemented measures in the catchment (table 12) and (2) their expected results on drought (table 13). There are four Co-Adapt pilot areas in the Aa of Weerijs catchment where NbS have been implemented (Somerset County Council, 2022).

Table 12

Pilot areas in the Aa or Weerijs catchment, reference and measures implemented or planned.

Pilot area	Document	Measure	Category NbS
Lodders	(Waterschap Brabantse Delta, 2021b)	Creation of 3 ha of wetlands to capture large runoff from the Aa of Weerijs and retain water for during droughts	Water sinks
Hereijgers	(Waterschap Brabantse Delta, 2022)	Construction of 2 - 2.5 ha of retention facilities for water storage and infiltration and ecological stepping stones along the Kleine Beek	Water sinks
Boontuinen	(Somerset County Council, 2022; Waterschap Brabantse Delta, 2021a)	Construction of 10 ha water storage area	Water sinks
Mortelbeek	(Somerset County Council, 2022; Waterschap Brabantse Delta, 2021a)	Construction of 6,5 ha water storage area	Water sinks

Table 13

Expected results of the measures in the four pilot areas in the Aa of Weerijs catchment, based on documentation from the Waterschap Brabantse Delta and the synthesis from the previous section.

Pilot area	Expected results Waterschap Brabantse Delta	Expected results based on synthesis field expertise and literature

Lodders	More storage capacity to both collect and buffer water. Evaluation: water storage is calculated 'on the front' by hydrologists.	Effective when primarily focused on drought
Hereijgers	Healthy balance in the area between living, working and climate resilience. Evaluation: meet the above impact.	Effective when primarily focused on drought
Boontuinen	More storage capacity and earlier capture and longer retention due to lower threshold and check valve. Evaluation: tracking water level of Aa of Weerijs online.	Effective when primarily focused on drought
Mortelbeek	More storage capacity and earlier capture and longer retention due to lower threshold and check valve. Evaluation: tracking water level of Aa of Weerijs online.	Effective when primarily focused on drought

4. Discussion and conclusion

4.1. Discussion

This study shows that influencing water sinks, runoff pathways and soil processes is most effective to mitigate drought, from both field expertise and scientific literature. The NbS that water professionals rated as best work through these parameters and processes. The examples they submitted are shown in table 14.

Table 14

Examples of effective NbS on drought

NbS with impact on..	Examples
Water sinks	- Bunds - Scrapes - Floodplain reconnection - SuDS - Improving infiltration - Basins - Keeping water levels higher in peat soils
Runoff pathways	- Riverbank lowering - Dams, leaky woody or debris - Weirs - Disrupting flow pathways to make them more complex - Increase ground surface roughness via installation of brash dams
Soil processes	- Soil aeration, e.g. sward lifting - Grassland management - Ploughing practices - Soil management trials - C-capture solutions e.g. working straw or wood in the soil

This results contributes to several goals formulated by Deltares (2022) in their 'HELP Guiding Principles for Drougt Risk Management under a Changing Climate', including:

- Principle 9: Mitigate the impact of drought and water scarcity on ecosystems and biodiversity
- Principle 10: Invest in nature-based and hybrid infrastructure.

In the Guiding Principles, Deltares (2022) also states that 'wetland restoration, floodplain restoration and groundwater recharge' are promising NbS to increase drought resilience, as we confirm in this study. This is in line with recent developments within the EU, such as the application for research on 'Demonstrating Nature-based Solutions for the sustainable management of water resources in a changing climate, with special attention to reducing the impacts of extreme droughts' (European Commission, 2023).

System restoration
Droughts affect the entire system of a catchment. NbS, on the other hand, often have a more localized effect. The question here is how solutions with localized effects can collectively restore the system. In addition, drought is often not the only challenge. One possible way to deal with this is to combine multiple NbS in a catchment. Based on our analysis, we have developed a tool to understand which NbS can be deployed to mitigate drought. The tool gives insight in various effective NbS, their working mechanism and which ecosystem services they support. The tool is presented in chapter 5. Recommendations.

Every problem is unique
The variety of NbS shows that their design is clearly strictly tied to the society from which the design originates and the local environment for which it is a solution. This means that an NbS in one catchment will not automatically be effective in another. Both the possibility for measures and their effectiveness depends for example on landscape, ecology, soil composition, amount of water runoff

and climate (Hovis et al., 2021). Therefore, the co-creation process for NbS should be done separately for each (sub)catchment.
Also, an NbS aimed at reducing flooding is not necessarily also effective in reducing drought. In this study, we looked at whether NbS initially developed for flooding also have an impact on drought. The question is whether this can be tested at all: flooding applies in an area around the stream, so NbS focusing on flooding will also be implemented in that area and have an impact. Drought can manifest itself in the whole catchment area and thus by definition requires different NbS in other locations. However, the analysis shows that the implemented NbS (primarily against flooding) are also effective for drought. This is positive as flooding is more often than drought the trigger for measures, even though drought is now often perceived as the biggest problem by farmers (Ine Soeten, Symposium Water+Land+Schap, January 2023).

Co-creation process
During the NbS development process through co-creation, stakeholders are involved. It is important to be aware that this is a constantly evolving process. At different stages, for example, different stakeholders are relevant. It may also be that, as in this study, the purpose of the NbS to be developed changes over time. Indeed, at the start, many of the catchments in this study appeared to have the goal of reducing flooding; in the next phase, drought reduction was added. Different ecological aspects involve different stakeholders because, as mentioned earlier, ecological aspects have different spatial coverage. So it is important to realize that different aspects of the development process (such as stakeholders, ecological aspect involved, spatial coverage) may have changed when entering the next step of co-creation. This means that the co-creation process must be gone through iteratively, in order to constantly adjust the development of the NbS.

Terminology
To ensure good cooperation between different stakeholders from multiple backgrounds, it is necessary to use the same terminology. However, even when professionals do not use jargon, there can be ambiguity about the meaning of terms. Using a questionnaire among 34 experts and 119 lay people, Venhuizen et al. (2019) compared definitions of water-related terms. They found that for 'river basin' and 'river' there was the biggest difference in interpretation between the two groups. This means that additional clarity needs to be created when communicating between them, for example by classifying used NbS by process function as Keesstra et al. (2018) have done. Their classification (table 2) appears to provide good tools to bring science and practice together in terms of terminology used (such as bunds and scrapes) and processes or parameters involved (such as water sinks).

Data collection for this study included a questionnaire and a webinar. This questionnaire was only completed by some of the recipients, so information may be incomplete. The submitted data from the questionnaire was categorised only after the webinar. Had this been done prior to the webinar, the results of the voting rounds could have been different as there would have been less overlap between the different options. After conducting the SLR, the NbS were re-categorised, which ultimately resulted in the parameter 'vegetation cover' scoring higher than 'soil processes'. This reclassification affected the final results.

4.2. Conclusions
The aim of this study is to evaluate the effectiveness of NbS on drought in brook catchments. This was investigated using three sub-questions.

In seven of the eight catchments, drought mitigation was a primary or secondary goal of the development of NbS. This means that besides flooding, drought is an important climate effect for which society is developing measures. NbS are also expected to influence drought, given the early relation of drought in the development process.

According to water professionals, water sinks, runoff pathways and soil processes are the most effective NbS during drought. Literature confirms the effectiveness. However, it cannot be quantified because of the high dependence on the type and size of the measure and the area. Thus, according to evidence-based practice and without further details, the listed measures are effective in reducing drought.

The expected results of the co-designed and implemented NbS in the Aa of Weerijs catchment are increased buffer capacity of water resulting in increased infiltration, increased amount of soil moisture and surface and underground water. Soil moisture drought and hydrological drought reduces, resulting in less socio-economic drought and ecological impacts. This will better meet the high water demand of tree nurseries.

The results found reflect the current literature: NbS are effective at mitigating climate change impacts. Quantification of mitigation is so far challenging due to the large differences between catchments. If the underlying processes (geomorphological, soil, surface and chemical) are considered in the design of flood measures, it is expected that after implementation of NbS in brook catchments, water storage capacity will increase and ecological and socio-economic drought will be reduced.

5. Recommendations

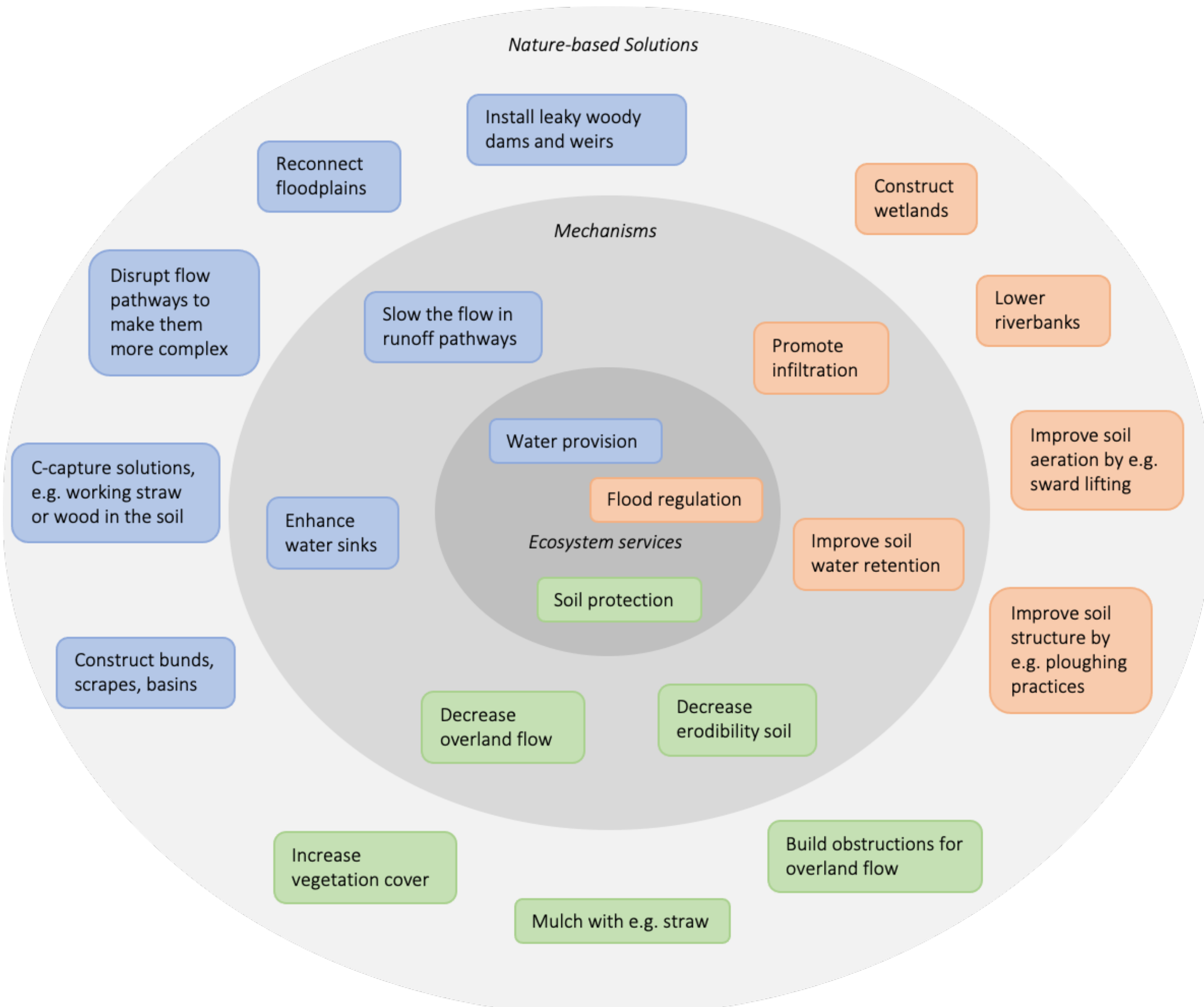
5.1. Recommendations for water professionals

1. Use the tool to pick effective NbS for drought

We developed a tool to give insight in the underlying mechanisms and ecosystem services of the NbS that are effective for drought mitigation (figure 5). We utilized all the NbS chosen as being effective by the water professionals from the submissions they did in the prequestionnaire. We started with the ecosystem services as describes in Keesstra et al. (2018), and used with the ones with effects on drought on the inner circle of the diagram. We then added a circle with the working mechanisms for those ecosystem services, also derived from Keesstra et al. (2018). The outer circle consists of NbS, chosen by the water professionals as being effective on drought. Details on location of these NbS, area of impact, mechanisms involved, and indicators are described in table 20 in Appendix D. A visual guiding landscape model is added in figure 6, Appendix E.

Figure 5

Tool with underlying mechanisms and ecosystem services of NbS that are effective for mitigation of drought. Colors are used to group the ecosystem services, mechanisms and NbS who belong together.



2. Invest in water sinks, runoff pathways and soil processes to mitigate drought
NbS that improve or work through water sinks, runoff pathways and soil processes are effective in reducing soil moisture drought and hydrological drought, according to evidence-based practice. Examples are shown in Table 14.

3. Strive for system recovery using the underlying processes and parameters
Apply different NbS at different locations of a catchment for whole-system restoration. Or focus on various NbS, effective on a certain ecosystem service, to improve that service throughout the whole catchment. Use the tool (figure 5) for this purpose.

5.2. Recommendations for science

1. Research on scaling up measures, system approach
Current challenges in implementing NbS include the need to scale up measures to regional level and above (Deltares, 2022). Integrating a system approach to this can help achieve synergies and linkage opportunities. This can be done by combining climate adaptation and climate mitigation, which can accelerate both and avoid making choices that can be regretted later. Among other things, this requires more synergy at the administrative level (Peeters et al., 2022).

2. Long-term monitoring of effects of NbS
Data collection over (several) decades could contribute greatly to research on the effectiveness of NbS. The effects of natural solutions manifest themselves more slowly than those of grey solutions, and (depending on the measure) can sometimes only be visible after 5-10 years (Keesstra et al., 2018). Therefore, a monitoring series of at least 10 years would greatly contribute to the possibility of evaluating effectiveness of NbS.

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Appendix A: Literature review on effectivity of NbS on drought

The following tables show the search terms used (table 15), search strings and results (table 16) of the literature search.

Table 15

Search terms used for the literature review.

Search term	Water storage solutions	Slow the flow measures	Soil processes	Nature-based Solutions	Effectivity	Drought
Alternatives	Bunds	Riverbank lowering	Carbon capture	Green solutions	Impact	
	Scrapes	Dams	Soil aeration		Assessment	
	Floodplain reconnection	Weirs	Grassland management		Efficiency	
	SuDS		Ploughing practices			
	Improving infiltration		Soil management			
	Basins					

Table 16

Used search string and results.

Search term	Results	Used
("water storage solutions" OR bunds OR scrapes OR "floodplain reconnection" OR SuDS OR "improving infiltration" OR basins) AND ("nature-based solution" OR "green solution") AND (effectivity OR impact OR assessment) AND drought	9	4
("slow the flow" OR "riverbank lowering" OR dams OR weirs) AND ("nature-based solution" OR "green solution") AND (effectivity OR impact OR assessment OR efficiency) AND drought	4	3
("soil process" OR "carbon" OR "soil aeration" OR "grassland management" OR "ploughing practice" OR "soil management") AND ("nature-based solution" OR "green solution") AND (effectivity OR impact OR assessment OR efficiency) AND drought	12	2

Appendix B: Data Concensus Decision Process

The water professionals present at the webinar are shown in table 17 based on relevant river basin. For the webinar, we simplified and aggregated the NbS. From this list, the water professionals indicated in the webinar which NbS they considered effective for drought (table 18). Table 19 describes the NbS as submitted by the water professionals. For the sake of usability and possibility of comparison, they have been categorised and combined.

Table 17

Number of water professionals at the webinar based on catchment area of Co-Adapt.

Catchment	Land	Attendees
1. Laakbeek	Belgium	7
2. The Culm	United Kingdom	2
3. Liane	France	1
4. Aa of Weerijs	The Netherlands	1
5. Porlock Vale	United Kingdom	1
6. Somerset Levels and Moors	United Kingdom	1
7. Vlissingen	The Netherlands	1
8. West-Flanders	Belgium	2
Not involved in any particular catchment area	The Netherlands	5
	Total	21

Table 18

List of implemented NbS, submitted through the pre-questionnaire, simplified for usability on the webinar and selection on effective on drought according to water professionals during the webinar.

Implemented NbS, from pre-questionnaire	Rated as effective in drought
C-capture solutions, e.g. working straw or wood in the soil	X
Gauge controlled drainage	X
Agroforestry	X
Keeping waterlevels higher in peat soils	X
Soil management trials	X
Ploughing practices, e.g. rough ploughing margins of maize fields	X
Soil aeration, e.g. sward lifting	X
Tree planting	X
Fascines	
Hedges	
Testing new plants and cultures that are working on soil structure	X
Hedgerows	X
Laying buffer strips along rivers	
Grassland management	X
Sediment trapping	
Slow the flow measures	X
Improving infiltration	X
Disrupting flow pathways to make them more complex	X
Increase ground surface roughness via installation of brash dams	
Riparian fencing	
Installing different Sustainable drainage solutions (SuDS)	X
Debris dams	X
Cross slope hedges	X
Riverbank lowering	X
Cross track drains	
Floodplain reconnection	X
Water storage solutions, e.g. scrapes and bunds	X
Riparian trees	X
River reconnection	X
Beavers, water moles and other river engineers	X

Table 19

NbS as described in questionnaire, selected by water professionals as having impact on drought, categorized by involved processes and parameters. Based on classifications by Keesstra et al. (2018).

NbS effectief op droogte zoals in pre-questionnaire	Processes	Parameters
Improving infiltration	Geomorphological processes	Water sinks
Floodplain reconnection	Geomorphological processes	Water sinks
Water storage and keeping water levels in peat soils higher (for flooding and drought)	Geomorphological processes	Water sinks
Slow the flow measures	Geomorphological processes	Runoff pathways
C-capture solutions (working straw or wood in the soil)	Chemical processes	Carbon content
Agroforestry	Surface processes	Vegetation cover
Soil aeration, e.g. sward lifting	Soil processes	Porosity
Riverbank lowering and bunds to store water	Geomorphological processes	Runoff pathways
Testing new plants and cultures that are working on soil structure	Soil processes	Soil structure
Hedgerows	Surface processes	Vegetation cover
Gauge controlled drainage	Geomorphological processes	Runoff pathways
Grassland management	Soil processes	-
Installing different Sustainable drainage solutions (SuDS)	Geomorphological processes	Water sinks
Cross slope hedges	Geomorphological processes	Hillslope geomorphology
Disrupting flow pathways to make them more complex	Geomorphological processes	Runoff pathways
Ploughing practices, rough ploughing margins of maize fields	Soil processes	Soil structure
Soil management trials	Soil processes	-
Debris dams	Geomorphological processes	Runoff pathways
River reconnection	Geomorphological processes	Connectivity
Tree planting	Surface processes	Vegetation cover
Riparian trees	Surface processes	Vegetation cover
Weirs	Geomorphological processes	Runoff pathways
Fascines	Surface processes	Vegetation cover
Hedges	Surface processes	Vegetation cover
Willow seedlings	Surface processes	Vegetation cover
Better soil aeration	Soil processes	Porosity
Ploughing practices	Soil processes	Soil structure
Alternative management practices that protect and build organic content in the soil	Soil processes	Carbon content
Hedgerows or trees	Surface processes	Vegetation cover
Increase ground surface roughness via installation of brash dams	Geomorphological processes	Runoff pathways
Scrapes to store water	Geomorphological processes	Water sinks
Construction of attenuation ponds	Geomorphological processes	Water sinks
Scrapes	Geomorphological processes	Water sinks
Bunds	Geomorphological processes	Water sinks
Leaky woody dams	Geomorphological processes	Runoff pathways
Pond creation & restoration	Geomorphological processes	Water sinks
Hedgebanks	Surface processes	Vegetation cover
Riparian fencing	Surface processes	Vegetation cover
Water basins	Geomorphological processes	Water sinks

Appendix C: Data on expected results

From: Plan Lodders (Waterschap Brabantse Delta, 2021b)
Wat is het beoogde effect? (waterberging, droogtebestrijding, biodiversiteit …)
Het effect van dit plan is dat er meer ruimte komt voor water bij wateroverlast en dat er in drogere perioden water kan worden vastgehouden. Daarnaast wordt er invulling gegeven aan de Ecologische Verbindingszone langs de Aa of Weerijs waardoor de ecologie en biodiversiteit kan toenemen in het gebied. Daarnaast ontstaat er voor de inwoners van Wernhout een prachtige omgeving waarlangs zij makkelijk en veilig kunnen wandelen.

Hoe wordt het effect gemeten?
Net als bij andere aangelegde EVZ's zal worden bekeken of ze ook functioneren zoals bedoeld. Voor wat betreft de waterberging en water vasthouden, dit zal aan de voorkant berekend worden door hydrologen van het waterschap. In de praktijk zal moeten blijken of de berekeningen ook overeenkomen met de werkelijkheid.

From: Plan aanpassingen waterbergingen (Waterschap Brabantse Delta, 2021a)
Wat is het beoogde effect?
Meer water bergen in het gebied en ook eerder door de inlaat te laten zakken en een terugslagklep te plaatsen. Door de terugslagklep zal worden voorkomen dat het water terugloopt en wordt er water vastgehouden in het gebied om ter plaatse te infiltreren waardoor het een positief effect heeft op de grondwaterstand.

Hoe gaan jullie het effect meten?
Door de waterstanden in de Aa of Weerijs online te volgen is er inzicht in het waterniveau in de Aa of Weerijs. Hierdoor kan precies worden gevolgd wanneer en hoeveel water er de bergingen instroomt.

From: Plan Hereijgers (Waterschap Brabantse Delta, 2022)
Wat is het beoogde effect?
Het beoogde effect is dat er een goed evenwicht ontstaat in het gebied De Hulsdonk waar het goed wonen en werken is in een klimaatbestendige omgeving.

Hoe gaan jullie het effect meten?
Het plan kan niet doorgaan als er niet wordt voldaan aan bovenstaand effect.

Appendix D: Details on effective NbS for drought

Table 20

Details on effective NbS for drought. Location in catchment, area of impact, mechanisms involved and indicator. Colors are used to group the ecosystem services, mechanisms and NbS, like in figure 5. For the area of impact: one symbol means local, two a bigger area and three the whole catchment. ⛰ *means geomorphological processes;* 🌳 *means surface processes and* ⛏ *means soil processes.*

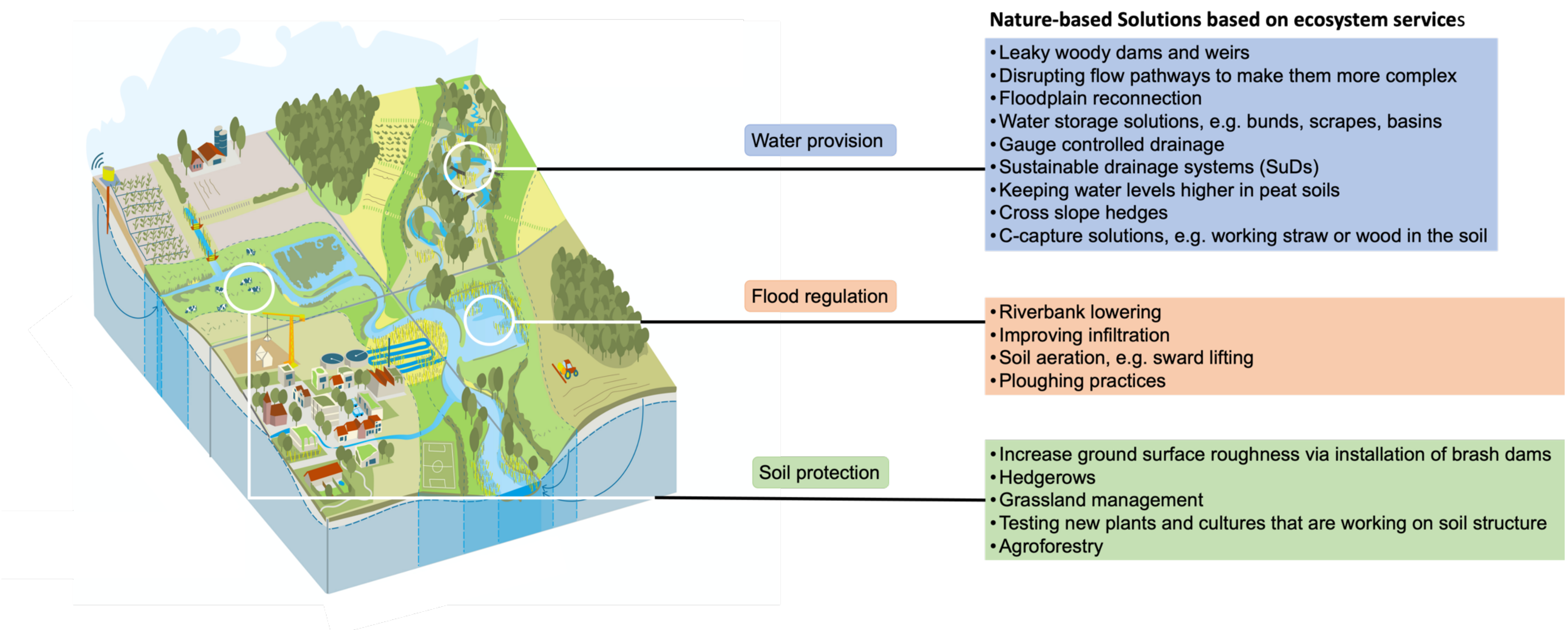
Location	NbS	Area of impact	Mechanism involved	Indicator
River	Leaky woody dams	⤢⤢	⛰	Runoff pathways
	Weirs	⤢⤢	⛰	Runoff pathways
	Disrupting flow pathways to make them more complex	⤢⤢⤢	⛰	Runoff pathways
	Increase ground surface roughness via installation of brash dams	⤢⤢	🌳	Surface roughness
Riverbank	Riverbank lowering	⤢	⛰	Runoff pathways
Wetland	Floodplain reconnection	⤢⤢	⛰	Water sinks
	Water storage solutions, e.g. bunds, scrapes, basins	⤢	⛰	Water sinks
	Gauge controlled drainage	⤢⤢	⛰	Runoff pathways
	Hedgerows	⤢	🌳	Vegetation cover
	Improving infiltration	⤢⤢	⛰	Water sinks
Dry area	SuDS	⤢⤢	⛰	Water sinks
	Water storage solutions, e.g. bunds, scrapes, basins	⤢	⛰	Water sinks
	Keeping water levels higher in peat soils	⤢	⛰	Water sinks
	Gauge controlled drainage	⤢⤢	⛰	Runoff pathways
	Cross slope hedges	⤢⤢	⛰	Hillslope morphology
	C-capture solutions, e.g. working straw or wood in the soil	⤢	⛏	Soil organic matter
	Grassland management	⤢	⛏	-
	Testing new plants and cultures that are working on soil structure	⤢	⛏	Soil structure
	Agroforestry	⤢⤢	🌳	Vegetation cover
	Hedgerows	⤢	🌳	Vegetation cover
	Soil aeration, e.g. sward lifting	⤢	⛏	Porosity
	Ploughing practices	⤢	⛏	Soil structure
	Improving infiltration	⤢	⛰	Water sinks

Appendix E: Guiding landscape model for spatial climate adaptation

This guiding landscape model (figure 6) visualizes what kind of NbS to implement where in a brook catchment. NbS are categorized in ecosystem services they support.

Figure 6

Guiding landscape model for spatial climate adaptation.



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