North Sea Region INTERREG Building with Nature

Final report Workpackage 4 (Catchments)

Final report Workpackage 4 (Catchments)
North Sea Region INTERREG Building with Nature

Ralph Schielen

Ministry of Infrastructure and Water Management-Rijkswaterstaat, The Netherlands and Delft University of Technology, The Netherlands

Chris Spray

University of Dundee, Scotland

Debi Garft

Scottish Government

Pär Persson

Länsstyrelsen Skåne, Sweden

Lukas Österling

Länsstyrelsen Skåne, Sweden

Stoffel Moeskops

Flanders Environment Agency, Belgium

October 2, 2020

Cover page, starting on top, going clock-wise: Stjørdalselva, Norway, Side channel near Waal River, The Netherlands, De Kleine Nete, Belgium, Råån, Sweden and Eddleston, Scotland.

1. Introduction

Within the Interreg North Sea Region (NSR), there are hundreds of kilometres of large rivers and thousands of kilometres of smaller streams. As the NSR is in general a highly developed area with a very high pressure of population and industry (although the degree varies throughout the NSR), most of the rivers and streams need some kind of management to provide safety for the surrounding municipalities, agricultural area and nature areas. This means that the rivers have to be maintained, and sometimes even be restrained. On the other hand, rivers and streams have many added values for instance as sources of biodiversity and as popular sites for recreation. There are often agricultural activities in the floodplains, sometimes there is economic activity and even habitation. Larger rivers also have an important function as navigational routes. The smaller streams fulfil an important function by connecting nature areas and they provide storage in times of extensive rainfall, to safeguard downstream municipalities from flooding. The larger rivers need to be shaped in such a way that the hinterland is sufficiently safe, meeting national standards. Here, the protection is often by levees, where in case of the smaller streams, protection is either in the form of low embankments or more often is absent and the surrounding land will flood if there is too much rainfall. Application of measures to slow down the flow is then typically something that can be done to lower the flood risk in the downstream areas.

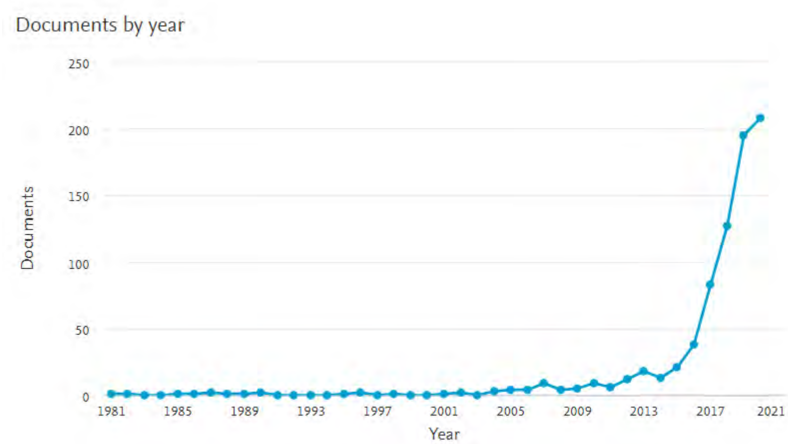
There are few pristine rivers left in NSR. Most of the larger rivers such as the Thay and Rhine are engineered to a great extent, and have high embankments or other flood defences for protection. Smaller rivers are also often engineered. In earlier times, they have been straightened or otherwise adapted such that their behaviour could be regularised and controlled. These river works come at a cost. Often, the morphological response takes years or even decades. In addition, what once seemed to be a good idea (straightening and controlling) now in places has turned out to cause serious problems with timing of flood peaks and being able to deal with high precipitation events. This is one of the reasons that increasingly, engineers and policymakers are looking for opportunities for Nature Based Solutions (NBS) to help reduce flood risks and also add additional values to the river and surrounding landscape. NBS can be seen as complementary to the set of grey or green-grey solutions, rather than substitutions and bring many additional benefits for the environment and society as well.

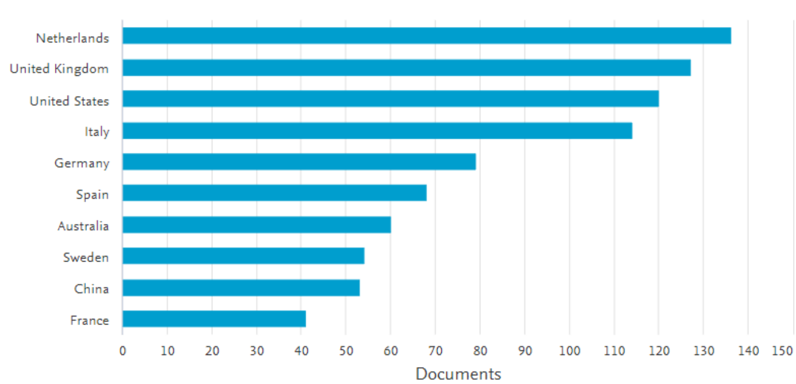
One of the main questions related to NBS nowadays is whether there is sufficient (scientific) evidence that they reduce flood risk and have the added values that they are claimed to have. To assess this in an objective manner, an assessment framework is needed which enables comparison of NBS with respect to each other and to their grey and grey-green alternatives. Setting up the first version of such an assessment framework is one of the goals of this INTERREG Building with Nature (BwN) project.

The primary objective of applying BwN (or using Natural and Nature Based features (NNBF), Nature Based Solutions (NBS), Natural Flood Management (NFM), Engineering with Nature (EwN), Working with Natural Processes or similar descriptions) is to reduce flood risk by using measures that retain or slow down the water in the upper catchment of a river, or that increase the discharge capacity in the middle catchment of a river. Retaining the water in the upper catchment obviously reduces the discharge downstream and hence, decreases the flood risk. Increasing the discharge capacity in the middle reach reduces the flood levels and hence also the flood risk. Where the natural and economic environment of the floodplain may allow, there may even be opportunities to temporarily store floodwaters on the floodplain itself under carefully controlled conditions.

To reach that goal (reduction of the flood risk) grey or a mixture of green/grey solutions can be used, but NBS (we will use the terms NBS, BwN and NFM interchangeably in this report) have the added attraction that they have co-benefits, including contributing to the increase of biodiversity and habitat enhancements, water quality improvements, groundwater recharge, carbon management and recreational opportunities, among other ecosystem services.

Over recent years, NBS (and the related terminology as introduced above) has become a booming subject in scientific research and literature. Results from Scopus indicate that up to 2004, the subject was nearly non-existent (figure 1.1). After that, an almost exponential growth is noticeable. In an editorial in Nature[1], it is mentioned that the development may be compared with the introduction of the term 'Biodiversity', which is now also generally used but was virtually unknown until 1985. If this parallel continues (and all signs point to that direction), the term NBS (and similar terms) will be used in the policy debate more and more and it becomes increasingly important to provide a solid scientific base for its meaning. This is the work of the scientific community which takes its task (considering the amount of publications) very seriously!





[1] Natural Language, The latest attempt to brand green practices is better than it sounds, 2017, Nature 541, pp133.

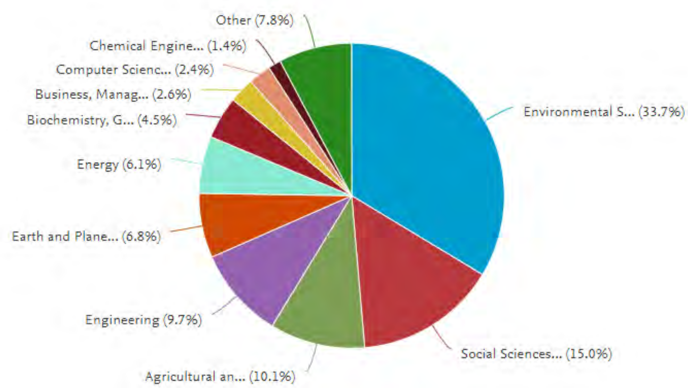


Figure 1.1: Scopus search results on “nature based solutions“, "nature inspired solutions“, “working with nature” and "building with nature“ (776 articles), retrieved on September 4, 2020.

Work Package 4 Case studies

Within this NSR Interreg BwN project, we studied the performance of NBS in 4 different cases in 4 different countries. We worked towards assessment frameworks, made comparisons between the jurisdiction and legislation with respect to NBS in the different countries and looked at modelling and monitoring tools that can be used. The different cases studies have been visited several times over the past 4 years to exchange experiences and discuss the results and approaches. Below, we describe the case studies briefly. In sections 2.1-2.4, they are discussed in more detail.

Scotland

The Scottish case study is the Eddleston Water, a tributary of the Tweed into which it discharges at its downstream confluence in the town of Peebles. After an initial scoping study completed in 2010, a series of restoration works were undertaken across the 69km^2 catchment in order to reduce flood risk to downstream communities and improve river habitats, whilst sustaining farming livelihoods in the valley. BwN-measures in the catchment include restoring 3km of straightened river channel into meandering reaches. In addition 207 hectares of riparian and headwater woodland has been planted with 330,000 native trees and 29 run-off attenuation features and ponds, have been constructed to slow the water down. Finally, 116 leaky dams (high flow restrictors) have been installed, also to slow the water down and hence decrease flood risk to downstream communities. Since the start, an intensive monitoring programme has covered hydrology and hydraulics, hydro-geomorphology and ecology. These data are being used to calibrate and verify hydraulic and morphological models, which can be utilised to assess the effectiveness of these measures and make predictions about the costs and benefits of building with nature at the catchment scale.

Netherlands

In the Netherlands, the case study did not involve a specific stretch of a particular river but was dedicated to a specific restoration measure, namely side channels (sometimes also called secondary channels). Side channels are a popular measure in the Netherlands (but also elsewhere in the world) where river restoration is concerned. The measures increases the discharge capacity by creating a secondary channel alongside the main channel with a length of several hundredths meters up to a few kilometres. Usually, there is a sill at the entrance to regulate the discharge. Side channels reduce flood levels and have added values with respect to biodiversity and recreation. On the other hand, we know from literature[2] that side channels aggrade within several years. Once that happens, they lose their function and therefore, maintenance is necessary. For these reasons, it is important to gain knowledge on sedimentation and erosion of side channels. The research done in this project contributes to that aim. It is foreseen to carry out measurements with respect to the discharge partitioning between the main channel and the side channel, and to carry out field experiments to find out what kind of sediment is deposited in the side channel (and how this relates to the sediment in the main channel).

Belgium

The Kleine Nete is a rain river which winds across the sandy north-east of Flanders as a blue-green ribbon. On one hand, the agriculture land, which is the principal land user along the Kleine Nete, stores the water in case of high floods. On the other hand, the valley of the Kleine Nete is ecologically very valuable, protected by Flemish and European legislation.

In the 1970s, the river was changed considerably, mainly by widening, deepening and straightening measures to facilitate agriculture. These measures increased flood risk for the downstream areas decreased biodiversity and lowered groundwater levels. To mitigate these effects, a restoration programme was set up, comprising of construction of a fish passage, creating ecological flooding zones and remeandering parts of the river. Creating awareness, responsibility and understanding of the river system among the local population is an important goal of this project. It also contributes to understanding the consequences of climate change.

Sweden

The Råån river is a small river in Sweden. In the upper part of the 193 km^2 catchment, the land use is mainly agricultural. In the middle part, the floodplains are used for cattle grazing while in the lower part, there is relatively much urban area. The upper part especially consists of dredged and channelised streams. As early as in the 1990s, restoration projects have been carried out, mainly to reduce transportion of nutrients and to improve biodiversity. Among the measures are construction of ponds, large shallow wetlands and transformation of existing ditches into two stage ditches. In a later stage, it was acknowledged that these measures also reduce flood risk. The measures are monitored and modelled and for this, especially the projects in the catchment of Lussebäcken (a tributary of the Råån) are considered.

---

[2] van Denderen, R. P. , Schielen, R. M. J., Straatsma, M., Kleinhans, M. G. & Hulscher, S. J. M. H. (2019). A characterization of side channel development. River research and applications, 35(9), 1597-1603. https://doi.org/10.1002/rra.3462

Indicator

To assess the effectiveness of the BwN project, a formal indicator (target) was set. WP4 produced a paper to demonstrate that it has met this target[3]. The paper makes a case for amending the indicator to:

"The Interreg North Sea Region Building with Nature project aims at managing new catchments using shared BwN techniques as a result of the effectiveness of project demonstrations, based on BwN principles. As an indicator, we use the lengths of the river or stream and we aim at improving 550 km or more."

WP4 has shown that at the strategic, policy and practical levels, it has achieved this aim. The strategic level recognises that BwN measures have indeed added values, and that there are multiple water bodies where BwN can be applied. The policy level relates to the fact that there are sufficient possibilities to apply BwN in the area of interest of INTERREG. And on the practical level, WP4 has demonstrated that the four case studies combined comprise some 636.5 km of river length that are now managed using BwN techniques; exceeding the aim of 550 km.

Distinction between small streams and large rivers

River catchments show a broad range in scale and physiography. In Europe, catchments vary in size. The can be as big as 1.3 million km^2 (Volga catchment, largest catchment in Europe), 800.000 km^2 (Danube catchment) or 185.000 km^2 (the Rhine catchment, considered in this project in The Netherlands), or as small as 5.000 km^2 (Tweed river, considered in Scotland), 570 km^2 (Kleine Nete, considered in Belgium) or even 20 km^2 (the catchment of the Lussebäcken, considered in Sweden). River catchments have fractal-like properties. Rivers have tributaries with a catchment of their own, and these tributaries have again (smaller) tributaries with their own catchments and so on. The NBS that we consider in the project can be applied to all catchments, independent of the scale and location. However, scale and location determine what and where NBS suit best. The measures are different in steep parts in mountainous areas, in less steep tributaries in the headwaters of larger rivers, and in (large) lowland rivers with very gentle slopes. In the headwater of the tributaries of the larger rivers, one typically wants to slow down the flow and retain the discharge. This might be done with leaky dams or tree planting in gentle sloped regions like Scotland and with re-meandering and retention ponds in almost flat regions like Belgium and The Netherlands. These measures reduce the discharge (and hence flood risk) towards the downstream regions. In larger scale lowland rivers with sometimes wide floodplains and intensive navigation like the Rhine river, NBS are more related to increasing the discharge conveyance of the river (and hence decreasing the flood levels). This is of course also related to the fact that in larger rivers, navigation is an important economic driver, which cannot be hindered by obstructing measures. An important consideration when applying NBS in tributaries, is that these measures also affect the timing of the flood peak. This is important with respect to potential synchronization of flood peaks of the main stem and the tributaries. Slowing down a flood peak in the tributaries, and hence reducing the flood risk (immediately) downstream might however lead to an increase in flood risks further downstream on the main river, because the flood peaks of the main stem and the tributaries now coincide.

[3] Schielen, R., Forbes, H., Spray, C., Moeskops, S., and Persson, P. (2019) , Achieving the Project Indicator of the Interreg North Sea Region Building with Nature Project, Internal Note INTERREG NSR BwN Project.

The recognition of the different scales and locations where NBS can be applied is related to the conceptual model of 'Source-Pathway-Receptor', which is used by flood managers to select NBS. Within this model, not only is the location and scale important but whether the risk comes from pluvial or fluvial flooding, or a combination.

2. Findings from the case studies

In this chapter, the main findings from the 4 different case studies are reviewed. In Table 2.1, we also briefly summarise the flood protection strategies in The Netherlands, Belgium, Scotland and Sweden.

Country	Approach
Netherlands	The Netherlands is a low lying country with approximately 25% of its land below mean sea level, and 60% of the population living in flood prone areas that generate 70% of GDP. Thus, flood protection is of utmost importance to the Dutch society. For the larger rivers (Rhine and Meuse) and canals, the primary defence against flooding is strong embankments with flood probabilities between 3% and 0.001 % per year. Since 2005, traditional approaches are combined with NBS in the Room for the River programme. NBS are also applied by the water boards for the regional water system. In the regional system, the approach is to slow down and retain the water, for the larger rivers, the approach is to increase the discharge capacity and hence lower the flood levels. To mitigate climate change effects, the Delta programme was established in 2009, in which additional measures and dike reinforcements are foreseen. The Netherlands also has a 24/7 operational prediction and flood warning system for the Rhine, Meuse, lakes and coastal area.
Belgium	With the introduction of the Decree on Integrated Water Management (2003), based on the European Water Framework Directive, the traditional engineer's vision of water drainage – recalibration of watercourses and maximum water flow, supplemented with dike-enclosed reservoirs – was adjusted. The three-step-principle became: (1) retaining water where it falls, (2) storing water where possible, (3) draining water as last solution. In the same period, the concepts of (semi-)natural flood plains, which allow the entire valley to carry water again, and NBS have been developed. However, the urban sprawl in Flanders, in terms of spatial planning, makes it difficult to implement these concepts. Also, there is a great reluctance to integrate existing unbuilt areas, which are usually nature reserves or agricultural areas, into the natural flooding character of watercourses. The struggle between the (im)possibility of constructing the necessary water buffers along rivers and the necessity to avoid flood damage wherever possible turned into the policy of Multilayer Water Safety (2015). A sustainable reduction of flood risk is achieved by a combination of measures based on Protection, Prevention and Preparedness.
Scotland	With the passing of the Flood Risk Management (Scotland) Act in 2009, Scotland's whole approach to flood protection fundamentally changed - from one that looked to solutions based on structural defences to one that embraces sustainable flood risk management. This new approach recognises that tackling the challenges from flooding, including climate change must be a risk-based approach based on partnerships working at a catchment scale, and employing a full range of potential measures. Along with improved flood warning and forecasting services, and stricter controls on building in floodplains, Scotland is looking to utilise both 'traditional' structural flood defences and Natural Flood Management (NFM) techniques. In taking forward this strategy, The Scottish Environment Protection Agency has mapped vulnerable communities at risk of flooding and areas where NFM measures may play a part in reducing that risk. Determining how effective such NFM measures can be, where to locate them, which ones to choose and what other benefits they can

	provide alongside flood risk reduction has been the focus of much research, including Scottish Government's long-running study on the Eddleston Water.
Sweden	In Sweden the responsibility for climate adaptation and flooding are divided in different national authorities. At national level the Civil Contingencies Agency (CCA) is responsible for the flooding directive, however the landowners are responsible to protect their own property and no authority or municipality is responsible for protection. The municipalities have monopoly to plan all activities in their territory. The County administrative boards (CAB) are responsible for the flood risk management plans for the flooding areas pointed out by CCA. The complicity of the Swedish system promotes local initiatives and engagement. At the end of 1980´s, eutrophication of water bodies and lack of biological diversity in the agricultural landscape was identified. When studying land use for the period 1812-1820 compared to today, the result indicated that about 90% of the original wetlands and about 50% of the streams had disappeared in Skåne, mainly due to drainage activities to improve farming but later also due to urbanization. The understanding of the destroyed hydrology resulted in recommendations to slow down and retain water in the landscape. After that, small projects started when landowners and municipalities worked together in the beginning of 1990s to implement NBS. Now the projects have grown bigger and are supported by the Swedish State both financial and by recommendations from several agencies as a good solution in many different topics, including the guidance for risk management plans.

Table 2.1: Concise overview of the flood protection strategies in The Netherlands, Belgium, Scotland and Sweden.

2.1 The Netherlands.

2.1.1 Introduction

Rather than a specific project at a specific location, the Dutch WP4 project is a set of measures, namely side channels. Side channels are secondary channels that are connected to the main channel but are in general much smaller and convey much less discharge. For this study, side channels are considered to be channels with a certain discharge for at least 6 months per year (so no stagnant water year-round) , parallel to the main channel and with an inflow and outflow which is connected to the main flow. Their width is typically in the order of several tenths to hundred meter, and their length can be as long as several kilometers. They have been constructed for ecological reasons (e.g. as part of projects of the Water Framework Directive) or for flood management reasons (e.g. within the Room for the River programme). Side channels are found at many different locations along the Dutch Rhine branches (also within the area of interest of this Interreg project). In the last two decades, more than 20 side channels have been constructed.
Side channels increase the discharge capacity of the river, and hence, reduce flood water levels. Besides, they have added values with respect to increasing biodiversity, and with respect to recreational possibilities. The also add to the well-being of people, in the sense that flood plains with side channels contribute to the image that people generally have of natural rivers. In this sense, side channels are a typical 'Building with Nature' measure.

Side channels used to be part of natural river systems but have disappeared in the recent decades due to engineering measures. Most rivers got trained and became confined to a single channel. Floodplains got more and more disconnected from the main channel. Side channels are hence part of the dynamic environment of the river. This means that they also experience the influence of a non-stationary hydrograph and the associated sedimentation and erosion patterns. To prevent excessive sedimentation at higher discharges, most side channels have a weir at the upstream entrance. This limits the discharge towards the side channel. At the downstream end, there is a risk of large transversal flows which might hinder navigation and should therefore be limited. It is known from literature[4] that eventually, all side channels close due to sedimentation. How this happens, and on what time scale, depends on many different factors. The notion as such, however, is very important with respect to operation and maintenance perspectives of the river management. If a side channel is constructed to reduce flood levels, and the channel aggrades up to a level that the conveyance capacity is almost zero, also the flood risk reduction vanishes. And if the side channel becomes part of the flood plain, also the impact on ecology is different than is the side channel still conveys discharge. For these reasons, it is important to gain knowledge on sedimentation and erosion of side channels.

The side channel system of Gameren in the Netherlands (along the Waal River, one of the Dutch Rhine branhces) is taken as an example and study object (figure 2.1.1). This is a system of two smaller and one larger (overarching) side channel, constructed between 1996 and 1999. The large channel has a bottle neck in the form of a bridge. This results in erosion immediately downstream of the bridge, and sedimentation downstream of the erosion pit. The system has been monitored for a long period of time, and hence provides an important data-source to study erosion and sedimentation processes.

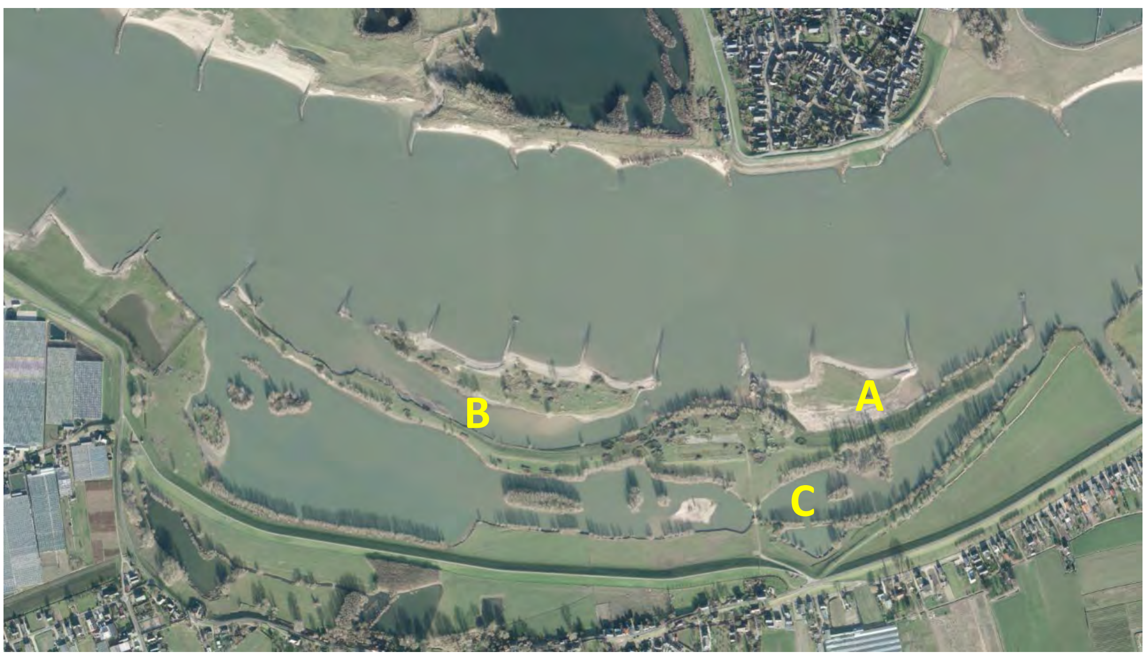


Figure 2.1.1: Aerial view of the side channel system at Gameren, along the Waal river in The Netherlands. The system consists out of an east channel (marked 'A'), a west channel (marked 'B') and a large channel (marked 'C').

In this INTERREG project, different projects related to side channels, or more general, to river restoration, are connected. An important connection is with the University of Twente, where a PhD-

[4] van Denderen, R. P. , Schielen, R. M. J., Straatsma, M., Kleinhans, M. G. , & Hulscher, S. J. M. H. (2019). A characterization of side channel development. River research and applications, 35(9), 1597-1603. https://doi.org/10.1002/rra.3462

study[5] has been carried out (finished in April 2019) on the subject of 'Side Channel Dynamics'. Part of the data gathering is done in the framework of this INTERREG project. Furthermore, there is an existing cooperation between the Environment Agency (EA, UK), the Army Corps of Engineers (USACE, USA) and Rijkswaterstaat (RWS, NL) on 'Natural and Nature Based Features'. In this cooperation, a handbook is written on coastal and fluvial aspects of NBS. This is closely related to work that is done in this INTERREG project. The experts of the BwN-project and the RWS-UK-USACE-cooperation regularly meet and exchange ideas and experiences.

Within this project, we also aim to develop assessment frameworks to compare NBS in different countries and on different scales (see also section 3). This contributes to quantify the added values of NBS with respect to grey or green-grey solutions which may help again to provide evidence, based on scientific research, for the functioning of BwN/NBS in rivers.

2.1.2 Deliverables

Inventory of side channels

As a first action, an inventory of side channels in the Netherlands was made. Within the Room for the River Programme (a EUR 2.3 billion programme to increase the flood safety in the Netherlands by applying NBS-like measures that increase the discharge capacity and lower flood levels, executed from 2002-2017) several of the 39 measures contain side channels. The same holds for the restoration project of the Meuse River. Also within the Water Framework Directive Programme (a directive to ensure that the quality of surface water and groundwater in Europe meets high standards (sound ecological status) by the year 2015/2027) numerous side channels have been constructed. A complete overview of all the side channels is given in figure 2.1.2

[5] Van Denderen, R.P. (2019), Side Channel Dynamics, PhD Thesis University of Twente

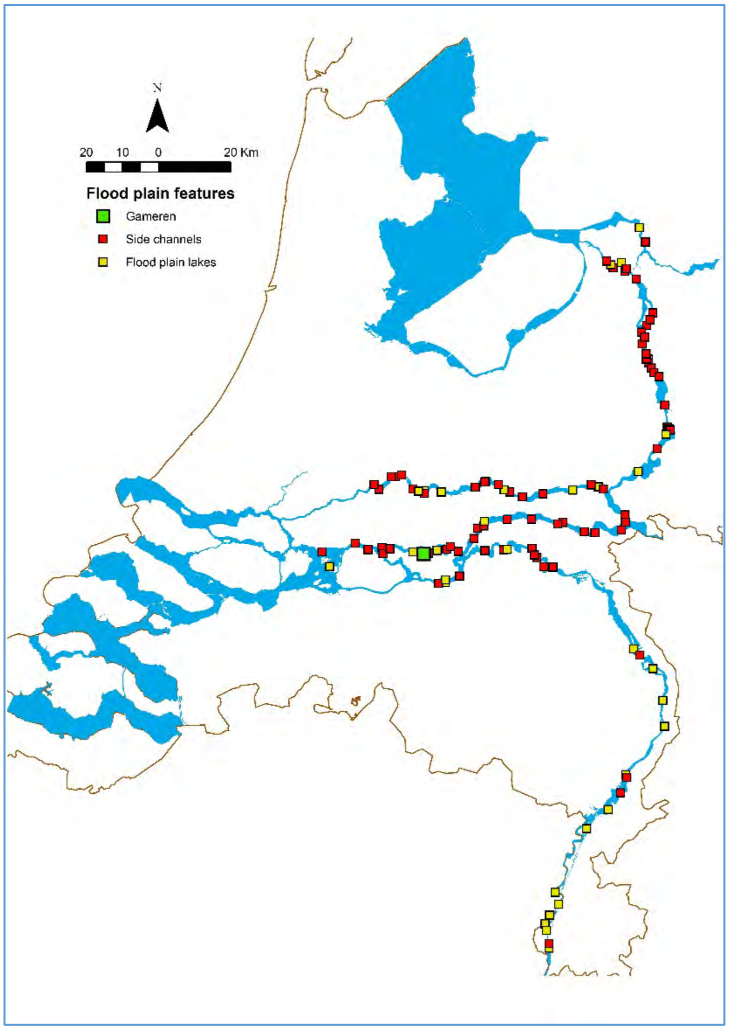


Figure 2.1.2: An overview of side channels in the Meuse and Rhine River. The Gameren side channel is indicated in green. 'Real' side channels are indicated in red, flood plain lakes are indicated in yellow.

The floodplain lakes are not 'real' side channels. These are often former sand extraction pits that are connected to the main channel. The red squares are a combination of side channels that are either connected at both the upstream and downstream side, or only at one side.

Morphological development of secondary channels: exploratory research

Based on this inventory, 17 side channels on 10 different locations have been selected for a closer study, by studying the hydraulic situation and coupling this to the morphological development. A comparison has been made between the original design and the current situation in the field. From that comparison, an assessment on whether the side channel still meets its original requirements was made and this is again a starting point for possible maintenance activities.

The analysis is based on (existing) hydraulic computations and on an analysis of a set of aerial photographs (available for a number of years). By comparing the images, sedimentation and erosion processes could be established (figure 2.1.3), and these are coupled to the actual occurred discharges (figure 2.1.4). The model results (available for a series of discharges) are used to interpret the different patterns. Is was concluded that almost all the side channels eventually aggrade with relative fine material, but the erosion itself strongly depends on the hydrograph.

The results can be used to derive guidelines for future design of side channels.

Figure 2.1.3: A result from the detailed study on the Gameren side channel system. Red indicates erosion, yellow is sedimentation, green is emerged vegetation and brown is disappeared vegetation, always between 2000 and 2019.

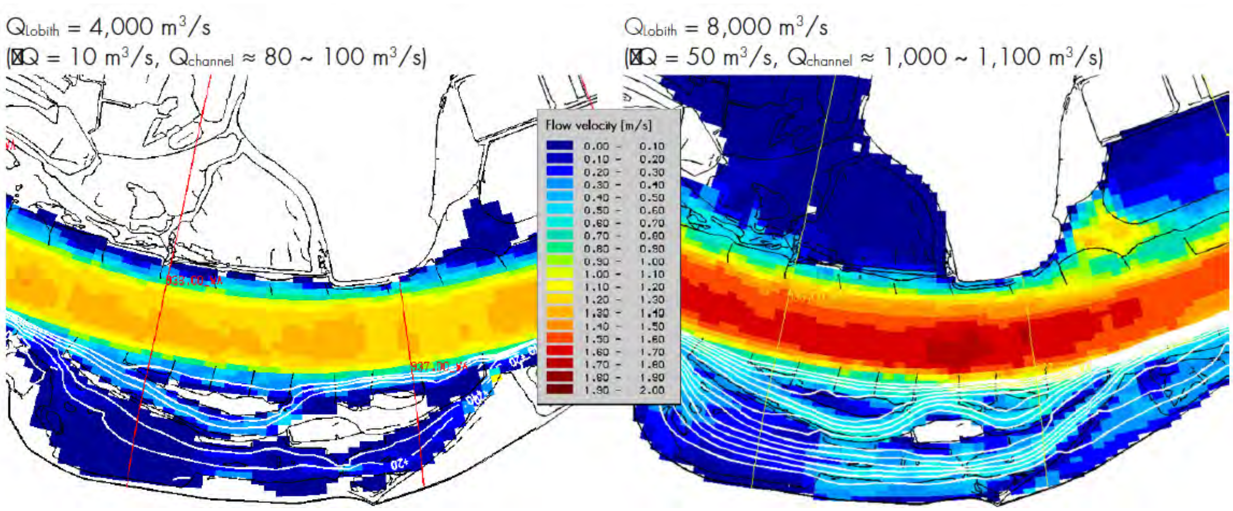


Figure 2.1.4: Model results for two discharges (left 4000 m^3/s at Lobith, corresponding to approx. 2.700 m^3/s for the Waal river at the location of the side channel, right 8.000 m^3/s at Lobith, corresponding to approx. 5.400 m^3/s for the Waal river at the location of the side channel) for the Gameren side channel system.

These results are important from the maintenance point of view. All side channels aggrade, and the rate is dependent on the hydrograph[6]. Therefore, insight into the aggradation contributes to efficient and effective management.

Discharge distribution between side channel and main channel

Knowledge on the distribution of discharge between the main channel and the side channel is also vital. In 2018-2019, measurements have been carried out at the Gameren side channel system at several discharge-stages to get an impression about this partitioning. Unfortunately, the discharge in the Waal River has not exceeded 3000 m3/s during the time of the measurements, and hence the data set is limited. The maximal discharge of the Waal river is almost 8.500 m^3/s (reached in 1926).

Results (figure 2.1.5) show that since the previous discharge measurements in 2002, the partitioning between main channel and side channels has hardly changed. It seems that the discharge towards the east channel is somewhat less compared to 2002, which might be explained by the morphological development of the channel. Since 2002, the bed level in the east channel increased (figure 2.1.6). Note also that the east channel starts to flow at considerable higher discharges than the west channel and the large channel. This is due to different inlet structures bed levels of the three side channels.

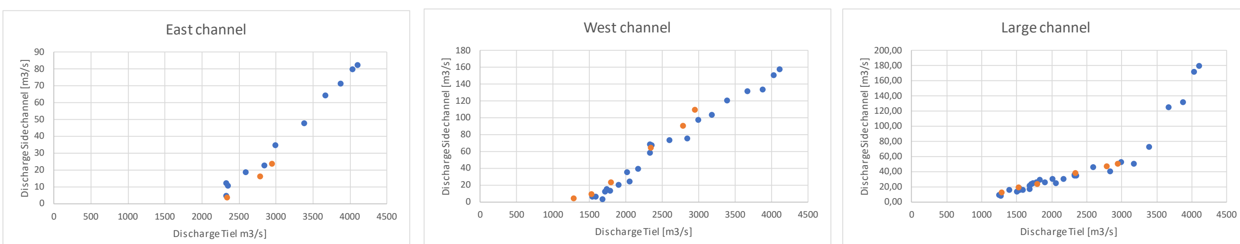


Figure 2.1.5: Discharge partitioning between main channel and side channels. In blue, the measurements of 2001-2002, in yellow the measurements of 2018-2019. In that latter period, the maximal discharge was 2938 m^3/s for the main channel (x-axis).

[6] Van Denderen, R. P. (2019). Side channel dynamics (chapter 4). PhD thesis, University of Twente, Enschede, The Netherlands. https://doi.org/10.3990/1.9789036547437

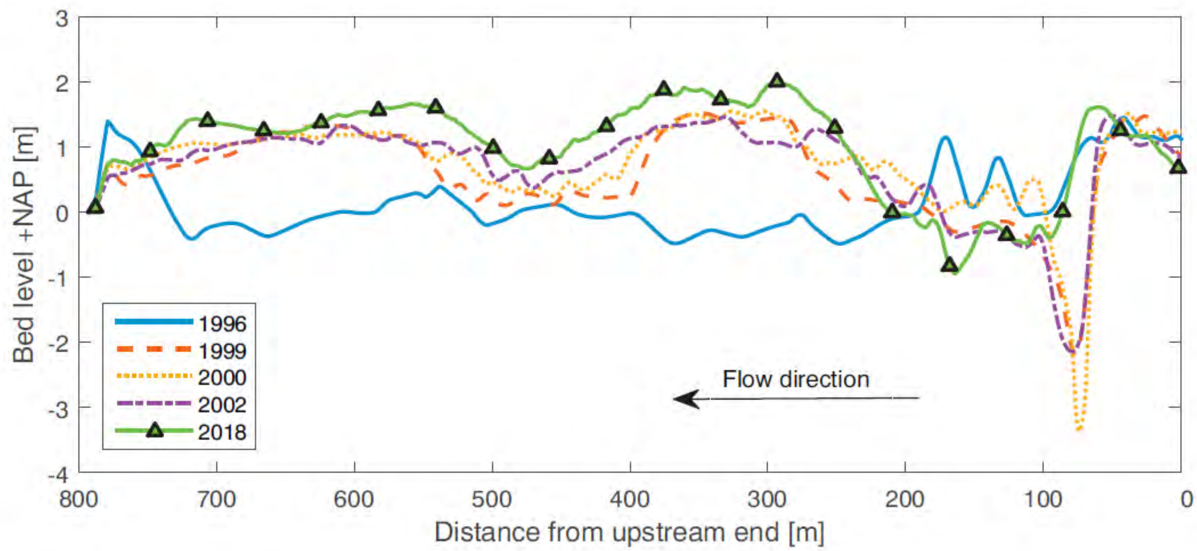


Figure 2.1.6: Bed elevation in the East-channel of the Gameren side channel system. Reproduced from Van Denderen, R.P., Schielen, R.M.J., Westerhof, S., Quartel, S. and Hulscher, S.J.M.H (2019), Explaining artificial side channel dynamics using data analysis and model calculations, Geomorphology (327), pp 93-110.

Bed composition side channels

Also, a measuring campaign took place to study the composition of the soil of the Gameren side channel system (figure 2.1.7). Simultaneously, dGPS measurements were carried out to measure the bed topography of the side channels. This work was done in cooperation with Rijkswaterstaat East Netherlands and the University of Twente. The results have been used for a BSc thesis of a student of the University of Twente (see the list of deliverables in chapter 6), were used in a paper[7] and contributed to the PhD thesis of Dr. R.P. Van Denderen. University of Twente. The campaign supported the insight that fine material that is transported as suspended bed material load in the main channel, was transported as bed material load in the side channel. The results have been used to analyze the side channel system of Gameren, and added to the general knowledge about side channel dynamics in the Netherlands.

[7] Denderen, R.P., Schielen, R.M.J., Westerhof, S., Quartel, S. and Hulscher, S.J.M.H (2019), Explaining artificial side channel dynamics using data analysis and model calculations, Geomorphology (327), pp 93-110.

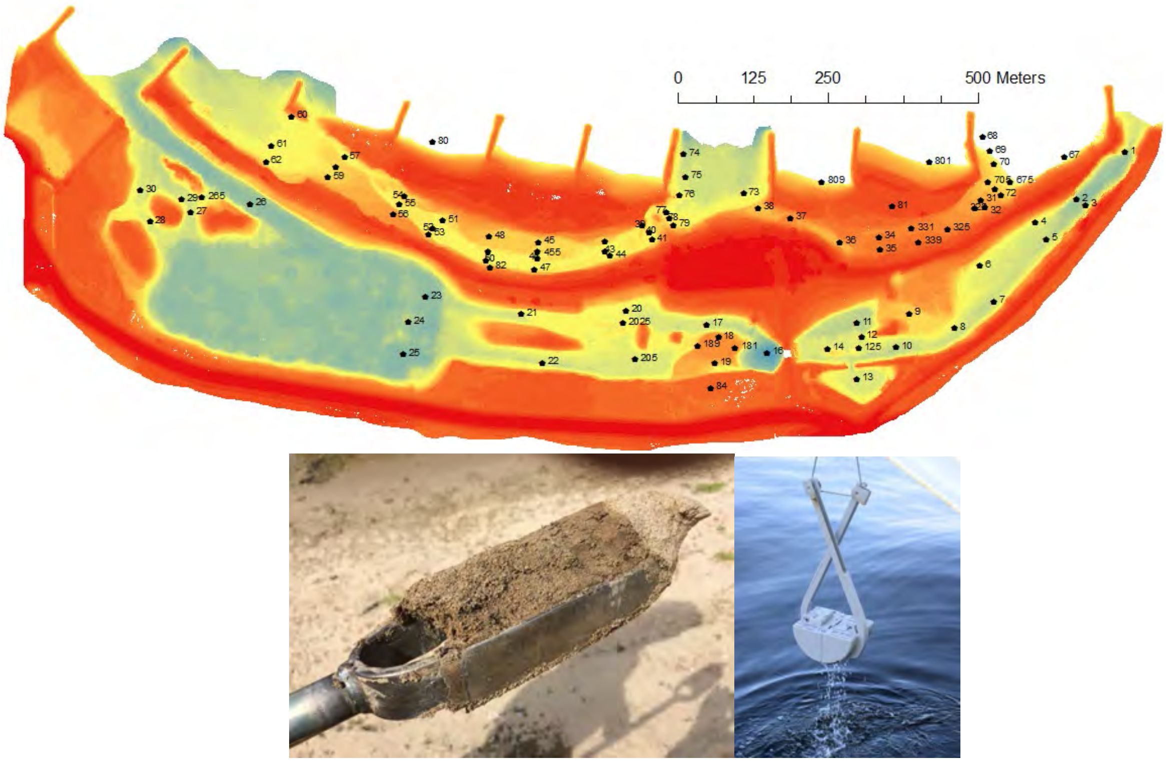


Figure 2.1.7: Location where samples have been taken and the instruments with which they have been taken.

Bed topography of side channels

Insight in to the time-evolution of the bed topography of side channels is crucial in order to understand the relation between discharges and the sedimentation behavior in side channels. This knowledge can be used to understand the time scales on which side channels may close (and hence lose their function). Rijkswaterstaat measures the bed topography of the main channel twice a year, but the side channels are measured far less frequently. This has to do with the fact that the channels are not always accessible with the vessels that carry out the monitoring. Therefore, a pilot was carried out to see if there was an alternative method available for monitoring the bed topography of side channels. For this, experiments have been carried out with a fishfinder, which is a small device that is used by fishermen to locate fish. The device sends out a signal, receives the reflection and is able to determine the location of fish. However, the data can also be used to measure the bed topography. In the pilot, the topography of one of the side channels has been measured by mounting the fish finder on a small boat and sail around in the side channel. The data was validated by dGPS readings. The conclusion was that the fishfinder is an alternative for multibeam measurements, although there are restrictions (figure 2.1.8). Measurements with the fishfinder need to be sufficiently dense, in order to be able to interpolate between the different tracks and get surface-wide information about the bed level. Also, it was recommended to carry along a dGPS in the vessel to increase the accuracy.

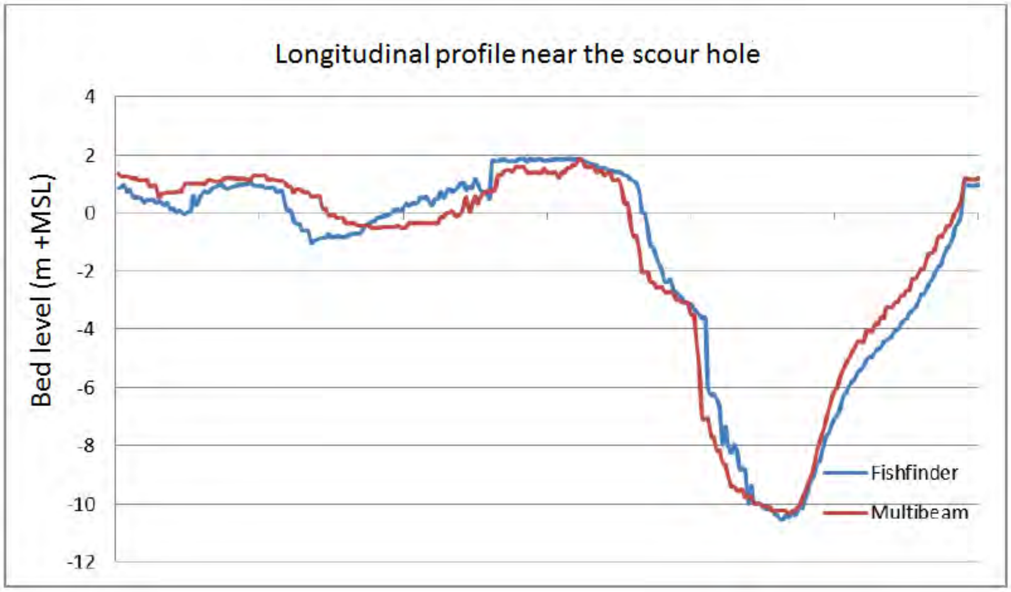


Figure 2.1.8: comparison between multibeam measurements and the fishfinder data, at a location near the bridge over the large channel in the Gameren side channel system.

Conclusion

The activities carried out in the framework of this Building with Nature project have been combined with existing projects within Rijkswaterstaat, and with more scientifically based projects at universities. The combination of these activities clearly contributed to insight in the functioning of side channels, with respect to erosion and sedimentation patterns, with a clear relation to the hydrograph. Besides, valuable insight in the timescale of closing of a side channel was gained. Moreover, it provided insight in the properties of side channels as possibility to apply as BwN. These insights have been used in the first version of an assessment framework for BwN, which has been developed within this BwN-project[8].

2.2 Belgium

2.2.1 Introduction

The Kleine Nete is a rain river which winds across the sandy north-east of Flanders as a blue-green ribbon. It is one of the most natural rivers in the dense populated Flanders. On one hand, the agriculture sector, which is the principal land user along the Kleine Nete, holds the water in case of high floods. Buildings are rare and so from a hydrological prspective, the valley seems mainly unspoiled. On the other hand, the valley of the Kleine Nete is ecologically very valuable, protected by Flemish and European legislation. Significant populations of rare fish species can still be found here.

However, the river itself has endured some changes in the 1970s. To make the wet valley grounds more suitable for large-scale agriculture, the river was straightened, broadened and deepened. This has several consequences. The water is evacuated more efficiently, which increases the flood risk in downstream areas. The groundwater levels went down due to the enhanced drainage, causing a loss of groundwater dependent habitat and species. It also meant a loss of natural habitat and migration facilities of biotic communities within the water system and consequently a decline of the ecological

[8] Huthoff, F. Ten Brinke, W., Schielen, R., Daggenvoorde, R., and Wegman, C. (2018), Evaluating Nature-Based Solutions, Best practices, frameworks and guidelines, Technical report PR3812.10, HKV Lijn in Water

value of the Kleine Nete valley. As the embankments are located very close to the river, they are vulnerable to erosion. Therefore, they need continuous maintenance. Water storage capacity has been lost by, for example, building of dikes, cutting off meanders and elevation of grounds by landfills from different sectors (agriculture, recreation, etc.).

To mitigate the major disturbance of the river system, a river restoration programme was set up. The goals are:

- Creation of more water storage capacity
- Realisation of ecological added value
- Restoration of the structure of the water course

The projects in the river restoration programme are:

- fish passages at weirs (established)
- excavation of a former sand disposal area of 15 ha (works in progress)
- creating ecological flooding zones at recreation areas (design ongoing)
- dike replacement and construction of a winter bed (established and proposed)
- remeandering and construction of a swamp area (established).

Figure 2.2.1: Overview river restoration programme Kleine Nete

Three recreation areas are situated along the Kleine Nete at the municipality of Kasterlee. These recreation areas have an economic function. Therefore, it is not obvious how one could easily make alterations to the water course here. The economic sector is on one hand vulnerable to the consequences of climate change, e.g. increased flood risk, and on the other hand not willingly to cede space which currently has an economic function to river adaptation works, e.g. water storage areas. It is a challenge to find innovative solutions that allow for multifunctional use of the space.

Rearranging the bank zone of the Kleine Nete, creates a win-win situation for both the river and the recreation areas. It means that we are looking for an innovative solution in which the functions of the water course and recreation are combined. This is understood as multifunctional use of space. The project can be considered as a pilot project / laboratory on how hard, rather than economic allocations can be conformed to water and ecological systems.

The recreation areas attract lots of people, which provides opportunities to install educational facilities to create flood-awareness. For most people, enterprises and even local authorities, climate change and its consequences are something they have heard of, but they don't know how it affects them nor which actions they should take. It is not considered a priority. The challenge is not only to inform the different stakeholders (local communities and authorities, enterprises, etc.), but also to involve them actively in the elaboration of development measures. This way creates more awareness, responsibility and understanding of the need for public works required.

The hydraulic impact of the river restoration programme is modelled in Infoworks RS (a 1D-river modelling package). The figure below gives the results for inundation once in 10 years.

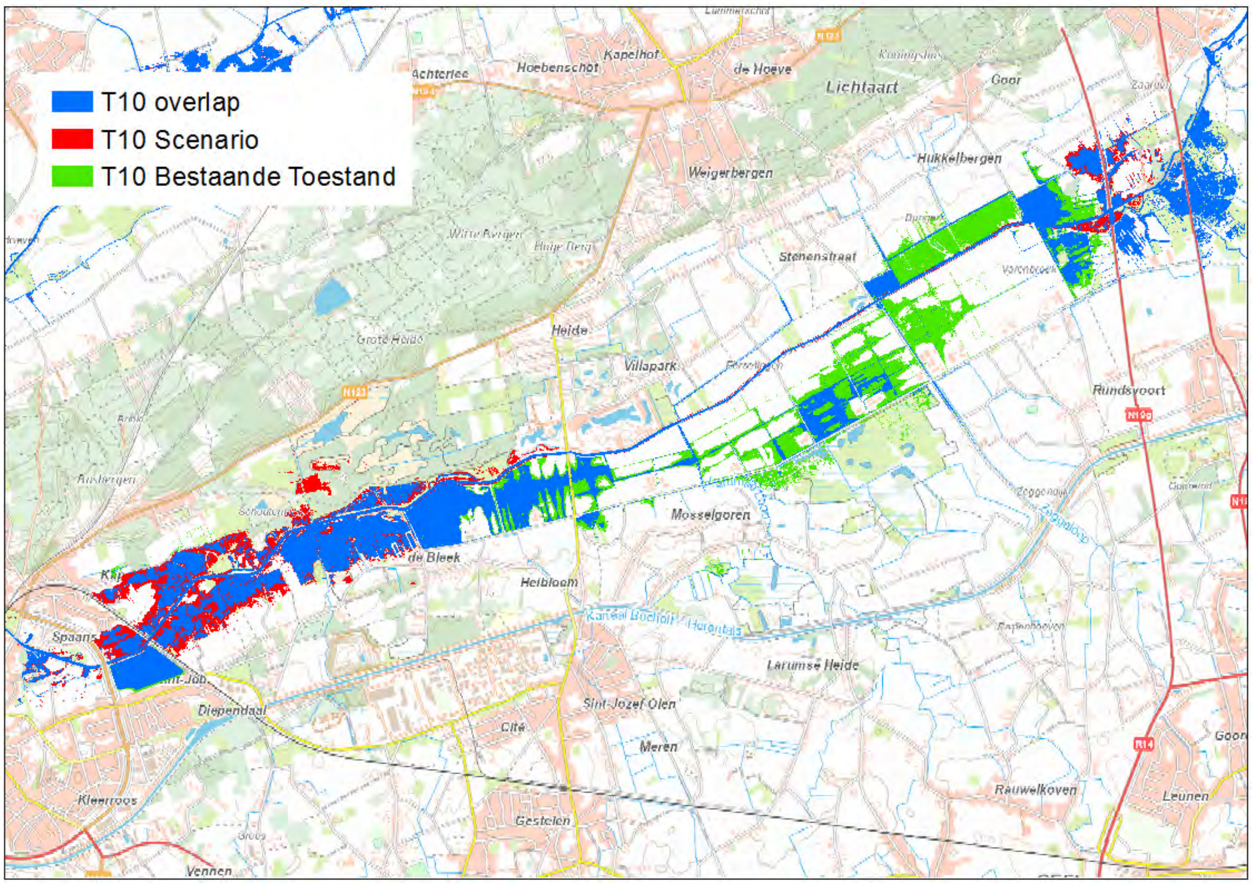


Figure 2.2.2: Change in inundation if river restoration programme is executed – inundations once in 10 years (blue: current inundation unchanged – red: additional inundation (allowed in nature area) – green: current inundation disappeared)

2.2.2 Deliverables

Analysis of project areas and definition of methodology

As a first step, the context of each of the three recreation areas was clarified. Clearly, the context differs for the three sites: the camping site *Korte Heide*, the amusement park *Bobbejaanland* and the recreation site *Ark van Noë*. An analysis was made of the specific characteristics at each site. This was done by using several thematic layers, e.g. water system, elevation model, accessibility, green structure. Any preconditions concerning the exploitation of the recreation areas were also listed. Additionally, the key stakeholders were defined.

To start the design study, a methodological approach was set up to explore as many potential solutions and design scenarios as possible. First of all, various water storage principles were identified at a conceptual level. A distinction was made between (1) dike relocation, (2) remeandering, (3) buffering and (4) sequential use. The purpose of (1) dike relocation is to widen the cross section of the river by constructing winter dikes. Remeandering (2) involves connecting a parallel water structure to the river. This can be done by connecting cut-off meanders to the Kleine Nete or by excavating new meanders. The connected meanders can serve as main channels or side channels of the Kleine Nete. The purpose of (3) buffering is to connect an external water buffer system to realise higher storage capacity. This external buffer system can be part of the river system, the groundwater system or, if appropriate, an artificial water buffer system. Finally, (4) sequential use refers to alternating a specific function after a particular period of time.

The best water storage principles to meet the objective set out in the river restoration programme were examined, including creating extra storage space, creating ecological added value and structurally restoring the watercourse. The spatial opportunities for each sub-area were also examined. Each sub-area has its own specific spatial characteristics and each water storage principle has a different impact on the landscape. Depending on the needs and characteristics of each sub-area, different combinations of interventions are possible.

Design study

A design study was carried out to gain a better insight into the water storage options at the three recreation areas. To this end, various spatial concepts were explored including, for example, relocating the dike, allowing the meander or parts of it to flow along with the stream, and using other water bodies for water buffering. Some of these options were then further developed into design options which, after careful consideration with stakeholders in the steering group, were used to select the preferential design. Within Work Package 4, two workshops were organised to gather ideas about possible measures.

As a next step, the preferred design was further developed and details were examined. This resulted in an elaborated vision with design plans and visualizations. This information was included in a report "*Design of ecological water storage areas in recreational areas along the Kleine Nete river*"[9].

The preferred design for the three recreation areas is described below.

Camping site *Korte Heide*

[9] Cluster landschap en stedenbouw, Design of ecological water storage areas in recreational areas along the Kleine Nete river, January 2019.

The design consists of:

- Reconnection of a part of the old, cut-off meander to the river. The other part will be kept in use as a fishing pond, as it is more difficult to create a new fish pond further from the river where the ground level is higher. To divert the water into the meander, an underwater dam will be placed in the main stream.
- The area between the meander and the river will be turned into an ecological place which can flood in case of storms with a return period of 10 years. Summer camping is still allowed, but there will be no infrastructure. A total number of 53 camp sites has to be removed for compensation of areas in the north.
- Two compensation zones will be used to relocate the 53 camp sites. At the moment, these zones are covered with conifers, which will be cut down (28.000 m²)
- A small stream around the camping site will be upgraded and connected to the Kleine Nete river system.

-

Figure 2.2.3: Preferred design Camping Site *Korte Heide*

Amusement park *Bobbejaanland*

The design consists of:

- Creating a 10m buffer strip between parking and river (loss of 50 parking places).
- Constructing a new meander: 4.50 m. bed-level width (loss of 164 parking places). To conduct the water into the meander, an underwater dam will be placed in the main stream.
- Creating a parking island between meander and Kleine Nete which can flood in case of storms with a return period of 10 years.
- Construction of a new two storey parking garage to compensate for loss of parking places. The garage itself will cause a loss of 96 parking places on the ground level. However one level of the garage will store 307 cars and therefore compensates for the loss of the existing spaces. If the

amusement park wishes to increase the parking capacity, it is possible to make a further level in the parking garage.

-

Figure 2.2.4: Preferential design Amusement Park *Bobbejaanland*

Recreation site *Ark van Noë*

The design consists of:

- Dike improvement works along the Kleine Nete using natural materials.
- Reconnection to the river of an old, cut-off meander. To conduct the water into the meander, an underwater dam will be placed in the main stream. This will be combined with a kayak quay.
- Re-organisation of the entrance to the site to increase the water experience. Parking places will be relocated to the north of the meander. Visitors will enter the site by a new footbridge.
- Rebuilding of facilities which will get lost due to the reconnection of the meander (children's farm, fishing pond, etc.)

-

Figure 2.2.5: Preferential design recreation site *Ark van Noë*

Studies to come to realization

The final goal is to build the preferred design in reality. In order to realise the desired construction works, different studies have to be executed. These studies are different for each recreation area, as they all have their own specific characteristics. For that reason, the path to come to realisation is different and independent for each recreation area.

Camping site *Korte Heide*

The preferential design does not fit within the existing spatial prescriptions. The procedure to change the spatial prescriptions has started and is ongoing, but will take at least until 2023. Different documents concerning this procedure are being composed. Related to this, a study about financial aspects of land prices, change of property, change in spatial prescriptions and more has also been started up.

Secondly, different studies to develop the design of the compensation areas are ongoing: allotment of the compensation areas, design of the utilities, etc.

In a later phase, the project will be fine-tuned by specific studies about e.g. environmental impact assessment, archaeological research, soil pollution research, soil mechanics research, topographical surveying, resulting in a final technical design. Contiguously, the application documents for a building license and the tender documents to appoint a constructor will be composed. The goal is to finish all this preparation work before 2023, so the works can start directly after the Development Plan Document is approved.

Amusement park *Bobbejaanland*

The political decision is made that the rearrangement of the bank zone should fit in to a broader masterplan that also counters other aspects like mobility. The development of this masterplan is set for the long term (2020 - 2030). In expectation of this masterplan, no specific actions are undertaken to realise the preferential design.

Recreation site *Ark van Noë*

The project has been fine-tuned by specific studies about e.g. environmental impact assessment, archaeological research, soil pollution research, soil mechanics research, topographical surveying and others, resulting in a final technical design. The Environmental Impact Assessment (EIA) report has to be approved before the application for a building licence can be submitted. The approval procedure of the EIA is ongoing and is expected to result in a positive advice in the autumn of 2020.

Contiguously, the application documents for a building license and the tender documents to appoint a constructor will be composed. The goal is to start the construction works in the autumn of 2021.

2.2 Sweden

2.2.1 Introduction

The catchment area of river Råån is situated near the city of Helsingborg. Land use is dominated by agriculture, especially in the upper parts, where a majority of the streams are dredged and canalised to improve drainage capacity (Table 1). In the middle parts the river runs through a valley where the floodplains are used for grazing by cattle. Less dredging has been done in this part and the river still meanders through the valley. In the lower parts much of the land is made up by urban area.

In 1991 the municipalities in the catchment of Råån started to reconstruct wetlands and ponds and restore streams in order to increase the retention time of water in the landscape. About 70 new wetlands have been constructed in the catchment of Råån. The constructed wetlands are very different and comprises small ponds (0,2 hectares) and bigger shallow wetlands up to 17 hectares. The projects have been funded by different public contributors and the Municipality of Helsingborg also have an own budget for water conservation.

Most of the case studies in Råån has taken place in The Lussebäcken stream, a small tributary (20 km^2) to Råån river. The stream has historically been straightened and deepened, like almost all water courses in the agricultural landscape in the south part of Sweden.

Furthermore, drainage and urbanization in the catchment has caused an increase in impermeable surfaces, and consequently created a faster runoff to the stream. This could potentially cause flooding in the city of Helsingborg (see *Figure 2.3.1*).

Since the end of the 1990s the Municipality of Helsingborg has performed various nature-based measures in the catchment of Lussebäcken. The aim has been to reduce peak flows, and at same time increase biodiversity and reduce nutrient transport to the sea. Approx. 20 ponds and wetlands have been constructed. A few stretches of the stream have also been rehabilitated to a two-stage channel design.

Table 2.3.1 Characteristics of river Råån catchment.

Catchment área: 193 Km^2					
Land use		Flow		Precipitation, average	700 mm/yr
Agriculture	81 %	HQ	33 m^3/s		
Urban	13 %	MHQ	15,8 m^3/s		
Forest	6 %	MQ	1,6 m^3/s		
		MLQ	0,12 m^3/s		

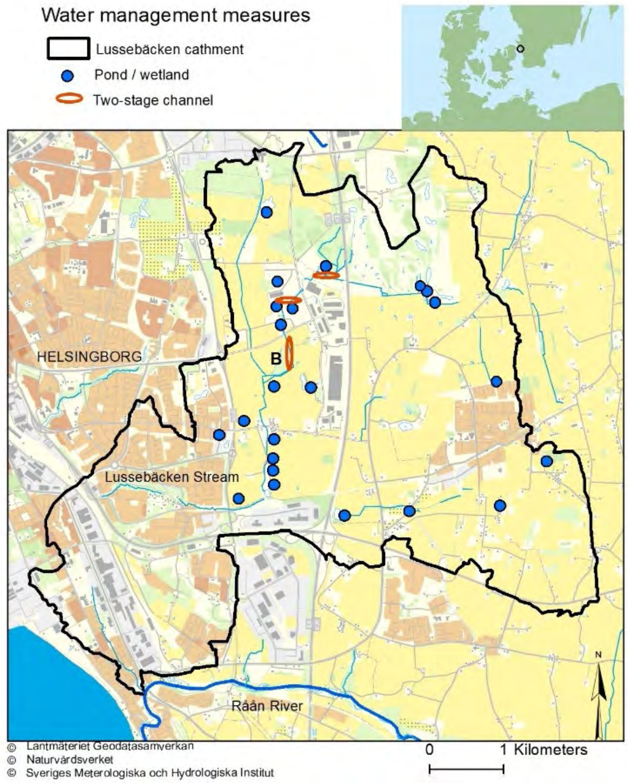


Figure 2.3.1. Water management measures in catchment of Lussebäcken. B shows the location of modelling discharge presented in figure 2.3.5.

Two-stage channels are designed to mimic the stable conditions found in natural streams. The design consists of a low-flow trapezoidal channel, with capacity to convey the often-recurring hydrological conditions. On top of the banks of the low-flow channel, small vegetated benches on both sides are situated to serve as a floodplain.

Building with Nature has provided an opportunity to study the effect of the implemented water management in the Lussebäcken catchment and River Råån. Focus has been on:

- the cumulative effect on hydrology
- the performance of two-stage channels of different designs and ages
- the effect of two-stage channels on nutrient transport
- the long-term effects on fish and invertebrates in Lussebäcken stream and Råån river.

Also, GIS analyses have been performed to identify:

- flood risk prone locations in the county of Skåne.

A hydraulic modelling (1D hydraulic model) has been used to compare the current state to a scenario without water management. In order to study the effect of the urbanization, the runoff coefficient has been differentiated based on the land use distribution in 1969 and 2019.

Hydraulic modelling has also been used to study the performance of two-stage channels on three stretches. The model was calibrated and validated using site-specific water level recordings and conservative-trace derived parameters.

Two of the studied two-stage channels were constructed in 2001-2002 and one stretch was constructed in 2015. The latter (see *Figure 2.32*) has no shading, and therefor has a very dense in-channel vegetation. As a result, the entire channel is filled with trapped fine sediments. One of the older stretches (see *Figure 2.3.3*) is partially shaded by growing trees and shrubs, but in-channel vegetation has led to heavy sedimentation. The stream demonstrates low level of sinuosity and no real riffle-pool sections. The other older stretch (see *Figure 2.3.4*) has a more natural like appearance. It is today heavily shaded by mature alder trees and thus lacks in-channel vegetation. The stream has regained a marked sinuosity and sediment is dominated by gravel and fine sand, but few real riffle-pool sections are present.

*Figure 2.3.2***.** The two-stage channels design was constructed in 2015. The lack of shading has led to a dense in-channel vegetation.

Figure 2.3.3. This stretch was constructed in 2002. It is only partially shaded. In-channel vegetation has led to heavy sedimentation. It lacks sinuosity and has no real riffle-pool sections.

*Figure 2.3.4***.** Constructed in 2001, this stretch is today heavily shaded by mature alder trees and thus lacks in-channel vegetation. It has regained a marked sinuosity and sediment is dominated by gravel and fine sand.

Transport and deposition of sediments and nutrients have been studied using SorbiCells (a passive measurement system with which concentrations of sediments and nutrients in water over a longer period can be measured), grab sampling and sediment traps. Two-stage channel floodplains can trap significant amount of sediment, and therefore phosphorous. Main-channel prevailing dimension and in-channel structures, as well as flow pattern distribution during overbank stage, are driving parameters.

Studies on the effect on biodiversity were done in the two-stage channels to assess impact on riparian biodiversity in contrast to a standard agricultural ditch. Analyses were also done to asses long term trends in monitoring data for benthic invertebrates and fish in the catchment of Rååån.

2.2.2 Deliverables

From the hydraulic modelling it is seen that the measures implemented in the catchment of Lussebäcken have a positive effect by reducing peak flows and flooding extent (see *Figure 2.3.5 and Figure 2.3.6*). Based on results from the flood mapping of the current state of the water course, it is concluded that Lussebäcken can withstand a 100-year flood event well, which would not be the case without the water management. Moreover, implemented measures have a far bigger effect on the hydraulic conditions than the increased urbanization between the years 1969 and 2019.

Even though the effects of implemented measures on hydrology are positive there is still room for optimization. The available volumes in the water management measures are not completely used. By adjusting the outlet capacity from ponds and wetland, either by new weir designs or smaller outlet diameters, several thousands of additional cubic meters can be further retained.

The hydraulic modelling of the two-stage channels in Lussebäcken compared to trapezoidal drainage channel shows that water depth associated with 1.5 year-recurrence can be reduced by ca. 5% and water velocity can be reduced by ca. 80%. This leads to an increase in hydraulic residence time which results in reduced erosion and increased retention of sediments and nutrients.

However, two of the stretches (*Figure 2.3.2* and 2.3.*3*) have raised water depth and low residence time due to dense in-channel vegetation. As seen in *Figure 2.3.4*, extended shading can significantly impede emergent in-channel vegetation. This highlights the importance of creating conditions, either by pre-emptive design and/or planned maintenance, that maintain low flow velocities high enough to prevent sediment accumulation and impede in-channel vegetation establishment. Early tree planting and species selection is therefore part of ensuring the safeguard of the two-stage channel hydraulic performance.

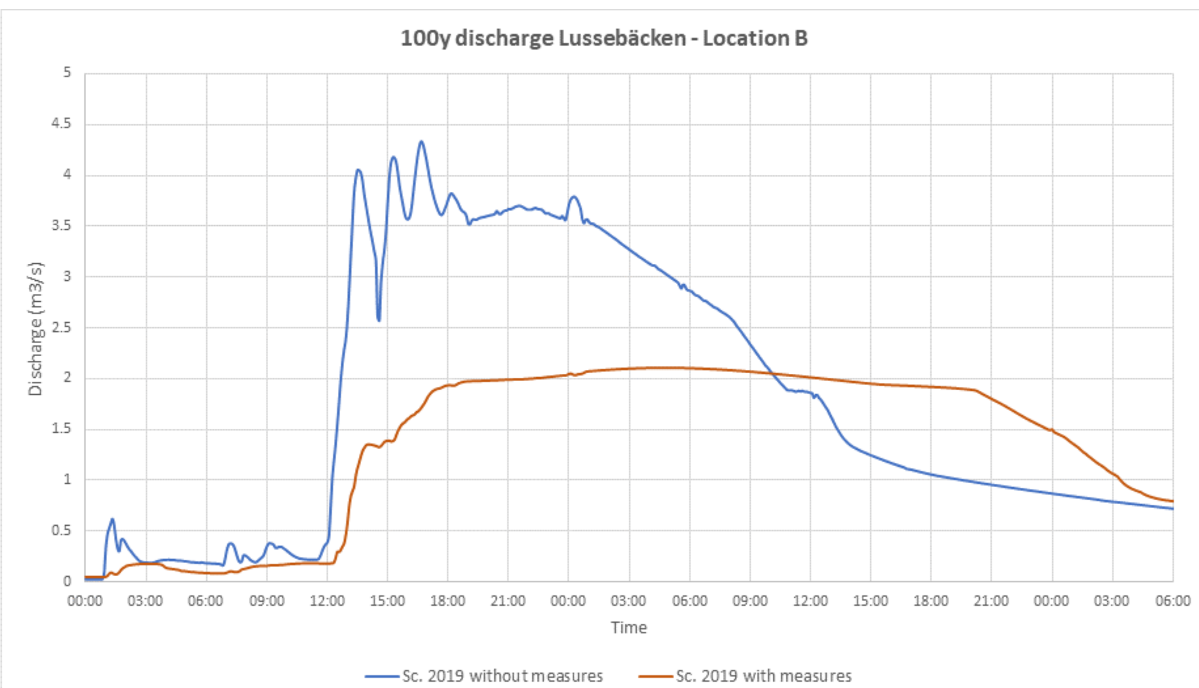


Figure 2.3.5. Modelling of discharge of a 100-year rainfall in location B (see *Figure 2.3.1*) with and without water management measures.

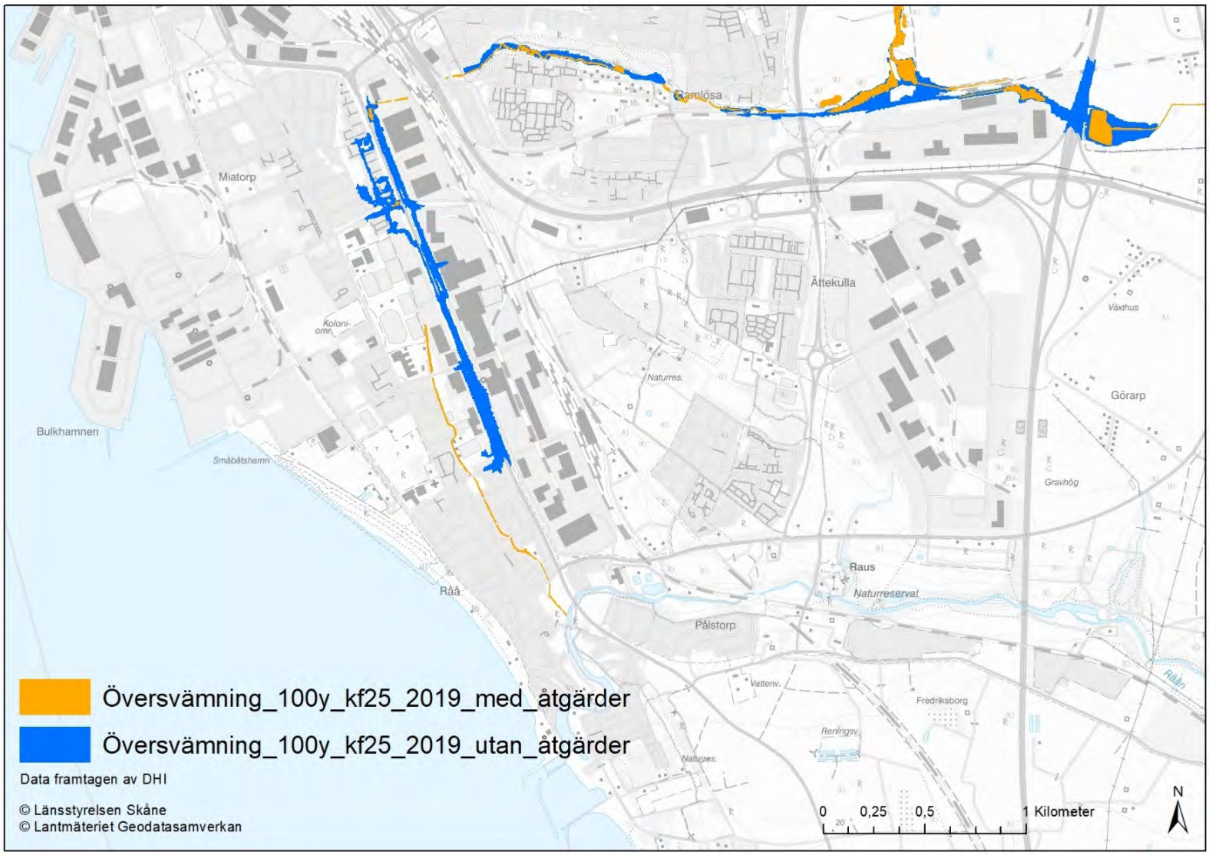


Figure 2.3.6. Flooded areas in the lower part of catchment Lussebäcken. The map shows flooded areas with measures (yellow) and without measures (blue) indicating that water is distributed in connection with measures upstream avoiding flooding downstream.

The study of nutrient transport shows that the amount of phosphorus collected on the studied two-stage channel floodplains although significant, is on the lower range when compared to amounts retained by wetlands in southern Sweden. This overall performance could significantly be improved by ensuring that re-suspended particles' transport is reduced by establishing vegetation on the floodplains, increasing overbank flow frequency and by substantially improving transversal exchange with the floodplains.

Improvement of the biodiversity of benthic invertebrates was observed for the mid and lower sites of Råån. The data could however not prove that the improvement was caused by the water management measures. Figure 2.3.7 shows an example of the results of benthic invertebrates for a location were measures has been implemented.

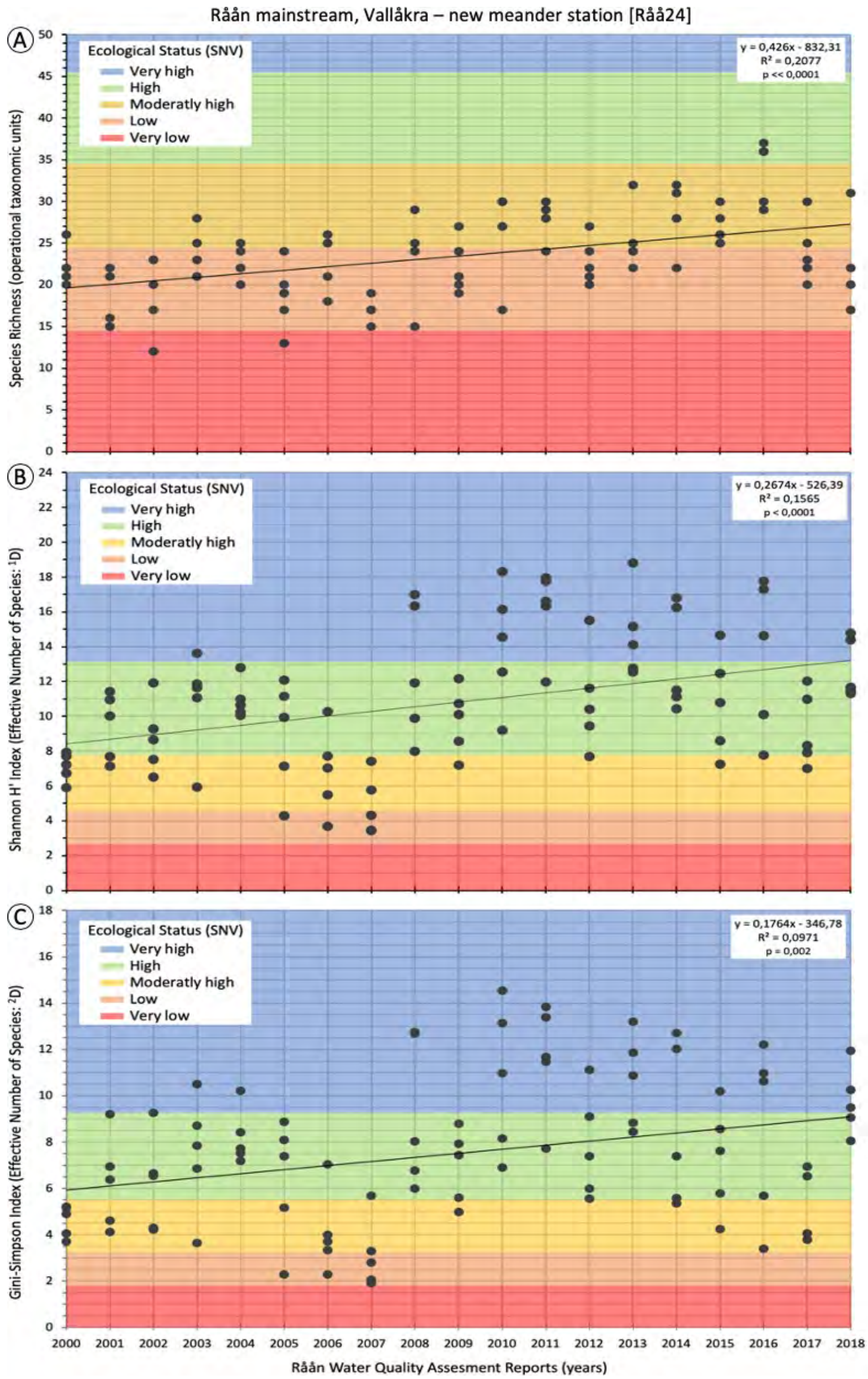


Figure 2.3.7. Benthic invertebrate diversity trend at Vallåkra – new meander station [SKA-Råå24] in the mid Råån reach: A) Species Richness; B) Shannon H' diversity index; and C) Gini- Simpson ENS evenness index. All indices represented as Equivalent Number Species.

2.4 Scotland

2.4.1 Introduction

The Eddleston Water Project (EWP) aims to reduce flood risk and restore the Eddleston Water for the benefit of the local community and wildlife. The EWP is:

- investigating the possibility of reducing the risk of flooding to the communities of Eddleston and Peebles by restoring some of the original natural features of the catchment;
- improving the river habitat for wildlife and fisheries;
- working with landowners and communities in the Eddleston valley to maximise the benefits they would gain from such work.

The Eddleston Water is a small tributary of the River Tweed, flowing 20 km north to south before reaching the main river in the town of Peebles. Over time, the course of the river has been extensively altered and long sections were straightened in the early 19th century. Other changes in land management, both in the river valley and on surrounding hill slopes, have also altered how the land drains. Together, these changes have resulted in an increased risk of flooding to several downstream communities, such as Eddleston Village and Peebles, as rainfall and flood waters travel ever more quickly and directly from the hill slopes and along the river channels towards these communities. At the same time, these changes have also damaged the river environment itself, leading to the loss of over a quarter of the river's original length, and habitat loss for plants and animals, including salmon and trout, as well as rare and protected species such as otters and lampreys.

Tweed Forum, project managers for the Eddleston study, have worked with land managers to introduce changes to current land management practices in order to slow water flow from the hills, create floodwater storage areas and reconnect the river with its floodplain. So far working with 20 farmers, the project has implemented a wide range of NFM measures, including:

- 207 hectares of riparian and headwater woodland planted with 330,000 native trees which will help increase rainfall interception, evapotranspiration, soil infiltration and reduce the speed of overland flow;
- 2.9km of previously straightened river channel re-meandered (see also figure 2.4.1 and 2.4.2). This has increased river length, reduced the slope and speed of flowing water and provided more space for floodwaters, as well as creating new habitats and improving the landscape;
- 116 'high flow restrictors' (engineered log structures) installed that will encourage out of bank flow and hold back water in the headwaters and
- 29 run-off attenuation features and ponds created. These wetland features have a good deal of 'free board' built in so that they store water during intense rainfall events.

The EWP works with local schools, colleges, scientists, policy makers, advisory services and farmers by hosting field trips and study tours to show what can be achieved on the ground to reduce the effects of flooding and achieve multiple benefits in a working landscape. Stakeholder engagement and knowledge exchange is a key element of the EWP.

Monitoring the effects of these measures is an important part of the EWP. A very detailed network of rain gauges, groundwater and river level gauges have been installed throughout the valley to collect data on how the changes affect river flows and flood frequencies. This is complemented by parallel monitoring programmes covering hydro-morphology and ecology which will reveal what changes occur to the river's habitats and wildlife, including fish, aquatic invertebrates and vegetation. Detailed monitoring and modelling of the groundwater has also been undertaken at a site close to Eddleston Village.

Figure 2.4.1: Aerial view of remeandered stretch of the Eddleston Water at Lake Wood looking downstream.

The EWP is a partnership initiative led by Tweed Forum, with the Scottish Government, Scottish Environment Protection Agency (SEPA) and University of Dundee. Other key partners include British Geological Survey and Scottish Borders Council, with further support from NatureScot, Scottish Forestry, National Farmers' Union of Scotland, Tweed Foundation, Forest Carbon and the Woodland Trust. Tweed Forum works closely with landowners and the local community who are so important to the project, so that everyone can contribute ideas and follow the project's progress.

The EWP is influencing how NFM is implemented in Scotland. Scotland's current flood risk management strategies and local flood risk management plans include a total of 104 actions with an NFM element, most of these being studies. These studies will further develop the contribution NFM can make to reduce flood risk to identified areas.

Figure 2.4.2: Remeandering the river channel at Milkiston, in 2016. Left: Gravel extraction, Right: Excavating the new channel, witnessed by some of the team-members from Work Package 4.

2.4.2 Deliverables

Funding from the Building with Nature programme has been used to enhance development of this long-term study of NFM in Scotland. New areas include detailed monitoring of aquatic invertebrates and fish populations; a fluvial audit of the whole catchment, and the improved monitoring of flows and water levels. In addition, a combined hydraulic-hydrological model of the catchment has been developed to explore the impact of different combinations of NFM measures. Finally, ongoing work is exploring the costs and benefits associated with the use of NFM measures, including the potential provision of a range of ecosystem services (over and above flood risk reductions), including biodiversity, carbon storage, water quality and recreation improvements, and how these can be integrated in to flood risk options appraisal.

Monitoring strategy:

The Eddleston Water project has taken an empirical approach from the outset with, latterly using this wealth of data to help build a combined hydraulic-hydrological catchment model. From the beginning, we have worked hard to ensure that monitoring of the different elements and parameters (hydrology, ecology, etc.) is coordinated both spatially across the catchment and temporally. To this end, an important part of the Monitoring Strategy was to establish the monitoring network before any NFM measures were introduced.

Following completion of the scoping study in 2009, the network of weather stations and river gauges was installed (figure 2.4.3), and two years of data were collected before the first re-meandering, log structures, ponds and tree planting were begun. Where possible, this 'Before and After' research design was enhanced by the addition of Controls where no NFM measures were introduce alongside the Impacted stretches, so that we had a full BACI design in place for investigation of, for example the impact of re-meandering the previously straightened stretches of the river channel. In addition, the funding from the EU Interreg Building with Nature programme has enabled the project to continue monitoring for more years than is usually possible, so that recovery of the river following restoration can be followed.

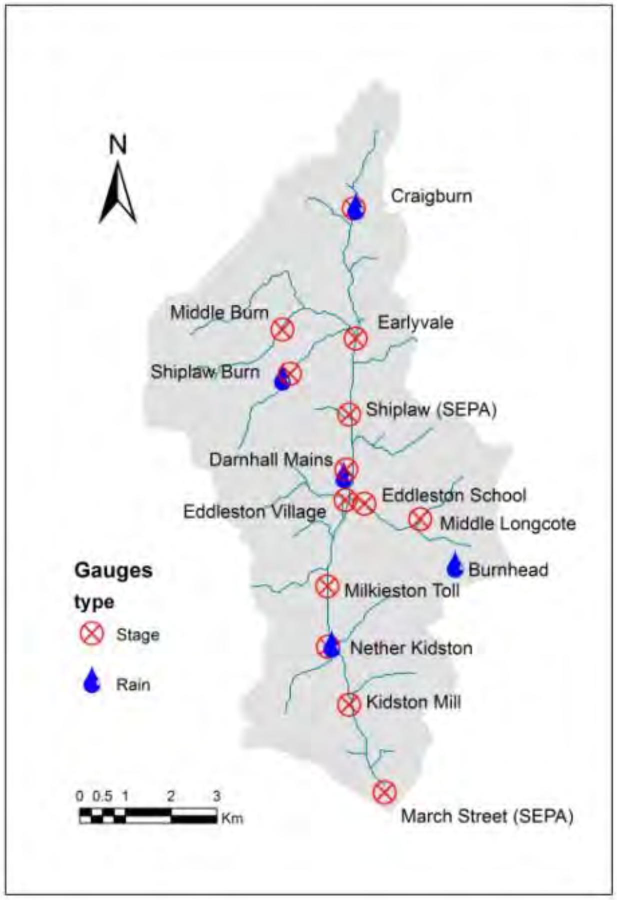


Figure 2.4.3: The Hydrological monitoring network, comprising 13 stream gauging stations and 4 Tipping Bucket Rainfall. Baseline data collected prior to any NFM measures from Spring 2011-2013

Engineered Log structures

116 engineered log structures (leaky barriers, see figure 2.4.4) have been installed in the headwater streams, using local materials available on site to build a series of structures on two streams. These work to temporarily hold back water in times of high flow, but to allow unhindered flow and fish passages underneath at other times. Their effectiveness in delaying peak flows and reducing flood peaks is being assessed in comparison to flows recorded in parallel streams where no structures have been put in place.

Emerging results show the effectiveness of installing these engineered log structures in the upper catchment, both in terms of delay in time of flood peak downstream and reductions in flood levels. Lag time between rainfall events and the resultant flood peaks in headwater streams where these NFM measures have been installed has shown an increase by over 2.6 hours compared to 'untreated' streams (see figure 2.4.5). This change remains statistically significant up to 25km^2, an empirical result not previously proven anywhere at this scale, and delays can still be identified in the catchment further downstream over 36km^2 in size. This is very encouraging, particularly as such measures are cheap to construct and could be rolled out elsewhere across the Scottish catchments[10].

Figure 2.4.4: Engineered log structures on the Middle Burn, August 2016

At these sites, we are also getting evidence that lag time actually inceases as flood events get bigger. The NFM measures are still maturing and being extended, such that their effectiveness can be expected to increase. The changes in flood peak are currently being examined, but it is clear that in the upper catchment, the 2-year return period flood peak has reduced by 30% since NFM measures were implemented, compared to only 8% in the lower catchment (where they are absent).

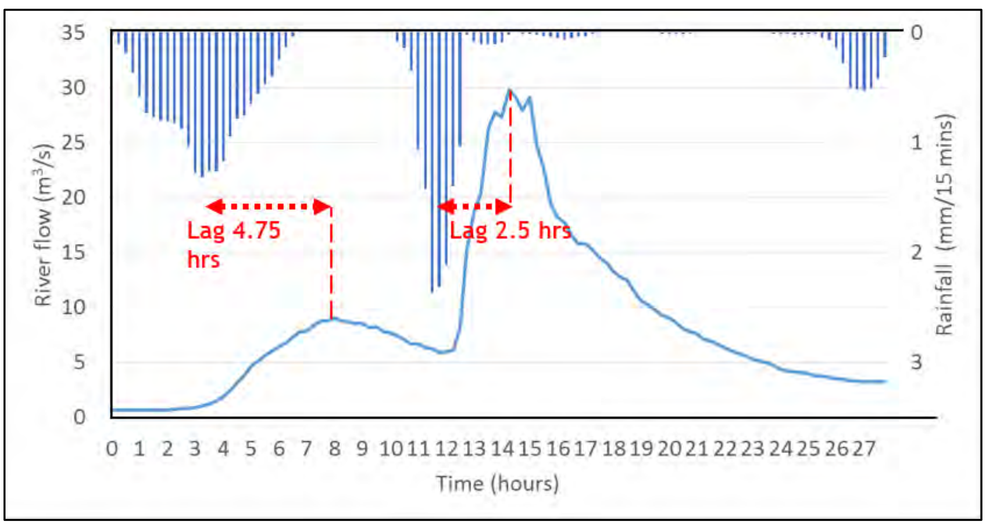


Figure 2.4.5: Lag time in hours from rain event to flood peak: Eddleston Water, 22/6/12. Rain event is on the upper axis, in mm/15 min.

[10] Black, Peskett, MacDonald, Young, Spray, Ball, Thomas & Werritty (2020), Natural flood management, lag time and catchment scale: results from an empirical nested catchment study, submitted to Journal of Flood Risk Management.

Re-meandering the river channel

The Eddleston Water was straightened and embanked for much of its length some 200 years ago in order to build first a road and then a railway, as well as to enable the drainage of surrounding farmland to improve crop production. As a result, the river both lost some of its length and has been cut off from its floodplain by high embankments, such that the river habitats were constrained by the embankments and degraded.

To date, five sections of the Eddleston Water have been re-meandered totaling 2.9kms, with four of these being almost contiguous stretches. The first two at Cringletie and Lake Wood have been the subject of detailed monitoring which, alongside two 'control' stretches at Shiphorn and Rosetta has taken the form of combined hydro-geomorphological and ecological studies, including sediment surveys, fish, aquatic macroinvertebrate and aquatic macrophyte sampling. Alongside this, the impact of re-meandering on flooding is being explored by a PhD student at Dundee University comparing the shape of the flood hydrographs before and after the meanders were created. Using this type of detailed hydrological, sediment and morphological monitoring is highly useful for assessing how rivers respond to restoration, as it provides insights into both the morphological structure at the reach scale and the condition of the local scale habitat units.

This sediment study indicates that restoration has increased the diversity of geomorphic units in the river channel and how well sorted these units are with different grain sizes. Stream power is likely to play an important role in recovery of the new channels, with the sites with the higher stream power showing greater diversity and sorting of sediment. Sinuosity of the new channel may also be key to recovery, with the Lake Wood remeander site (sinuosity 1.46) showing greater diversity than the Cringletie one (1.08). It also highlights that recovery takes time as these sites are not fully recovered yet and more adjustment is necessary to improve condition. This in turn highlights the need for monitoring schemes that are able to operate over these longer-term timescales.

The parallel ecological studies have demonstrated a strong response of macroinvertebrates to habitat reconfiguration at the two re-meandered sites, Cringletie and Lake Wood, but the precise role of habitat composition in mediating these changes remains unclear. What is clear though is that remeandering led to significant increases in channel length (8-46%) and associated new habitats. The results from the fish sampling programme show that all sampled sites from restored areas are now as productive as unrestored sites (i.e. complete recovery from channel construction) with no difference between the densities and lengths of salmon and trout fry. However, using density as a measure does not consider the relative abundance of habitat. Restored reaches of the channel have a length that is now between 8% and 46% greater than the length of the previous unrestored channel, so it is likely that the restored sections are now producing more fry than if they remained unrestored.. The new sections of channel may still be underdeveloped, as the scarcity of bank undercuts and woody debris features coupled with the immaturity of riparian trees means that cover is not yet fully developed, leading to the possibility that maximum fish abundance here is yet to be realised.

Tree Planting and Pond creation

The effectiveness of wide-spread tree planting (figure 2.4.5-right) on flood generation and flows will take many years to be fully realised as the trees grow, but their impact in Eddleston has already been demonstrated through earlier modelling work[11] who showed the impacts of afforestation on peak river flows under UKCP09 climate change projections and on additional ecosystem services. They found that investment in riparian woodland delivers a significant positive net present value, with much of the benefit arising from additional ecosystem co-benefits rather than just flood risk reduction alone.

Monitoring of the ponds (figure 2.4.6-left) created across the catchment is ongoing, with the focus on the potential storage volume that these can hold in times of flood. Modelling will help assess their potential effectiveness. Further ponds are being designed at present with implementation planned in the coming year if possible.

Figure 2.4.6: Native tree planting in the upper catchment (left) and pond creation at Kidston Mill 2017 (right)

Modelling the effectiveness and benefits of NFM measures:

We have developed a linked hydrological-hydraulic model of the catchment, using as its base the freely available HEC-RAS software, with lumped ReFH2 sub-catchment and reach-scale lateral inputs. The model uses our very detailed DTM and is calibrated with data collected within the project. It uses the most effective methods available to represent the performance of different types of NFM measure and is readily transferable to other catchments. Results show, for example by simulating pre and post NFM implementation scenarios that an extra 6% floodplain storage volume was created by NFM measures at Lake Wood. Interestingly, the potential flood risk reduction for distributed NFM measures is fairly independent of flood return period, providing enhanced landscape resilience, and which together across the catchment have been initially modelled at around 5%. The modelling work has since been upscaled to show similar potential at even larger catchment scales[12].

Finally, ongoing work on costs and benefits of taking a BwN approach to reducing the risk and damages from flooding shows early promise in terms of net benefits and multiple ecosystem services. In addition to damages avoided from flood risk reduction, this provides values for the other ecosystem service benefits provided by NFM measures (carbon, biodiversity, fisheries, recreation, water quality, timber, agriculture & education). Currently we are exploring how multiple benefits that enhance natural and

[11] Dittrich, R., Ball, T., Wreford, A., Moran, D. and Spray, C.J., (2018) A cost-benefit analysis of afforestation as a climate change adaptation measure to reduce flood risk, Journal of Flood Risk Management 12 (4), https://doi.org/10.1111/jfr3.12482

[12] Hankin, B., Page,T., McShane, G., Chappell, N., Spray, C., Black, A. & Comins, L. (2020). How can we plan resilient systems of nature-based mitigation measures in larger catchments for flood risk reduction now and in the future? Proceedings of the European Conference on Flood Risk, Budapest.

social capital can be integrated into flood management measures options appraisal by integrating our new approach to assessing the value of Building with Nature measures alongside that of traditional structural engineering.

3. Overall achievements

Assessment Framework

One of the starting points of the BwN project was to provide science based evidence that NBS can be a sustainable solution, used as an additional or alternative to grey (or green/grey) or in combination with grey (or green-grey) measures to reduce flood risk (taking into account also other measures as warnings or property level resilience). NBS approach provides greater multiple benefits than grey (or green/grey) measures. In order to make this assessment, a framework that is capable of objectively comparing and valuing the various NBS is needed. Work Package 4 set up an assessment framework and the individual projects in the Netherlands, Belgium and Scotland were used as case studies. In addition, in the Scottish situation, our latest cost-benefit modelling work looks not just to value NFM measures, but to identify how their assessment can be fully integrated in to the 'standard' options appraisal processes currently used by Scottish Government and SEPA for all new flood schemes.

Inspiration for the framework has been found in the literature[13]. Many of these studies emphasise the need for a thorough problem definition and a system approach to come to a solution (rather than looking at the isolated case). Once the solution is established, they indicate the importance of adaptive management and monitoring and learning. In the whole process, stakeholder involvement is crucial.

The new assessment framework (which is based on the framework of the Netherlands Environmental Assessment Agency PBL (PBL, 2016), developed for the Dutch Delta Programme (DP 2015, 2014)) proposed using these findings in a slightly different setting. We define four key elements - Efficiency, Effectiveness, Social support and Flexibility. Where and if the appropiate indicators can be provided for these key elements, they can form a useful tool to compare different BwN (as already indicated, also often called Nature Based Solutions (NBS) in the literature) in various countries, but also to compare individual NBS and their alternatives. Effectiveness as a key element is relatively new, and is coupled to Outcome, which is defined as the degree to which the measure solves the societal problem. Outcome

[13] Calliari, E., Staccione, A., Mysiak, J. (2019) An assessment framework for climate-proof nature-based solutions, Science of The Total Environment 656, 691-700, https://doi.org/10.1016/j.scitotenv.2018.11.341

Nesshöver, C., T. Assmuth, K. Irvine, G. Rusch, K.Waylen, B. Delbaere, D. Haase, L. Jones-Walters, H. Keune, E. Kovacs, K. Krauze, M. Külvik, F. Rey, J. van Dijk, O. Vistad, M. Wilkinson, H. Wittmer,(2017) The science, policy and practice of nature-based solutions: An interdisciplinary perspective, Science of The Total Environment, 579, 1215-1227, https://doi.org/10.1016/j.scitotenv.2016.11.106.

Klostermann, J., Van de Sandt, K., Harley, M., Hildén, M., Leiter, T., Van Minnen, J., Pietersen, N., and Van Bree, L., (2018) Towards a framework to assess, compare and develop monitoring and evaluation of climate change adaptation in Europe. Mitig. Adapt. Strateg. Glob. Change, 23, 187-209.

Raymond, C.M., Frantzeskaki, N., Kabisch, N., Berry, P., Breil, M., Razvan Nita, M., Geneletti, D., and Calfapietra, C., (2017) A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas, Environmental Science & Policy, 77, 15-24, ISSN 1462-9011, https://doi.org/10.1016/j.envsci.2017.07.008.

differs from Output. We applied the framework to three case studies Scotland (Eddleston), Belgium (De Kleine Nete) and the Netherlands (side channels). This showed that the right choice of indicators is critical, but also that the framework is a promising tool if the indicators have already been established in the early design phase of the programme. Monitoring (of the indicators) throughout all phases of the project (design, implementation and evolution) is crucial to assess whether NBS is indeed the right choice to solve the problem. Applying this to each of the case studies showed that important information about design and implementation is not always monitored which makes assessing the solutions difficult.

In a recent MSc thesis at Delft University of Technology, the concepts of an assessment framework and the coupling to the United Nations Development Goals (UN-SDG) have been elaborated, and the framework has been tested using the Eddleston data[14].

Governance Framework

The assessment framework can be used to compare different NBS with respect to design, implementation and evolution, based on preset criteria, but it does not cover the question of governance. This however, can be key, because often it is this that ultimately determines whether a measure could potentially be seen as acceptable in the first place, and them whether it can be implemented. Thus, whilst flooding is recognised as a major challenge in all countries taking part in this project, to date widespread uptake of building with nature measures has not followed the pace of policy promotion.

Working together across the countries with interest in river catchments, we examined governance factors that influence the introduction and implementation of natural flood management (NFM) policies and practices to reduce flood risk. We highlight that the governance settings differ considerably between countries, but that in all of them there is increasing policy interest in the potential for novel land-management interventions to be utilised as part of sustainable flood risk management at the catchment scale. The specific aims of the study were to (1) identify the legal policies, practices and instruments than lead to successful implementation of NBS, and (2) determine the primary barriers to implementing of NBS and hence to effective governance. However, the degree to which NBS is 'required' and promoted by government, and the enthusiasm with which building with nature is met by diverse stakeholders is constrained by the nature of flood risk itself and how this is perceived.

If the flood risk is clearly present and a flood has national consequences that affect large parts of the population and economy, the roles and responsibilities have a more formal nature and are clearly laid down in primary legislation. The planning of measures that reduce flood risk is part of the integrated water management approach. This is for example the case in the Netherlands, where the threat comes from the larger rivers Rhine and Meuse and where a potential dike breach could paralyze the country. If the risk comes from smaller streams and there is room for measures that reduce the risk by holding back and attenuating the water, measures are generally part of an integrated solution, and are used alongside other solutions that influence land use. In these cases, effective stakeholder participation and

[14] Andrikouloulou, T. (2020), Nature Based Solutions for Fluvial Flood Mitigation, an integrated assessment framework, MSc thesis Delft University of Technology, The Netherlands.

communication is vital for implementation of measures, as the land in often privately owned. This is for instance the case in Scotland.

Notwithstanding major differences in this framing of flood management, we report widespread enthusiasm for partnership working to deliver NFM integrated with options for wider multiple land-management benefits. Governance differences influence collaboration of relevant stakeholders, impacting the uptake and ease of delivery of NFM measures. Effective progress requires stakeholder engagement that encourages the inclusion of a 'bottom-up' approach, an ideal in governance that, at least at a local level shows evidence of success in delivery of NFM, though challenges remain from a national perspective.

Apart from country specific practices, we identified general barriers and challenges that are common to all. Among these, we highlight the utilization, management and maintenance of NBS, the lack of an integrated assessment framework (including cost-benefit valuation and options appraisal) for evaluating nature-based and other flood risk reduction options and the sectoral barriers that exist between policy making and financing. Nevertheless, the research clearly showed a profound willingness to build the science evidence base of its effectiveness under different scenarios.

Modelling

During this project, partners used hydraulic, hydrological or morphological models to a greater or lesser extent. No single model or combination of models is used by all partners. Each partner preferred a different specific model. This was in part due to legacy (the models have already been used for a considerable period of time in the different organizations) but also because the models are appropriate for the specific task that is required. One aspect of note is the advantages seen in using freely available software, as opposed to a proliferation of individually developed company or organisation-specific software, hence avoiding any accompanying Intellectual Property Rights challenges as to use and further development. A table with the models, some properties of the models and the reason why those models are used can be found in Annex A.

Due to the fact that there is such a variety of models in use, it could be worth undertaking a benchmark modelling study in which the different models are compared to each other with respect to performance, accuracy, ease of use, calculation times, etc. The Eddleston-catchment laboratory in Scotland might act as a base case for such a benchmark study, because over the years, a huge dataset of hydraulic and morphological data has been built up, as well as ecological data. In addition, the development of the Eddleston combined hydraulic-hydrological model used freely available software, so its use could also be trialled in other catchments.

Ecology

The studies in Sweden and Scotland also undertook extensive ecological monitoring. In Sweden, fish species and the density of the species have been monitored annually since 1988, using electrofishing. Also, macro-invertebrates have been monitored since 1999, in different locations, annually. A more intensified monitoring campaign of macro invertebrates took place in the summer of 2019, using pit fall traps in two stage ditches. The discharge is monitored in the main stream of the Råån river, on a daily basis.

In Scotland, monitoring of aquatic invertebrates (number of taxa and individuals) is part of a detailed 'before-after:control-impact' (BACI design) study of the impact of remeandering on river habitat structure (channel geomorphology and sediment grain size) and on ecology. Begun in 2012 before any NFM measures were implemented, both geomorphology and invertebrate monitoring focusses on two remeandered reaches and 2 control reaches. Invertebrate sampling occurs twice per year on 100m stretches, with sample effort apportioned to different flow types (Run, Riffle, Slack, Glide and Pool). Fish surveys involved fully quantitative electrofishing sampling based on Scottish Fisheries Coordination Centre protocols and have been carried out annually since 2017 in three consecutive years on meandered and control sections, recording numbers and density of trout and salmon, as well as size and weight. Daily mean flow characteristics are monitored at 12 different locations on the Eddleston.

In the Netherlands, extensive ecological monitoring is carried out for the European Water Framework Directive. Within this NSR Interreg Building with Nature project, no additional ecological data was monitored or analyzed. At different locations along the Rhine branches, sediment samples at the locations of the side channels have been taken and analyzed with respect to grain size distribution. That data is used to analyze what sediment is directed into the side channel, and how that affects the sedimentation and erosion behavior. Water levels are monitored at several locations along the Rhine branches, with a frequency of once every 10 minutes. The water levels are then transformed into discharges with the aid of a stage-discharge relation.

For the river restoration project of the Kleine Nete in Flanders, no specific monitoring is executed. Monitoring is limited to the general monitoring at fixed locations in order to fulfill at the European Water Framework Directive. This consist of physico-chemical parameters, macro-invertebrates (e.g. insects, worms), macrophytes (algae, moss, fern), phytobenthos and phytoplankton. According to the monitoring results, the water quality of the Kleine Nete is categorised to be in a moderate condition. Water levels are registered at various gauge stations and can be consulted in real time on an online portal of all Flemish water managers (www.waterinfo.be). Here you can find the actual water levels, historical data of water levels, rainfall data and forecast. Also a short term (48hr) and long term prediction are available.

Making the Business case for Building with Nature[15]

The Eddleston study was chosen as one of three different business cases within the Work Package 5 of Building with Nature programme; each with a different focus and lessons learned. The Eddleston business case differs from the others in that primarily it was set up as a research platform. It focusses on the potential of natural flood management (NFM) measures; the involvement of stakeholders; and how a business case can be set up, so that it supports design and decision making in the case of implementing NFM measures on a catchment scale.

The overall conclusions of the business case were that the case for NFM needs to be based not just on its benefits in terms of flood risk reduction or the improvement of ecological status, although both represent important objectives and venues for financing NFM, but also on the wider ecosystem service

[15] Spray, C.J., Fiselier, J. & Moons, S (2020). Building with Nature – Elaborated business case Eddleston Water. Final Report for Work Package 5 - Upscaling. INTERREG NSR BwN Project.

benefits related to NFM. In developing a NFM based flood protection strategy, one needs to consider hybrid combinations with conventional flood protection structures, property flood resilience and flood insurance – as part of a total package of Sustainable Flood Risk Management. Other existing sources for funding such as those relating to afforestation and carbon storage also need to be considered.

The wider framework for setting a business case for NFM is ideally therefore set within the context of an integrated catchment plan, and should encompass other relevant ecosystem service benefits, recognising how these may contribute to local communities and support the business model of individual farms and landowners. This framework is much more comprehensive than a traditional formal flood protection scheme study which has a much more narrow focus.

The implementation of NFM measures requires the cooperation of landowners and farmers, something that may require a fundamental rethink of agricultural support mechanisms, with potentially payments for the provision of 'flood risk reduction' ecosystem services being seen as an increasingly important tool in this respect. However, a fully comprehensive planning process based on the voluntary participation of stakeholders may also require a coordinating organization that knows the area and its stakeholders, and holds their trust (such as Tweed Forum). Building such an organization takes time, and hence building a business case, or even building with nature, starts with building a network with people, before designing and assessing potential measures.

4. Knowledge agenda

The projects in the four different countries, and the WP4-meetings between 2015 and 2020 have led to increased knowledge about possibilities to apply BwN, as well as the added values and methods to implement and assess the effectiveness and value of BwN. However, there are still knowledge gaps. Identifying them, and putting them in a knowledge agenda highlights potential topics to be addressed in a future project. In this way, the scientific evidence that BwN can indeed contributes to a more resilient and robust river landscape, continues to grow and this will help accelerate the implementation and mainstreaming of this approach along the riverine parts of the North Sea Region.

Taking into account all the different Work Packages of this project, four overarching main barriers have been identified that act as barriers to the uptake and mainstreaming of BwN projects. These are:

(1) **Scientific evidence:** Lack of knowledge on individual and system performance and monitoring
(2) **Local understanding:** Under appreciation of the local context and importance of stakeholders
(3) **Non-bankable business case:** understanding benefit streams and optimizing funding arrangements
(4) **Governance and Institutional gap**: Suboptimal governmental and institutional setting

The first and last are of particular relevance to all WP4 partners, with the shared work on governance being especially relevant to the last one. The second is one of the main concerns within the Scottish case where almost all the measures were accompanied by very intense and well organised stakeholder participation processes. This was necessary because most of the land is privately owned, and without commitment of the stakeholders, very few actions could be done in the first place. The third one is also discussed in the context of the work done in the Eddleston on cost-benefit analyses and for Work Package 5 on the Business case for BwN.

The 4 main barriers can be translated to WP4 (i.e. catchments) and be made more specific. This results in:

(1) **Scientific evidence:**

This main conclusion for coastal environments and catchments easily translates into catchment specific findings. Over the complete range of the catchment (i.e. from headwaters (Scotland) up to middle reach of smaller streams (Belgium) and smaller streams flowing into a delta-like environment (Sweden) and main rivers flowing into the delta (The Netherlands)), there is a lack of scientific research that proves that BwN-measures have indeed added value with respect to grey or green/grey alternatives. It is the purpose of the cases in the different countries to generate (additional) scientific evidence. An important tool in this is the development of the monitoring schemes and the data gathering (especially Scotland and Sweden) and the efforts to develop appropriate assessment frameworks (joint work with The Netherlands as linking pin). Finally, the development of focused modelling tools which can be transferable between catchments is a key consideration, as seen in the Eddleston.

(2) Local understanding

The studies in Scotland and Belgium have shown that involvement of local stakeholders and proper communication with the general public is vital to appraise,enable and select measures to be considered and implemented in the field in the first place. From the Eddleston case study, it is clear that for privately owned land, communication with the land-owners to raise awareness is necessary to construct measures. Even if there is no issue about who owns the land (like for instance in the flood plains of the Dutch rivers), it is still important to have an appropriate communication with involved communities to raise the awareness and hence to get support instead of resistance. Resistance may lead to legal procedures and substantial delay in the planning and construction.

(3) Non-bankable business case:

From the developments of the Belgium project (the projects related to the amusement park and the camping site), it is clear that political developments and stakeholder issues hamper a bankable business case on the short term. More studies and getting more support is necessary to make progress. On the other hand, the developments in the Eddleston catchment are a good example where good communication and involvement with stakeholders and land owners, together with a long lasting monitoring program helps in getting funds to support a financially healthy project. Also the communication to the public (with progress information, leaflets, field-signs, etc) contributes to this. The situation in the Netherlands, where flood protection is partly a governmental task, the issue of bankable business cases is less problematic because projects are often directly related to the reduction of flood risk for which finance is available. Making the business case for BwN may require new forms of valuation, not solely of flood damages avoided, but also the added value provided by different ecosystem services, such as carbon management, water quality improvements and biodiversity enhancement delivered as part of BwN measures.

(4) **Governance and Institutional gap**:

Looking at the national governance structures and legal procedures required to construct BwN measures, it is clear that there are substantial barriers which can hinder implementation. The procedures differ in each country. Landownership often plays a crucial role in implementing measures, as does the lack of evidence that BwN measures can lower flood risk compared to grey and green/grey solutions. In most countries, it is acknowledged that BwN measures also gives multiple benefits that grey infrastructure does not give. Providing scientific evidence for that acknowledgement adds to mainstreaming of BwN. A proper assessment framework to weight the various aspects of BwN measures both before and after implementation would help in promoting BwN. Indeed, as noted in the cost-benefit work on the Eddleston, standard Flood Scheme Options Appraisal processes need to be changed so as to enable the assessment of BwN options alongside and integrated with more traditional structural and other solutions. Also, improvement of supportive legislation, regulatory frameworks and more targeted funding possibilities could help in the implementation of BwN.

From these points, we recommend the following for future research:

- Develop an appropriate assessment framework for BwN measures. Make a connection to the UN Sustainable Development Goals to show the added value of BwN in contributing to a better and more sustainable future for the world. Improve the empirical basis for better understanding of BwN measures’ performance.
- At the planning stage, invest in long term (10 years and longer) monitoring programmes (ecological, morphological, flood risk, social support, etc) and analyze the data scientific evidence about the functioning of the BwN measures.
- Map the local stakeholders, social networks, NGOs, inhabitants of (local) communities, and map the associated networks to provide a solid support for BwN measures. Develop new approaches to participatory decision-making, involving all key stakeholders
- It will be advisable to study BwN in more detail depending on the exact position within the catchment where BwN measures may be implemented, including a focus on the potential advantages of using BwN in an urban development. It is clear that catchments vary in geographical scale, and that flood risk problems may occur anywhere in the catchment (headwaters, middle reach, delta). To a certain extent, the position in the catchment will determine which BwN-measures will achieve ‘best’ results in terms of effectiveness and value (where ‘best’ has to be defined, probably with the use of a proper assessment framework).
- Invest in modelling tools for ecology, morphology and hydraulics. Perform benchmark studies to learn from the different models and implement best practices. In this respect, also invest in remote sensing tools and the associated analysis of satellite and remote sensing data because they can be used not only to quickly construct detailed Digital Terrain Models (DTMs) which can be used to set up models, but for rapid monitoring and assessment of river habitats and floods. Use the models to describe the effectiveness of BwN measures at catchment scale as well as on medium scale (order 500 m.-several km.).
- Strengthen the policy and legal frameworks to support the implementation of BwN. Strengthening can be on a local, national and even international (European) scale. Although in some countries, there is a legal requirement to consider BwN measures as an alternative, there is still a need to support possible implementation of BwN as integral part of flood risk appraisal.

5. Recommendations for Policy

Like the knowledge agenda, also overarching (i.e. considering all the Work Packages, cross country and cross parties) recommendations for policy have been made and put forward in a series of Policy Briefs[16]. These recommendations connect to the four barriers identified and to the knowledge agenda. They include the need to:

(1) Create a solid performance evidence base and a BwN assessment framework.
(2) Involve and align (local) stakeholders from the initial phase onwards.
(3) Agree on how to value multiple benefits and functions.
(4) Support member states in implementing BwN in national regulations.

In four national policy briefs (see Section 6 for the list of deliverables), these recommendations have been translated to specific catchment recommendations.

The policy brief of **Sweden** identifies that coordination between the different stakeholders (agriculture and drainage companies, amongst others) should be improved to stimulate the use of BwN. Governance in investment programmes and national policies is needed, as well as revision of the EU Common Agricultural Policy (CAP) to achieve sound land use and flood management. Also, legislation is lacking behind the application of BwN. In particular, the revision of the old system of permits for drainage companies is needed so that water is retained in appropriate places within the catchment area. Direct payment to agriculture which is not in line with climate adaptation should not be given. Municipalities should identify and designate areas where water can be retained.

The Scotland policy brief addresses the issue of funding for BwN. To secure funding, evidence that BwN measures can help mitigate flood risks and have added values is needed. Assessing the role of natural flood management (NFM) measures in protecting communities and land is already in Scottish legislation but it is also important that incentives for land owners to implement BwN are available. Similar to the situation in Sweden, Scotland notes that novel forms of partnerships may be necessary to fully and properly implement BwN. A specific challenge in Scotland is the need to interact with many landowners. It is found that involving this group at an early stage of the planning is absolutely necessary to make progress although it was also noted that a lack of a common methodology for including NFM measures within project appraisal was a barrier. Therefore, one of the key recommendations is that one should adopt a clearly articulated, holistic vision as part of integrated water resource management at a catchment scale.

In **The Netherlands**, the policy brief addresses the need for a proper assessment framework with the right indicators to compare the BwN measures to each other and to their green/grey-green alternatives. This issue was also raised in the Scottish policy brief. The purpose of the assessment framework is not to make a sharp distinction between green solutions or grey solutions. Very often, a solution has elements of both sides of the green-grey spectrum. The assessment framework can also be used to provide the evidence base that is mentioned in the Scotland policy brief. It is also stated that (long term) monitoring is essential to get the necessary data for evaluation and assessment (and adaptive management).

[16] Building with Nature for flood resilience, A policy brief by the EU Interreg North Sea Region project Building with Nature, https://northsearegion.eu/media/12484/interreg_bwn_policy_brief_web-version_final.pdf

Finally, it is clearly stated that acknowledgement of location and scale within the catchment is important for the particular choice of BwN measures.

In **Belgium**, the focus of the policy brief is on avoiding damage. Retaining the water where is falls is obviously the best at-source measure to avoid damage, but often this is not enough alone, due to the ever increasing rainfall due to climate change. Therefore, the government in Belgium is also advocating the concept of (semi)natural flood plains. In this, constructing transverse dams is a key element as, in this way, water can also be temporarily stored in the valley. On the other hand, there i competition with both agriculture and nature. New legislation that calls a halt to inappropriate or inadmissible construction in flood-prone areas should limit the damage in case of flooding. It is noted that the choice between a collective protection or one more individually oriented, requires a thorough social debate. Indeed all flood management now requires a participatory debate. People prone to flooding may accept the risk of flooding, as long as they can see proof that the water authorities have done their maximum to take reasonable measures to keep the water away.

Combining the insights of the local policy briefs on catchments, it is concluded that without local support of the people, land owners and stakeholders, and without supporting legislation, it is very hard to actually implement measures, and the planning and implementation process can be delayed substantially. Governmental support also needs to be present, which is why it is important to show that BwN can indeed help solve the (flood risk) issue. And off course, there needs to be sufficient funding to construct the measure.

Research agenda from policy point of view

The findings from the policy briefs leads to the following suggestion for a research agenda from policy point of view:

Building on the observations above, the research agenda needs to include a focus on:

- Improving the empirical evidence base for the effectiveness of different types of BwN measures
- Extending the catchment scale over which significant impacts of BwN measures can be demonstrated
- Developing better combined models of catchment processes that enable the impact of combinations of BwN measures to be assessed at the catchment scale
- Developing accepted and proven standards and tools for valuing multiple benefits and functions of BwN measures
- Understanding the barriers and opportunities for acceptance and uptake of BwN measures

6. Output

General: National Policy Briefs.

Nature based solutions demand assessment framework, A catchment-oriented Policy Brief from the Interreg North Sea Region Building with Nature project by Rijkswaterstaat, The Netherlands https://northsearegion.eu/media/12586/rijkswaterstaat-nl_policy_brief_catchment.pdf

Funding for Building with Nature and Natural Flood Management A catchment oriented Policy Brief from the Interreg North Sea Region Building with Nature project, by the Eddleston Water Project Team,

Scotland
https://northsearegion.eu/media/12384/final-template-national-policy-brief_scotland_catchment_cs.pdf

How to avoid damage caused by flooding? Policy Brief from the Interreg North Sea Region Building with Nature project by the Flanders Environment Agency, Belgium.
https://northsearegion.eu/media/12387/vmm_national-policy-brief-catchment_2.pdf

Nature based solutions demand better coordination in catchments. Policy Brief from the Interreg North Sea Region Building with Nature project by Länsstyrelsen Skåne, Sweden.
https://northsearegion.eu/media/12482/skaane-policy-brief-catchment-20200220-1.pdf

Output The Netherlands:

Andrikouloulou, T. (2020), Nature Based Solutions for Fluvial Flood Mitigation, an integrated assessment framework, MSc thesis Delft University of Technology, The Netherlands.

Meijer, D., and Van Winden, A. (2020) Morphological development of secondary channels, Building with Nature, Exploratory research of morphological development of secondary channels, Technical report RWS188, RiQuest, Stroming and Kragten (also available in Dutch, entitled Morfologische ontwikkeling van nevengeulen, Building with Nature, Verkennend onderzoek naar de morfologische ontwikkeling van nevenguelen).

Huthoff, F., Ten Brinke, W., Schielen, R. (2019), The added value of Nature-Based Solutions, In Land of Rivers , proceedings of the NCR days 2019 Utrecht University Campus, Utrecht, Netherlands, https://ncr-web.org/wp-content/uploads/2019/01/ncr-43-ncrdays2019-bookofabstracts-web.pdf

Schielen, R., Baldal, E., Garft, D., and Spray, C.,(2019) Assessing the potential for Nature Based Solutions to contribute to flood risk reduction: evidence from recent studies, accepted abstract for International Conference on Flood Management-8 2020, Iowa, USA.

Schielen, R., Forbes, H., Spray, C., Moeskops, S., and Persson, P. (2019) , Achieving the Project Indicator of the Interreg North Sea Region Building with Nature Project, Internal Note INTERREG NSR BwN Project.

Van Denderen, R.P. (2019), Side Channel Dynamics, PhD Thesis University of Twente

Van Denderen, R.P., Schielen, Hulscher, S.J.M.H. (2019), Measuring and modeling the development of side channels, In Land of Rivers , proceedings of the NCR days 2019 Utrecht University Campus, Utrecht, Netherlands, https://ncr-web.org/wp-content/uploads/2019/01/ncr-43-ncrdays2019-bookofabstracts-web.pdf

Van Denderen, R.P., Schielen, R.M.J., Westerhof, S.G., Quartel, S., Hulscher, S.J.M.H. (2019), Explaining artificial side channel dynamics using data analysis and model calculations, Geomorphology 327, pp93-110, 10.1016/j.geomorph.2018.10.016

Huthoff, F. Ten Brinke, W., Schielen, R., Daggenvoorde, R., and Wegman, C. (2018), Evaluating Nature-Based Solutions, Best practices, frameworks and guidelines, Technical report PR3812.10, HKV Lijn in Water. https://northsearegion.eu/media/11653/report_pr3812_evaluatingnbs_final_29112018-2.pdf

Pol, J.C. and Lokin, L.R., (2018) Bedlevel measurements side channel Gameren, measurements with a fishfinder, Technical report 3763.10 HKV Lijn in Water (Only available in Dutch, entitled Bodemhoogte nevengeul Gameren, metingen met fishfinder). This report has been translated by R. Schielen in English, entitled Determination of the bed level at the Gameren side channel: measurements with a Fishfinder)

Schielen, R., Baldal, E., Comins, L., Forbes, H., Garft, D., Spray, C., Quartel, S., Wilkinson, M., (2018), An assessment of Building with Nature (BwN) measures: A comparative case study from Scotland and the Netherlands, Geophysical Research Abstracts, Vol. 20, EGU2018, poster available with the same authors and title., https://northsearegion.eu/media/4412/egu2018-schielenetal-assessment-bwn.pdf

Quartel, S., Schielen, R. and Kater, E. (2018) Increasing Flood Safety with Side Channels: a Nature-Based Solution along the Rhine, Poster presented at the Coordination Meeting in Schoorl, The Netherlands.

Schielen, R., Quartel, S., Spray, C., Persson, P., Moeskops, S., and Comins, L. (2017), Effectiveness of climate change adaptation measures: Working towards a science-evidence base, in Proceedings of ICFM-7, Leeds, 2017. Poster available, entitled Working towards a science-evidence base for Building with Nature solutions: Effectiveness of climate change adaptation measures, https://northsearegion.eu/media/4411/intcnfleeds-def.pdf

Westerhof, S. (2017), Variation of sediment grainsizes in side channels: case study side channels Gameren, BSc-thesis University of Twente (Only available in Dutch, entitled: Variatie korrelgrootte van sediment in nevengeulen; Casus nevengeulen Gamerense waard)

Output Belgium

Antea Group (2020), Environmental Impact Assessment Ark van Noë

Antea Group (2020), Soil investigation report Ark van Noë

Antea Group (2020), Technical design Ark van Noë

Gate Archaeology (2020), Archaeological research Ark van Noë

Mythra Lawyers (2020), Memorandum concerning fiscal aspects in case of redevelopment of Camping Korte Heide.

Vlaamse Landmaatschappij (2020), Memorandum concerning legal instruments for land development of Camping Korte Heide.

Cluster landschap en stedenbouw (2019), Design of ecological water storage areas in recreational areas along the Kleine Nete river.

Flanders Environment Agency (2019), Stakeholder Engagement in Flanders

Flanders Environment Agency (2019), Tender documents Technical Design of remeandering Kleine Nete at recreation site Ark van Noë.

K3H Architects (2019), Allotment plan of camping Korte Heide.

Flanders Environment Agency (2018), Poster: Creating ecological flooding zones at recreation areas Kleine Nete (BE), Building with Nature

Output Sweden

Reports in the project

Flood analysis Lussebäcken, Helsingborg , Hydraulic impact of urbanization and effect of implemented water management measures https://www.lansstyrelsen.se/skane/tjanster/publikationer/flood-analysis-lussebacken-helsingborg.html

Lussebäcken, Helsingborg Municipality, Evaluation of the hydraulic performance of two-stage channels through comparative analysis-joint field.modelling approach https://www.lansstyrelsen.se/download/18.3db3ed8a171ac1fbfcb131c2/1589811033790/Lussebäcken-hydraulic%20performance%20of%20two-stage%20channels.pdf

Råån, Helsingborg Municipality, Field evaluation of two-stage channels impact on local biodiversity and nutrient retention potential https://www.lansstyrelsen.se/download/18.3db3ed8a171ac1fbfcb131f2/1589811406446/Råån%20-%20two%20stage%20channels%20impact%20on%20biodiversity%20and%20nutrient%20retention.pdf

USER GUIDE – ENGLISH SUMMARY, Map service tool: Water and Climate – Climate change, freshwater discharge and sea levels in relation to landscape topography and land use, https://www.lansstyrelsen.se/download/18.3db3ed8a171ac1fbfcb11022/1589551109894/USER_GUIDE_FINAL.pdf

Poster: Study sites in Scania, Sweden, Building with Nature, Pär Persson, Thorbjörn Nilsson, Charlotte Carlsson, Lukas Österling, Henrik Djerv, https://northsearegion.eu/media/4426/utkast_poster_per.pdf

Link to Map service tool, https://ext-geoportal.lansstyrelsen.se/standard/?appid=d2372b43847c46a6b3ae89bdd2d8aeac

Other

Lacoursiere, J.O., Karlsson, C., Persson, P. and Guymer, I. (2020), Calibrating hydraulic models through in-situ conservative tracing– An example of 2-stage vegetated channels from Southern-Sweden in proceedings of the 6th IAHR Europe Congress, June 30th – July 2nd, 2020, Warsaw, Poland.

Utande Estallo, N., and Nsabimana, B. (2019), Sustainable Drainage Systems Assessment and Optimisation-A case study for Lussebäcken Catchment, Helsingborg, MSc thesis Lund University, https://lup.lub.lu.se/student-papers/search/publication/8992765

Output Scotland

Black, A., Peskett, L., MacDonald, A., Young, A., Spray, C., Ball, T., Thomas, H. & Werritty, A (in review). Natural flood management, lag time and catchment scale: results from an empirical nested catchment study. Journal of Flood Risk Management.

Spray, C., Schielen, R., Forbes, H., Staubo, I., Osterling, L., Persson, P., Scholiers, R., Moeskops, S. & Lassen, A. (in review). Governance lessons for effective implementation of catchment-based natural flood management – as shared international perspective. Hydrological Sciences Journal.

Spray, C.J., Fiselier, J. & Moons, S (2020). Building with Nature – Elaborated business case Eddleston Water. Final Report for Work Package 5 - Upscaling. INTERREG NSR BwN Project.

Hankin, B., Page,T., McShane, G., Chappell, N., Spray, C., Black, A. & Comins, L. (2020). How can we plan resilient systems of nature-based mitigation measures in larger catchments for flood risk reduction now and in the future? Proceedings of the European Conference on Flood Risk, Budapest.

Mott MacDonald (2020). Integrating Natural Capital into Flood risk management appraisal. Report for INTERREG NSR BwN Project, September 2020 (plus Natural Capital Flood Risk Management Appraisal User Guide).

Eddleston Water restoration project: Fish monitoring programme 2017 – 2019, June 2020. Eddleston Water restoration project: Fish monitoring programme 2017 – 2019. Report for INTERREG NSR BwN Project, June 2020.

JBA (2020). Eddleston Water Hydrologic and Hydraulic Modelling of NFM: Phase 2 Final Report. Report for INTERREG NSR BwN Project, June 2020 (plus Eddleston Water Modelling User-Guide).

Reid, H., Bromley, C., Martinez, R. & Spray, C. (2020).Impact of the restoration of meanders on the distribution and grain size of geomorphic units within the Eddleston Water. Report for INTERREG NSR BwN Project, May 2020.

Williams, R. (2020). Eddleston Water: Geomorphic Unit Mapping. Report for INTERREG NSR BwN Project, May 2020.

Eddleston Water Restoration Project: Macroinvertebrate responses 2012-2019. Report for INTERREG NSR BwN Project, April 2020.

JBA (2020). Ecosystem Service Benefits of Eddleston Water NFM Measures: Economic Analysis. Report for INTERREG NSR BwN Project, March 2020

JBA (2019). Eddleston Water Hydrologic and Hydraulic Modelling of NFM: Phase 1 Scoping Report. Report for INTERREG NSR BwN Project, April 2019

Eddleston Water Fluvial Audit final report (plus full record of location photographs). Report for INTERREG NSR BwN Project, August 2018

7. Work package 4 meetings

August 10-12, 2016: Edinburgh, Scotland

September 8-9, 2016: Malmö, Sweden

January 25-27, 2017: Antwerp, Belgium

March 7-8, 2017: Lemvig, Denmark

June 23-24, 2017: Arnhem, The Netherlands

December 19-20, 2017: Edinburgh, Scotland

March 8-10, 2018: Haarlem, The Netherlands

June 13-15, 2018: Trondheim, Norway

September 5-6, 2018: Dundee, Scotland

February 12-13, 2019: Malmö, Sweden

November 19, 2019: Amsterdam, The Netherlands

The INTERREG Building with Nature Work Package 4 Team, Edinburg-meeting, 2016.

The INTERREG Building with Nature Work Package 4 Team, Arnhem-meeting, The Netherlands, 2017.

The INTERREG Building with Nature Work Package 4 Team, Trondheim-meeting, 2018.

Annex A: WP4: Modelling tools

Partner: Flanders Environment Agency

Scientific question that the model is being used for?	Name of modelling approach	Hydraulic/Hydrological?	Type of model (e.g. 1D/2D or lumped/parsimonious/distributed)	Why do you use it for this scientific question?
Scenario analysis of measures in the water system	Infoworks RS software	Hydraulic	Quasi 2D	To know the hydraulic impact of different measures
Predictions of water levels and discharges	Infoworks RS + Floodworks software	Hydraulic + hydrological	Quasi 2D	It is being used in crisis management
Scenario analysis of pumping regimes, river restoration measures, changes of drainage systems, …	MODFLOW software	Hydro(geo)logical	3D	To predict the impact of complex alternative groundwater management scenarios where a 3D approach is recommended
Mapping of pluvial floods	JFLOW software	Hydraulic	2D	For policy quantification of the impact of climate evolutions and land use changes on floods, impact of flood protection measures, in context of building permit
Estimation of upward flows, in specific low flows	iFramework – 2D open hydrologic modeling toolbox	Hydrologic	Lumped and distributed	Input for water quality modelling, estimation of water availability during periods of drought (also climate change), in context of permit for abstractions
Water quality in rivers – Flanders wide	PEGopera software	Hydraulic	1D	In context of Water Framework Directive
Modelling of nutrient emissions	ARCNEMO toolbox	Hydrological	Distributed	In context of Water Framework Directive
Erosion and sediment transport modelling in river	Open toolbox based on Curve Numbers + Integrated	Hydrological	Distributed	Estimation of erosion towards rivers and sediment transport in river for better management (dredging)

	Catchment Modelling (ICM software)			

Partner: Sweden – Lansstyrelsen Skana

Scientific question that the model is being used for?	Name of modelling approach	Hydraulic/Hydrological?	Type of model (e.g. 1D/2D or lumped/parsimonious/distributed)	Why do you use it for this scientific question?
Discharge	Mike 11	hydraulic	1D	Used in former projects
Discharge/Rainfall	Mike urban + Mike Flood	hydraulic	1D?	Used in former projects
Channels	MOUSE	hydraulic	1D	Used in former projects

Partner: Scottish Group

Scientific question that the model is being used for?	Name of modelling approach	Hydraulic/Hydrological?	Type of model (e.g. 1D/2D or lumped/parsimonious/distributed)	Why do you use it for this scientific question?
Understanding better the effect of -- debris flow restrictors at a reach level, (the Middle Burn), and of floodplain woodland (Longcote Burn)	HEC-RAS	Hydraulic, using hydrological input from gauges	1D	Gives ability to assess effect of structures and channel/ floodplain roughness on flows in a dynamic sense Intensive monitoring in middle burn further assist calibration Widely accepted and large literature on applications open access license with no restrictions
1) Scaling up from reach to subcatchment level 2) Looking at timing and routing effects of changes to broad hydrological parameters in subcatchments	HEC-HMS	Hydrological	Lumped, with facility for gridded inputs to rainfall	Allows the broad effects of e.g afforestation of sub-catchments, and timing of measures that cause delays in flow peaks (see HEC-RAS above) to be scaled up Widely accepted and large literature open access license with no restrictions
Examining the passage of water through catchment stores under baseline condition* * It is hoped to extend this to include distributed modelling of effects of measures (hillslope afforestation, upstream storage and channel and floodplain restoration at a future stage)	MIKE-SHE/ MIKE 11	Hydrological, with coupling to MIKE 11 1D channel model	Distributed coupled to 1D	Allows the use of all the spatial datasets (land use, geology, soils and channel survey) at a fine level of detail. Eddleston model runs on a 50m grid Strong academic pedigree and wide literature Commercial MIKE-SHE has more capabilities than SHETRAN (analogous open source programme) in terms of GUI, user-friendliness of input and output, and facility to couple to channel hydraulic model.

Andrew Black (Dundee)				
Catchment characterisation	FEH CD-ROM (now provided instead by FEH Web Service)	GIS	GIS – distributed	Provides the gridded data sets from which standard flood peak estimates can be made
Flood peak (and design hydrograph shape) estimation	ReFH Spreadsheet Tool (subsequently withdrawn, replaced by ReFH v2 which can be licenced from WHS/CEH)	Hydrological	Lumped	Ready and contemporary means of flood peak estimation
Flood peak estimation (statistical)	FEH Web Service	Hydrological	Lumped	Ready and contemporary means of flood peak estimation: complements ReFH approach
Impact of NFM features	Pond Network Model impact	Hydrological - and Quasi-Hydraulic	Semi-distributed	Aggregate impact of attenuation and storage
,,	HiPiMs/ CITYCAT	Hydraulic	2D Hydraulic 1m DEM	Local impacts of features
,,	Flood Impact Model FIM	Hydrological	Semi-distributed sub-catchment model	Routing through the river network, addressing synchronisation issues
,,	SHETRAN	Hydrological	Fully Distributed and Deterministic	Total hydrological cycle – especially land use change
Flood Risk	FEH and design storms	Hydrological statistical	Lumped	Standard method
Forest Research				
What effect tree planting on the Burnhead catchment could have on runoff and stream flows	Soil Conservation Service Curve Number analysis on the effect of land use change on flows	Hydrological	Rainfall-Runoff modelling using the SCS CN method within the HEC-HMS modelling system	Method has been applied on a number of catchments by FR and other organisations (e.g. Halcrow) to assess effect of landuse change. Thomas, H., Nisbet, T. R. (2016) Slowing the flow in pickering: quantifying the effect of catchment woodland planting on flooding using the soil conservation service curve number method. International Journal of Safety and Security Engineering 6(3): 466 – 474.
Scottish Borders Council				
What is the standard of protection for properties at risk of flooding from the Eddleston Water and what options may be	Unsteady, upstream boundary forced by estimates of peak flows derived using the FEH Statistical pooling group methodology.	Hydraulic	1D (extended cross sections using LIDAR) Flood Modeller Pro	Simple approach that suitably reproduces flood flows, allows determination of the number of properties at risk and testing of flood protection measures.

able to mitigate some of this flood risk?				
Subsurface flow in hillslopes	Hillslope slice model	Groundwater	2D vertical slice finite element model	Integrates different datatypes to test hypotheses
Component of quickflow versus slow flow in sub catchments	Combined hydrometric stable isotope analysis	Hydrological	Lumped parameter model – analytical and statistical methods	Helps integrate hydrometric and geochemical data
Characterise the 3D Geology of floodplains	GIS3D	Geological	3D geological model	Helps integrate different geological observations to build a 3D model

Partner: The Netherlands - Rijkswaterstaat

Scientific question that the model is being used for?	Name of modelling approach	Hydraulic/Hydrological?	Type of model (e.g. 1D/2D or lumped/parsimonious/distributed)	Why do you use it for this scientific question?
Calculating (differences in) waterlevels for measures (licenses, water framework directive, room for the river, etc).	WAQUA	Hydraulic	2D	This model has been used by RWS for a very long time, and has been developed partly by the research institutes of RWS (in collaboration with Deltares).So it's actually a legacy thing that this is still used. WAQUA is closely related to BASELINE, in which the geographical data is stored. This is used to derive the grid, bathymetry, weirs, frictions, etc.
Scenario-analysis and monte carlo analysis of hydraulic problems. Large stretches and long periods in time. (Simple) Long term morphological calculations	SOBEK	Hydraulic/morphological	1D	Before 2D was feasible (because of the calculation times), SOBEK was widely used. Now it is only used for scenario analysis or monte carlo analysis where many calculations have to be made. SOBEK is still used in research applications (eg studying the influence of sea level rise for 2100 and beyond).

Detailed Morphological computations to study the morphological effects of measures.	Delft3D	Morphological	2D/3D	Also based on BASELINE. State of the art model of RWS/Deltares. Use is partly based on legacy. RWS is well aware of the morphological consequences of its measures (e.g. for navigation). Effects have to be calculated to get insight in maintenance. Only morphological changes in the navigation channel are calculated.
Mixed models: combinations of 1D/2D	SOBEK 1D/2D	Hydraulic	1D/2D	Intermediate models. Used for instance in the FEWS-suite, which is used for daily predictions.
Daily predictions of waterlevels and discharges	FEWS-Suite	Hydraulic/hydrological	1D/2D	FEWS is the standard environment in which the daily discharge/waterlevels are calculated, used to indicate when the situation in the river area becomes dangerous/critical. Used for predictions.
Next generation WAQUA/Delft3D: hydraulic and morphological (effect) calculations of measures.	DFlow-FM	Hydraulic/morphological	1D/2D/3D	This is the next generation of models, currently under development and partially already in use. It is a complete suite, in which the 2D-version is based on Flexible mesh (triangles instead of a curvilinear mesh). This introduces more flexibility in modelling complex configurations. Still experimental. Open source.