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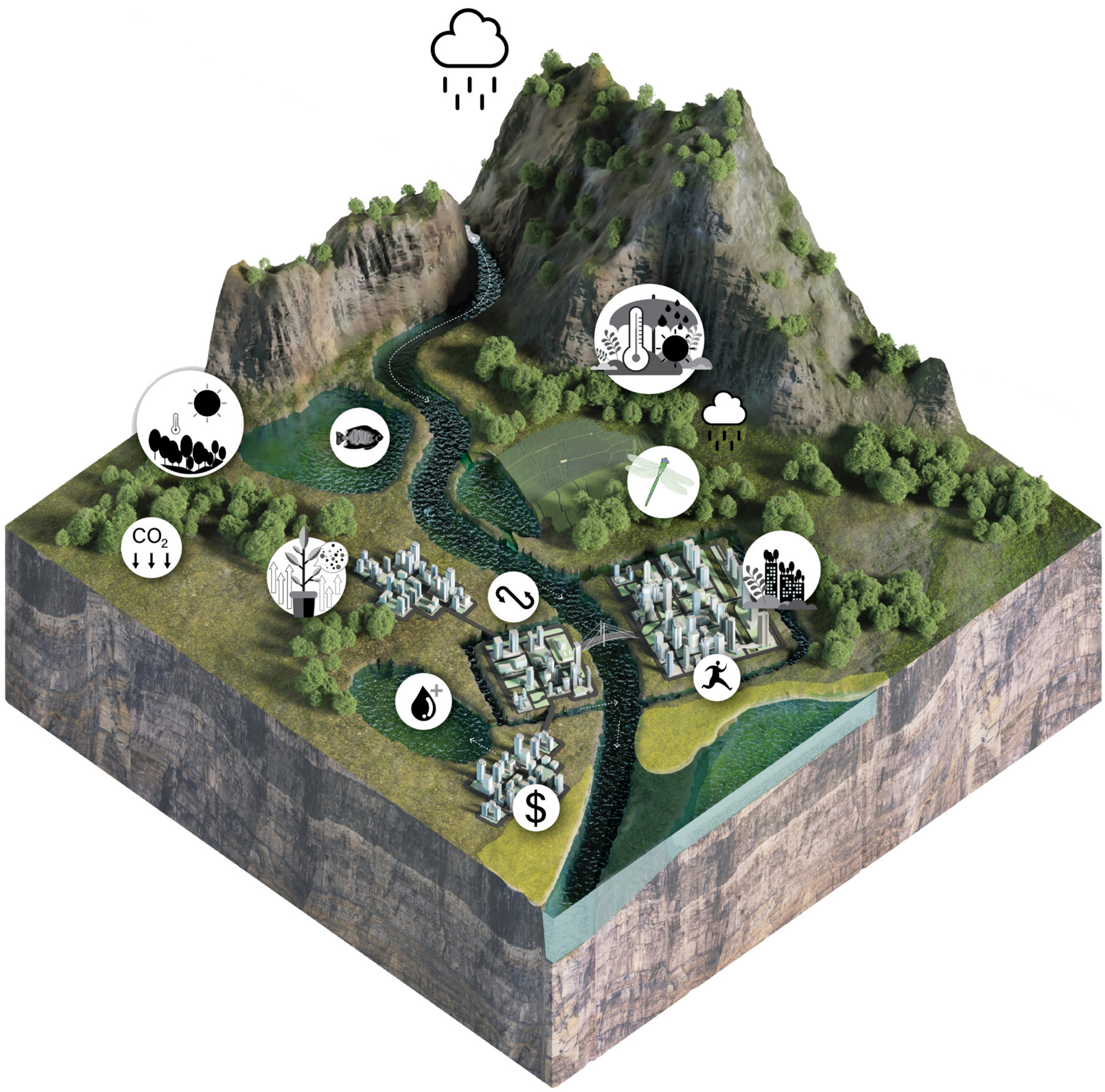

Evaluation of Nature-Based Solutions for Hydro-Meteorological Risk Reduction

Laddaporn Ruangpan

Evaluation of Nature-Based Solutions for Hydro-Meteorological Risk Reduction

DISSERTATION

for the purpose of obtaining the degree of doctor
at Delft University of Technology
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chair of the Board for Doctorates
and
in fulfillment of the requirement of the Rector of IHE Delft Institute for Water Education, Prof.dr. E.J. Moors,
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by

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ถึงครอบครัวที่รัก ขอขอบคุณที่อยู่ข้างๆตลอดและขอขอบคุณที่เชื่อมั่นว่าเด็กคนนี้จะทำได้ แม้ว่าเราจะอยู่ไกลกันแต่ทุกคนก็ยังให้ความรักและการสนับสนุนการเดินทางในการเรียนปริญญาเอกนี้ โดยเฉพาะ พ่อ แม่ มอส ป้าอ้อย น้าสาวเปียว พี่ฟ้า ที่คอยเป็นห่วงและให้กำลังใจ ขอขอบคุณที่ให้มิ้ลค์ได้ออกทำตามความฝันของตัวเอง รักทุกคน

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Thank you all

Milk Laddaporn Ruangpan

SUMMARY

The risks of extreme hydro-meteorological hazards, such as floods, droughts or storm surges, are expected to increase significantly due to climate change, population growth, land use change and other pressures. These risks have high impacts on societies, the environment and the economy. To address these challenges, effective methods for risk reduction are necessary to mitigate the impacts. While traditional ‘grey infrastructure’ approaches, such as dikes, sewage systems, and dams, are often used, they are generally not flexible enough to deal with future uncertainty.

Nature-Based Solutions (NBS) have emerged as flexible and cost-effective options for mitigating these hazards by utilizing nature-inspired interventions like afforestation, river restoration and wetland restoration. NBS not only combat climate change and reduce hydro-meteorological risks but also generate co-benefits such as biodiversity enhancement, recreational opportunities, and temperature reduction; thereby contributing to various Sustainable Development Goals (SDGs). The risk reduction benefits and co-benefits of NBS is the subject of this research.

To gain insights into the current state of scientific literature on hydro-meteorological risk reduction through NBS, a systematic review of existing literature was conducted. The review identified directions for future research based on current knowledge gaps. It highlighted the need for methodologies that can help the decision-making process in selecting NBS and evaluating their performance both before and after the implementation of NBS. There should also be more efforts in the development of assessment tools that incorporate new technologies such as real-time control systems and coupled models that provide more active and integrated operational solutions.

Based on these identified knowledge gaps, the research aims to develop and implement a methodological framework for evaluation of Nature-Based Solutions for hydro-meteorological risk reduction and co-benefits enhancement to support the decision-making process and performance evaluation. The evaluation framework consists of two main evaluation processes, which are ex-ante evaluation and ex-post evaluation. The ex-ante evaluation was applied to the Tamnava river basin, Serbia, while the ex-post evaluation was conducted in the Rangsit area, Thailand.

As part of the framework on ex-ante evaluation, an innovative methodology to select potential measures for reducing hydro-meteorological risk and simultaneously offering co-benefits has been developed and tested. This methodology involves a preliminary selection process that screens potential measures based on local characteristics, followed by a multi-criteria analysis (MCA) framework that incorporates stakeholders' preferences. The MCA framework aids in prioritizing the top five to ten most suitable NBS measures for the specific situation. The advantage of this framework is that it allows stakeholders

to express their preferences on their desired benefits from an NBS measure as well the specific measures themselves.

Additionally, the research developed a methodology for the economic assessment of these prioritised measures, which expands on traditional economic risk assessment by including the co-benefits of NBS. The economic assessment in this study is based on a life-cycle cost-benefit analysis (CBA), including net present value (NPV) and benefit/cost ratio (B/C). The results obtained by applying the method to a case study In Serbia show that show that considering co-benefits significantly improves the economic viability of NBS for flood mitigation. Thus, it is important to consider co-benefits when planning mitigation strategies. The developed methodology serves as a valuable tool for practitioners, researchers, and planners, enabling them to effectively integrate co-benefits into the economic assessment of flood risk reduction measure during the decision-making process.

For ex-post evaluation NBS, the research also developed a framework for assessing the performance, considering both qualitative and quantitative benefits and incorporating stakeholder preferences. The framework aims to provide decision-makers with a tangible understanding of the benefits of NBS, thereby enhancing their credibility and encouraging their widespread adoption as a preferred choice in mainstream infrastructure development. A case study utilising this framework conducted in Thailand demonstrated the positive impact of NBS (specifically furrows in agricultural land) for flood mitigation and other co-benefits. The results obtained can be used by farmers to improve their production, enhance resilience to climate change, and benefit their communities.

Moreover, the research explores the potential of using real-time control (RTC) to further improve the functionality of NBS. This is achieved by upgrading existing passively-controlled NBSs systems to Smart NBS through active RTC and developing a Digital Twin for the Rangsit case. The results highlight the potential for using RTC to improve the irrigation and drainage system operation as well as NBS implementation to reduce flooding. These results represent an essential starting point toward Smart Solutions utilizing Real-Time Control for flood reduction and water allocation.

In conclusion, this research contributes to the improvement of decision-making processes and NBS evaluation and decision-making processes, both before and after implementation of NBS. It provides valuable insights for practitioners and researchers to enhance the effectiveness and credibility of NBS, considering their risk reduction benefits and co-benefits.

SAMENVATTING

De risico's van extreme hydro-meteorologische gevaren, zoals overstromingen, droogtes en stormvloeden, zullen naar verwachting aanzienlijk toenemen als gevolg van klimaatverandering, bevolkingsgroei, veranderingen in landgebruik en andere factoren. Deze risico's hebben grote gevolgen voor samenlevingen, het milieu en de economie. Om deze uitdagingen aan te pakken, zijn effectieve risicobeperkingsmethoden nodig om de nadelige gevolgen te verminderen. Hoewel er vaak gebruik wordt gemaakt van traditionele 'grijze infrastructuur', zoals dijken, rioleringssystemen en dammen, zijn deze over het algemeen niet flexibel genoeg om met toekomstige onzekerheid om te gaan.

Op de natuur-gebaseerde oplossingen (Nature-Based Solutions, NBS) hebben zicht ontpopt als flexibele en kosteneffectieve opties om deze gevaren te beperken door gebruik te maken van op de natuur geïnspireerde ingrepen zoals bebossing, rivierherstel en herstel van drasland. NBS bestrijden niet alleen klimaatverandering en verminderen hydro-meteorologische risico's, maar leveren bovendien ook nevenvoordelen op, zoals verbetering van de biodiversiteit, recreatiemogelijkheden en temperatuurverlaging. Zo dragen NBS bij aan verschillende duurzame ontwikkelingsdoelen (Sustainable Development Goals, SDG's). Dit onderzoek richt zich op de voordelen en nevenvoordelen van NBS voor risicovermindering van hydro-meteorologische gevaren.

Om inzicht te krijgen in de huidige stand van de wetenschappelijke literatuur over hydro-meteorologische risicobeperking door NBS, werd een systematisch overzicht van bestaande literatuur opgesteld. Dit overzicht identificeerde richtingen voor toekomstig onderzoek op basis van de huidige hiaten in de kennis. Er werd gewezen op de behoefte aan methodologieën die hulp kunnen bieden tijdens besluitvormingsprocessen door het selecteren van NBS en het evalueren van hun prestaties zowel voor als na de implementatie van NBS. Er moeten ook meer inspanningen worden geleverd voor de ontwikkeling van beoordelingsinstrumenten die nieuwe technologieën integreren, zoals realtime regelsystemen en gekoppelde modellen die meer actieve en geïntegreerde operationele oplossingen bieden.

Op basis van deze geïdentificeerde hiaten in de kennis beoogt het onderzoek de ontwikkeling en implementatie van een methodologisch kader voor de evaluatie van NBS voor hydro-meteorologische risicobeperking en verbetering van nevenvoordelen. Het evaluatiekader bestaat uit twee belangrijke evaluatieprocessen, namelijk een evaluatie vooraf (ex-ante) en een evaluatie achteraf (ex-post). De ex-ante evaluatie werd toegepast op het stroomgebied van de Tamnava rivier in Servië, terwijl de ex-post evaluatie werd uitgevoerd in het Rangsit gebied in Thailand.

Als onderdeel van het kader voor ex-ante evaluatie is een innovatieve methodologie ontwikkeld en getest voor het selecteren van potentiële maatregelen voor het verminderen van hydro-meteorologische risico's en het tegelijkertijd bieden van nevenvoordelen. Deze methodologie omvat een voorbereidend selectieproces dat potentiële maatregelen doorlicht op basis van lokale kenmerken, gevolgd door een multicriteria-analyse (MCA) waarin de voorkeuren van belanghebbenden worden meegenomen. Het MCA-kader helpt bij het prioriteren van de vijf tot tien meest geschikte NBS-maatregelen voor de betreffende situatie. Het voordeel van dit kader is dat belanghebbenden hun voorkeuren kunnen uitspreken over de gewenste voordelen van een NBS-maatregel evenals de specifieke maatregelen zelf.

Daarnaast ontwikkelde het onderzoek een methodologie voor de economische beoordeling van deze geprioriteerde maatregelen, die verder gaat dan de traditionele economische risicobeoordeling door de nevenvoordelen van NBS mee te nemen. De economische beoordeling in deze studie is gebaseerd op een levenscycluskosten-batenanalyse, inclusief de netto contante waarde en de kosten-batenverhouding. De resultaten die verkregen zijn door de methode toe te passen op een casestudy in Servië laten zien dat het in beschouwing nemen van nevenvoordelen de economische levensvatbaarheid van NBS voor overstromingsrisico beperking aanzienlijk verbetert. Het is dan ook belangrijk om rekening te houden met nevenvoordelen bij het plannen van mitigatiestrategieën. De ontwikkelde methodologie is een waardevol hulpmiddel voor mensen in de praktijk, onderzoekers en planners, dat hen in staat stelt om tijdens het besluitvormingsproces op effectieve wijze nevenvoordelen te kunnen integreren in de economische beoordeling van maatregelen om de overstromingsrisico's te beperken.

Voor de ex-post evaluatie van NBS ontwikkelde het onderzoek ook een kader voor de beoordeling van de prestaties, waarbij zowel kwalitatieve als kwantitatieve voordelen in aanmerking worden genomen en rekening wordt gehouden met de voorkeuren van belanghebbenden. Het kader is bedoeld om besluitvormers een tastbaar begrip te geven van de voordelen van NBS, waardoor hun geloofwaardigheid wordt vergroot en hun wijdverspreide toepassing als voorkeurskeuze bij de ontwikkeling van reguliere infrastructuur wordt aangemoedigd. Een casestudy die gebruik maakte van dit kader en werd uitgevoerd in Thailand, toonde de positieve impact aan van NBS (met name groeven in landbouwgrond) voor het beperken van overstromingen en andere bijkomende voordelen. De verkregen resultaten kunnen door boeren worden gebruikt om hun productie te verbeteren, de veerkracht tegen klimaatverandering te vergroten en ten goede te komen aan de lokale gemeenschap.

Bovendien verkent het onderzoek het potentieel van het gebruik van real-time besturing (real-time control, RTC) om de functionaliteit van NBS verder te verbeteren. Dit wordt bereikt door bestaande passief bestuurde NBS-systemen te upgraden naar Slimme NBS door actieve RTC en het ontwikkelen van een Digitaal Tweelingmodel voor de Rangsit-casestudy. De resultaten benadrukken het potentieel voor het gebruik van RTC om de werking van irrigatie- en drainagesystemen te verbeteren, evenals NBS-implementatie om overstromingen te verminderen. Deze resultaten vormen een belangrijk startpunt voor slimme oplossingen die RTC gebruiken om overstromingen te verminderen en water toe te kennen.

Concluderend draagt dit onderzoek bij aan de verbetering van besluitvormingsprocessen en NBS-evaluatie en -besluitvorming, zowel voor als na de implementatie van NBS. Het biedt waardevolle inzichten voor mensen in de praktijk en onderzoekers om de effectiviteit en geloofwaardigheid van NBS te vergroten, terwijl er rekening wordt gehouden met de voordelen van risicobeperking en nevenvoordelen.

CONTENTS

1

INTRODUCTION[1]

[1] This chapter is an edited version of the journal publication: Ruangpan, L., Vojinovic, Z., Di Sabatino, S., Leo, L.S., Capobianco, V., Oen, A.M.P., Mcclain, M.E., Lopez-Gunn, E., 2020. Nature-based solutions for hydro-meteorological risk reduction: a state-of-the-art review of the research area. Nat. Hazards Earth Syst. Sci. 20, 243–270. https://doi.org/10.5194/nhess-20-243-2020

1.1 BACKGROUND

1.1.1 Definitions and theoretical backgrounds of NBS

There are several terms and concepts relating to NBS which have been used interchangeably in the literature to date. The two most prominent definitions are from the European Commission and International Union for Conservation of Nature (IUCN). The European Commission defines Nature-Based Solutions as "*Solutions that aim to help societies address a variety of environmental, social and economic challenges in sustainable ways. They are actions inspired by, supported by or copied from nature; both using and enhancing existing solutions to challenges, as well as exploring more novel solutions. Nature-based solutions use the features and complex system processes of nature, such as its ability to store carbon and regulate water flows, in order to achieve desired outcomes, such as reduced disaster risk and an environment that improves human well-being and socially inclusive green growth"* (European Commission, 2015). The IUCN has proposed a definition of NBS as "*actions to protect, sustainably manage and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits*" (Cohen-Shacham et al., 2016). Eggermont et al. (2015) proposed a typology characterising NBS into three types: i) NBS that address a better use of natural/protected ecosystems (no or minimal intervention), which fits with how IUCN frames NBS; ii) NBS for sustainability and multi-functionality of managed ecosystems and iii) NBSs for the design and the management of new ecosystems, which is more representative of the definition given by the European Commission.

In this research NBS is a collective term for innovative solutions to solve different types of societal and environmental challenges, based on natural processes and ecosystems. Therefore, it is considered as an "umbrella concept" covering a range of different ecosystem-related approaches and linked concepts (Cohen-Shacham et al., 2016; Nesshöver et al., 2017), that provides an integrated way to look at different issues simultaneously. Due to the diverse policy origins, NBS terminology has evolved in the literature to emphasize different aspects of natural processes or functions. In this regard, nine different terms are commonly used in the scientific literature in the context of hydro-meteorological risk reduction: Low Impact Developments (LIDs), Best Management Practices (BMPs), Water Sensitive Urban Design (WSUD), Sustainable Urban Drainage Systems (SUDs), Green Infrastructure (GI), Blue-Green Infrastructure (BGI), Ecosystem-based Adaptation (EbA) and Ecosystem-based Disaster Risk Reduction (Eco-DRR). The timeline of each term, based on their appearance in literature is shown in Figure 1.1 and their definitions are given in Table 1.1.

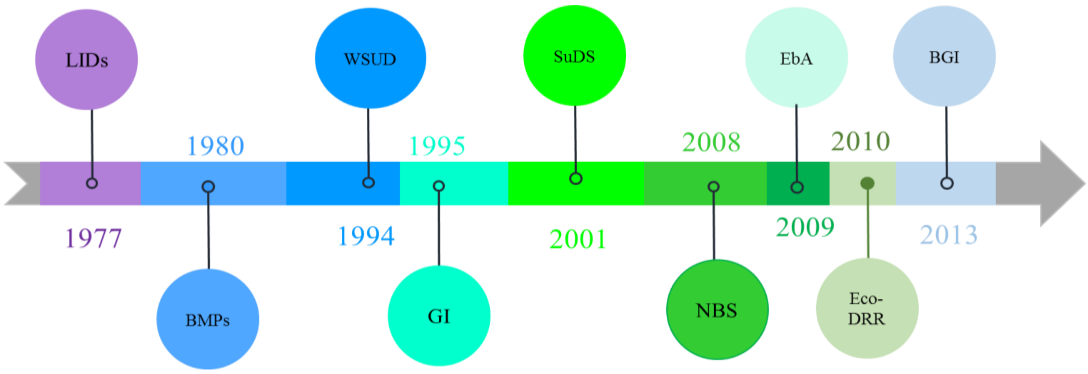


Figure 1.1. Timeline/year of origin of each terminology (Low Impact Developments (LIDs), Best Management Practices (BMPs), Water Sensitive Urban Design (WSUD), Green Infrastructure (GI), Sustainable Urban Drainage Systems (SUDs), Nature-Based Solitions (NBS), Ecosystem-based Adaptation (EbA), Ecosystem-based Disaster Risk Reduction (Eco-DRR) and Blue-Green Infrastructure (BGI)) based on their appearance in publications

The commonalities between NBS and its sister concepts are that they take participatory, holistic, integrated approaches, using nature to enhance adaptive capacity, reduce hydro-meteorological risk, increase resilience, improve water quality, increase the opportunities for recreation, improve human well-being and health, enhance vegetation growth and connect habitat and biodiversity. More information on the history, scope, application and underlying principle of terms of SUDs, LIDs, BMPs, WSUD and GI can be found in Fletcher et al. (2015) while the relationship between NBS, GI/BGI, and EbA is described in detail by Nesshöver et al. (2017).

Although all terms are based on a common idea, which is embedded in the umbrella concept of NBS, differences in definition reflect their historical perspectives and knowledge base that were relevant at the time of the research (Fletcher et al., 2015). The distinguishing characteristic between NBS and its sister concepts is how they address social, economic and environmental challenges (Faivre et al., 2018). Some terms such as SUDs, LIDs, and WSUD refer to NBS that specifically address stormwater management. They use landscape features to transform from a linear approach of conventional stormwater management into a more cyclical approach where drainage, water supply, and ecosystems are treated as part of the same system, mimicking more natural water flows (Liu and Jensen, 2018). GI/BGI focus more on technology-based infrastructures by applying natural alternatives (Nesshöver et al., 2017) for solving a specific activity (i.e., urban planning or stormwater). EbA looks at long-term changes within the conservation of biodiversity, ecosystem services and climate change, while Eco-DRR is more focused on immediate and medium-term impacts from the risk of weather, climate and non-climate- related hazards. EbA is often seen as a subset of NBS that is explicitly concerned with climate change adaptation through the use of nature (Kabisch et al., 2016a).

Table 1.1. Glossary of terminologies and their geographical usage

Terminology	Definition/Objectives/Purpose	Commonly used in	Reference
Low Impact Development (LIDs)	*"LID is used as a retro- fit designed to reduce the stress on urban stormwater infrastructure and/or create the resiliency to adapt to climate changes, LID relies heavily on infiltration and evapotranspiration and attempts to incorporate natural features into design."*	- United States - New Zealand	(Eckart et al., 2017)
Best management practices (BMPs)	*"A device, practice or method for removing, reducing, retarding or preventing targeted stormwater runoff constituents, pollutants and contaminants from reaching receiving waters"*	- United States - Canada	(Strecker et al., 2001)
Water Sensitive Urban Design (WSUD)	*"Manage the water balance, maintain and where possible enhance water quality, encourage water conservation and maintain water-related environmental and recreational opportunities".*	- Australia	(Whelans consultants et al., 1994)
Sustainable Urban Drainage Systems (SUDs)	*"Replicate the natural drainage processes of an area – typically through the use of vegetation-based interventions such as swales, water gardens and green roofs, which increase localised infiltration, attenuation and/or detention of stormwater"*	- United Kingdom	(Ossa-Moreno et al., 2017)
Green Infrastructure (GI)	*"The network of natural and semi-natural areas, features and green spaces in rural and urban, and terrestrial, freshwater, coastal and marine areas, which together enhance ecosystem health and resilience, contribute to biodiversity conservation and benefit human populations through the maintenance and enhancement of ecosystem services"*	- United States - United Kingdom	(Naumann et al., 2011)
Ecosystem-based Adaptation (EbA)	*"The use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change."*	- Canada - Europe	(CBD, 2009)
Ecosystem-based disaster risk reduction (Eco-DRR)	*"The sustainable management, conservation, and restoration of ecosystems to reduce disaster risk, with the aim of achieving sustainable and resilient development"*	- Europe - United States	(Estrella and Saalismaa, 2013)
Blue-Green Infrastructure (BGI)	*"BGI provides a range of services that include; water supply, climate regulation, pollution control and hazard regulation (blue services/goods), crops, food and timber, wild species diversity, detoxification, cultural services (physical health, aesthetics, spiritual), plus abilities to adapt to and mitigate climate change"*	- United Kingdom	(Lawson et al., 2014)
Nature-Based Solution	*"NBS aim to help societies address a variety of environmental, social and economic challenges in sustainable ways. They are actions inspired by, supported by or copied from nature; both using and enhancing existing solutions to challenges, as well as exploring more novel solutions."*	- Europe	(European Commission (EC), 2015)

From the above discussion, it can be concluded that EbA, Eco-DRR and GI/BGI provide more specific solutions to more specific issues. One key distinction is that unlike the sister concepts, the concept of NBS is more open to different interpretations, which can be useful in encouraging stakeholders to take part in the process of identifying solutions. Moreover, features of NBS provide an alternative to work with existing measures or grey infrastructures. Therefore, it is important to note that very often a combination between natural and traditional engineering solutions (a.k.a. “hybrid” solutions) is likely to produce more effective results than any of these measures alone, especially when their co-benefits are taken into consideration (Alves et al., 2019).

An important advance in the science and practice of NBS is given by the EKLIPSE Expert Working Group, which developed the first version of a multi-dimensional impact evaluation framework to support planning and evaluation of NBS projects. The document includes a list of impacts, indicators and methods for assessing the performance of NBS in dealing with some major societal challenges (Raymond et al., 2017b). Lafortezza et al., (2018) reviewed different case studies around the world where NBS have been applied from micro-scale to macro-scale. Furthermore, an overview of how different NBS measures can regulate ecosystem services (i.e., soil protection, water quality, flood regulation, and water provision) has been carried out by Keesstra et al., (2018).

1.1.2 Hydro-meteorological risks

Hydro-meteorological risks (HMRs) refer to the probability of damage occurring within a specific time period as a result of hazards originating from meteorological and hydrological events (Merz et al., 2010). These risks have significant impacts on human activities, infrastructure, and the natural environment. Some common examples of hydro-meteorological risks include floods, droughts, storm surges, and landslides (Debele et al., 2019). These hazards pose significant risks when they occur individually, but they can also lead to even greater challenges when they coincide or compound each other in a given environment. For example, heavy rainfall during a storm surge can worsen coastal flooding, while a drought followed by intense rainfall can lead to flash floods and landslides (Sahani et al., 2019a).

According to EM-DAT records from 1970 to 2019, hydro-meteorological hazards (HMHs) accounted for 50% of all reported disasters, 45% of all reported deaths and 74% of all reported economic losses. This equates to approximately 2.06 million lives lost and economic losses of US$3.6 trillion. On average, hydro-meteorological hazard events occurred daily over the past 50 years, which resulted in the loss of 115 people, and causing US$ 202 million in losses daily (World Meteorological Organization, 2021). Unfortunately, recent studies indicate that the intensity, duration, scale, and frequent of these events are expected to increase and become worse due to global warming and climate change (Gaitán et al., 2019; Guerreiro et al., 2018; Kreibich et al., 2014; Norén et al., 2016; Sippel and Otto, 2014). Next to climate change, others changes such as land use, urbanisation, and population growth also significantly contribute to increasing hydrometeorological risk (Field et al., 2012; Hooijer et al., 2004; Thieken et al., 2016).

Recognizing the combined impact of these drivers, it becomes imperative to implement effective strategies that address climate change, encourage sustainable land use practices, and enhance resilience. If we are not able to plan proper management strategies, HMRs will likely increase in the future. Thus, measures that enable adaptation to changing conditions and reduce vulnerabilities should be recognized as crucial. By adopting comprehensive approaches, the risks associated with hydro-meteorological events can be effectively mitigate to ensure the protection of lives, infrastructure and environments. However, effectively managing risks driven by HMHs is a complex process, requiring a variety of methods, tools and datasets to assess options and make decisions (Sahani et al., 2019a).

While the generic frameworks in this study cover all of these HM risks, the primary focus in the chosen case studies (Serbia and Thailand) are flooding and (to a lesser extent) drought. The summary of historical flooding for the case studies are summarised in the Table 1.2

Table 1.2 Summary of historical flooding for the case studies

Case studies	Historical flood events	Flood magnitude
Tamnava, Serbia	1999, 2006, 2009	• More than 6,000 ha of land were flooded • 480 residental building and 2500 inhabitatants were affacted
	May 2014	• 180 m^3/s at Koceljeva town (around 100 year ruturn period) • Dicharge 150 m^3/s at UB town (around 200 year ruturn period)
Rangsit, Thailand	October 2011	• 35.6 % of NBS areas were flooded • 1.5 m flood depth at Raphiphat canal station
	October 2016	• 0.5 m flood depth at Raphiphat canal station

1.1.3 Benefits of NBS

The benefits of NBS in this research are divided into two categories; primary benefits and co-benefits. A primary benefit refers to HMR reduction benefit by mitigating the impact of HMH while co-benefits refer to additional positive outcomes such as social, economic and environmental enhancements that are achieved alongside a primary benefit. This distinction is made because the main the primary purpose of implementing NBS in this study is to reduce risk. Since NBS are regarded as sustainable solutions that use ecosystem services to provide multiple benefits for human well-being and the environment, it is important to consider both aspects in the analysis.

Both primary and co-benefits of NBS can help to achieve many of the 2030 Agenda for Sustainable Development Goals (SDGs). The recent publication shows how NBS can contribute to achieving the SDGs (Seifollahi-Aghmiuni et al., 2019). This publication reports that wetland ecosystem services in positively interact with SDG 1 (no poverty), SDG 2 (zero hunger), SDG 3 (good health and well-being), SDG 6 (clean water and sanitation), SDG 7 (affordable and clean energy), SDG 11 (sustainable cities and communities), SDG 12 (responsible consumption and production), SDG 13 (climate action), SDG 14 (life below water) and SDG 15 (life on land). Reasons that NBS can provide these benefits is that they give more consideration to landscape function, adaptive and multi-functionality design (Lennon et al., 2014; Vojinovic et al., 2017), restoring naturally occurring ecosystems and promoting desirable soil (Keesstra et al., 2018).

The literature to date shows that multiple challenges can be addressed through NBS now and in the future'. These challenges include reducing flood risk (Song et al., 2018), storing and infiltrating rainfall run-off, delaying and reducing surface runoff, reducing erosion and particulate transport (Loperfido et al., 2014), recharging groundwater discharge, reducing pollution from surface water (O'Donnell et al., 2018)**,** increasing nutrient retention and removal (Loperfido et al., 2014), maintaining soil moisture, and enhancing vegetation growth. Such benefits help in reaching SDG 6 - ensuring sustainable water management.

Beyond primary benefit on water management, the case for NBS includes their ability to provide additional benefits in improving socio-economic aspects (SDG 11) and human well-being (SDG 3) through recreational areas and aesthetic value (Song et al., 2018), as well as encouraging tourism through the access to nature (Sutton-Grier et al., 2018). Wheeler et al., (2010) quantified the volume and intensity of children's physical activity in greenspace and found that time in greenspace is more likely to lead to greater activity intensity amongst children. The use of NBS can bring economic benefits (SDG 1 and SDG 8) in different ways, such as reduced/prevented damage costs from hydro-meteorological events, energy savings from the reduction of stormwater that typically needs to be treated in a public sewerage system, and carbon savings from reduced building energy consumption (heating and cooling) (Soares et al., 2011). Such energy and carbons savings will help contribute to SDG 13.

The environmental benefits of NBS measures can have various positive impacts. Some of the most important are the ability to enhance environmental and ecosystem services by connecting habitat and biodiversity (Hoang et al., 2018; Reguero et al., 2018; Thorslund et al., 2017), increasing carbon consequences, reducing air and noise pollution (O'Donnell et al., 2018); and mitigating the urban heat island effect (Majidi et al., 2019;

Raymond et al., 2017a). Zhang and Chui, (2019) reviewed the hydrological and bio-ecological benefits of NBS across spatial scales and suggested that there should be more research at the catchment scale to consider the full benefits of NBS.

The hydrological and water quality benefits of NBS have been widely reviewed and discussed, but there are few articles that focus on evaluating the co-benefits of NBS. Doing so could help raise awareness and enhance the institutional and social acceptance of these measures (Pagano et al., 2019). Hoang et al., (2018) proposed a new integrated methodology using a GIS approach to assess the benefits of NBS, which include habitat connectivity, recreational accessibility, traffic movement, noise propagation, carbon sequestration, pollutant trapping and water quality. Mills et al., (2016) assessed air pollution reduction based on tree canopy cover. Alves et al., (2019) presented a novel methodology for evaluating co-benefits for NBS applications in urban contexts. Fenner (2017) recommended that their spatial distribution should be assessed through multi-functional design making it possible to identify how this is valuable to stakeholders and where the overall aggregated benefits occur.

However, there is still a need for deeper understanding of the assessment of multi-benefits from NBS (Liu et al., 2017) as there is a lack of information on the values of ecosystem and multi-related ecosystems economic valuation.

1.1.4 Socio-economic influence on implementation of NBS

Investing in NBS for hydro-meteorological risk reduction is essential to ensure the capability for future socio-economic development (Faivre et al., 2018). In this respect, the European Commission has been investing considerably in the research and innovation of NBS or EbA, and some recent efforts have been placed on practical demonstration of NBS for climate change adaptation and risk prevention (Faivre et al., 2017). The European Commission is dedicated to bring innovative ‘sciences-policy-society’ mechanisms, open consultations, and knowledge-exchange platforms to engage society in improving the condition for implementation of NBS (Faivre et al., 2017). There are various web-portals, networks and initiatives that address NBS at European, national and sub-national levels (Table 1.3)

Denjean et al. (2017) noted that the people who propose NBS are in many cases ecologists and biologists who have been trained within a very different scientific paradigm and thus speak a ‘different language’ to the key decision makers, who are often civil and financial engineers, contractors and financing officers. Hence, this may limit the feasibility of implementation of NBS.

Table 1.3 An overview of web-portals, networks and initiatives that address Nature-Based Solutions

Name	References/ Website	Terminology used	Scale level	Funded by	Proposes
OPPLA	(Oppla, 2019)	Nature-Based Solution, Natural capital, Ecosystem services	Europe	FP7 (EC)	A new knowledge marketplace - EU repository of NBS; a place where the latest thinking on ecosystem services, natural capital and nature-based solutions is brought together.
BiodivERsA	(Biodivera, 2019)	Ecosystem services	Europe	Horizon 2020 (EC)	A network of funding organizations promoting research on biodiversity and ecosystem services.
BISE	(BISE, 2019)	Ecosystem services, Green infrastructures	Europe	EC	A single entry point for data and information on biodiversity supporting the implementation of the EU strategy and the Aichi targets in Europe.
ThinkNature	(ThinkNature, 2019)	Nature-Based Solution	Europe	Horizon 2020 (EC)	A multi-stakeholder communication platform that supports dialog and understanding of NBS.
ClimateADAPT	(Climate ADAPT, 2019)	EbA, Nature-Based Solution, GI	Europe	EC, EEA	A platform that supports Europe in adapting to climate change by helping users to access and share data and information relevant for CCIVA.
Natural Water Retention Measures	(NWRM, 2019)	Natural water retention measures	Europe	EC	A platform that gathers information on NWRM at EU level.
Urban Nature Atlas	(NATURVATION, 2019)	Nature-Based Solution	Europe	Horizon 2020 (EC)	A platform that contains around 1000 examples of Nature-Based Solutions from across 100 European cities.
Disaster Risk Management Knowledge Centre	(DRMKC, 2019)	Eco-DRR	Europe	EC	A platform that provides a networked approach to the science-policy interface in DRM.
Natural Hazards – Nature Based Solutions	(World Bank et al., 2019)	Nature-Based Solution	Global	The World Bank	A project map that provides a list of nature-based projects that are sortable by implementing organisation, targeted hazard, and type of

Name	References/ Website	Terminology used	Scale level	Funded by	Proposes
					nature-based solution, geographic location, cost, benefits, and more.
Nature-based Solutions Initiative	(Nature-based Solutions Initiative, 2019)	Nature-Based Solution	Global	International Institute for Environment and Development (IIED)	The global policy platform that provides information about climate change adaptation planning across the globe openly available and easy to explore.
weADAPT	(SEI, 2019)	Ecosystem-based Adaptation	Global	Stockholm Environment Institute (SEI)	A collaborative platform on climate adaptation issues, which allows practitioners, researchers and policy-makers to access credible, high-quality information and connect.
Nature of Cities	(The Nature of Cities, 2019)	Green Infrastructures	Global		An international platform for transdisciplinary dialogue concerning urban solutions.
ClimateScan	(ClimateScan, 2019)	Blue-Green Infrastructures	Global	EC	Global online tool which acts as a guide for projects and initiatives on urban resilience, climate proofing and climate adaptation around the world.
Partnership for Environment and Disaster Risk Reduction (PEDRR)	(PEDRR, 2019)	Ecosystem-based Adaptation	Global		PEDRR aims to promote and scale-up implementation of Eco-DRR and ensure it is mainstreamed in development planning at global, national and local levels, in line with the SFDRR.
PANORAMA	(PANORAMA, 2019)	Ecosystem-based Adaptation,	Global	IUCN, GIZ, UNDP	It aims to document and promote examples of inspiring solutions across development topics, to enable cross-sectoral learning and upscaling of successes

Very few articles study actions or processes in relation to stakeholder participation. However, those that do so stress the importance of involving stakeholders in the evaluation and implementation of NBS and the current practical limitations of implementing NBS. One of the important reasons is to ensure that stakeholders and local government are fully aware of the multiple benefits of NBS so that they can better integrate them into planning for sustainable cities (Ishimatsu et al., 2017). For example, Liu and Jensen, (2018) and Chou, (2016) claim that the implementation of NBS with visible benefits on the landscape and the liveability of the city (in terms of amenities, recreation, green growth, and microclimate) can create positive attitudes among stakeholders towards applying NBS. Moreover, as the implementation of NBS is often a costly investment for local communities, and the facilities are expected to be in place for at least a decade, it is essential for stakeholders to know the effectiveness of NBS (Semadeni-Davies et al., 2008). Involving the community with authorities in both the planning and implementing process can be a very useful strategy (Dalimunthe, 2018). In a case study of the Great Plains in the US, Vogel et al., (2015) addressed how local perceptions of NBS effectiveness and applicability limit its adoption. One of the factors was a lack of awareness of NBS and support from stakeholders and authorities. In another case in Portland, Oregon, USA, Thorne et al., (2018) concluded that the limited adoption of NBS is caused by the lack of confidence in public preferences and socio-political structures, as well as the uncertainty regarding scientific evidence related to physical processes. To solve this, they suggested that both socio-political and biophysical uncertainties must be identified and managed within the framework for designing and delivering sustainable urban flood risk management. Han and Kuhlicke, (2019), reviewed factors shaping people's perceptions of NBS in relation to reducing hydro-meteorological risks. The review concluded that future empirical studies focusing on perceptions of NBS should consider careful sampling of different NBSs and conducting comparative analyses among different NBS projects.

Schifman et al., (2017) proposed a Framework for Adaptive Socio-Hydrology (FrASH) that can be used in NBS planning and implementation by bringing ideas together from socio-hydrology, the capacity for adaptation, participation and inclusiveness, and organised action. The framework also helps in creating a connected network between municipalities, public works departments, organisations and people in the community. This potentially allows for the management of resilience in the system at multiple scales.

Often, it is not as easy to address socio-economic issues as technical questions. These socio-economic issues include perception and acceptance, policies, interdisciplinary nature, education, and documenting the economic benefit of NBS implementation (Alves et al., 2018b; Santoro et al., 2019; Vogel et al., 2015). Nevertheless, social science research (i.e. surveys, interviews, and focus groups) helps to review and gain insights into the obstacles and motivations for implementing NBS, as well as to understand a community's resilience and stakeholders' risk perception (Matthews et al., 2015; Santoro et al., 2019). Moreover, research into the socio-political dynamics of NBS is still lacking; there are few case studies available that critically evaluate the politics of NBS in the role of community mobilization (Triyanti and Chu, 2018). Not only it is essential to involve stakeholders in the selection, planning, design and implementation of NBS, but it is also important for bridging gaps between researchers, engineers, politicians, managers and stakeholders. This may help to improve our capacity for using both small and large scale NBS. There are well documentations of policy arrangements, scientific niches and current status of governance studies of NBS that were reviewed by Scarano, (2017); Triyanti and Chu, (2018); Wolff et al., (2023)

1.2 LESSONS LEARNT FROM NBS LITERATURE REVIEW

In this research NBS for hydro-meteorological risk reduction have been divided into small- and large-scale solutions (Figure 1.2). “Small-scale NBS” are usually referred to as NBS at the urban or local scale (i.e., buildings, streets, roofs, or houses), while NBS in rural areas, river basins and at the regional scale are referred to as “large-scale NBS” (Figure 1.2).

Figure 1.2. Illustration of large- and small-scale Nature-Based-Solutions (NBS); Large-scale NBS A illustrates NBS in mountainous regions (e.g., afforestation, slope stabilization, etc.), Large-scale NBS B illustrates NBS along river corridors (e.g., widening river, retention basins, etc.) and Large-scale NBS C illustrates NBS in coastal regions (e.g., sand dunes, protection dikes/walls, etc.); Typical examples of Small-scale NBS are green roofs, green walls, rain gardens, swales, bio-retention, etc.

1.2.1 Small-scale NBS

Small scale NBS are usually applied to a specific location such as a single building or a street. However, for some cases, a single NBS is not sufficient to control a large amount of runoff. Therefore, this review discusses the application and effectiveness of both individual NBS and multiple-NBS combinations. A majority of research discusses the effectiveness of a single/individual NBS site, while only a few articles discuss the effectiveness of multiple NBS sites. A summary of effectiveness, co-benefits and costs of NBS measures at small scale is shown in Table 1.4.

To date, various types of single NBS sites have been studied with objectives such as reduction of the flood peak (Carpenter and Kaluvakolanu, 2011; Ercolani et al., 2018; Liao et al., 2015; Mei et al., 2018; Yang et al., 2018), delay/attenuation of the flood peak (Ishimatsu et al., 2017), reduction of volume of combined sewer overflows (Burszta-Adamiak and Mrowiec, 2013) and reduction of surface runoff volume (Lee et al., 2013; Shafique and Kim, 2018). The review found just three articles that discuss the reduction of drought risk by using NBS. Lottering et al. (2015) used NBS to reduce water consumption in suburban areas, while Radonic (2019) showed that rainwater harvesting can help reduce household water consumption. Finally, Wang et al., (2019) demonstrated that forests can significantly mitigate drought impacts and protect water supplies for crop irrigation.

The most common NBS measures in urban areas appear to be intensive green roofs (Burszta-Adamiak and Mrowiec, 2013; Carpenter and Kaluvakolanu, 2011; Ercolani et al., 2018), extensive green roofs (Cipolla et al., 2016; Lee et al., 2013), rain gardens (Ishimatsu et al., 2017), rainwater harvesting (Khastagir and Jayasuriya, 2010), dry detention ponds (Liew et al., 2012), permeable pavements (Shafique et al., 2018), bio-retention (Khan et al., 2013; Olszewski and Allen, 2013), vegetated swales (Woznicki et al., 2018) and trees (Mills et al., 2016).

The literature to date acknowledges that the effectiveness of NBS greatly depends on the magnitude and frequency of rainfall events. Green roofs are recognized in reducing peak flows more effectively for smaller magnitude frequent storms than for larger magnitude infrequent storms (see for example, Ercolani et al., 2018). There are also reports that rain gardens are more effective in dealing with small discharges of rainwater (Ishimatsu et al., 2017). Swales and permeable pavements are more effective for flood reduction during heavier and shorter rainfall events. Zölch et al. (2017) suggested that the effectiveness of NBS should be directly linked to their ability to increase (as much as possible) the storage capacities within the area of interest, while using open spaces that have not been used previously and/or while providing benefits to other areas for urban planning. However, the authors of these studies investigated the performance of such measures individually (i.e. at the specific/local/single site) without evaluating them in combination with other NBS sites or in hybrid combinations.

Table 1.4. Summary of runoff volume and peak flow reduction effectiveness, co-benefits and costs of small scale NBS measures

Measures	**References**	**Case studies**	**Area/ volume covered by NBS**	**Effectiveness**		**Co-benefits**	**Cost/ m²***
				Runoff volume reduction	Peak flow reduction		
Porous pavement	Shafique et al., (2018)	Seoul, Korea	1050 m^2	~30–65%	-	• Removing diffuse pollution • Enhancing recharge to groundwater	~$252
	Damodaram et al., 2010	Texas, USA	2.99 km^2	-	~10% - 30%		
Green roofs	(Burszta-Adamiak and Mrowiec, 2013)	Wroclaw, Poland	2.88 m^2	-	~54%-96%	• Reducing nutrient loadings. • Saving energy • Reducing air pollution • Increasing amenity value	~$564
	(Ercolani et al., 2018)	Milan, Italy	0.39 km^2	~15%-70%	~10-80%		
	(Carpenter and Kaluvakolanu, 2011)	Michigan, USA	325. 2 m^2	~68.25%	~88.86%		
Rain gardens	(Ishimatsu et al., 2017)	Japan	1.862 m^2	~36-100%	-	• Providing a scenic amenity. • Increasing the median property value • Increasing biodiversity	~$501
	(Goncalves et al., 2018)	Joinville, Brazil	34,139 m^2	50%	~48.5%		
Vegetated swales	(Luan et al., 2017)	Beijing, China	157 m^3	~0.3–3.0%.	~2.2%	• Reducing of pollutants • Increasing biodiversity	~$371
	(Huang et al., 2014)	Haihe basin, China	1,500 m^3	9.60%	~23.56%		
Rainwater harvesting	(Khastagir and Jayasuriya, 2010)	Melbourne, Australia	1 m^3 -5 m^3	~57.8%-78.7%	-	• Improving water quality (TN was reduced around 72%-80%)	~$865/ m^3
	(Damodaram et al., 2010)	Texas, USA	1.5 km^2	-	~8%-10%		
Dry detention pond	(Liew et al., 2012)	Selangor, Malaysia	65,000 m^2	-	~33-46%	• Providing recreational benefits.	

Measures	References	Case studies	Area/ volume covered by NBS	Effectiveness		Co-benefits	Cost/ m^2*
				Runoff volume reduction	Peak flow reduction		
Detention pond	(Damodaram et al., 2010)	Texas, USA	73,372 m^3	-	~20%	• Providing biodiversity benefits	~$60
	(Goncalves et al., 2018)	Joinville, Brazil	9,700 m^3	55.7%	~43.3%	• Providing recreational benefits.	
Bio-retention	(Luan et al., 2017)	Beijing, China	945.93 m^3	~10.2–12.1%	-	• Reducing TSS pollution • Reducing TP pollution	~$534
	(Huang et al., 2014)	Haihe River basin, China	1,708.6 m^3	9.10%	~41.65%		
	Khan et al., 2013;	Calgary	48 m^3	~90%	-		
Infiltration trench	(Huang et al., 2014)	Haihe River, China	3,576 m^3	30.80%	~19.44%	• Reducing water pollutant • Improving water quality.	~$74
	(Goncalves et al., 2018)	Joinville, Brazil	34,139 m^2	55.9%	~53.4%		
Green roof and Porous pavement	(Damodaram et al., 2010)	Texas, USA	4.49 km^2	-	~10%-35%	• Saving energy • Increasing amenity value	
Swale and Porous pavement	(Behroozi et al., 2018)	Tehran, Iran	-	5%-32%	~10%-21%	• Decreasing TSS 50-60%	
Rainwater harvesting and Porous pavement	(Damodaram et al., 2010)	Texas, USA	4.49 km^2	-	~20%-40%	• Removing diffuse pollution	
Detention pond and Raingarden	(Goncalves et al., 2018)	Joinville, Brazil	18,327 m^2	70.8%	~60.0%	• Providing a scenic amenity	
Detention pond and Infiltration trench	(Goncalves et al., 2018)	Joinville, Brazil	18,327 m^2	75.1%	~67.8%	• Improving surface water quality.	

***Remark** Cost of each measure is based on CNT (2009); De Risi et al. (2018); Nordman et al. (2018)

Several studies evaluated the performance of multiple (or combined) NBS measures (i.e., a train of NBS) (See for example Damodaram et al., 2010; Dong et al., 2017; Huang et al., 2014; Luan et al., 2017). One of the most successful international projects in combining several NBS measures at the urban scale is the “Sponge City Programme (SCP)” in China. The SCP project was commissioned in 2014 with the aim to implement both concepts and practices of LIDs/NBS as well as various comprehensive urban water management strategies (Chan et al., 2018). Nowadays, the concept (‘Sponge City’) is widely used for a city increases resilience to climate change. It also combines several systems, such as source control system, urban drainage system, and emergency discharge system.

Porous pavements are one of the most popular measures to be combined with other NBS for urban run-off management. Examples of this are described in Hu et al. (2017) who used inundation modelling to evaluate the effectiveness of rainwater harvesting and pervious pavement as retrofitting technologies for flood inundation mitigation of an urbanized watershed. Damodaram et al. (2010) concluded that the combination of rainwater harvesting and permeable pavements is likely to be more effective than pond storage for small storms, while ponds are likely to be effective in managing runoff from the more intense storms.

Several studies argue that multiple NBS measures can lead to a more significant change in runoff regime and more effective long term strategies than single NBS measures (Webber et al., 2018) . For example, Wu et al. (2018) simulated eight scenarios changing the percentage of combined green roof and permeable pavement in an urban setting. The results show that when green roofs and permeable pavements are applied at all possible locations, a 28% reduction in maximum inundation can be obtained. In comparison, scenarios implementing either green roofs or permeable pavements alone at all possible areas experienced a reduction of 14%. One of the main reasons for the superior performance of combined NBS is that they work in parallel, each treating a different portion of run-off generated from the sub-catchment (Pappalardo et al., 2017). For these combinations, the spatial distribution should be carefully considered because it can improve the runoff regime better when compared to centralised NBS (Loperfido et al., 2014).

Further research on the use of combined NBS and grey infrastructure (i.e., hybrid measures) is desirable as only three contributions were found during the review. Alves et al., (2016) presented a novel method to select, evaluate and place different hybrid measures for retrofitting urban drainage systems. However, only fundamental aspects were touched upon in the methodology and they suggested future work should include the possibility of considering stakeholders’ preferences or flexibility within the method. In the work of Vojinovic et al. (2017), a methodological framework that combines ecosystem services (flood protection, education, art/culture, recreation and tourism) with economic analysis for the selection of multifunctional measures and consideration of small and large scale NBS has been discussed for the case of Ayutthaya in Thailand. Onuma and Tsuge, (2018) compared the cost-benefits and performance of NBS and grey infrastructures, concluding that NBS are likely to be more effective when implemented through cooperation with local people, whereas hybrid solutions are more effective than a single NBS in terms of performance.

The main limitation of the above studies is that they only assess the effectiveness of NBS at urban scales. This may not be sufficient for large events, as climate change is likely to increase the frequency and intensity of future events (Qin et al. 2013). A large scale NBS could be a solution for storm events with large magnitude and long duration, which is usually the case for disaster risk reduction applications, and therefore research in this direction is highly desirable (Giacomoni et al. 2012). Although Fu et al., (2018) analysed variations in runoff for different scales and land-uses, the impact of NBS was only examined for the small urban scale. Another limitation is that none of these contributions incorporated cost-benefit analyses (CBA). CBA can be used as a tool to support the decision-making process as they compare the feasibility of implementation costs and the potential benefits of NBS.

1.2.2 Large-scale NBS

Large-scale water balance, water fluxes, water management and ecosystem services are affected by future changes such as climate change, land use changes, water use changes and population growth. To address such challenges, large scale NBS are needed to make more space for water to retain, decelerate, infiltrate, bypass, and discharge (Cheng et al., 2017; Thorslund et al., 2017). Generally, a large-scale NBS combines different NBS within a larger system to achieve better long-term strategies. There are some examples of NBS measures for hydro-meteorological risk reduction summarized in McVittie et al., (2018) and Sahani et al., (2019). A summary of effectiveness, co-benefits and cost of large scale NBS measures is shown in Table 1.5.

Few articles have addressed the combined behaviour of NBS at large scales. One of the possible reasons for this is that large-scale systems are more complex than small-scale systems. The most common large-scale NBS are flood storage basins (De Risi et al., 2018), preservation and regeneration of forests in flood-prone areas (Bhattacharjee and Behera, 2018), making more room for the river (Klijn et al., 2013), river restoration (Chou, 2016), wetlands (Thorslund et al., 2017), and mountain forestation (Casteller et al., 2018).

A classic example of a large-scale NBS implementation is the ‘Room for the River Programme’ implemented along the Rhine and Meuse rivers in the Netherlands. The Room for the River Programme consisted of 39 local projects based on nine different types of measures (Klijn et al., 2013). These measures are flood plain lowering, dike relocation, groyne lowering, summer bed deepening, water storage, bypass/floodway, high water channels, obstacle removal and dike strengthening. The benefits that the programme achieved are more than just reducing flooding, also increasing opportunities for recreation, habitat and biodiversity in the area (Klijn et al., 2013). Another case study of a large scale NBS is the Laojie river project in Taoyuan City in Taiwan. The study focused on changing the channelised, culverted, flood-controlled watercourse into an accessible green infrastructure corridor for the public (Chou, 2016). The landscape changes resulting from this project have increased recreation activities and improved the aesthetic value in the area.

Table 1.5. Summary of effectiveness, co-benefits and costs of large scale NBS measures

Measures	References	Case studies	Area/ volume covered by NBS	Effectiveness	Co-benefits	Cost
De-culverting (river restoration)	(Chou, 2016)	Laojie River, Taiwan	3 km	• It can reduce flood risk up to 100 year return period	• Increasing landscape value • Increasing recreational value	~€16 million
Floodplain lowering	(Klijn et al., 2013).	Deventer Netherlands	5.01 km^2	• It can reduce water level 19 cm	• Increasing nature area • Increasing agriculture value	~€136 million
Dike relocation/floodplain lowering	(Klijn et al., 2013).	Nijmegen/ Lent, Netherlands	2.42 km^2	• It can reduce water level 34 cm	• Increasing floodplain area • Increasing recreational value	~€342 million
Floodwater storage	(Klijn et al., 2013).	Volkenrak-Zoommeer	200 million m^3	• It can reduce water level 50 cm	• Increasing habitat and biodiversity in the area • Increasing recreational value	~€386 million
Green floodway	(Klijn et al., 2013).	Veessen-Wapenveld	14.10 km^2	• It can reduce water level 71 cm	• Increasing floodplain area • Increasing recreational value	
Wetlands (Mangroves and salt Marshes)	(Gedan et al., 2011; Van Coppenolle et al., 2018)			• It can mitigate storm surge 80% • It can protect against tsunami impacts	• Providing shoreline protection services	

NBS may benefit people in coastal areas by reducing risk from storm surges, wave energy, coastal flooding as well as erosion as documented by several authors (see, for example, Coppenolle, 2018; Joyce et al., 2017; Ruckelshaus et al., 2016; Sutton-Grier et al., 2018). NBS for coastal areas can be implemented either at large or small scales. They include dunes, beaches, oyster and coral reefs, mangroves, seagrass beds and marshes. These measures can also provide habitat for different species such as fish, birds, and other wildlife (Ruckelshaus et al., 2016). Schoonees et al., (2019) provided lists of general recommendations, technical guidelines and policies, and design considerations for NBS in coastal areas. However, only a few articles focused on the potential benefits of NBS in coastal areas.

Casteller et al. (2018) concluded that native mountain forests could be used to reduce hydro-meteorological risk such as flash floods and landslides. Moreover, the use of NBS in different forest ecosystems to reduce shallow landslide impacts should be addressed (de Jesús Arce-Mojica et al., 2019). To reduce the impact of large-scale hydro-meteorological events, more research is needed on large-scale NBS and their hybrid combinations designed to attenuate flows and improve drainage.

1.3 EX-ANTE EVALUATIONS

Ex-ante evaluation refers to an assessment performed before implementation of a project. Its objective is to identify and estimate values and assumptions related to the expected effects and costs associated with various strategies. These evaluations provide a foundation for the assessment of potential performance of alternative strategies (Associated Programme on Flood Management, 2015).

1.3.1 Selection of NBS

NBS shortlist selection is an initial step in the ex-ante evaluations, which is performed before implementation of a project. It has been a well-accepted fact that not all NBS are suitable for all conditions. Therefore, it is important to consider the feasibility and constraints at the site at an early stage in the selection process. The first consideration in selecting NBS is to define the objective such as the target area (i.e. urban, rural) and performance requirements such as quantity and/or quality (Romnée and De Herde, 2015; Zhang and Chui, 2018). For example, Pappalardo et al., (2017) chose permeable pavements and green roofs because they can detain runoff or enhance infiltration to the subsoil. Another approach is to consider both primary benefits and key co-benefits. For instance, Majidi et al., (2019) developed a framework to select NBS to reduce flood risk and enhance human thermal comfort (reducing heat stress). Many authors suggest restricting the choice of appropriate NBS based on common site constraints such as land use, soil type, groundwater depth, catchment characteristics, political and financial regulations, amenities, environmental requirements and space available (Eaton, 2018;

Joyce et al., 2017; Nordman et al., 2018; Oraei Zare et al., 2012). For example, Eaton (2018) selected bio-retention measures because these are more suitable in low-density residential land use. Moreover, the study of Reynaud et al., (2017) describes how the type of NBS has an impact on individuals' preference for ecosystem services. Therefore, a screening analysis is necessary to select the NBS measures that are best suited to local constraints and objectives, providing decision-makers with valuable information. The way forward in the selection of NBS is to consider spatial planning principles to locate the position for measures. Spatial planning principles can facilitate and stimulate discussion among local communities, researchers, policy-makers and government authorities.

1.3.2 Evaluation of NBS

There are several frameworks and methods that can be used to evaluate the performance of NBS. One of the most popular evaluation approaches is to analyse, simulate and model hydrology, hydraulics and water balance processes. This information is then used to support decision makers, planners and stakeholders in their evaluation of performance and potential of NBS by comparing modelled results against the current situation, baseline scenario or targets (Jia et al., 2015).

In addition to hydrological and hydraulic analyses, cost-benefit analyses are often used to select and evaluate NBS (Huang et al., 2018; Nordman et al., 2018; Watson et al., 2016; Webber et al., 2018). The common benefits considered include prevented damage costs, omitted infrastructures, and prevented agricultural losses. One cost-benefit approach is to evaluate NBS by applying the whole life cycle costing approach (LCC) including construction, operation, maintenance and opportunity costs (Nordman et al., 2018) and Return on Investment (ROI) (De Risi et al., 2018). Recently, the guideline for project developers on assessing the benefits and costs of NBSs for climate resilience has been developed by Van Zanten et al., (2023). However, it should be noted that the guideline provided offers a broad overview of assessing the benefits and costs of NBS, rather than providing detailed information on estimating the specific benefits of individual measures. Additionally, while the guideline does include some case studies, it primarily focuses on urban and coastal areas, potentially limiting the breadth of its applicability to other environments.

Another method for the evaluation of NBS is multi-criteria analysis (MCA), which has the potential to integrate and overcome the differences between social and technical approaches (Loc et al., 2017). It can be used to structure complex issues and help find a better understanding of costs and benefits. Such analysis is useful for decision makers when there are multiple and conflicting criteria to be considered (Alves et al., 2018a; Loos and Rogers, 2016). An MCA takes different criteria into account and assigns weights to each criterion. This process can produce a ranking of the different measures that can be implemented in the case study (Chow et al., 2014; Jia et al., 2015). For example, Loc et al. (2017), integrated the results from numerical modelling and social surveys into a MCA and ranked the alternatives based on the evaluation criteria of flood mitigation, pollutant removal and aesthetics. Loos and Rogers (2016) applied multi-attribute utility theory (MAUT) to assess utility values for each alternative by assuming that preference and utility are independent from each other. Petit-Boix et al. (2017) recommended that future research should combine the economic value of the predicted material and ecological damage, risk assessment models and environmental impacts of NBS.

From the discussion above, it can be observed that there are still challenges in evaluating intangible benefits of NBS and incorporating stakeholders' preferences into the process. For complex systems with a large number of scenarios and parameters, simple trial-and-error methods may not be the feasible approach. In such cases, an automated optimisation method could be effectively applied to handle these tasks and to combine the above-mentioned methods. There is also a challenge in combining a range of aspects that can and cannot be expressed in monetary terms into the same framework of analysis.

1.3.3 Tools for selection and evaluation of NBS

Since effectively managing risks driven by HMHs is a complex process, tools for selecting, evaluating and operating NBS are required. As these tools generally provide structured frameworks and methodologies for different purposes, they can be used in enabling stakeholders to make informed decisions as well as implementing NBS in a systematic and efficient manner.

Recently, several selection and evaluation tools have been developed in order to assist stakeholders in screening, selecting and visualising NBS measures. Examples of web-based applications developed to screen urban NBS measures are Green-blue design tool (atelier GROENBLAUW, 2019), PEARL KB (PEARL, 2019), Climate Adaptation App (Bosch Slabbers et al., 2019) and Naturally resilient communities solutions (Naturally Resilient Communities, 2019). These web-based tools allow the user to filter NBS in relation to their problem type, measure, land use, scale, and location.

In addition to the above, there are also tools that combine both the selection and evaluation processes together to use as a planning support system tool. An example is the SUDs selection and location (SUDSLOC) tool, which is a GIS tool linked to an integrated 1D hydraulic sewer model and a 2D surface model. UrbanBEATS (the Urban Biophysical Environments and Technologies Simulator) aims to support the planning and implementation of WSUD infrastructure in urban environments (Kuller et al., 2018). Other tools that can be used to select and evaluate potential NBS interventions are Long-Term Hydrologic Impact Assessment-Low Impact Development (L-THIA-LID) (Ahiablame et al., 2012; Liu et al., 2015) and the GIS-based tool called Adaptation Support Tool (AST) (Voskamp and Van de Ven, 2015). Although these tools can be useful in assisting decision makers, some of them may not be suitable for every location and scale. For example, source data required into L-THIA-LID only covers the United States and QUADEAU (Romnée and De Herde, 2015) is only suitable for urban stormwater management in a public space scale.

In addition to the above, other models such as MIKE packages developed by DHI (Semadeni-Davies et al., 2008; Vojinovic et al., 2013), Soil and Water Assessment Tool (SWAT) (Cheng et al., 2017), IHMORS (Herrera et al., 2017), and Urban Water Optioneering Tool (UWOT) (Rozos et al., 2013) can be effectively used in the analysis NBS effectiveness.

To date, very few tools have been developed to calculate multiple benefits of NBS in monetary terms as well as to address their qualitative benefits. Some examples are Benefits of SUDs Tool (BeST), which provides a structured approach to evaluating potential benefits of NBS (Digman et al., 2017; Fenner, 2017; O'Donnell et al., 2018), and the MUSIC tool (Model for Urban Stormwater Improvement Conceptualization), which is a conceptual planning and design tool that also contains a life cycle costing module for different NBS that are implemented in Australia (Khastagir and Jayasuriya, 2010; Schubert et al., 2017).

There are also other tools that can be used for modelling stormwater management options and/or assessing economic aspects of NBS in urban areas. These are documented in the work of Jayasooriya and Ng (2014). However, most of these tools only focus on small-scale NBS such as bio-retentions, pervious pavements, green roofs, swales, retention ponds, biofiltration and rainwater harvesting. There are few tools that can address river and coastal flood protection measures and droughts, while none of the tools can be used to reduce the risk from landslides and storm surges. A lack of information systems, information clusters and platforms for information exchange between authorities and practitioners has been recognized by Kabisch et al. (2016).

1.4 EX-POST EVALUATION

Ex-post evaluation refers to an assessment that takes place at the end of a project, at specific points during the later stage of its implementation, or after measures have been implemented (Associated Programme on Flood Management, 2015). This evaluation aims to examine the actual outcomes, impacts, and performance of the project compared to the anticipated or desired results. In other words, its primary tasks are, to assess the performance of implemented measures, to identify the strengths and weaknesses of the measures, to operate and improve the performance, and to provide guidance for future development and modifications of similar measures (Haber, 2007).

Monitoring and evaluation are one of the main activities of ex-post evaluation, which can lead to new insights into NBS functioning and active learning (even from failures), which can help to improve future NBS implementation (Connop et al., 2016). Monitoring and evaluation should be planned at the beginning of the project. Monitoring condition before, during and after the implementation of the measures is essential to check its performance and sustainability.

The indicators are usually used to monitor and assess performance of implemented measures. To do so, it is important to carefully select and agree on the appropriate indicators (Vojinovic, 2015; WMO, 2007; World Wildlife Fund, 2016) and they should cover all aspects and objectives of the project, including integrated environmental performance, health and well-being benefits, civil participation and transferability of NBS actions (Kabisch et al., 2016b; Raymond et al., 2017a, 2017b). The indicators can be used to show how results will be measured and provide an overview of change over time. Different indicators require different monitoring data collection methods, which can be quantitative and qualitative (e.g., measurements, field observation, questionnaires and satellite data), and different monitoring frequencies (e.g., short-term, intermediate and long-term).

Since not all assessments can be done with modelling alone, interviews and fieldwork are often neccessary. For instance, Chou (2016) used eighteen open questions from six topics, namely: accessibility; activities; public facilities; environmental quality; ecological value; and flood prevention. These questions are used to evaluate the qualitative performance of river restoration. However, some of the methods are only appropriate for small scale applications and cannot be applied in large catchments. Yang et al. (2018) proposed Relative Performance Evaluation (RPE) methods, which use a score to calculate the performance for all alternatives. This score is calculated as the weighted sum of the scores of individual indicators.

By ‘evaluation’, we refer to the process of comparing data between a baseline scenario and after implementation. Baselines are often based on the data before implementing measures and a threshold target, but could also be based on the impact of events in the past. Methods for evaluating the effectiveness of NBS should take changing dynamics of the system in both the spatial and temporal scales into account (Gari et al., 2015; Raymond et al., 2017b, 2017a). Raymond et al., (2017b) provide an extensive application guide for addressing strategies of ex-post assessments of monitoring of the actual efficiency of NBS. This application can be used to evaluate alternative solutions and monitor implemented measures.

Another significant advance in the science and practice of NBS for practitioners in evaluating the impact of implemented measures is the ‘Evaluating the impact of nature-based solution handbook’ (European Commission, 2021a), which is the result of a collaborative effort of 17 EU-funded Horizon 2020 NBS projects and collaborating institutions such as the European Environment Agency (EEA) and the Joint Research Centre (JRC), as part of the European Taskforce for NBS Impact Assessment. This handbook provides practitioners with a comprehensive Nature-based Solutions (NBS) impact assessment framework and a robust set of indicators and methodologies to assess the impacts of NBS across 12 societal challenges: Climate Resilience; Water Management; Natural and Climate Hazards; Green Space Management; Biodiversity; Air Quality; Place Regeneration; Knowledge and Social Capacity Building for Sustainable Urban Transformation; Participatory Planning and Governance; Social Justice and Social Cohesion; Health and Well-being; New Economic Opportunities and Green Jobs. However, there is still lack of evidence regarding the application of this framework or evaluation of implemented NBS in practice.

After monitoring and evaluating NBS, it is important to improve their overall performance continuously. In this regard, exploring the use of sensors, regulators, telemetry and Supervisory Control and Data Acquisition (SCADA) systems, and real-time control of NBS becomes crucial for enhancing efficient and effective operation. Implementing these technologies can significantly improve the functionality of NBS and ensure optimal operation. Such configurations, which are based on the use of real-time control technology for operation of NBS, can be referred to as "Smart NBS". The value of exploring Smart NBS configurations may be particularly beneficial for hybrid systems, where NBS sites need to be configured to work closely with different kinds of measures. Moreover, Smart NBS have the potential to not only deliver society co-benefits but also to ensure acceptance and long-term sustainability (Li and Nassauer, 2021). The potential of NBS to help build smart, sustainable and resilient cities has been investigated by UNEP, (2021).

1.5 KNOWLEDGE GAPS AND FUTURE RESEARCH PROSPECTS

An overview of some research gaps and future research prospects is given in Table 1.6. This table indicates subjects or areas in which knowledge is missing or insufficient. The knowledge gaps have been divided to two subjects based on the most relevant evaluation subjects related to NBS, which are; ex-ante and ex-post evaluations. Some of the key challenges are summarised below.

There is a clear gap between the amount of research on small scale NBS in urban areas and large scale NBS at the catchment (river basin), rural, and regional scale. The reason for this is that a large-scale system is more complex than a small system. Therefore, research and frameworks that deal with the problem of reducing hydro-meteorological risk by upscaling NBS from urban scale to catchment (river basin) scale would be beneficial, as would research into how the natural processes of large scale NBS change over time. Furthermore, there are only a few studies that combine NBS at both small- and large-scale, and further research in this direction is highly desirable.

Since there is no single NBS solution that can fully solve all problems, every project needs to be designed to address a particular challenge in its local contexts and in its respective community. Therefore, an understanding of site conditions is necessary for NBS to achieve the target of the project.

Based on the findings of the literature review, there are still challenges in relation to methods and tools for planning and implementing NBS. These include improving and developing methods for assessing co-benefits (especially socio and ecological benefits, i.e. aesthetics values, community liveability, and human health), frameworks and methods for evaluating large-scale NBS and "hybrid measures" (i.e. combinations of grey infrastructure and small and large scale NBS).

There are also challenges in incorporating local stakeholder participation within the framework and models and within the assessment and implementation process. Other challenges regarding governance are to develop guidance on effective models of governance, provide insights information on actors, institutions and legal instruments and other requirements that are relevant for implementing NBS. The reason for this is the lack of workable frameworks that can bring together a variety of stakeholder groups. Moreover, there is still a lack of finance studies and guidelines for cost-effective implementation, maintenance and operation of NBS projects, and mechanisms that can be used to promote new business and finance models for successful implementation of NBS.

There should also be more efforts in the development of assessment tools that incorporate new technologies such as real-time control systems, forecast models, and coupled models to provide more active and integrated operational solutions (i.e., SMART NBS). There is a need for the development of databases that include functions, benefits, and costs of large and small scale NBS to facilitate future research.

Table 1.6. Overview of knowledge gaps and potential future research prospects

Subjects	Knowledge Gaps	Future research prospects	Research questions proposed in this research
1. Ex-ante evaluation	Combination of small and large scale NBS with grey infrastructure.	• Development of a framework and methods to upscale NBS from small to large scale. • Development of a framework, methods and tools to select, evaluate, and design hybrid measures for HMR reduction	
	Application to hydro-meteorological risk reduction	• Development of a framework, methods and tools to select, evaluate, and design large scale NBS individually and in hybrid combinations for HMR reduction • Development of typologies and guidelines for NBS design, implementation, operation and maintenance. • Application of NBS to reduce the risk of droughts, landslides and storm surges.	

Subjects	Knowledge Gaps	Future research prospects	Research questions proposed in this research
	Framework for selection of NBS	• Defining the role of ecosystems in terms of risk reduction, socio-economic and hydro-geomorphological settings • Combining planning and stakeholders' participation in the co-selection process**	What methodology would be applicable and feasible for selection of NBS?
	Framework for cost and benefits analysis	• Combining economic value of ecological damage and environmental impact, including the "invisible" ecosystem services • Application of the whole life cycle costing and return on investment within the cost-benefit analysis of NBS** • Comparing costs and benefits between NBS, GI and hybrid measures • Defining opportunity costs and trade-offs of NBS implementation	How can the cost, flood risk reduction and co-benefits of NBS be integrated in economic assessment?
	Framework for optimal configuration of NBS	• Use of optimisation techniques to maximise the main benefit and co-benefits of NBS while minimising their costs. • Assessing the effectiveness of solutions on short and long terms	
	Combination between multi-criteria and qualitative research	• Use of multi-criteria and qualitative research in evaluation of NBS** • Application of qualitative research methods and interviews to effectiveness of NBS**	What methodology would be applicable and feasible for selection of NBS?
	Application of new technologies and concepts	• Use of novel modelling techniques such as complex adaptive systems models and serious games.	
	Web-based decision support tools/systems	• Development of databases of small and large scale NBS for hydro-meteorological risk reduction** • Development of platforms, info-systems and clusters for exchange knowledge. • Development of tools to support decision makers in selecting and evaluating hybrid measures. • Development of tools to assess the multiple-benefits for small and large scale NBS and their hybrid combinations.	What methodology would be applicable and feasible for selection of NBS?
	Framework for multifunctional design	• Development of a framework and methods to support multifunctional design. • Application of novel landscape design techniques. • Combining the knowledge from landscape architecture and water engineering	

Subjects	Knowledge Gaps	Future research prospects	Research questions proposed in this research
	Frameworks for effective stakeholder involvement and co-creation	• Frameworks for involvement of stakeholders in the selection, evaluation, design, implementation, and monitoring of NBS (i.e., the co-called co-creation process)**	What methodology would be applicable and feasible for selection of NBS?
	Desirable governance structures to support effective implementation and operation of NBS at different scales and contexts	• Information concerning legal instruments and requirements. • Compilation of data and information concerning multiple actors and institutions which are relevant to impliment NBS • Understanding water governance structures, drivers, barriers and mechanism for enabling system transformation • Development of methods for evaluation of social, political and institutional dimensions	
	Desirable finance models (e.g., public-private partnerships, blended financing, etc.)	• Development of finance guidance for implementing maintaining and operating NBS projects • Guidelines concerning development of new business and finance models • Development of financial mechanisms to engage public and private sectors in the implementation of NBS	
	Bridging gaps between science-practice-policy	• Bridging gaps between researchers, engineers, authorities and local stakeholders. • Bringing innovation to engage society in implementing and improving NBS.	
Ex-post evaluation	Assessment of multi-benefits of NBS	• Quantification of co-benefits** • Development of a framework, methods and tools to evaluate wide ranging intangible and tangible benefits** • Gaining deeper understanding of NBS benefits for human well-being	What is the method that can be used to evaluate effectiveness of implemented NBS?
	Assessment of ecosystem capacity	• Long–term monitoring and evaluation of ecosystem performance and function before and after the disaster • Addressing the complexity of coupled social and ecological systems	
	Application of new technologies and concepts (real-time control system, Digital wins)	• Integration of real-time monitoring and control technologies for NBS operation** • Use of novel modelling techniques such as complex adaptive systems models and serious games.	Can the existing/implemented NBS benefit from an RTC technology?

Remark **Theses are the knowledge gaps that have been addressed in this thesis.

1.6 RESEARCH OBJECTIVES

Based on the knowledge gaps and identified future research, the main objective of this dissertation is:

To develop and implement the methodological framework for evaluation of Nature-Based Solutions for hydro-meteorological risk reduction and co-benefits enhancement.

The specific objectives are:

1. To develop methodologies that can be used for Ex-Ante Evaluation of NBS in relation to hydro-meteorological risk reduction and co-benefits enhancement
2. To develop methodologies that can be used for Ex-Post evaluation of NBS in relation to hydro-meteorological risk reduction and co-benefits enhancement

1.7 RESEARCH QUESTIONS

Given the objectives, the main research question can be formulated to facilitate the accomplishment of the research as follow:

How can the primary benefits and co-benefits of NBS for hydro-meteorological risk reduction be evaluated?

Specifically, the present research addressed the following specific research questions:
RQ1: What methodology would be applicable and feasible for the selection and assessment of potential NBS?
RQ2: How can the cost, flood risk reduction and co-benefits of NBS be integrated in economic assessment?
RQ3: How can the performance of implemented NBS be evaluated?
RQ4: Can methods such as RTC technology improve the performance of implemented NBS?

1.8 RESEARCH APPROACH

The research approach for this dissertation aims to address the limitations of current research on NBSs by developing evaluations approaches for NBS in both planning and post-implementation processes. The aim is to support the decision-making and performance evaluation of large-scale NBS to reduce HMR (i.e., primary benefits) and enhance co-benefits. This research is divided to two main processes, each oriented towards addressing specific research objectives and questions (Figure 1.3).

The first process Ex-ante evaluation, which focusses on planning for potential NBS. It involves identifying and quantifying effective measures based on the best available scientific knowledge and technical means. This process begins with the selection of feasible NBS, including preliminary selection (screening) of NBS and a Multi-criteria analysis (MCA) framework. A catalogue of NBS was developed to provide an extensive list of measures for hydro-meteorological risk reduction. The MCA framework ranks the measures and considers co-benefits, which are then prioritised for economic assessment. Economic assessment is conducted using the life cycle cost-benefit analysis, which can have a significant impact on decision making regarding NBS. This research compares the results of economic assessment of NBS with and without co-benefits by using Net Present Value (NPV) and Benefit Cost Ratio (BCR).

The second process is Ex-post evaluation, which involves evaluating implemented NBS. It can be through various methods, including comparing a baseline with monitored data, conducting stakeholder interviews, or collecting field data. The framework for ex-post evaluation aims to evaluate the effectiveness of NBS for HMR reduction and co-benefits, and to improve their effectiveness by introducing real-time control (RTC) strategies.

By implementing these research processes, this dissertation aims to contribute to the understanding and improvement of NBS for HMR reduction. The research approaches each objective and research question through a systematic evaluation of NBS, incorporating stakeholder preferences, economic assessments, and post-implementation monitoring. This approach ensures a robust analysis of NBS effectiveness, cost-benefit considerations, and potential enhancements through RTC strategies.

1.9 THESIS OUTLINE

This thesis is structured in seven chapters, as presented in Figure 1.3. The figure illustrates the different chapters, their interconnection within the evaluation process, and their relevance to the research objectives and questions.

Chapter 1 provides a review of the theoretical background and state-of-the-art review of the research area. It also outlines the research objectives and questions and provides an overview of the thesis structure.

Chapter 2 describes the overall framework for evaluating NBSs for HMR reduction. It establishes the foundation for the subsequent chapters and explains how they relate to the research questions.

Chapter 3 presents a methodology that incorporates stakeholders' preferences into MCA framework. This methodology serves as a tool for HMR mitigation measures. It consists of a preliminary selection of feasible measures, followed by an MCA framework that integrates the co-benefits along with HMR characteristics and local physical features.

Chapter 4 presents a methodology for economic assessment of NBS for flood risk reduction and co-benefits enhancement. The analysis is conducted through a lifespan cost-benefit analysis, considering the economic implications of implementing NBS.

Chapter 5 provides a framework for assessing benefits of implemented NBS. The framework aims to quantify the benefits and co-benefits of implemented NBS. The framework was tested and validated on a case study of NBS in Thailand.

Chapter 6 investigates the feasibility of RTC for NBS operation in order to reduce flooding and improve their effectiveness. The work highlights the potential of using RTC to improve the irrigation and drainage system operation as well as NBS implementation.

Chapter 7 provides the reflection on the main strengths and limitations of the research work conducted in this thesis. It also presents an outlook on the topic in general, identifying new gaps and future research directions that can further contribute to the development of NBS for HMR reduction.

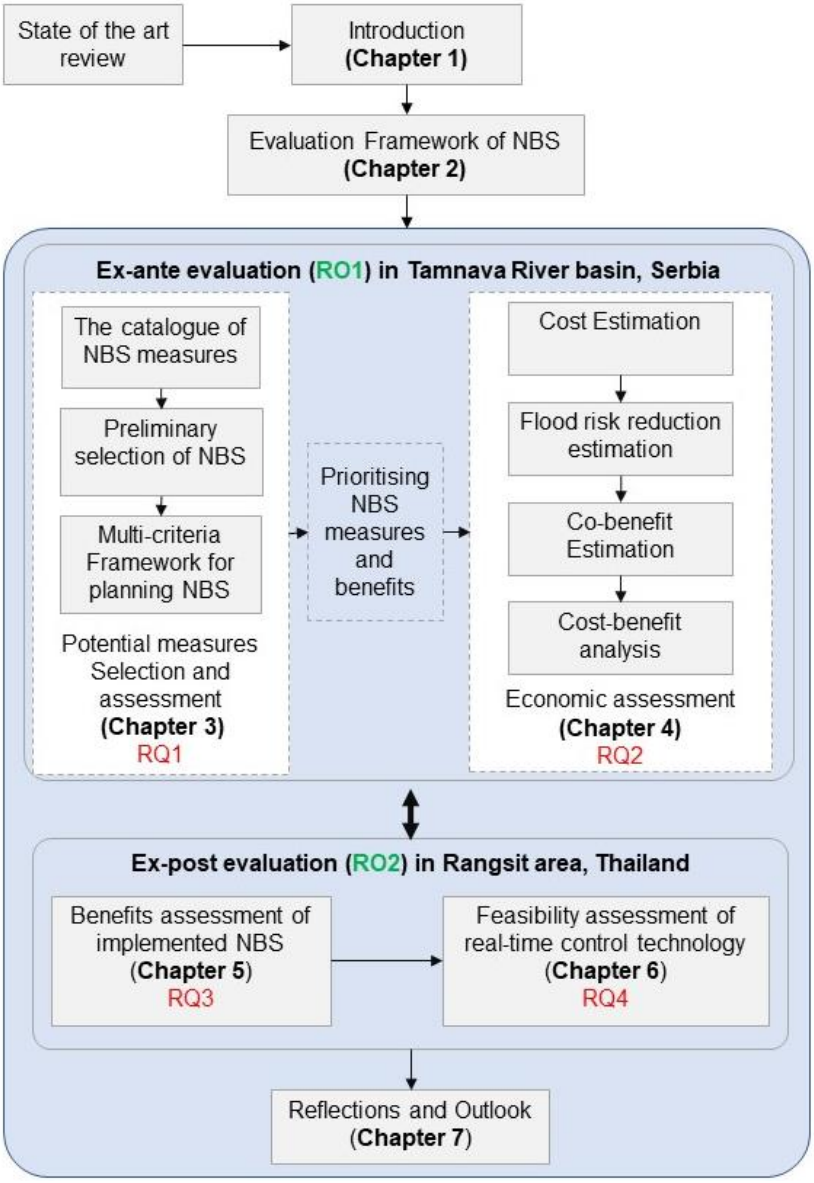


Figure 1.3. Overview of the methodology and outlines of the thesis

2

A Framework for Evaluating Performance of Large-Scale Nature-Based Solutions[2]

Over recent decades, hydro-meteorological disasters appear to be becoming more intense and frequent. Nature-Based Solutions (NBS) have been introduced to address hydro-meteorological risks as they offer the possibility of working closely with nature. This provides solutions to adapt to future changes in climate and society, as well as to achieve multiple benefits to services and functions of ecosystems. However, the performance and efficiency of NBS for hydro-meteorological risk reduction are still highly uncertain. Scientists and decision-makers require holistic perspectives and frameworks to help understand, evaluate and design NBS in such a way that can minimize social and economic losses, reduce environmental impacts and increase resilience to hydro-meteorological events. Therefore, methods or frameworks that can be used to evaluate NBS performance are necessary. In this work, a framework for evaluating large-scale NBS for hydro-meteorological risks is presented. The evaluation framework is separated into three main stages; identification of Indicators, before implementation (ex-ante) evaluation and after implementation (ex-post) evaluation. Developing a framework will be useful in assisting and supporting communities that wish to implement NBS for hydro-meteorological risk reduction, as well as communities that have implemented NBS and wish to assess their effectiveness.

[2] This chapter is an edited version of Ruangpan, L., Vojinovic, Z., 2022. A Framework for Evaluating Performance of Large-Scale Nature-Based Solutions to Reduce Hydro-Meteorological Risks and Enhance Co-benefits - Advances in Hydroinformatics, in: Gourbesville, P., Caignaert, G. (Eds.), Springer Nature Singapore, Singapore, pp. 515–527.

2.1 INTRODUCTION

Every year disasters caused by natural hazards affect millions of people around the world. The incidence and frequency of these hazards have increased during the past few decades (Guha-sapir, D., Hoyois and Below, 2015; Kishore et al., 2018; World Economic Forum, 2019). This situation can be viewed as a result of our disconnected developments underpinning broader global environmental and sustainability problems (Gunderson and Folke, 2011), as well as our fragmented ways of dealing with natural disasters (Matyas and Pelling, 2015).

Nature-Based Solutions (NBS) are inherently flexible and will naturally adapt to changing conditions (Cohen-Shacham et al., 2016). In addition to helping minimizing risks, NBS measures provide several other benefits. NBS have been used in numerous cases especially in runoff reduction or flood risk reduction in urban areas. Only implementing small NBS at urban scales may not be sufficient for large events as the frequency and intensity of futures events may increase due to future changes. Large scale NBS (i.e., as applied in rural areas, river basins, and/or at the regional scale) may provide a more significant impact in different management scenarios (Ruangpan et al., 2020a).

NBS require holistic perspectives and frameworks to help scientists and decision-makers to understand their complexity and to evaluate and design them in such a way that can minimize social and economic losses, reduce environmental impacts and increase resilience to hydro-meteorological events. The uncertainty of effectiveness of NBS for hydro-meteorological risk reduction are still highly. Therefore, the methods or frameworks that can be used to assess the performance is necessary.

For implemented NBS, the monitoring and evaluation process can be significantly enhanced to help to determine whether NBS are actually working, will NBS adapt to expected climate change or can NBS perform better. However, there is still a lack of methods that can be used to help in answering the above questions.

The present work presents a framework for evaluating large-scale NBS for hydro-meteorological risks. The evaluation framework consists of three main stages; identification of Indicators, before implementation (ex-ante) evaluation and after implementation (ex-post) evaluation. The work is developed within the EC-funded HORIZON 2020 RECONECT project (Regenerating Ecosystems with Nature-based solutions for hydro-meteorological risk rEduCTion) (RECONECT, 2018).

2.2 DEFINE THE EVALUATION FRAMEWORK

The evaluation framework can be used to guide the process of evaluation. Developing a framework will be useful in assisting and supporting communities that wish to implement NBS for hydro-meteorological risk reduction, as well as communities that have implemented NBS and wish to assess their effectiveness.

To develop the evaluation framework, a systematic review of existing literature was performed. The literature is based on the Scopus database which focuses on publication from 2007 onwards. The literature was selected based on relevant terminologies related to NBS such as Low Impact Developments (LIDs), Best Management Practices (BMPs), Water Sensitive Urban Design (WSUD), Sustainable Urban Drainage Systems (SuDS), Green Infrastructure (GI), Blue-Green Infrastructure (BGI), Ecosystem-based Adaptation (EbA) and Ecosystem-based Disaster Risk Reduction (Eco-DRR) (Ruangpan et al., 2020a).

There are various factors and processes in the evaluation of NBS that have been proposed in the literature. The framework will be developed on these scientific principles and studies by answering the questions below;

1) What are the factors that are involved in the performance process?

In the first question, the potential factors that are used to evaluate the performance of NBS are considered. Some examples include; indicators, local constraints, stakeholders, costs, benefits, and climate changes. The reason that we need to consider these factors is that different projects may have different requirements and interests.

2) What is the potential use of this framework?

Typically, we need to consider multiple aspects which depend on the objectives of the project, as each project may view the performance of NBS differently. For example; some projects may only want to estimate the feasibility of potential future measures while others may want to assess the performance of currently implemented NBS and how can they be improved. According to APFM, (2015) there is a time dimension of evaluation, which is before and after the action. Evaluation before the action is ex-ante evaluation while evaluation after action is ex-post evaluation.

3) What methods are appropriate in order to evaluate NBS?

As a consequence of the above questions, the evaluation framework is separated into two processes, which are ex-ante evaluation and ex-post evaluation. These evaluations will provide answers to communities and decision makers as to what are the processes and methods that they should follow.

2.3 AN EVALUATION FRAMEWORK OF NBS

The objective of this framework is to help in the decision-making process and performance evaluation of large-scale NBS to reduce hydro-meteorological risk and enhance their co-benefits. The framework is divided into 3 stages (Figure 2.1). The first stage is the identification of indicators for both quantitative and qualitative benefits of NBS. This includes identifying the main benefits and co-benefits of NBS. The next stage is the planning for potential NBS (Ex-ante evaluation). Ex-ante assessment defines the potential measures that are quantified as effective by applying the best scientific knowledge and technical means. The last stage is the evaluation of implemented NBS (Ex-post evaluation). Ex-post evaluation can be done in different ways such as comparing a baseline with monitored data, interviewing stakeholders or collecting data the field. Ex-post assessment often introduces operational strategies in order to achieve the maximum benefits.

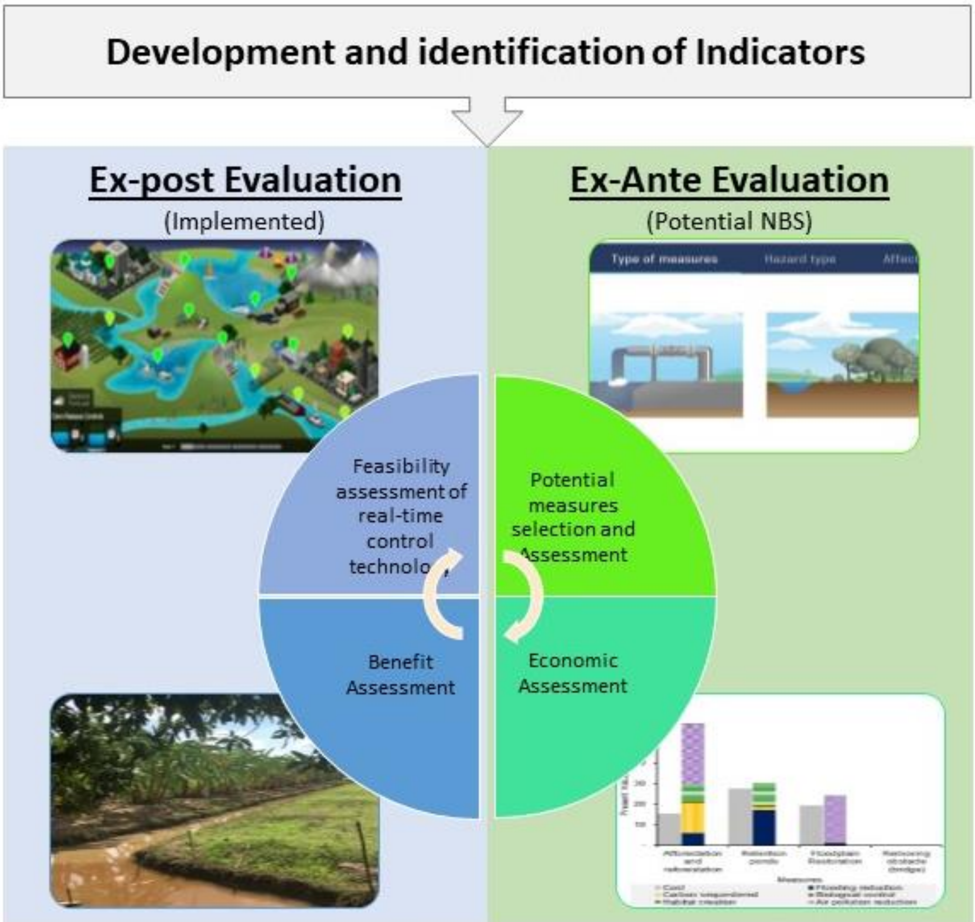


Figure 2.1. An overall framework for evaluating performance of large-scale nature-based solutions to reduce hydro-meteorological risks and enhance co-benefits

2.3.1 Identification of Indicators

Since there is no universally agreed set of indicators and variables that can be used for every NBS case study, it is necessary to develop a tool that supports the selection of specific indicators and variables, reflecting a variety of local contexts and situations. The idea is to narrow down the number of indicators to ensure that they are useful and effective in their provision of information. In the RECONECT project, we have developed an indicator framework and tool to help decision makers to select relevant indicators for their case studies. The indicator tool is in the excels format. The framework applied for the development of indicators and variables is illustrated in Figure 2.2.

The framework starts from an NBS 'Solution' and proceeds through 'Challenges', 'Goals', 'Sub-Goals' in order to come up with the list of 'Indicators' and 'Variables':

1. **Solution** refers to a particular site where a solution has already been implemented or it will be implemented.
2. **Challenge** refers to RECONECT challenge areas: Water, Nature and People.
3. **Goal** represents a theme/topic within the challenge area (these could be water quantity, water quality, habitat structure, biodiversity, socio-economic and human well-being).
4. **Sub-Goals** are subthemes within 'Goals' which will be assessed through indicators.
5. **Indicators,** which are derived from variables, are the first, most basic, *metrics or aspects* which can be used to measure, describe or assess the change and state of sub-goals over a period of time.
6. **Variables,** which are the most basic component of indicators, are data which can be used to monitor/measure and assess change in the state of indicators.

A framework for evaluating performance is carried out in relation to three categories of challenges i.e., WATER, NATURE and PEOPLE. The WATER challenge addresses questions related to hydro-meteorological risks. This includes watershed runoff and river, coastal, and groundwater processes. Also, some interactions with urban areas will be addressed as well. The NATURE challenge addresses questions related to habitat structure and the biodiversity of flora and fauna. Implementation of large-scale NBS has the potential to improve habitat conditions, species territorial expansion and colonization of new areas. The PEOPLE challenge addresses questions concerning social and economic benefits, with implications for human health and well-being, and resilience to impacts from hydro-meteorological events.

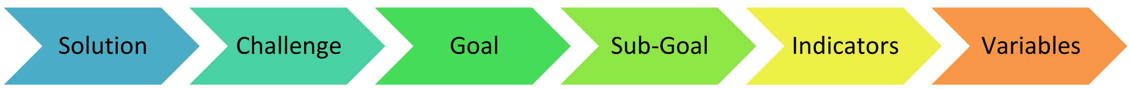


Figure 2.2. Framework for the development of indicators and variables

2.3.2 Ex-ante evaluation

Ex-ante evaluation, also known as pre-evaluation, is conducted before a project, policy or decisions is implemented. The evaluation aims to identify and estimate the potential values of NBS before the implementation of a project. This evaluation includes the local knowledge, scientific knowledge, and technical means. The ex-ante evaluation framework consists of two phases; selection and assessment potential NBS and Economic assessment of nature-based solutions.

Selection and assessment potential NBS

The phase on of ex-ante evaluation includes preliminary selection (screening) of NBS and Multi-criteria analysis framework. The RECONECT database was developed to provide an extensive list of measures for hydro-meteorological risk reduction.

The first step in this phase is the preliminary selection to define the potential measures that are applicable or feasible to the case study based on the local characteristics. The selection is based on six filters, i.e., measure types, hazard types, affected areas, potential areas, potential location, project types and land use types (Ruangpan et al., 2020c).

The second step is a multi-criteria analysis framework (MCA) to select and rank potential measures (Ruangpan et al., 2020c). This framework allows the stakeholders to give their preferences on the benefits of NBS and select measures that are more suitable or applicable to implement. MCA employ three methodologies, namely weighting, scoring and ranking. The criteria used in this MCA framework is based on the RECONECT indicator framework, which are referred to as goals and sub-goals. The criteria are weighted according to their relative importance and used to score options. The more detailed of this work can be found in Chapter 3.

Economic assessment of NBS

The phase two ex-ante evaluation is focus on economic assessment of NBS for primary benefits (risk reduction) and co-benefits. The economic assessment process consists of four main components: cost estimation, benefit estimation, value adjustment, and cost-benefit analysis.

The cost estimation component includes capital expenditures and Maintenance and operational expenditures. Capital expenditures cover research costs, land acquisition, and construction costs. Maintenance and operational expenditures, known as OPEX, are also considered to ensure the continued functionality of the NBS over its lifespan. An optimism bias is applied to account for unknown factors and adequate project budgeting.

The primary benefit estimation focuses on risk reduction. It involves assessing hazard and vulnerability and calculating the Expected Annual Damage (EAD) using a hydrodynamic model and damage curves. The EAD represents the estimated annual cost of damage. By comparing the EAD values before and after implementing NBS measures, the Expected

Annual Avoided Damage (EAAD) is calculated, serving as an indicator of the measures' effectiveness.

The co-benefits estimation involves assessing the positive outcomes resulting from NBS implementation. A multi-criteria analysis framework is used to select relevant co-benefits. Since not all co-benefits can be easily quantified in monetary terms, prioritization is necessary for valuation purposes. The next step is to characterize the relationships between NBS measures and co-benefits by assessing biophysical indicators. Once the changes in these indicators are identified, various valuation methods can be applied. These methods include market value, avoided damages, and transfer methods, The choice of valuation method depends on the specific co-benefit being assessed.

To ensure comparability, values obtained from different contexts are adjusted. Standardization is done for both the year of value and general price levels using consumer price indices. Additionally, when transferring values between countries with different currencies, exchange rates are employed to standardize the currency into a common unit.

The cost-benefit analysis is conducted through a life-cycle approach, considering the annual benefits of NBS over the project's lifespan. The Net Present Value (NPV) and Benefit-Cost Ratio (BCR) are used as economic efficiency indicators. NPV calculates the net economic benefits by comparing the present value of expected costs and benefits. The BCR compares the present value of benefits to the present value of costs.

By following this methodology, an assessment of the economic viability of NBS for flood risk reduction, including both primary benefits and co-benefits, can be conducted. More detailed of the methodology and its application can be found in Chapter 4.

2.3.3 Ex-post evaluation

The ex-post evaluation, also known as post-evaluation, takes place after a project, policy, or decision has been implemented and its outcomes have been observed. It aims to assess the actual performance, effectiveness, efficiency, and sustainability of the implemented action. The ex-post evaluation consists of two different phases, which are benefits assessment of implemented NBSs and evaluation of benefits from real-time control strategies.

Benefits assessment of implemented NBS

The first phase of ex-post evaluation is benefits assessment of implemented nature-based solutions. This phase generates insights on what works, what does not work and why. One of the goals of this research is to demonstrate and further upscale large-scale NBS. To support this goal, it is important to develop monitoring and evaluation procedures that can be applied to different types of NBS and their local contexts and settings. In order to assess the performance of solutions, indicator selection, baseline estimation and solution monitoring and evaluation are all important. In this framework, the performance evaluation consists of risk reduction and co-benefits (impact on community and nature).

The framework consists of five main steps aimed at assessing the impacts of NBS and providing recommendations for improvement. The framework begins with the selection of benefit challenges (water, nature, and people) based on stakeholder needs and relevance to the NBS. Indicators are then chosen for each benefit challenges through stakeholder conversations. Stakeholder input is crucial during this process as it ensures that the chosen indicators provide meaningful insights into the solutions. Once the indicators are selected, they are evaluated numerically by calculating their performance values. This can be done using various methods, including monitored data, conducting stakeholder interviews, or collecting field data. The calculation involves comparing the indicator values between the case study area with the NBS (Area A) and the comparison area without NBS (Area B). Subsequently, the indicator values are converted into scores, and stakeholders have the option to assign weights to indicate the importance of specific indicators. The NBS grade is then determined by averaging the scores, incorporating all the assessed benefits. The grade ranges from 1 (indicating no benefits) to 5 (indicating numerous benefits). Lastly, recommendations are provided for all indicators or those with low scores, including stakeholder involvement, data collection and analysis improvements, maintenance of NBS, monitoring, and planning for better balance and cost reduction.

Overall, the framework provides a systematic approach to assess the performance and benefits of NBS, ensuring stakeholder engagement and delivering recommendations for improvement. More detailed of the framework and its application can be found in Chapter 5.

Feasibility assessment of real-time control technology

The effectiveness of NBSs can be further improved by incorporating Real-Time Control (RTC) techniques. The methodology involves upgrading an existing passively-controlled NBS system to a “Smart NBS” by introducing RTC and developing a Digital Twin for the Rangsit case (Figure 2.3). The concept of Smart NBSs involves enhancing the functioning of NBSs by integrating modelling, monitoring, and system control technologies. This integration creates a Smart Solution that improves performance and enables faster decision-making.

Digital Twin technology, which combines models with diverse data sources to simulate and predict the behaviour of the physical world, plays a significant role in managing and operating water systems in the context of Smart NBSs.

RTC involves automatically controlling structures in real-time based on pre-established rules and current hydraulic and weather conditions. It offers advantages such as improved water storage management, flood prevention, system operation, operational cost reduction, and system capacity optimisation. By implementing RTC in NBSs, the performance of grey infrastructure elements like pumping stations, weirs, sluices, inlets, and outlets can be enhanced.

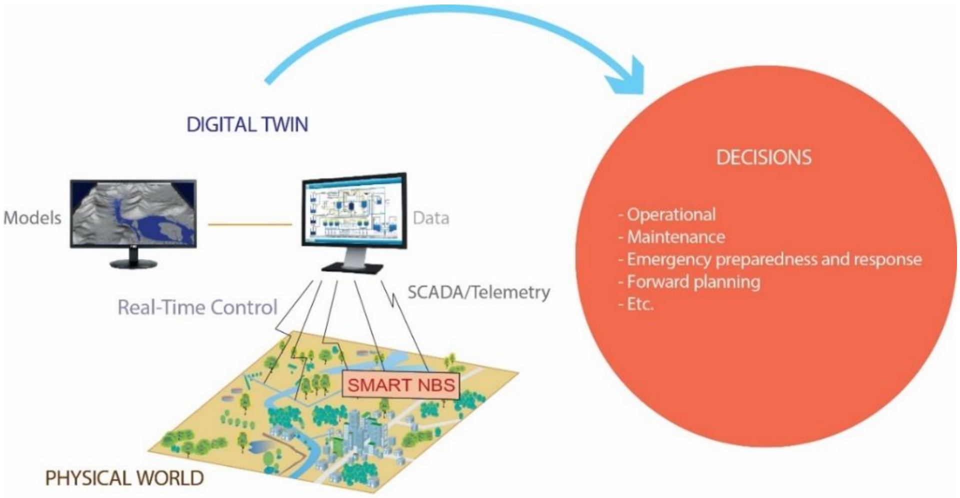


Figure 2.3. Incorporating Real-time Control and Digital Twins towards a Smart NBS

Key decisions in this methodology include selecting the Proportional-Integral-Derivative (PID) control strategy, tuning PID parameters, strategically placing sensors, designing flood scenarios, and choosing performance evaluation metrics. These decisions contribute to effectively evaluating the feasibility, effectiveness, and additional benefits of the upgraded Smart-NBS system.

The control is performed using PID controllers to regulate the operation NBS components based on error signals and control algorithms. The PID controllers used in the RTC system require appropriate tuning of their parameters to ensure optimal performance. The decision on how to tune these parameters is crucial for achieving the desired control response. Various methods, such as manual tuning or automated tuning algorithms, can be employed to determine the optimal values for the PID parameters. The decision on the specific tuning approach depends on the complexity of the system, available data, and the expertise of the researchers.

Real-time control is enabled by monitoring water levels and discharge time series using sensors installed in critical NBS locations. This data is essential for the PID controllers to make informed decisions and adjust the system operation accordingly.

The research involves testing the Smart-NBS system with RTC under various flood scenarios to evaluate its performance across different flood conditions. Factors such as flood magnitude, duration, and frequency should be considered when defining the scenarios. The decision on scenario design should reflect the real flood events that the NBS system will likely encounter in the study area.

To evaluate the feasibility of the RTC system, the performance of the Smart NBS with RTC is compared to systems without RTC or additional storage. The decision on which metrics to use depends on the research objectives and the desired outcomes of the NBS system. Key performance indicators, such as water level reduction, system capacity utilization, and water distribution equity, are commonly used to evaluate flood reduction and water management. The decision on the specific metrics helps quantify the benefits of RTC and enables comparison with alternative systems or approaches.

The research highlights the potential of using RTC to improve the operation of the irrigation and drainage system and enhance the implementation of NBSs for flood reduction. It also emphasizes the role of Smart Solutions and Digital Twins in utilizing RTC for flood reduction and water allocation. By combining online modelling, monitoring, and system control technologies, RTC can deliver more efficient ecosystem services and aid in responding to the effects of climate change. More detailed can be found in Chapter 6.

2.4 CONCLUSIONS

The proposed framework aims to evaluate performance of large-scale NBS for reducing hydro-meteorological risks and enhancing co-benefits. This involves the development of novel methods to evaluate NBS measures for both before and after implementation. The framework can be used to guide the decision-makers in the selection and evaluation of measures in river basin scale.

The framework consists of three stages. The first stage is to identify the main benefits and co-benefits of NBS that the project would like to achieve by using the RECONECT indicator selection tool. These selected indicators are used for both the selection of potential measures and the evaluation of implemented measures. The second stage is the ex-ante evaluation, which focuses on the planning process to define the potential measures that are considered effective. The final stage is Ex-post evaluation, which can be done in different ways such as comparing a baseline with monitoring data, interviewing stakeholders or collecting data in the field. The results of this evaluation will help to understand the effectiveness and impact of implemented measures. Ex-post assessment often introduces operational strategies in order to achieve the maximum benefits.

Each stage of the proposed framework has been applied to case studies in the RECONECT projects. The ex-ante evaluation is applied to Tamnava river basin in Serbia, which more detailed of the work are presented in Chapter 3 and 4. The ex-post evaluation is applied to a case study in Thailand, Rangsit area, the detailed of the work are presented in Chapter 5 and Chapter 6.

3

SELECTION AND ASSESSMENT OF POTENTIAL NATURE-BASED SOLUTIONS[3]

Hydro-meteorological risks are a growing issue for societies, economies and environments around the world. An effective, sustainable response to such risks and their future uncertainty requires a paradigm shift in our research and practical efforts. In this respect, Nature-Based Solutions (NBSs) offer the potential to achieve a more effective and flexible response to hydro-meteorological risks, while also enhancing human well-being and biodiversity. The present paper describes a new methodology that incorporates stakeholders' preferences into a multi-criteria analysis framework, as part of a tool for selecting risk mitigation measures. The methodology has been applied to Tamnava river basin in Serbia and Nangang river basin in Taiwan within the EC-funded RECONECT project. The results highlight the importance of involving stakeholders in the early stages of projects in order to achieve successful implementation of NBSs. The methodology can assist decision-makers in formulating desirable benefits and co-benefits, and can enable a systematic and transparent NBSs planning process.

[3] This chapter is based on Ruangpan, L., Vojinovic, Z., Plavšić, J., Doong, D.-J., Bahlmann, T., Alves, A., Tseng, L.-H., Randelović, A., Todorović, A., Kocic, Z., Beljinac, V., Wu, M.-H., Lo, W.-C., Perez-Lapeña, B., Franca, M.J., 2020b. Incorporating stakeholders' preferences into a multi-criteria framework for planning large-scale Nature-Based Solutions. Ambio. https://doi.org/10.1007/s13280-020-01419-4

3.1 INTRODUCTION

Hydro-meteorological risks, such as flooding, will become more extreme and increase in frequency in the foreseeable future. These risks are identified as one of the most likely and impacting risks in global reports (World Economic Forum 2019), as they cause a significant impact on human life, the economy, and the environment. After a heavy rain or other extreme weather events, various types of inundation can occur, such as flash floods in steep areas, fluvial floods in floodplains, pluvial floods in urban areas and storm surges in coastal zones (WMO 2011). According to EM-DAT (2017), between 1951-2017 floods caused US$ 765 billion of damage and killed almost 24 million people globally. These statistics show that there is an urgent need to develop effective flood management and mitigation measures to minimise consequences as much as possible.

In the past, the most common approaches to reduce flood risks were related to 'hard' engineering works or so-called grey infrastructure (EEA, 2017). Examples of such measures include construction of dams, dikes, levees, pipe systems and other structures to control flooding. Generally, grey infrastructure solely reduces hazards in the considered areas, but does not necessarily bring additional benefits, nor does it deal with the future uncertainties related to climate change, land-use change and urbanisation. Past experiences with risk strategies have clearly shown that implementing grey infrastructure alone cannot provide complete protection (EEA, 2017), due to its inability to adequately adapt to future uncertainty and increasing climate change (Courtney et al., 2013; UNEP, 2014). Furthermore, grey infrastructure often has negative consequences in the environment and ecosystems.

The concept of Nature-Based Solutions (NBSs) has been used to describe measures that can be used for both hydro-meteorological risk reduction and climate change adaptation and mitigation, while at the same time enhancing ecosystems (e.g., Debele et al. 2019). The term NBS is often used as an umbrella term for many concepts such as: Low Impact Developments (LIDs), Best Management Practices (BMPs), Water Sensitive Urban Design (WSUD), Sustainable Urban Drainage Systems (SuDS), Green Infrastructure (GI), Blue-Green Infrastructure (BGI), Ecosystem-based Adaptation (EbA) and Ecosystem-based Disaster Risk Reduction (Eco-DRR). These terms are mainly used to address small-scale NBSs which are applied at the urban or local scale, whereas large-scale NBSs are usually applied in rural areas, river basins and/or at the regional scale (Ruangpan et al., 2020a).

However, selecting appropriate NBS measures is still a challenge due to specific local constraints and social-economic conditions (Ruangpan et al., 2020a). No single NBS can solve all problems and NBSs are not yet easy to implement in practice. The most suitable solution will depend on local necessities and characteristics. To improve acceptance and implementation of NBSs, decision support tools can be used by considering multiple stakeholders' views, trade-offs, and feasible measures (De Brito and Evers, 2016). A flexible decision tool capable of integrating multiple objectives is thus required.

The methods and tools facilitating selection of appropriate NBS measures are reviewed by Alves et al., (2018b); Jayasooriya and Ng, (2014b); Lerer et al., (2015); Ruangpan et al., (2020a). Most previous studies only focus on urban areas and are still far from being able to systematically support integrated assessment of NBS. Multi Criteria Analysis (MCA), or as it is sometimes called Multi Criteria Decision Making (MCDM) is one of the most popular decision support tools in hydro-meteorological risk management. It can provide a systematic framework to deal with complex decision-making situations with multiple objectives.

There is an extensive literature on MCA application in flood risk management that has been reviewed by De Brito and Evers (2016). MCA techniques have been employed in a wide variety of flood risk problems; namely Shivaprasad Sharma et al. (2018) for flood risk assessment; Dang et al., (2011)for evaluation of the most important flood risk parameters; Fernández and Lutz, (2010) for flood hazard mapping, Azibi and Vanderpooten (2003) for selecting grey infrastructures to reduce flood risk; and Shan et al. (2012) for reservoir flood control and emergency management problems. However, few applications of MCA tools exist for the selection of NBS measures.

Martin et al., (2007) carried out the first application of MCA for LID/BMP selection by applying Elimination and Choice that Translates Reality (ELECTRE) for the analysis. Young et al. (2010), Aceves and Fuamba (2016) and Alves et al. (2018b), used stakeholder weighting for criteria such as water quality, environmental, economic benefits, but not for the measures. The stakeholders' weighting of measures is important, since it can be used to enhance identification of the suitable measures for the specific case study. Loc et al. (2017) collected stakeholders' NBS preferences, but these preferences were not included in the MCA. From the studies referenced above, it can be seen that there are still some barriers in applying MCA for NBS: (i) they have only been applied to pluvial floods at the urban scale; (ii) weighting for measures are not included in MCA process, (iii) only a few co-benefits have been included as criteria in MCA.

Given these knowledge gaps, this study aims to develop a methodology for the first time to select NBS measures by integrating a preliminary selection tool with a multi-criteria analysis framework for different scales (i.e., urban area, river basin, coastal area) and hazard types (i.e., pluvial floods, fluvial floods, flash flood, coastal floods drought, and landslides). This new methodology also incorporates stakeholders' preferences for both assessment criteria and potential measures into the MCA framework. Involving stakeholders into an MCA can introduce additional relevant local data and considerations into the process of measure selection that might otherwise be unnoticed/disregarded by the engineers. In this way, a selection of the most suitable and effective measures for a specific area and hazard type is ensured. This is important for the successful implementation and sustainable exploitation of a specific measure and, therefore, for long-term risk reduction and effective water resources management. Another highlight of this methodology is that it includes a wide range of criteria for the both main benefit (reduction of hydro-meteorological risks) and co-benefits (improvement of water quantity, protection and enhancement of habitats, safeguard of biodiversity, and socio-economic and human well-being).

For proof of concept, the proposed methodology has been used in the planning of NBS measures to reduce the impact of fluvial flooding at the river basin scale. NBS measures have been selected and ranked for two case studies within the EC-funded RECONECT project, namely the Tamnava River basin in Serbia and the Nangang River in Taiwan.

3.2 METHODOLOGY FOR SELECTING MEASURES

3.2.1 Methodology structure

This section describes the overall methodology used for selecting potential measures, as well as the database of NBS used as an input. To set up the database, a large set of measures for hydro-meteorological risk reduction has been collected based on a literature review of adaptation and mitigation measures, including grey infrastructure, river restoration, NBSs and their related terms (i.e., LIDs, BMPs, WSUD, SuDS, GI, BGI, EbA, Eco-DRR). The collected information for each measure includes its description, spatial scale of applicability (e.g., river basin, urban area, and coastal zone), possible locations for implementation, properties, and possible benefits.

The methodology consists of two steps: the preliminary selection of measures, and the multi-criteria analysis framework, as shown as in Fig 1. This figure presents the different steps of the methodology that the decision maker needs to follow to select the most suitable measures. This should be applied in the first stage of the planning process to restrict the choice of appropriate measures according to the problems and objectives of a project. The subsequent sections describe the preliminary selection of measures (screening), followed by the criteria chosen for the MCA framework and the processes in this framework (i.e., scoring, weighting and ranking, as shown in Figure 3.1).

3.2.2 Preliminary selection (screening)

The database is developed in this study to provide an extensive list of measures for hydro-meteorological risk reduction. From this list, suitable options for a specific situation need to be singled out. Since not all measures are suitable for all locations and all hazard types, six filters are used in this process to narrow down the list of measures (Figure 3.1). The first filter is the measure type, which can be NBS or grey infrastructure.

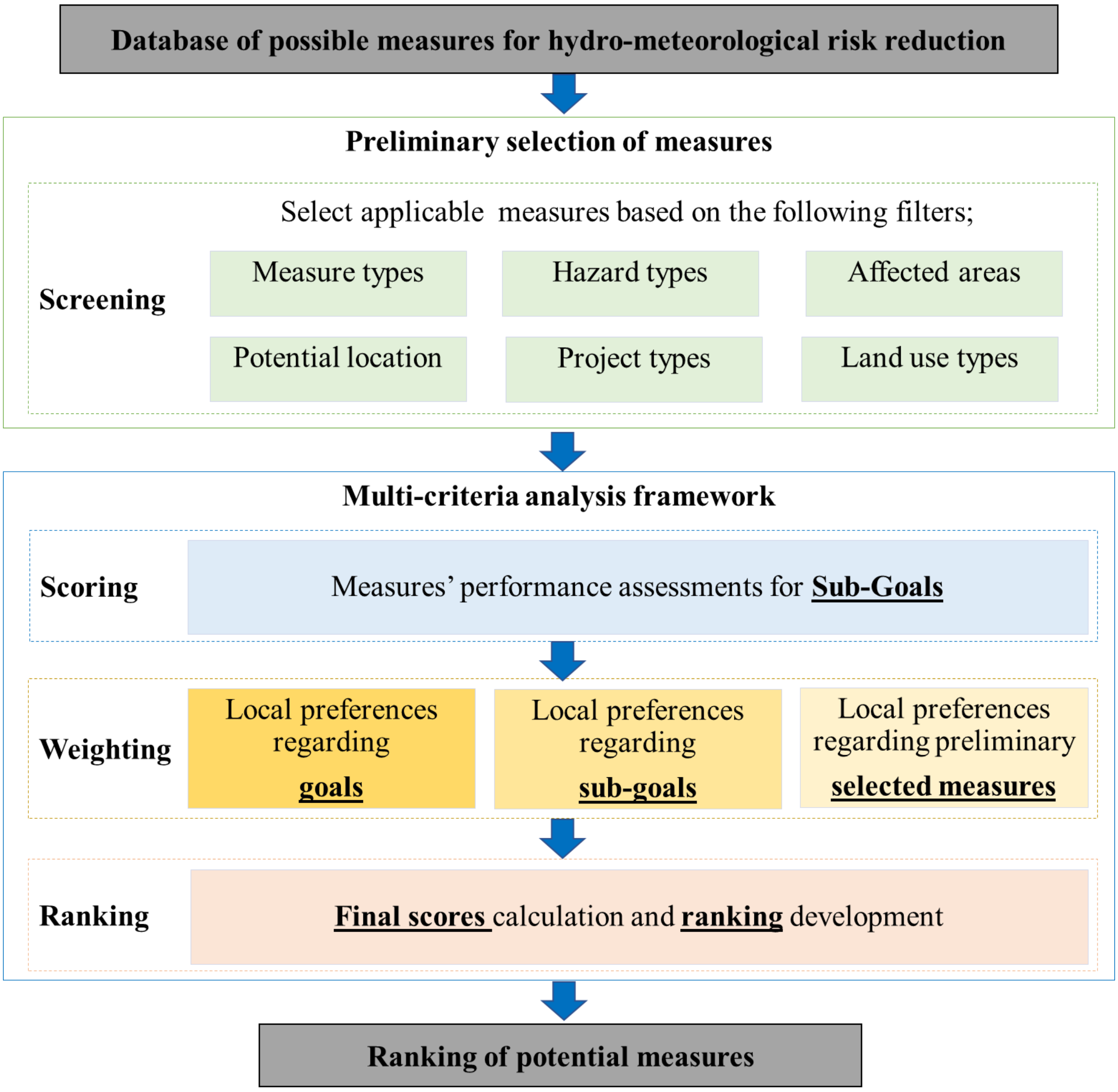


Figure 3.1. Proposed methodology for selecting potential Nature-Based Solutions measures, including preliminary selection and Multi-Criteria Analysis framework

The second filter is hazard type, as the consequences of an event vary greatly depending on the hazard (e.g., floodplain restoration is suitable for fluvial floods but not pluvial floods). Considered hazard types include pluvial flooding, fluvial flooding, coastal flooding/storm surges, flash flooding, droughts, and landslides.

Thirdly, the affected area of such problems must be defined as either urban area, non-urban area or both. In the fourth filter, the users identify the potential location for implementation of measures. There are two main types of locations for implementation; urban areas and non-urban areas. Non-urban areas include mountainous area, coastal area and river basin. If the case study is a river basin, the location within the basin also needs to be defined as upper course, middle course or lower course (Figure 3.2). It should be noted that at this stage no precise location (micro-location) has to be defined.

The fifth filter is the type of project that would be implemented; i.e., whether the completely new measures are to be implemented or existing measures are to be improved. The final filter is the prevalent land surface type in the area (e.g., artificial surfaces, agricultural areas, forest and semi natural areas, wetlands, or water bodies). Within each filter multiple selections can be made, for example, users can include both urban and non-urban measures in the filter. The data can be collected by using the questionnaire in Appendix A.1. The questionnaire should be given to technical stakeholders in the area as it requires technical knowledge.

- ❑ Urban area
- ❑ Non-urban area
  - ❑ Mountainous area
  - ❑ Coastal area
  - ❑ River basin
    - ❑ Upper Course (Mountainous and source zone)
    - ❑ Middle course (Middle of river)
    - ❑ Lower course (Floodplain or/and Delta area)

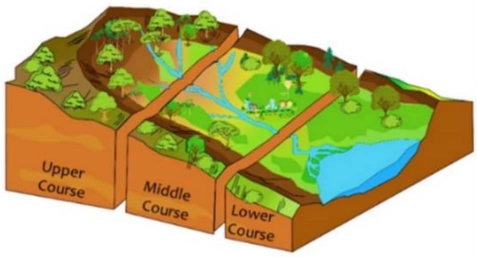


Figure 3.2. Example of filter (Potential location), with optional sub-filters.

3.2.3 Multi-criteria Analysis

The innovative stakeholder preference process has been built into the Multi-Criteria Analysis (MCA) framework of the proposed methodology. MCA is a framework for ranking the overall performance of decision options against multiple objectives, which can be used to support complex decision-making situations. MCA is used in this study to select and rank NBS measures as it has the ability to integrate and overcome the differences between technical and social approaches (Loc et al., 2017). MCA also allows for the assessment of possible measures with diverse criteria defined by different units, both quantitative and qualitative.

The most common MCA method that has been used in flood risk management is the Analytical Hierarchy Process (AHP), which is a relatively flexible and easily applicable method (De Brito and Evers, 2016). However, in this type of MCA, only a limited number of alternatives can be considered at the same time because AHP uses pairwise comparisons, in which each criterion is compared to the others (Guarini et al., 2018; Vaidya and Kumar, 2006). In the proposed framework, there are 25 criteria (see Section 2.3.2), thus, AHP is not suitable, since the large number of possible comparisons would increase the process length and complexity for the user.

The MCA in this research is based on the weighted summation method (or linear additive model), which is a special form of Multi-Attribute Value Theory (MAVT) (Belton, 1999).

For clarification, the following components of the weighted summation method used in this research are defined here:

- Measure: a potential NBS or grey infrastructure measure obtained after the screening process,
- Criteria: potential impacts used to evaluate measures; in this case criteria are being referred to as goals and sub-goals,
- Scores: values used to quantify the performance of each measure in meeting each sub-goal.
- Weights: values given by stakeholders to indicate the importance of each goal, sub-goal and measure,
- Weighted scores of sub-goals/goals: for each measure, this is the sub-goal/goal score multiplied by its weight obtained after processing stakeholder weighting results,
- Criteria score: for each measure, this is summation of all the weighted goal scores,
- Final scores: for each measure, the final score is obtained by multiplying the criteria score by the measure weight.

There are many benefits in using weighted summation. Firstly, it makes the 'incomparable' attributes comparable and prioritises them by assigning weights. The ranking can be obtained by multiplying each score (i.e., level of potential impacts) by its weight, followed by summing the weighted scores of all criteria. This process provides not only a ranking of the measures, but also clearly shows strengths and weaknesses of the measures. Secondly, weighted summation provides transparency to the evaluation process due to its simplicity (Marttunen et al. 2015; Guarini et al. 2018). Therefore, the method is very suitable to be used in participatory processes.

In this framework, we can combine stakeholders' opinions and preferences (weights) with the potential impacts of NBS (scores) in the ranking of measures. The weights are assessed from a survey of relevant stakeholders in participatory processes. The scores have been collected to quantify the performance of each measure based on literature and expert judgement. Based on this ranking, the decision-maker takes a decision on which measures will need to be further analysed in detail.

Criteria used in MCA framework

In order to address the impacts of implementing NBS measures, it is necessary to define criteria taking the primary risk reduction benefit into account, as well as the social, economic and environmental implications of the measures (Boruff et al. 2005). In this framework, the criteria are based on those defined in the RECONECT indicator framework, which itself was derived from existing studies (Raymond et al. 2017). The criteria are referred to as goals and sub-goals in this framework, since they have a hierarchical structure, see Table 3.1.

The goals include hydro-meteorological risk reduction, water quality, habitat structure, biodiversity, socio-economics and human well-being. These 6 goals are further divided into 19 sub-goals. All of these criteria are relevant for future NBS studies, but the specific type of hydro-meteorological risk may change depending on the area. For example, if pluvial, fluvial or flash floods are selected as the hazard type in the preliminary selection, then flood risk reduction will be the sub-goal. The reason that the other sub-goals remain unchanged is that they relate to co-benefits, and are therefore applicable to all case studies.

Both goals and sub-goals are weighted by stakeholders, but only the sub-goals are used to assess qualitative performance with measures (scoring). These are described in the following sections.

Table 3.1. Hierarchical structure of Criteria in MCA

Goals	**Sub-Goals**
Hydro-meteorological risk	{Type of Risk reduction that corresponds to selected hazard}*
Water Quality	Improve water quality in rivers/watercourses, lakes/ponds
	Improve coastal water quality
	Improve groundwater quality
Habitat structure	Increase habitat area (quantity)
	Habitat provision and distribution (quality)
	To reflect ecological status and physical structure of habitats
Biodiversity	Change in Land use
	To maintain and enhance biodiversity
	Reduce disturbance to ecosystems
Social-economic	Increase recreational opportunities
	Education and awareness about NBS
	Maintain and if possible enhance cultural values
	Accessibility
	Improve Community Cohesion
	Encourage new business models and other community benefits
	Stimulate/increase economic benefits
Human well-being	Direct health and well-being impacts
	Indirect health and well-being impacts

*Remark *The HM risk sub-goals depend on the hazard type in the preliminary selection*

Potential impact assessment (scoring)

Potential positive and negative impacts of measures on specific sub-goals are assessed by giving a score to reflect the performance of the sub-goals. The scoring is based on converting qualitative and quantitative data (obtained from a literature review and expert judgement) into a standard scoring system for different sub-goals (see Table 3.2). The reason for this is that standardised quantitative data is required for the weighted summation method.

Table 3.2. Score level with its qualitative description

Score	Qualitative description	Score	Qualitative description
5	Very high positive impact	-1	Very low negative impact
4	High positive impact	-2	Low negative impact
3	Medium positive impact	-3	Medium negative impact
2	Low positive impact	-4	High negative impact
1	Very low positive impact	-5	Very high negative impact
0	No impact		

The key resources used to assess the qualitative measure performance include reports, online guides, online tools, case studies, and scientific articles (Alves et al., 2018b, 2018a; CIRIA, 2014; DEFRA, 2019; Klijn et al., 2013; Leonardo Mantilla Niño, 2019; NWRM, 2013; The River Restoration Centre, 2014; UNaLab, 2019; Van Coppenolle et al., 2018; Watkin et al., 2019; Woods Ballard et al., 2015, 2007). Some resources include very detailed information on potential impacts of specific measures. For example, The EU Natural Water Retention Measures project has published a series of benefit tables for different types of NBS measures (i.e., agricultural, forest, hydro-morphological and urban) in terms of ecosystem services, policy objects, and biophysical impacts (NWRM, 2015).

In this study, the potential impacts for each sub-goal have been assessed by using indicators (see list in Appendix A.2), then averaging them to their sub-goal. The assessment was generated by assigning a score based on the qualitative descriptions. Scoring of criteria is performed as follows: 5 (Very high positive impact) to 1 (Very low positive impact); 0 (No impact); and -1 (Very low negative impact) to -5 (very high negative impact), as shown in Table 3.2. For example, if there is a very high negative impact in habitat area, this is given a score of -5, but if the measures can significantly improve or extend the habitat area, this is given a score of 5. These score levels were used to build a performance metric for each measure and each sub-goal.

Preferences (weighting)

Since the criteria are not always equally important, a weighting can be attributed to each criterion considered to reflect the degree of its importance. Applying the weighted summation method is only possible if information about the priorities of criteria is available.

Weighting is based on the direct rating method. Usually, the direct rating method uses the judgement of participants/stakeholders, who associate a number in the 0-100 range with the value of each option on the criterion (Dodgson et al., 2009). However, to make this process simpler and easier for participants, they only need to choose weight from 0 to 10 for each criterion and measure. Weight 0 indicates that the criterion is insignificant and can be ignored, weight 5 suggests that it is relatively (moderately) important, and 10 represents the most important criterion among all criteria considered. After the stakeholders give the weights to the criteria, the weights are normalised to have the sum of the weights of each goal equal to one.

In this framework, the weighting is conducted in three steps. Firstly, the stakeholders give their preferences with respect to the six main goals. Then, they give the weights to the 19 sub-goals. Lastly, the stakeholders select which measures are more suitable or applicable to implement. For example, if detention ponds have a high potential for implementing in the area, the stakeholders could give a weight of 9, but if there is no space and this measure is not suitable, the stakeholders could give a weight of 0. The weights for goals and sub-goals can be obtained by using the questionnaire in Appendix A.3 on different groups of stakeholders, while the weights on applicable measures can be obtained by using the questionnaire in Appendix A.4. There are different methods that can be used to collect the questionnaire responses, such as workshops, digital questionnaires (Microsoft Word), or online survey platforms (Google Forms, Survey Monkey). To obtain the 'overall' weight for a criterion from several stakeholders, one can organise group discussions to try to get consensus or to average the weights from the different stakeholders.

Prioritisation (ranking)

The last step of the framework is the prioritisation of measures through ranking (see Figure 1). Ranking of the measures is based on their final score, which is the result of the weighted summation method. After assigning scores for each sub-goal to all the measures and computing the weights for each sub-goal by compiling stakeholders' surveys, the ranking based on the weighted summation method can be calculated by following these steps below.

Firstly, all the assigned weights for both sub-goals and goals need to be normalised on a scale from 0 to 1 (Equation 3-1). This is done in order to keep the weights logically distributed.

$$W_i = \frac{\omega_i}{\sum \omega_i} \qquad \textit{Equation 3-1}$$

where W_i is normalised weight so that $\sum W_i = 1$, and ω_i is the original weight given to the goal and sub-goal (i).

Secondly, the score of each measure (m_j) for each goal $S_{goal}(m_j)$ can be calculated as the summation of all the weighted sub-goal scores related to that goal (Equation 3-2).

$$S_{goal}(m_j) = \sum_{i=1}^{N} W_{subgoal_i} S_{subgoal_{i,j}} \qquad \textit{Equation 3-2}$$

where N is a number of sub-goals within the goal, $W_{subgoal_i}$ is the normalised weight for sub-goal (i) and $S_{subgoal_{i,j}}$ is the score for sub-goal (i) for measure m_j.

Thirdly, the score of each measure (m_j) accounting for all criteria ($S_{criteria}$ (m_j)) can be calculated as the summation of all the weighted goal scores (Equation 3-3).

$$S_{criteria}(m_j) = \sum_{k=1}^{L} W_{goal_k} S_{goal_{k,j}} \qquad \textit{Equation 3-3}$$

where L is a number of goals, W_{goal_k} is the normalised weight for goal (k) and $S_{goal_{k,j}}$ is the score for goal (k) for measure m_j.

Next, the positive value of $S_{criteria}(m_j)$ is normalised to take values between 0 and 1 (5 is the maximum criteria score), however, negative scores are given a value of 0 (Equation 3-4). The reason for this is that only measures that have a positive impact will be considered, while the other measures will be omitted from further analyses for decision making.

$$S_{criteria_{normalised}}(m_j) = \begin{cases} \frac{S_{criteria}}{5} & if\ S_{criteria} \geq 0 \\ 0 & if\ S_{criteria} < 0 \end{cases} \qquad \textit{Equation 3-4}$$

The last step is to calculate the final score for each measure, $S_{final}(m_j)$, based on which the measures will be ranked. This can be obtained by multiplying the $S_{criteria_{normalised}}(m_j)$ by measure weights $W(m_j)$, which have also been normalised (Equation 3-5).

$$Score_{final}(m_j) = S_{criteria_{normalised},j}\ W_j \qquad \textit{Equation 3-5}$$

This additional step is intended to prevent the selection of a measure that might still not be suitable for the area of interest or might not be accepted for local community.

3.3 CASE STUDIES

3.3.1 General information of the case studies

The methodology can be used for selecting both NBS measures and the combination between NBS and grey infrastructure, for different hazard types and spatial scales. The methodology is here applied to the selection of NBS measures for fluvial flooding at river basin scale in two case studies of RECONECT projects, namely the Tamnava river basin in Serbia and the Nangang river basin in Taiwan.

The Tamnava catchment, located in western Serbia, is a sub-catchment of the Kolubara river and covers an area of 730 km^2 (Figure 3.3A). The Tamnava basin contains two main rivers, the Tamnava and the Ub. The Tamnava river originates in hilly regions (altitudes 400-450 m.a.s.l.), flowing in the middle course through a mildly steep area while the downstream reach of the river is mostly flat. The land use in the catchment is mainly agricultural and residential area. The most significant recent floods occurred in 1999, 2006, 2009, and 2014. In 1999, 6000 ha of land were flooded, and 480 residential buildings and 2050 inhabitants were affected. In 2006 and 2009 similar events with similar consequences occurred. The most severe problems were caused by the flood in May 2014, when the population, economy, infrastructure and natural resources along Tamnava and its tributaries suffered enormous damage (Stanić et al., 2018). Therefore, strategies to reduce flood risk level and the impacts of extreme events are needed.

The Nangang catchment, located in central Taiwan, is a sub-catchment of Dadu River Basin. The Nangang catchment is surrounded by mountainous terrain (altitudes > 1000 m.a.s.l.) with a catchment size of around 440 km^2. The mainstream part of the catchment is prone to landslides and flooding caused by heavy rainfall. The land use in the catchment is mainly agricultural and residential. Huge damages and loss of lives were recorded during Typhoon Toraji (2001) and Typhoon Kalmaegi (2008). The study area of focus is located at the Niuxiangchu levee system (see Figure 3.3B). The studied river reach is roughly 4 km, and the channel is shallow and narrow, which causes high flow velocity and often leads to inundation and riverbank erosion. Since the study area is close to one of the largest cities in the area and frequently suffers from inundation, measures for reducing hazard risks are required.

3.3.2 Data collection for the case studies

Data collection in this study is based on Microsoft Word and Google Forms questionnaires. The data collection consists of 3 types of questionnaires; 1) questionnaire for collecting local information for preliminary selection of measures (Appendix A.1), 2) questionnaire for collecting goals and sub-goals weights (Appendix A.3), and 3) questionnaire for collecting weights on applicable measures (Appendix A.4). All questionnaires were sent to RECONECT partners in the case studies. Both case studies used the same questionnaires and both partners for the case studies are academic institutions who collaborate closely with stakeholders in their area.

The questionnaire for collecting local information (Appendix A.1) was filled in directly by the local RECONECT partners in May 2019 for the Serbia case, and in October 2019 for the Taiwan case. The partners were selected due to their technical knowledge of the case studies.

After that, the local partners explained the purpose of the questionnaire on goal and sub-goal weights (Appendix A.3) to respective stakeholder organisations in their case studies (e.g., academia, civil society/NGO´s, local authorities, citizens and political representatives), as well as how it technically should be filled in. The questionnaire was then sent out to those organisations to get a set of responses for that particular case study. In the end, there were two sets of responses from the two case studies addressed in the present work.

After the preliminary selection analysis is performed using the results of the first questionnaire, the questionnaire for collecting weights on applicable measures is developed (Appendix A.4). The local partners sent this questionnaire to technical stakeholders (e.g., academia and local authorities) to fill in.

3.4 RESULTS

3.4.1 Application of the preliminary selection

The database contains, in total, 78 NBS and grey measures, which can be used for the reduction of hydro-meteorological risks. A preliminary selection of potential measures for each case study was performed to define potential measures based on hazard type, affected area, potential location and land surface type, as shown in Table 3.3. This information was provided by the local RECONECT partners, as explained in Section 3.3.2

This table shows that the potential location, project types and land surface types are different between the two case studies. Therefore, these different inputs lead to different results of the initial measures selected for the two basins. The selected filters resulted in eighteen measures for the Tamnava river basin and twelve for the Nangang river (Table 4). These measures were considered in the MCA.

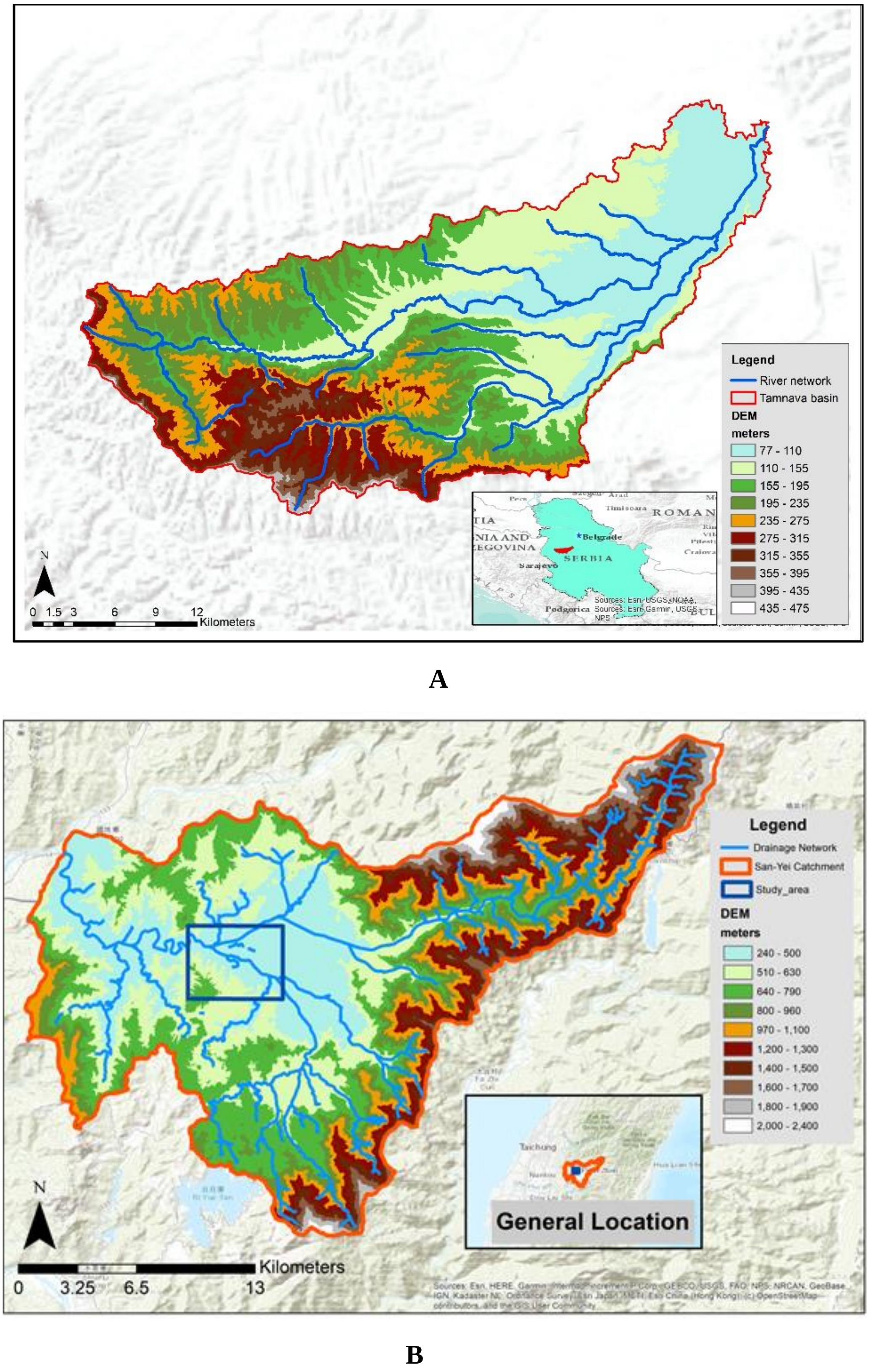


Figure 3.3. Location of the case studies: Tamnava river basin, Serbia (A) and Nangang River basin, Taiwan (B)

Table 3.3. Local information that is used as input for preliminary selection

Filters	Tamnava river basin	Nangang river basin
Type of measures	Nature-Based Solutions	Nature-Based Solutions
Hazard type	Fluvial flooding	Fluvial flooding
The affected area	Urban and non-urban area	Urban and non-urban area
Potential location	Non-urban area: Upper course and middle course of river basin	Non-urban area: Middle course of river basin
Project type	Implementation of new measures Improvement of existing measures	Improvement or expansion of existing measures
Land surface	Agriculture areas/ Forest and semi-natural areas /water bodies	Agriculture areas/water bodies

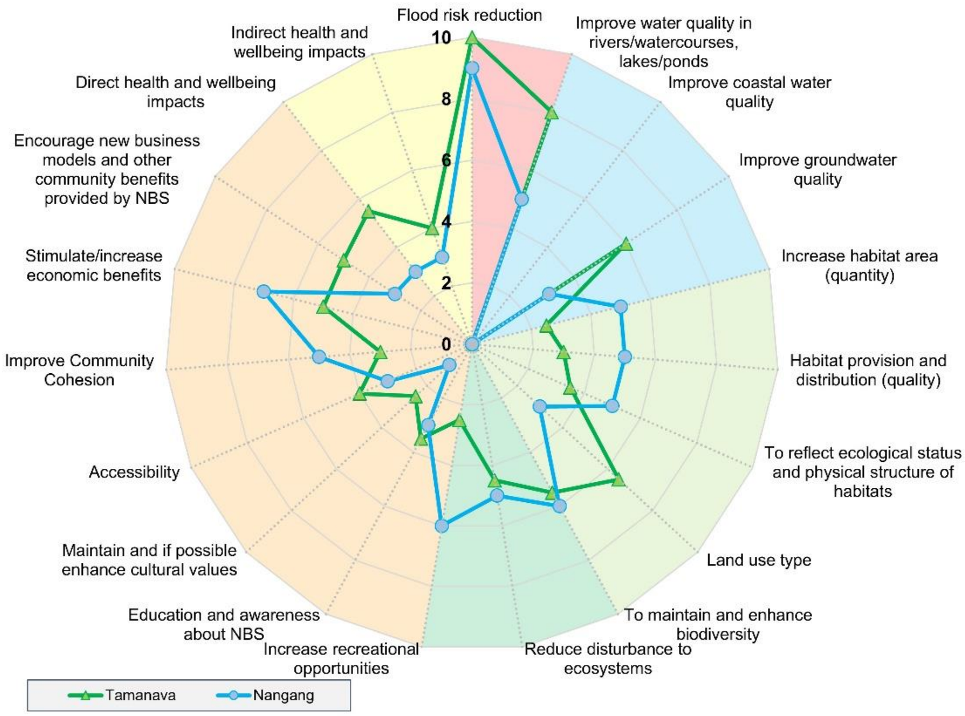
3.4.2 Application of the multi-criteria analysis

Criteria weights

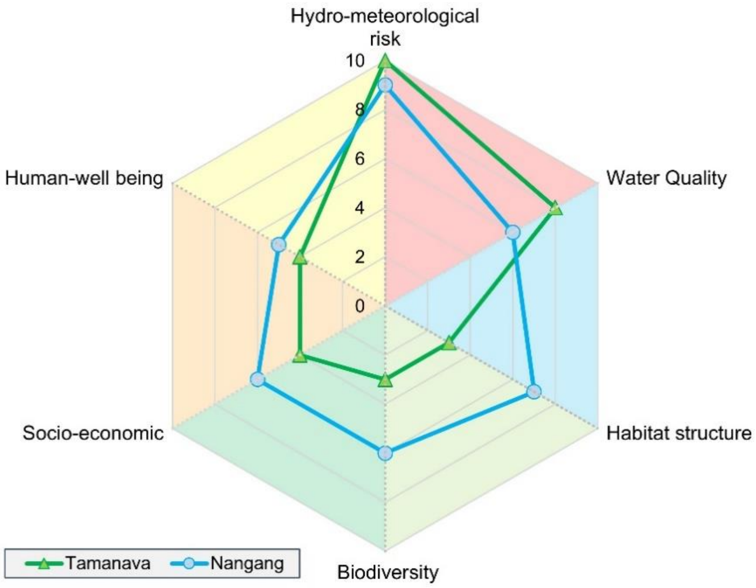
The criteria weights for the goals and sub-goals were derived based on stakeholders' opinions and judgements. These weights identify the importance of the main benefits and co-benefits of NBS measures in the area, and can also represent the trade-offs between NBS benefits. The weights were collected based on the questionnaires in Appendix A.3 as explained in Section 3.3.2. The data collection was done online since it was not possible during this study to organise a face-to-face workshop. There were four responses from academic and local authorities in Serbia, while ten responses were received from academia, civil society/NGO´s, local authorities, citizens and political representatives in Taiwan. The average weight of these responses has been used as the "overall" weight for a criterion from the individual weights of stakeholders in questionnaires.

The assigned overall weight for sub-goals and goals in the two basins are shown in Figure 3.4A and 3.4B, respectively. The possible range for the weights is from zero (i.e., not important) to ten (i.e., the most important). In relation to the relative weights among main goals, hydro-meteorological risk reduction is the most important benefit for both case studies (Figure 3.4B). A lower weight was given to co-benefits such as enhancing habitat structure, improving socio-economic, whereas a higher importance was given to water quality. The lowest weight was given to human well-being impacts, as it is not their priority for the case studies.

For the weights of sub-goals related to water quality, the most important benefit is to improve surface water quality, while the coastal water quality is not important as both case studies are not close to the coastal area. The weight for water quality is high for Tamnava because there is an intensive use of pesticides in agriculture and coal mining that deteriorate water quality. From the results, it can be seen that the given weight is sensible.



A



B

Figure 3.4. Weighting results of Tamnava and Nangang case studies. A: Relative importance of evaluating sub-goals, and B: Relative importance of evaluating main goals.

For habitat structure enhancement, changes in land use types are the most important factors for the Tamnava river basin, but the least important for the Nangang river. Among socio-economic benefits, simulate/increase economic benefits was given the highest weight because the stakeholders think that a better economy will help flood risk reduction, since current state of the economy is insufficient to assure satisfactory level of risk reduction.

Comparing the results between the two case studies, the assigned weights have a similar pattern for both sub-goals and goals. However, for the Tamnava case, higher weights are given to the 'reduce flood risk' and 'improve water quality' goals than Nangang, and lower for the goals related to enhancing habitat structure, biodiversity, socio-economy, and human well-being (Figure 3.4B). Importantly, for both cases, the weights for goals and corresponding sub-goals are consistent as shown in Figure 3.4 (relationship between goals and sub-goals is shown in Table 3.1). It should be noted, however, that comparing the results from the two case studies is made difficult due to the limited number of responses.

Criteria ranking

The ranking of the measures was performed as the weighted summation of criteria score based on their previously assigned sub-goal scores and the average weights collected from the stakeholders (Section 4.2.1). The normalised criteria scores and their relative ranking of measures in both the Tamnava and Nangang basins are shown in Figure 3.5. This figures also shows the potential benefits, co-benefits and trade-offs of NBSs.

From the ranking of both case studies, it can be observed that floodplain enlargement/restoration has the highest score, as it can provide a number of benefits, including increased flood storage, clean water and open space for recreation, wildlife habitats and biodiversity. On the other hand, measures that work on obstacles (i.e., removing obstacles and lowering groynes) are scored relatively low, as they cannot provide as many co-benefits as other measures.

The measures that are only applicable to Tamnava score highly on co-benefits, especially the measures that can provide a high positive impact on water quality (such as reforestation and afforestation), which is seen as an important benefit for the area (Figure 3.5A). Reforestation and afforestation are also able to provide high positive impacts for human well-being, because trees can help to increase mental well-being, reduce chronic stress, mitigate the heat island effect, and improve air pollution (Raymond et al., 2017a; Wheeler et al., 2010). However, these co-benefits require a trade-off with flood risk reduction.

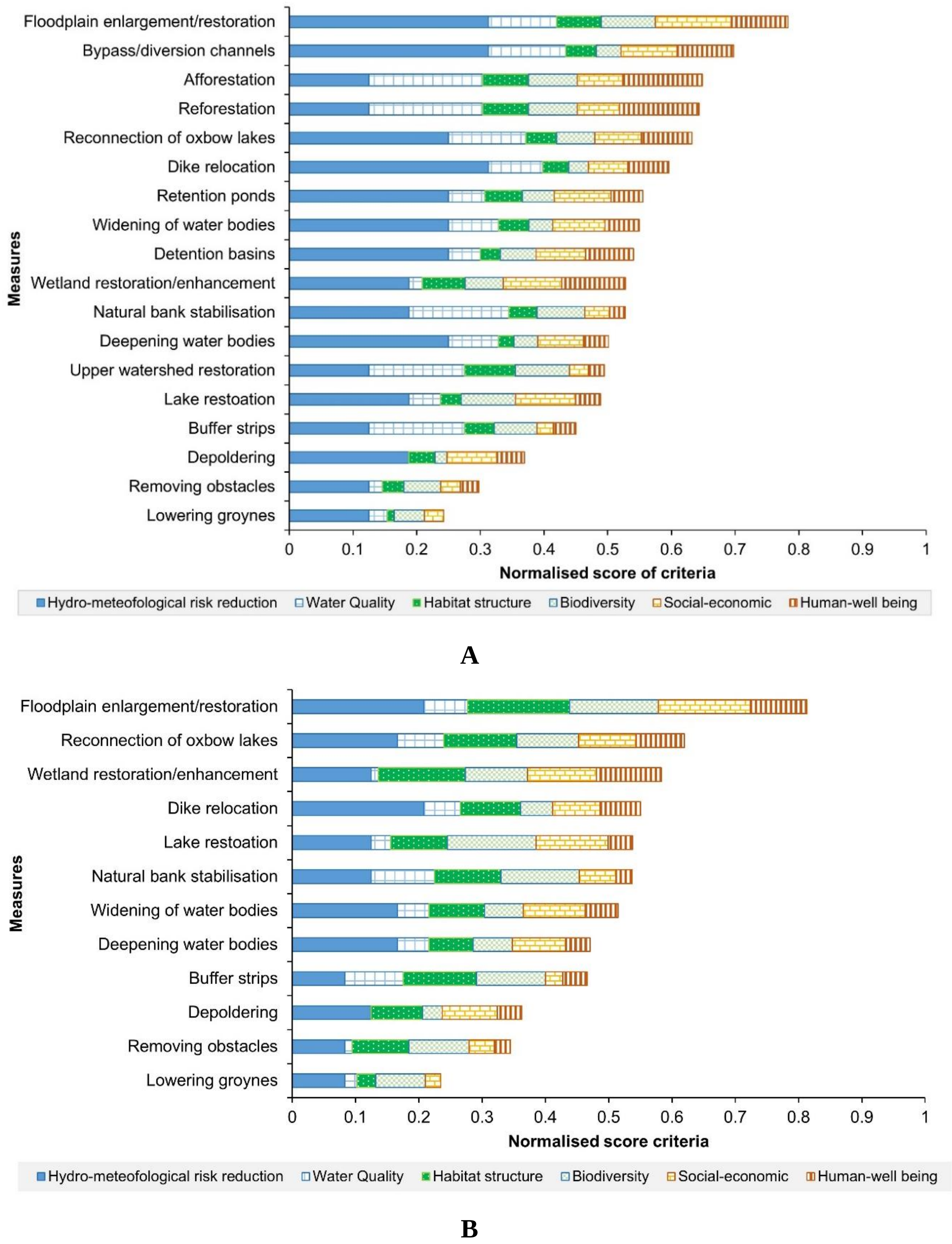


Figure 3.5. Criteria score and ranking of measures for case studies: Tamnava river basin, Serbia (A) and Nangang River, Taiwan (B)

For the Nangang case study, the measures that can provide multiple benefits score highly (such as reconnection of oxbow lakes, wetland restoration and lake restoration), as the co-benefits are seen as relatively important (Figure 3.5B). The benefits provided by wetland and lake restoration to people are: flood risk reduction, water quality improvement, habitat for wildlife, biodiversity support, recreation and aesthetics. Wetland ecosystem services also have a positive interaction to 10 Sustainable Development Goals (SDGs) (Seifollahi-Aghmiuni et al., 2019). The results also show the advantage of including additional criteria (co-benefits), apart from risk reduction. For example, if only risk reduction is considered, measures like dike relocation will have a higher rank than afforestation for Tamnava and wetland restoration for Nangang, despite having very little co-benefits.

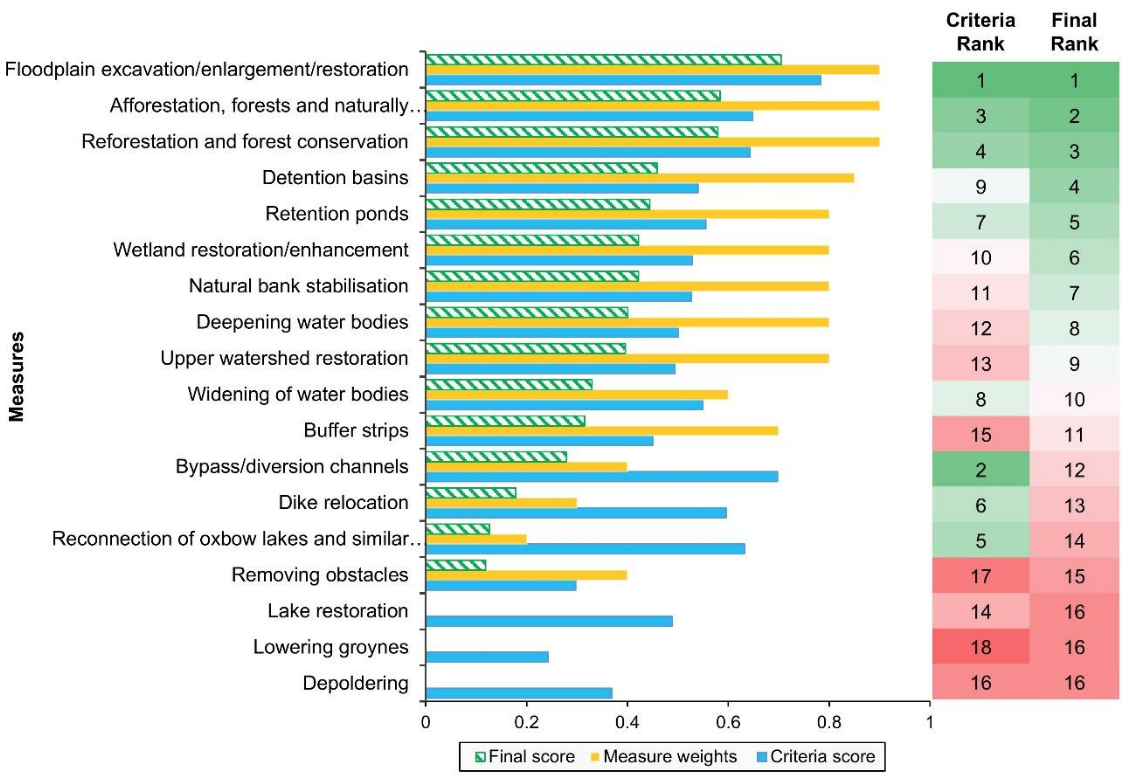
Prioritisation of measures

This section shows the prioritisation of measures, which is based on their final ranking. The ranking of the measures was performed based on their normalised criteria score and the average measure weights collected from the technical stakeholders. In Serbia, these technical stakeholders were a local authority and an academic institution, and in Taiwan the only response came from academia. The influence of the stakeholders' weights on the final ranking is also shown. In order to compare the criteria score and final score, both were normalised on a scale of 0-1 and shown in Figure 3.6 with their relative ranking.

Floodplain excavation/restoration can be seen as the best solution for both case studies, with and without stakeholders' preferences. Some measures are not possible to implement in the area, such as depoldering (since there are no polders present in the area) and lowering groynes (there are no groynes present).

Figure 3.6A shows the final ranks of the measures for the Tamnava river basin. It can be observed that the measures involving existing features have a lower rank when measure preferences are included. On the other hand, the measures that need completely new implementation, like a bypass channel, now rank high. The reason for this is that in the current situation there are no possibilities for implementing such a measure in the catchment.

For the Nangang river, it can be seen that five measures out of twelve are not suitable (see Figure 3.6B), even though they perform well based on the criteria ranking. This is due to the fact that the case study area does not currently have the associated features (groynes, lakes etc.). This result, therefore, shows the importance of including the preference measures into the analysis.



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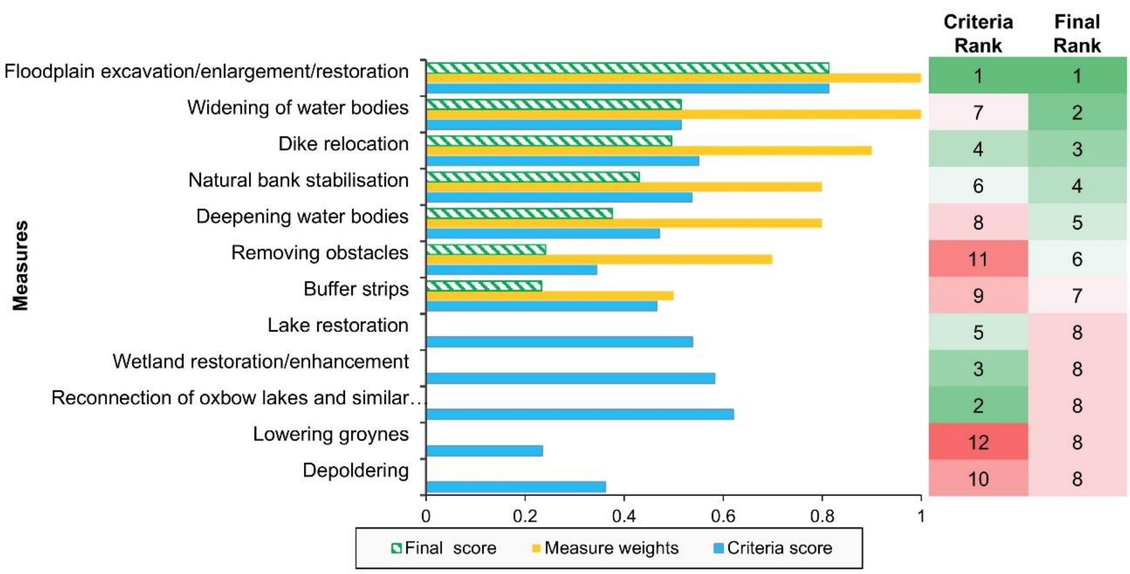

B

Figure 3.6. Final ranking of measures based on measures weights of the case studies: Tamnava river basin, Serbia (A) and Nangang River, Taiwan (B)

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3.5 DISCUSSION

From the above results, it can be seen that the preliminary selection process can help to eliminate the measures that are not relevant to the problem, location or characteristics of the area. This process is important in identifying potential NBSs that are suitable to the project (Romnée and De Herde 2015; Zhang and Chui 2018).

The multi-criteria analysis framework used to select NBS measures for river basin scale considers a number of criteria categorised under hydro-meteorological risk, water quality, habitat structure, biodiversity, socio-economic and human well-being aspects

Outcomes of the MCA were derived from previously assigned sub-goal scores and the weights collected from the stakeholders. The results show that the proposed methodology can be used to analyse the performance of measures with a holistic approach, by taking into account not only the primary goal of risk reduction but also related co-benefits such as water quality, ecosystem services, socio-economic aspects, human well-being, and economic factors. Moreover, including all these benefits in the framework can help the stakeholders and decision makers to recognise trade-offs of NBS. In considering trade-offs, risk reduction and ecological and social outcomes need to be acknowledged so that both communities and ecosystems benefit from NBS measures (Brink et al., 2016a). Applying the methodology to two case studies proved that MCA is a very good starting point for identifying and ranking measures for reducing risk reduction and enhancing other benefits. Similar results have been obtained by Van Ierland et al. (2013) and Jayasooriya et al. (2019).

From the criteria weights, it can be observed that risk reduction is considered the most important benefit, followed by water quality, whereas biodiversity and habitat structure benefits were not so important for the area. However, this could be a possible bias or uncertainty due to the nature of weighting. The source of this uncertainty could be from their profession. For example, risk managers may give a higher weight for risk than environmental and social benefits, while environmental authorities may think that environmental benefits are more important than risk and social benefits.

Therefore, we recommend decision making and policy management studies based on a larger sample of stakeholder responses are needed to examine uncertainties in the weights, and sensitivity of the final ranking of the measures to the weights assigned by the stakeholders. It would be particularly important to compare responses of different groups of stakeholders, such as local authorities, civil protection or academia. Moreover, analysing the larger sample of stakeholder responses can indicate the needs of different groups, and, hence, facilitate further improvements of the goal/sub-goal list.

The criteria ranking results show the ranking of measures and the potential benefits, co-benefits and trade-offs of NBS. Floodplain enlargement/restoration has the highest scores in the case studies as it can provide multiple benefits, such as giving more room for the river, improving water quality, providing more space for recreation activities, protecting people and properties, and enhancing habitat and biodiversity. The results also show that if only risk reduction is considered, measures such as dike relocation or widening of water bodies will have a higher rank, since they have a high positive impact in risk reduction. As a result, it is important to include both main benefit and co-benefits into an analysis so that communities and ecosystems can benefit from selected NBS measures. Similar results have been obtained by Alves et al. (2018a); Kuller et al. (2019). Even though a measure achieves a higher rank for total benefit, attention needs to be paid to the trade-off on risk reduction as it is the main objective for implementing NBS.

In many studies, MCA uses criteria scores for the final ranking or results (Aceves and Fuamba, 2016; Loc et al., 2017; Young et al., 2010). However, in this study, stakeholders' weights on the measures are included into MCA. The difference in the ranking of the criteria scores and final scores provides interesting results. For example, removing obstacles from the riverbed, which is technically viable solution, was disregarded in the final ranking in the Tamnava basin, since effectiveness and benefits from this particular solution were not recognised by the stakeholders. Similarly, lake restoration performed very well in criteria scores, but not in the final score as the measure is not suitable for the case studies. This shows the importance of including this step in the MCA framework. The results also showed that the pre-selection process does not account for local characteristics in detail. Therefore, it might be beneficial for management and decision making to define the applicability of measures directly after the preliminary selection intended to eliminate non-applicable measures in the analysis.

However, there is a limitation in this final ranking process, which is that giving weights to measures seems more suitable to technical stakeholders than general stakeholders. The reason for this is that giving weights for the measures requires some technical knowledge. Therefore, it may be better to obtain weights from a face-to-face workshop rather than individual questionnaires.

It is also recommended that this methodology should be incorporated into a web-based decision-making tool, providing, therefore, a simple and easy application for users. This has been suggested in a recent review article by De Brito and Evers (2016). Moreover, a spatial allocation method should be developed to define potential specific location for the selected measures. Finally, methods for further evaluation highly ranked measures and combinations thereof should be developed through 1D-2D hydrodynamic models, cost-benefit analysis and optimisation.

3.6 CONCLUSION

This paper proposes an innovative methodology for selecting potential measures which reduce hydro-meteorological risk as a main objective, and simultaneously offer co-benefits. This methodology consists of a preliminary selection of feasible measures for hydro-meteorological risk reduction, followed by a multi criteria analysis framework. This provides an easy-to-use decision support tool, aimed at planners and decision-makers, which systematically and transparently defines suitable measures.

The methodology presented here upscale from previously developed methods discussed in the introduction. The first improvement consists in the inclusion of different types of hazards and scales (i.e., river basin, coastal zone, or urban area) into the analysis. Secondly, this method includes a wide range of possible NBS benefits (reduction of hydro-meteorological risks, improvement of water quantity, protection and enhancement of habitats, safeguard of biodiversity, and socio-economic and human well-being). By including these criteria into MCA (Multi Criteria Analysis), the methodology results in a different ranking of the measures compared to the traditional ranking based on risk reduction alone. Thirdly, it provides the opportunity for decision-makers to define preferences among these benefits. Involving stakeholders in the process of measure selection in an MCA can introduce additional relevant aspects that might be unnoticed by engineers. Lastly, the methodology enables decision-makers to identify the most suitable and preferable NBS measures for the area, which can help obtain more realistic results in relation to suitability of measures to the case studies.

Based on the preliminary selection process, all measures chosen may not be applicable in the study area, as this selection process does not include detailed local conditions. These are taken into account in the MCA phase of the present work, hence the methodology can be used to ensure that the selected measures are quite suitable for the basin of interest.

The application of the methodology to two case studies proved its usefulness for decision making for river basin planning. It helps planners and decision makes to select potential measures and formulate desirable benefits and co-benefits at the basin scale

4

Economic assessment of Nature-Based Solutions[4]

Flooding is expected to increase due to climate change, urbanisation, and land use change. To address this issue, Nature-Based Solutions (NBS) are often adopted as innovative and sustainable flood risk management methods. Besides the flood risk reduction benefits, NBS offer co-benefits for the environment and society. However, these co-benefits are rarely considered in flood risk management due to the inherent complexities of incorporating them into economic assessments. This research addresses this gap by developing a comprehensive methodology that integrates the monetary analysis of co-benefits with flood risk reduction in economic assessments. In doing so, it aspires to provide a more holistic view of the impact of NBS in flood risk management. The assessment employs a structured framework known as the life-cycle cost-benefit analysis approach, utilising key indicators such as net present value and benefit cost ratio. The methodology has been applied to the Tamnava basin in Serbia, offering valuable insights for practitioners, researchers, and planners seeking to assess the co-benefits of NBS and integrate them into economic assessments. The results show that when considering flood risk reduction alone, all measures have higher costs than the benefits derived from avoiding flood damage. However, when incorporating co-benefits, several NBS have a net positive economic impact, including afforestation/reforestation and retention basins with cost-benefit ratios of 3.5 and 5.6 respectively. This suggests that incorporating co-benefits into economic assessments can significantly increase the overall economic efficiency and viability of NBS.

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[4] This chapter is based on: Ruangpan, L., Vojinovic, Z., Plavšić, J., Curran, A., Rosic, N., Pudar, R., Savic, D., Brdjanovic, D., 2023. Economic assessment of Nature-Based Solutions to reduce flood risk and enhance co-benefits. J. Environ. Manage. Under review

4.1 INTRODUCTION

Continued global temperature rise is expected to change the global water cycle, including precipitation patterns and the intensity of wet and dry events, as highlighted by the Intergovernmental Panel on Climate Change (IPCC, 2021). Simultaneously, the combined changes of climate change, urban development, population growth and land use are increasing flood risk in watersheds globally (Alfieri et al., 2017; Jongman et al., 2012; Najibi and Devineni, 2018; Tellman et al., 2021). In response to these challenges, there is a need for investing adaptation strategies that protect people, properties, infrastructure and the environment from flooding (Jongman et al., 2015).

In recent years, Nature-Based Solutions (NBSs) have gained attention and have been adopted by policymakers as innovative and sustainable approaches to flood risk management (FRM) and climate change adaptation (Cohen-Shacham et al., 2016; Ruangpan et al., 2020b; Schindler et al., 2014). NBSs are actions inspired by, supported by or copied from nature. They can also generate co-benefits, i.e. additional positive outcomes such as social, economic and environmental enhancements alongside a primary benefit (European Commission, 2015). Co-benefits of NBS may include carbon sequestration, enhancing biodiversity, recreational activities, controlling sediment erosion, and reducing air pollution, among others.

To identify the most effective and efficient flood risk management strategies, quantitative evaluation is essential. While several studies have been carried out to assess the performance of small-scale (i.e. urban) NBS, limited attention has been given to large-scale (i.e. catchment) NBS (Kumar et al., 2021; Ruangpan et al., 2020b). However, previous studies on the catchment scale have only focused on the benefits of risk reduction and have not considered NBSs co-benefits (Hu et al., 2017; Klijn et al., 2018; Wagenaar et al., 2019). For example, Te Linde et al. (2010) evaluated the effectiveness of flood management measures focusing on reducing flood-peak discharges and water levels for different locations along the Rhine, while Jonkman et al. (2013) primarily focused on estimating the cost of adapting measures. Research suggests that the assessment of both costs and benefits should be considered, as economic assessment is a key step in the decision/planning process to select and evaluate NBS (Alves et al., 2019; Ghafourian et al., 2021; Le Coent et al., 2023; Vojinovic et al., 2016; Wild et al., 2017).

Cost-benefit analysis (CBA) is a common method used for economic evaluation in flood risk management. However, traditional CBA studies often narrow their focus to expected annual damage (EAD) reduction and overlook the potential co-benefits of the measures (e.g., improving water quality, enhancing biodiversity, or increasing habitat structure). For instance, Wagenaar et al., (2019) evaluate adaptation measures for reducing flood risk by using CBA to compare the costs of measures with the expected flood damage reduction. Therefore, a methodology for incorporating co-benefits into CBA is still needed as it is essential for maximising the potential of NBS. Furthermore, assessing co-benefits is crucial for anticipating trade-offs and capturing economic, social, and ecological outcomes of implementing NBSs (Alves et al., 2020a). By quantifying the diverse co-benefits, decision-makers, policymakers, and stakeholders can make well-informed choices and investments, ensuring the most effective and efficient use of resources.

From the studies referenced above, it can be seen that there are still some knowledge gaps in economic assessment for flood risk management. Specifically, these are: (i) estimating only the cost of adapting measures but not the benefits; (ii) focusing on expected flood damage reduction as the only benefit of implementing measures; (iii) including co-benefits at the urban scale rather than on river catchment.

To address the knowledge gaps mentioned above, this research aims to develop a methodology for the economic assessment of NBSs at a river basin scale. The methodology expands beyond the traditional flood risk management evaluation by incorporating co-benefits, thus considering environmental and socio-economic values of NBSs. This economic assessment is based on a cost-benefit analysis (CBA) using Net Present Value (NPV) and Benefit Cost Ratio (BCR). To achieve this, the proposed methodology has been applied to the process of planning NBS measures for a case study within the Tamnava River basin in Serbia, as part of the EC-funded RECONECT project (RECONECT, 2018).

4.2 METHODOLOGY

4.2.1 Overall methodology

This study focuses on conducting an economic assessment of NBSs by expanding on traditional economic flood risk assessment to include the co-benefits of NBSs. In order to assess the performance of NBS, it is necessary to select applicable measures and determine their associated benefits. However, not all the benefits can be easily quantified in monetary terms, thus, the priority should be given to the most significant co-benefits or co-benefits that can be readily quantified.

The economic assessment process comprises four main components: cost estimation, benefit estimation, value adjustment and cost-benefit analysis – all of which are explained in detail in the following sections. Figure 4.1 shows the complete process for assessment of NBS, with the economic assessment process highlighted in blue. The cost estimation includes capital expenditures and maintenance and operational expenditures. The benefits are identified and divided into two categories; main benefits (i.e., risk reduction benefits) and co-benefits. Risk reduction benefits are based on expected annual avoided damage (EAAD), while the co-benefits are assessed by determining the value of change in biophysical indicators. This study employs the value transfer method for assessing monetary value by adjusting value to the local contexts (e.g. year of implementation, currency). Finally, both the benefits and costs of NBS are evaluated and compared using life-cycle CBA (LCCBA).

CBA is a theoretical analysis technique that evaluates whether it is economically beneficial to enact a project, as it provides important information for the identification, option analysis and appraisal of investments. Two metrics commonly used in LCCBA are NPV and BCR. The reason that NPV and BCR are selected is that they account for the time value of money by discounting future cash flows back to their present values using a discount rate. This is crucial because it recognizes that a euro today is worth more than a euro received in the future. Moreover, NPV provides an absolute monetary value, making it easier to interpret. A positive NPV indicates that a project is expected to generate a surplus, while a negative NPV suggests a deficit. BCR, although a relative value, clearly indicates whether benefits outweigh costs (BCR > 1) or not (BCR < 1). This allows for a comprehensive evaluation of the economic viability of NBS, considering both the primary risk reduction benefits and the additional co-benefits they provide.

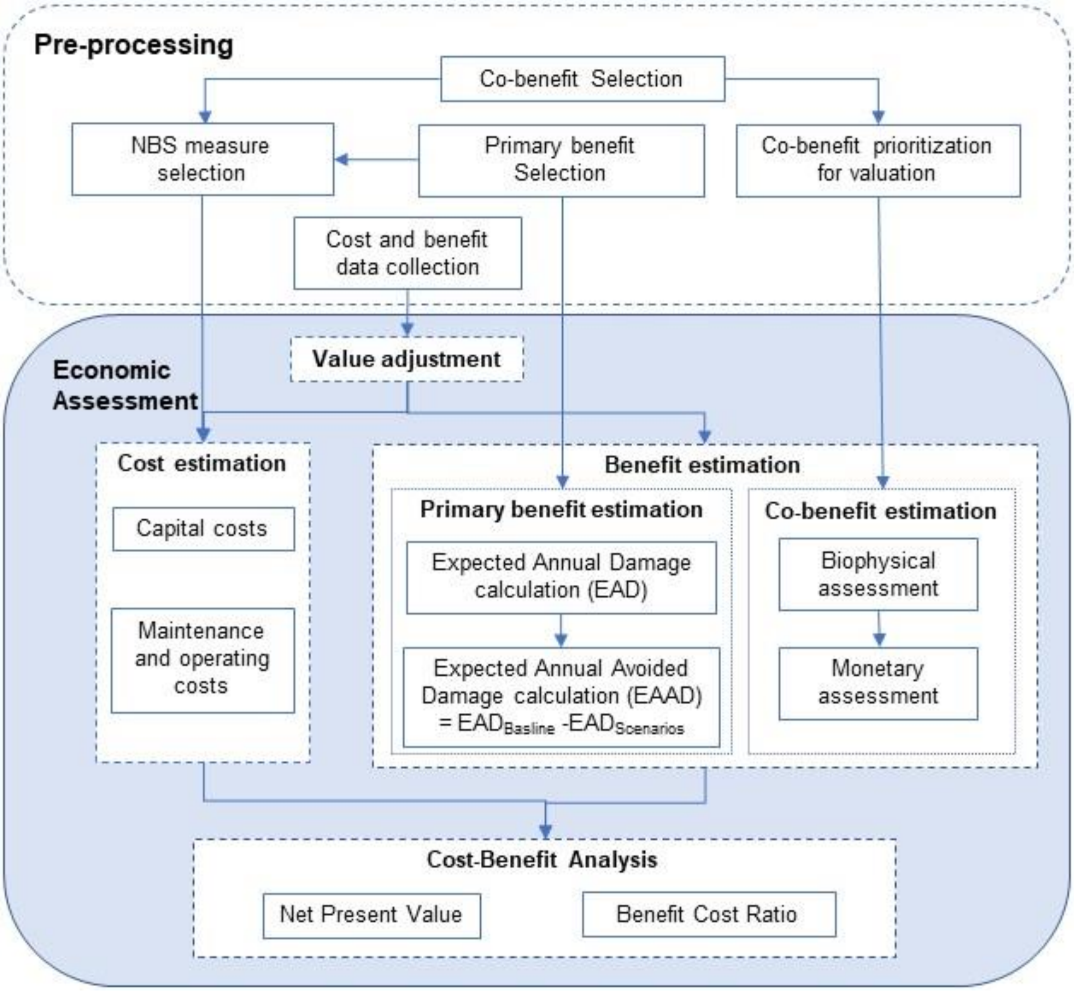


Figure 4.1. Overall Methodology for economic assessment of Nature-Based Solutions for flood risk reduction and co-benefits

4.2.2 Cost estimation

The life-cycle cost (LCC) of proposed NBS measures includes the capital expenditure as well as the maintenance and operation. LCC analysis provides valuable information for ensuring the continued functionality of the NBS throughout its lifespan.

Capital expenditure or CAPEX entails various costs, including research costs, land acquisition and construction costs. These capital costs are assumed to be incurred at the beginning of the project (year zero) and therefore do not need to be discounted in time. Maintenance and operation expenditures, also known as Operational Expenditure or OPEX, are the day-to-day management, maintenance and operation expenditures required to keep a measure performing as expected.

In line with the Flood and Coastal Erosion Risk Management Appraisal Guidance (Environment Agency, 2010), an optimism bias is typically applied for unknown factors and to ensure adequate project budgeting. An optimism bias of 60% is commonly used for projects at an early stage of consideration, while a value of 30% is utilised for a more detailed project stage. This percentage is added to the original estimate and used in the cost-benefit calculations.

4.2.3 Primary benefit estimation

The primary benefit estimation is based on the flood risk reduction. Flood risk assessment consists of flood hazard and vulnerability assessment (Klijn et al., 2015; Sahani et al., 2019b; Vojinovic, 2015; Vojinović, 2012). EAD is a common indicator and has increasingly been applied to quantify flood risk (Alves et al., 2019; Klijn et al., 2015; Wagenaar et al., 2019). EAD can be used to quantify the economic impact of potential hazards or risks, providing decision-makers with a clear and measurable understanding of the expected monetary losses on an annual basis.

To quantify EAD, flood damage should be calculated, ideally using a hydrodynamic model and damage curve. Hydrodynamic models such as HEC-RAS, MIKE, LISFLOOD and others provide flood characteristics such as the extent of the affected area, velocities, and depths. For an in-depth exploration of hydrodynamic models, a comprehensive review is available in Jodhani et al., (2023).

Furthermore, the damage data caused by these floods can be derived from functions that establish the relationship between flood depth and damage for different types of assets, i.e. depth-damage curves. One well-established source for such depth-damage data is the publication titled "Global Flood Depth-Damage Functions: Methodology and the Database with Guidelines" by Huizinga et al. (2017) whereas issues concerning 1D and 2D models for estimation of hazards and damages can be found in Vojinovic and Tutulic (2009). Also, issues concerning terrain data collection and processing (e.g., filtering) for the purpose of mapping hazards can be found in Abdullah et al., (2012) and Abdullah, (2020)

The EAD for a specific year is calculated by integrating the exceedance probability of expected flood damage cost per year for all possible flooding events (Delelegn et al., 2011). This calculation considers the likelihood of different flood scenarios and their associated costs, providing valuable insights into the expected annual impact of flooding (Equation 4-1).

$$EAD = \int_{f=0}^{\infty} Damage(z_f)df \qquad \textit{Equation 4-1}$$

Where EAD is expected annual damage (euro/year), *f* is frequency of occurrence (inverse of return period), and Damage is the flood damage (euro) due to the flood level z_f corresponding to the event frequency *f*.

Under the assumption that it is a continuous function of the return period, the Equation 4-2 can be used (Delelegn et al., 2011):

$$EAD = \sum_{i=1}^{n}\left(\frac{Damage_{i+1}+Damage_i}{2}\times\left(\frac{1}{R_i}-\frac{1}{R_{i+1}}\right)\right) \qquad \textit{Equation 4-2}$$

where, $Damage_i$ is the flood damage (euro) corresponding to return period event R_i, and n is the number of return period considered.

After calculating EAD, the Expected Annual Avoided Damage (EAAD) can be calculated by comparing the EAD values before and after implementing these measures. EAAD serves as a meaningful indicator to assess the effectiveness of measures implemented for risk reduction.

4.2.4 Co-benefits estimation

In addition to flood risk reduction estimation, co-benefits of NBS are also estimated in this research to provide additional benefits beyond flood risk reduction. Incorporating co-benefits into NBS planning and implementation provides a holistic approach to addressing flood risk and broader socio-environmental challenges.

Estimating the co-benefits of NBS involves a systematic assessment of the potential positive outcomes that arise from their implementation. Figure 4.2 shows the conceptual framework to estimate the value of co-benefits used in this research, adapted from Hérivaux et al. (2019). The first step is identifying the relevant co-benefits specific to the case study. In this research, a multi-criteria analysis framework developed by Ruangpan et al., (2020b) was employed to select the preferable co-benefits. Since not all the co-benefits can be quantified in monetary terms, it is necessary to prioritise them for valuation purposes.

The next step involves characterising the relationships between NBS measures and co-benefits (i.e., changes in the environmental condition and benefits). This can be achieved by assessing biophysical indicators, such as water storage expressed in m^3/year or habitat creation expressed in m^2.

Once the change in biophysical indicators is identified, various valuation methods can be applied. Several methods are available for valuating co-benefits of NBSs, such as market value, avoided damages, travel cost method, contingent valuation and contingent choice benefits (value), and transfer methods. A comprehensive and detailed overview of these valuation methods can be found in Brander (2014).

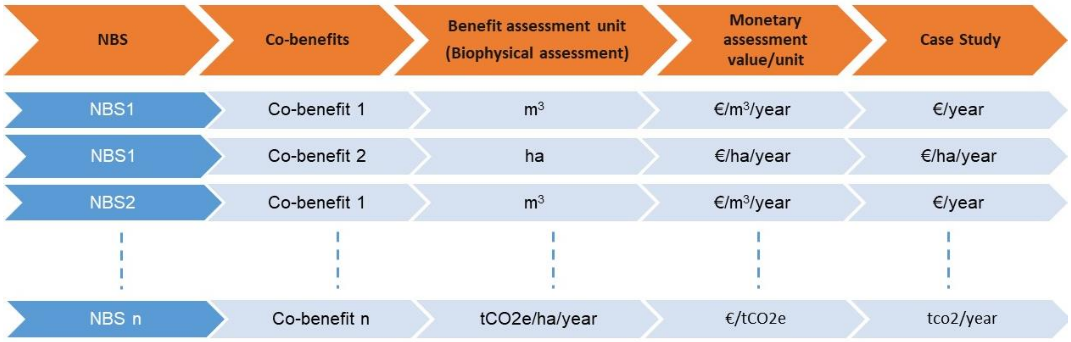


Figure 4.2. The conceptual framework for estimating the value of co-benefits (adapted from Hérivaux et al. (2019))

The selection of suitable economic valuation methods for the co-benefits associated with NBS should align with the specific characteristics and objectives of the assessment. Practical considerations include:

- When co-benefits possess clear market value or can be traded in existing markets, the market value method can be used. This approach is apt for valuing co-benefits such as increased agricultural productivity, and carbon sequestration prices.
- When co-benefit values are contingent on resources not traded in traditional markets, revealed preference methods like the travel cost method, hedonic pricing, and averting behaviour can be employed. These methods are particularly valuable for assessing co-benefits associated with activities like educational trips, recreational visits, and increase in property values.
- When co-benefits are contingent on individuals' willingness to pay, contingent valuation methods can be applied. This approach allows for the valuation of co-benefits where individuals express their willingness to pay for non-market benefits, such as change in erosion, or visiting the NBS site.
- When co-benefits involve the replacement cost of resources, methods like habitat creation costs can be utilised.
- When assessing co-benefits related to risk reduction and damage prevention, the avoided damage cost method can be used.

4.2.5 Adjusting value to different contexts

Accounting for differences in characteristics between the study site and the policy site is challenging when conducting accurate and credible value transfers (Brander, 2014). The study site refers to a site elsewhere mentioned in the existing literature (i.e., reports, research articles), while the policy site refers to a current case study of interest. Considering the rarity of finding values that perfectly align with the specific context, it becomes necessary to adjust transferred values to reflect the unique characteristics of the situation at hand accurately. This research adapted two steps from Brander, (2014) to address this challenge and enhance the accuracy of the transferred values.

Firstly, year of value and general price levels should be standardised. In most cases, values obtained from study sites differ from those applicable to policy sites due to variations in the years when the assessments were conducted. Therefore, when transferring values from a study site that were estimated for previous years to inform current decisions, it is necessary to adjust historical values to the same base. The adjustment can be accomplished by using the available consumer price index (CPI), which measures an economy's annual rate of price change. CPI data is available from the World Bank World Development Indicators (World Bank, 2022). Equation 4-3 can be employed to standardise the general price levels and ensure comparability.

$$Value_p = Value_s \, x \, \frac{CPI_p}{CPI_s} \qquad \textit{Equation 4-3}$$

where: $Value_p$ = Value at the policy site, $Value_s$ = Value at the study site, CPI_P = consumer price index for the year of the policy site assessment, CPI_S = consumer price index for the year of the study site valuation

Secondly, currency should be standardised when transferring values from a study site conducted in one country to a policy site in another country that used different currencies. This standardisation ensures that all the values are expressed in the same monetary unit to compare the cost and benefits. In this research, the currency is standardised into the EURO. The transfer of values between countries can be achieved by using exchange rates, as shown in Equation 4-4.

$$Value_p = Value_s \, x \, PPP \qquad \textit{Equation 4-4}$$

where: $value_p$ = Value in currency of the policy site, $value_s$ = Value in currency of the study site, PPP = purchasing power parity adjusted exchange rate between policy and study site currencies

4.2.6 Cost-benefit analysis

NBS measures are economically assessed through life-cycle cost-benefit analysis (CBA). CBA is a theoretical analysis technique that evaluates whether it is economically beneficial to enact the project, as it provides important information for the identification, option analysis and appraisal of investments. This CBA involves evaluating values benefits and costs over the project's lifespan, considering that the annual benefits of NBS will continue into the future. By thinking about how much future benefits are worth today, decision makers can compare benefits that are produced at various points in time. This process of converting the value of all future benefits into present terms is called discounting. Discounting requires carefully selecting a discount rate, which determines to what extent the value of future benefits will be reduced when translating them into present terms.

This study proposes the NPV and BCR as economic efficiency indicators to perform a cost-benefit analysis. NPV represents the difference between the present value of all expected costs and benefits of the project over its lifetime. This can provide insight into the total net economic benefits that a measure generates in the long term. A positive NPV indicates that the project is expected to generate more benefits than costs and is considered financially favourable. Conversely, a negative NPV suggests that the project is likely to result in more costs than benefits. The NPV can be estimated by using Equation 4-5

$$NPV = \sum_{t=0}^{T} \frac{(EAD_{t,ref} - EAD_{t,\,measures}) + CB_t}{(1+dr)^t} - \left(Cost_{exp} + \sum_{t=0}^{T} \frac{OM_t}{(1+dr)^t}\right)\ x\ optimal\ bias \quad \text{Equation 4-5}$$

where $EAD_{t,ref}$ is the expected annual damage of baseline in year t (euro/year), $EAD_{t,\,measures}$ is the expected annual damage of implementing measures in year t (euro/year), CB is the total co-benefits from implementing measures per year in year t (euro/year), dr is the discount rate of future value, and the investment horizon is T year, $Cost_{cap}$ is the capital costs (euro), and OM_t is the operation and management cost in year t (euro/year)

Conversely, The BCR indicates the relative benefits generated per unit of investment. It is calculated by dividing the total present value of benefits by the total present value of costs, as seen in Equation 4-6. A BCR greater than 1 indicates that the project is expected to deliver more benefits than costs and is considered economically favourable. Conversely, a BCR of less than 1 suggests that the project's costs are expected to outweigh its benefits.

$$BCR = \frac{\sum_{t=0}^{T} \frac{(EAD_{t,ref} - EAD_{t,\,measures}) + CB_t}{(1+dr)^t}}{\left(Cost_{exp} + \sum_{t=0}^{T} \frac{OM_t}{(1+dr)^t}\right)\ x\ optimal\ bias} \quad \text{Equation 4-6}$$

where notation is the same as for Equation 4-5

4.3 CASE STUDY

4.3.1 Description of the study area

The methodology used in this research builds upon work carried out by the EC-funded RECONECT project in the Tamnava River basin of Serbia. The Tamnava River basin is a tributary of the Kolubara River in the western part of Serbia, eventually flowing into the Danube. The three main rivers in the Tamnava River basin are Tamnava, Ub, and Gračica. The basin covers a total area of 726 km^2. With 79.3% of the total area, the predominant land-use in the river basin is agriculture, while urban and industrial land use is limited to small population centres, such as towns of Ub and Koceljeva, comprising only 1.2% of the area.

The Tamnava river basin is prone to torrential rainfall, particularly during May and July, and has experienced significant recent flooding in 1999, 2006, 2009 and 2014. The flooding that occurred between April and May 2014 was the worst experienced in the West Balkans region this century (Plavšić et al., 2014). This caused significant damage to people, housing and the environment, with losses estimated at over €1.5 billion. Consequently, many studies were initiated to improve the basin's resilience to flood hazards. The most important of these is by UNDP Serbia (2016), which attempts to comprehensively evaluate various proposed flood mitigation measures in the Kolubara watershed. Another study by, Pudar et al. (2020) investigated the benefits of implementing green and grey flood mitigation measures for the Tamnava river basin.

The present research uses part of the results from UNDP Serbia (2016) and Pudar et al. (2020), focusing on the Tamnava river basin as the starting point. The hydrodynamic model developed in the UNDP study is also incorporated into this research with improvements.

4.3.2 Nature-Based solutions measures and co-benefits selection

NBS measures and their benefits have been selected based on incorporating stakeholders' preferences into a multi-criteria framework for planning large-scale Nature-Based Solutions as proposed by Ruangpan et al. (2020). This analysis involved considering local characteristics and incorporating stakeholders' preferences. The results of applying the method provide a ranking of applicable measures and the most preferable benefits. From this ranking, the top three measures were selected. Additionally, an extra measure, proposed by stakeholders, was included in the assessment process.

The location of measures has been analysed by using the planning and suitability assessment method developed by Mubeen et al., (2021). This method considers various factors to assess the suitability of different areas. By utilising this approach, the study identified locations for implementing the NBS measures.

The NBSs to reduce flooding risks and enhance co-benefits analysed in this study include afforestation/reforestation, retention basins, floodplain restoration, and removing obstructions (e.g. bridge). Removing obstructions is conserved as NBS because it allows the water to flow naturally without obstruction in the flow path. The description of NBS measures are explained in Table 4.1, and the location of the measures are shown in Figure 4.3.

Since not all co-benefits can be easily expressed in monetary terms, in this research, the prioritisation of co-benefits focused on those that could be quantitatively assessed. These included carbon sequestration, biological control, habitat creation, air pollution reduction and Education (through school nature trips). By assigning value to these co-benefits, it was possible to incorporate them into the economic assessment of the NBS measures.

Table 4.1. The description and size of selected NBS measures

Measures	Description	Size of the measures
Afforestation/reforestation	They are mostly located in the upper basin	• 1409.41 ha
Retention basins	Large retention pond is located at the upstream part of Tamnava river and smaller retention pond is located at the upstream part of Gračica river.	• Total volume of 14,190,000 m^3 • Total area of 239 ha
Floodplain restoration – dike relocation	Dikes at the section 7 are moved back for 30 meters on each side of the river	• 4.074 km on the left bank • 3.927 km on the right bank • Total area of 24 ha
Removing obstructions	Reconstructing the bridge at 10 km around upstream from the downstream of Tamnava river	

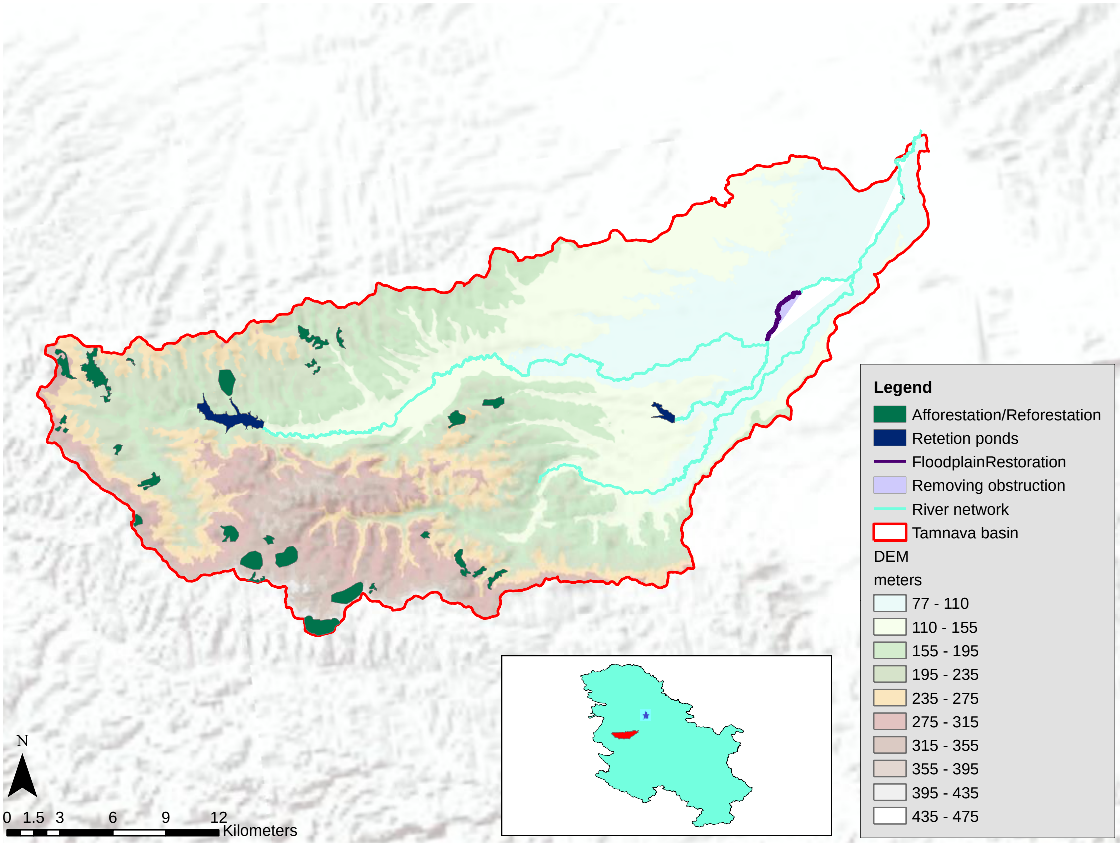


Figure 4.3. Case study map with the location of selected NBS

4.4 Application to the case study

4.4.1 Cost estimation

The cost associated with the NBS strategies in this research is based on the concept of the LCC. It considers various cost components, including capital expenditures, and maintenance and operation expenditures. To estimate these costs, a literature review was conducted, and values were transferred from other relevant studies. The unit cost information was sourced from reputable studies such as Aerts, (2018); Altamirano and de Rijke, (2017); Ayres et al., (2014); NWRM, (2015); World Bank, (2021).

After reviewing the costs, the cost was adjusted to the year 2022 for Serbia context as the base year to ensure the consistency. Subsequently, each cost was transformed into unit costs in euro (€), such as €/m^3 for retention pond and €/m^2 for floodplain restoration, to standardise the cost assessment. Whenever several unit cost values are available, the average value is used for estimation with 30% of the optimal bias.

Finally, the values were verified with the stakeholders during the co-creation process. The summary of results, including the implementation cost and maintenance and operation costs per year, is presented in Table 4.2.

Table 4.2. The implementation cost, maintenance and operation costs per year

NBS measures	Implementation cost (million euro)	Maintenance and operation cost (million euro/year)
Afforestation/reforestation	8.841	0.242
Retention basins	15.475	0.471
Floodplain restoration	14.464	0.043
Removing obstruction	0. 217	-

From Table 4.2, it can be seen that afforestation/reforestation have relatively lower implementation costs compared to retention basins and floodplain restoration, but the floodplain restoration has very low maintenance and operation cost. Removing obstruction has the lowest implementation cost, and no maintenance/operation cost.

4.4.2 Primary benefit estimation- Expected Annual Avoided Damage

The flood risk assessment was conducted by integrating water level results from a hydrodynamic model, exposure (land use) and vulnerability data (damage curves), and historical maximum damage data. The hydrological (HEC-HMS) and hydrodynamic (HEC-RAS) models used in this research are based on the model initially developed and calibrated by UNDP Serbia, (2016) for studying an extreme flood event in May 2014. The original hydrodynamic model was one dimensional (1D), and used to simulate levee breaches, overtopping, and backwater effects during flood events in May 2014 (Pudar et al., 2020). The model was further developed and calibrated in this research to include 2D effects (1D-2D), thus enabling enhanced hydrodynamic simulations and flood inundation estimation for different scenarios.

The flood inundation outputs from the hydrodynamic simulation were converted into high-resolution water depth grids. These grids are based on were Light Detection and Ranging (LiDAR) sensing data with a 1-meter resolution, to calculate the flood damage in the area.

After estimating flood inundation, the direct flood damage cost was calculated. Direct flood damage assessment used in this study relied on Depth-damage functions (DDF) developed by Pudar et al., (2020). The direct flood damage encompassed; physical damage to buildings (residential/public), physical damage to building contents and equipment, damage to crops, physical damage to roadway infrastructure, and losses related to temporary displacement of the affected population.

While direct losses capture the immediate physical damage caused by flooding, many researchers have recognised the importance of considering indirect losses to account for broader impacts and consequences. For example, Koks et al., (2015) showed that the expected annual damage of indirect losses is 65 percent of direct losses, Tanoue et al., (2020) estimated that the indirect economic loss of flooding in 2011 in Thailand is 70 percent of economic direct losses, Carrera et al., (2013) approximated indirect losses amount to around a fifth (19 to 22 percent) of the direct losses for the po and (Sieg et al., 2019) showed that the indirect economic impacts of a flood event in 2013 was 70% to 90% of the direct economic impacts. These studies indicate that indirect impacts are highly variable and can almost be as large as direct. However, due to the unavailability of indirect damage data for the case study, this research estimated indirect economic losses based on the percentage of direct losses reported in those studies, which is 70%.

The calculation of total damage for different return periods under five scenarios is presented in Figure 4.4. The results indicate that retention basins provide the greatest damage reduction (about 20%) for all return periods except the 1000-year return, where the afforestation leads to lower damage. On the other hand, removing obstruction shows minimal difference in damage costs compared to baseline scenarios. A similar pattern can be observed for the floodplain restoration. However, floodplain restoration has a higher impact in reducing damage especially particularly during larger flood events.

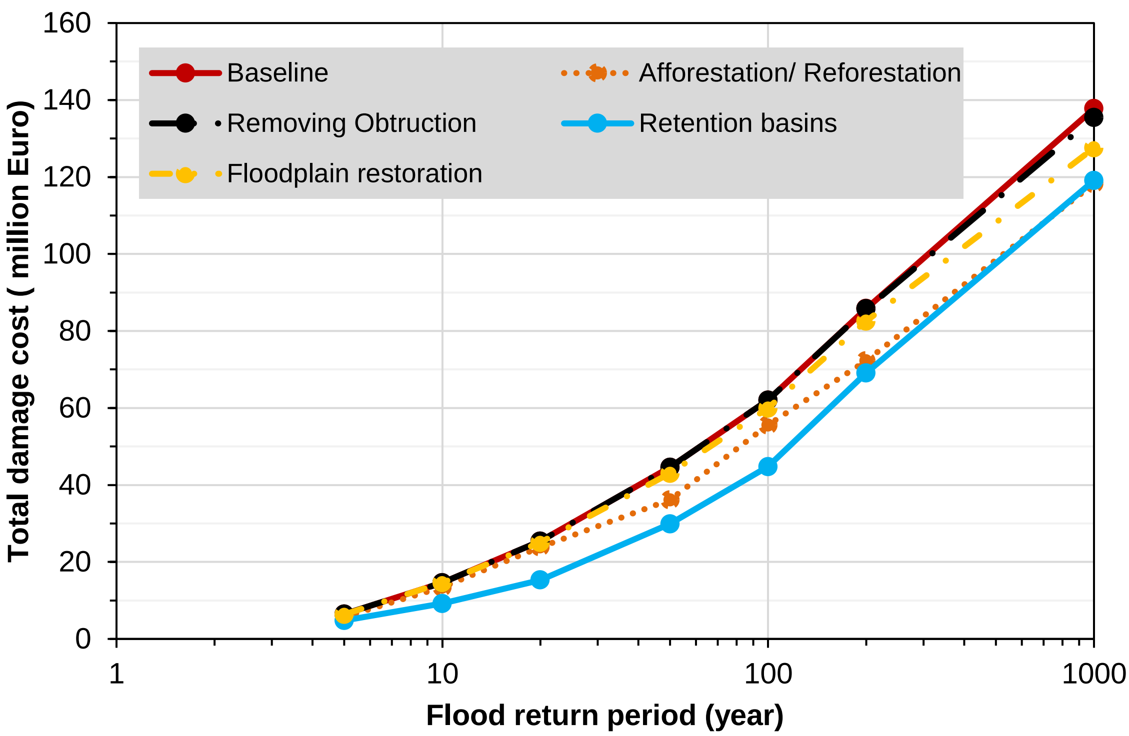


Figure 4.4. An overview of total damage cost of various flood return period for baseline and four NBS measures

In Table 4.3 the calculated EAD and EAAD are provided for all of the above scenarios. As previously stated, the EAD represents the total cost of damage incurred due to flooding and is a crucial measure for assessing the potential impacts of flooding in the area. It is clear from both the damage calculation (Figure 4.4) and the EAD values that the greatest benefits achieved in terms of reducing losses compared to the baseline scenario are obtained under retention basins scenario, followed by afforestation/reforestation. The retention basins scenario has a value almost three times higher than afforestation/reforestation (Table 4.3).

Table 4.3. Expected Annual Damage (EAD) and Expected Annual Avoided Damage (EAAD) for each scenario

Measures	**EAD (million euro/year)**	**EAAD (million euro/year)**
Baseline	4.325	-
Afforestation/reforestation	3.838	0.488
Retention basins	2.931	1.394
Floodplain restoration	4.228	0.097
Removing obstruction	4.320	0.005

4.4.3 Co-benefits estimation

Five co-benefits have been selected for the purpose of the co-benefit valuation in relation to NBS: carbon sequestration, biological control, habitat creation, air pollution reduction and Education (NBS school trips). Carbon sequestration refers to the process of capturing and storing carbon dioxide, leading to a reduction in social costs associated with carbon emissions. By implementing NBS, the need for costly carbon emission mitigation measures can be avoided, thereby providing a financial benefit. Biological control involves reducing the needs for interventions to restore and maintain the natural balance within ecosystems. This helps enhance the resilience and functionality of ecosystems, leading to potential cost savings in restoration efforts. The value of habitat creation is derived from the avoided costs of establishing habitats for various forms of wildlife, including birds, mammals, fish, reptiles, and insects. By implementing NBS, which inherently creates or restores habitats, the expenses that would otherwise be incurred to establish these habitats can be avoided. Air pollution reduction is another co-benefit provided by NBS. A reduction in air pollution leads to potential health benefits and cost savings associated with healthcare and air pollution mitigation. Education, specifically through NBS school trips, is estimated from the cost that educational organisations pay to visit NBS sites, which becomes an economic benefit in society. These trips provide valuable educational experiences for students, fostering knowledge and awareness of NBS and their associated benefits.

To assess the economic value of the co-benefits associated with NBS, a comprehensive approach involving scientific research, modelling techniques, and data analysis is required. This process entails collecting diverse data and various methods to quantify both the biophysical indicators and the monetary value of the co-benefits. The relevant information and methodologies for this purpose were obtained through an extensive literature review, for which the details can be found in Table 4.4.

The valuation methods used in this study are; the market value method for carbon sequestration, avoided damage method for air pollution reduction and biological control, travel cost method for Education (NBS trip), and contingent choice benefits for habitat creation.

By employing a range of techniques and data sources, the evaluation allows for a comprehensive understanding of the potential impacts and economic value associated with implementing NBS. The valuation results of co-benefits per year for each scenario used for cost-benefits are shown in Table 4.5.

These results show the contribution of each NBS measure to each co-benefit. In term of the benefits per year among these measures, afforestation/reforestation has the highest annual value (€2.62 million) in terms of overall benefits apart from habitat creation. However, when considering the first year alone, retention basins provide a higher benefit amounting to €11 million, due to the immediate habitat creation and the subsequent cost avoidance. While floodplain restoration shows a lower value compared to afforestation/reforestation and retention basins, it still plays a significant role in providing co-benefits.

Table 4.4. Co-benefits assessment matrix

No	Assessment matrix		Biophysical assessment Method			Estimate monetary value/unit			Case study metrics			
	Measures	**Co-benefits**	**Calculation Source**	**Unit**	**Assessment method/value**	**Estimate source**	**Unit**	**Estimate price**	**Price for the case study**	**Unit**	**Biophysical assessment**	**unit**
1	Afforestation and Reforestation	Carbon sequestration	WCC_carbon Calculation	tCO2e/ha/year	Dynamic	(Tradingeconomics, 2023)	€/tCO2e	90.21	90.21	€/tCO2e	9,251.8*	tco2/year
2	Afforestation and Reforestation	Biological control	(Pudar, 2021)	ha	GIS approach	(Pudar, 2021)	€/ha/year	32.8	32.8	€/ha/year	1409.41	ha/year
3	Afforestation and Reforestation	Habitat creation	(Environment Agency, 2015)	ha	GIS approach	(Environment Agency, 2015)	£/ha/year	245	465	€/ha/year	1409.41	ha
4	Afforestation and Reforestation	Reduce air pollution										tonnes /year
4.1	Afforestation and Reforestation	NO_2	(CNT, 2008)	lbs/tree/year	1.1	(McPherson et al. 2006)	$/lb	3.34	2.28	€/kg	906	tonnes /year
4.2	Afforestation and Reforestation	SO_2	(CNT, 2008)	lbs/tree/year	0.69	(McPherson et al. 2006)	$/lb	2.06	1.41	€/kg	529	tonnes /year
4.3	Afforestation and Reforestation	O_3	(CNT, 2008)	lbs/tree/year	0.28	(McPherson et al. 2006)	$/lb	3.34	2.28	€/kg	214	tonnes /year
4.4	Afforestation and Reforestation	PM-10	(CNT, 2008)		0.35	(McPherson et al. 2006)	$/lb	2.84	1.94	€/kg	268	tonnes /year
5	Afforestation and Reforestation	Education	(Mourato et al, 2010)	No. NBS trips/year	2	(Mourato et al, 2010)	£/trip	18.71	18	€/trip	2	trips/year
6	Retention basins	Carbon sequestration	(Badiou et al. 2011)	tCO2e/ha/year	3.21	(Tradingeconomics, 2023)	€/tCO2e	90.21	90.21	€/tCO2e	832.2	tco2 /year
7	Retention basins	Biological control	(Pudar, 2021)	ha	GIS approach	(Pudar, 2021)	€/ha/year	197.8	197.8	€/ha/year	256.06	Ha/year
8	Retention basins	Habitat creation	(Environment Agency, 2015)	ha	GIS approach	(Environment Agency, 2015)	£/har	1,900	3,610	€/ha	256.06	Ha

No	Assessment matrix		Biophysical assessment Method			Estimate monetary value/unit			Case study metrics			
	Measures	Co-benefits	Calculation Source	Unit	Assessment method/value	Estimate source	Unit	Estimate price	Price for the case study	Unit	Biophysical assessment	unit
9	Retention basins	Education	(Mourato et al, 2010)	No. NBS trips/year	2	(Mourato et al, 2010)	£/trip	18.71	18	€/trip	2	trips/ year
10	Floodplain restoration	Carbon sequestration	(Badiou et al. 2011)	tCO2e/ha/ year	8.3	(Tradingeconomics, 2023)	€/tCO2e	90.21	90.21	€/tCO2e	199.2	tco2/ year
11	Floodplain restoration	Biological control	(Pudar, 2021)	ha	GIS approach	(Pudar, 2021)	€/ha/year	97.8	97.8	€/ha/year	24	Ha
12	Floodplain restoration	Habitat creation	(Environment Agency, 2015)	ha	GIS approach	(Environment Agency, 2015)	£/ha/year	70	140	€/ha/year	24	Ha
13	Floodplain restoration	Reduce air pollution										tonnes /year
13.1	Floodplain restoration	NO_2	(Gopalakrishnan et al., 2019)	g/m2/year	0.25	(McPherson et al. 2006)	€/tonne	7000	2.28	€/kg	60	tonnes /year
13.2	Floodplain restoration	SO_2			0.14	(McPherson et al. 2006)		4000	1.41	€/kg	33.6	tonnes /year
13.3	Floodplain restoration	O_3			2.43	(McPherson et al. 2006)		2400	2.28	€/kg	583	tonnes /year
13.4	Floodplain restoration	PM-2.5			0.03	BeTa Version E1.02a in Netherlands year 2000		1800	3344.03	€/tonne	7.2	tonnes /year
14	Floodplain restoration	Education	(Mourato et al, 2010)	No. NBS trips/year	2	(Mourato et al, 2010)	£/trip	18.71	18	€/trip	2	trips/ year

Table 4.5. Monetary values of co-benefits for each scenario

Co-benefits	Measures				Unit
	Afforestation/ Reforestation	**Retention basins**	**floodplain restoration**	**Removing obstruction**	
Carbon sequestration	83,461	75,073	11,680	-	euro/year
Biological control	46,228	50,649	-	-	euro/year
Habitat creation	8,126,566	11,404,997	41,053	-	euro
Air pollution reduction	1,510,324		1,153,288	-	euro/year
NO_2	726,271		90,081	-	euro/year
SO_2	298,627		31,113	-	euro/year
O_3	230,562		875,592	-	euro/year
PM-10	254,862		-	-	euro/year
PM-2.5	-		156,500	-	euro/year
Education (NBS trips)	62	62	62.47	-	euro/year

4.4.4 Cost-benefits analysis

The cost-benefits analysis includes the calculation of NPV and BCR for all measures, in terms of both the flood damage reduction benefit alone and the total benefit. The results of the CBA for a 30 years Life cycle with 3% discount rate are presented in Figure 4.5. The life-cycle and discount rate values are selected as they are recommended by the European Commission, (2021) for infrastructural projects with co-financing from different funds.

The NPV of the primary benefit (flood risk reduction) and the total cost is plotted for each measure with orange bars in Figure 4.5A. The results show that all measures have negative NPV, meaning that the project is likely to result in more costs than benefits in terms of flood risk reduction alone. However, when the flood reduction is combined with co-benefits, the NPV becomes positive for afforestation/ reforestation, retention basins as well as floodplain restoration (indicated by green hatched bars in Figure 4.5A). This indicates that these measures can generate a positive financial impact when considering additional benefits to flood risk reduction. In contrast, the NPV remains negative for the measure of removing obstructions, indicating that it may result in financial losses even when considering all benefits.

Similarly, a BCR calculated based on flood damage reduction alone is less than one calculated for all measures. This suggests that when evaluating the project solely based on flood reduction, the costs are expected to outweigh the benefits. However, when the flood reduction is combined with co-benefits, the BCR is higher than 1 for all measures except removing obstruction as shown in Green dot bar in Figure 4.5B. This implies that when considering the additional benefits, these measures become more cost-effective. It is interesting to note that while the BCR of retention basin for flood risk reduction is almost double that of afforestation, the NPV between these two measures are relatively close.

From the results, it can be seen that while retention basins may have a better economic impact when considering flood reduction alone, afforestation and reforestation has the highest economic impact when both flood risk reduction and co-benefits are considered.

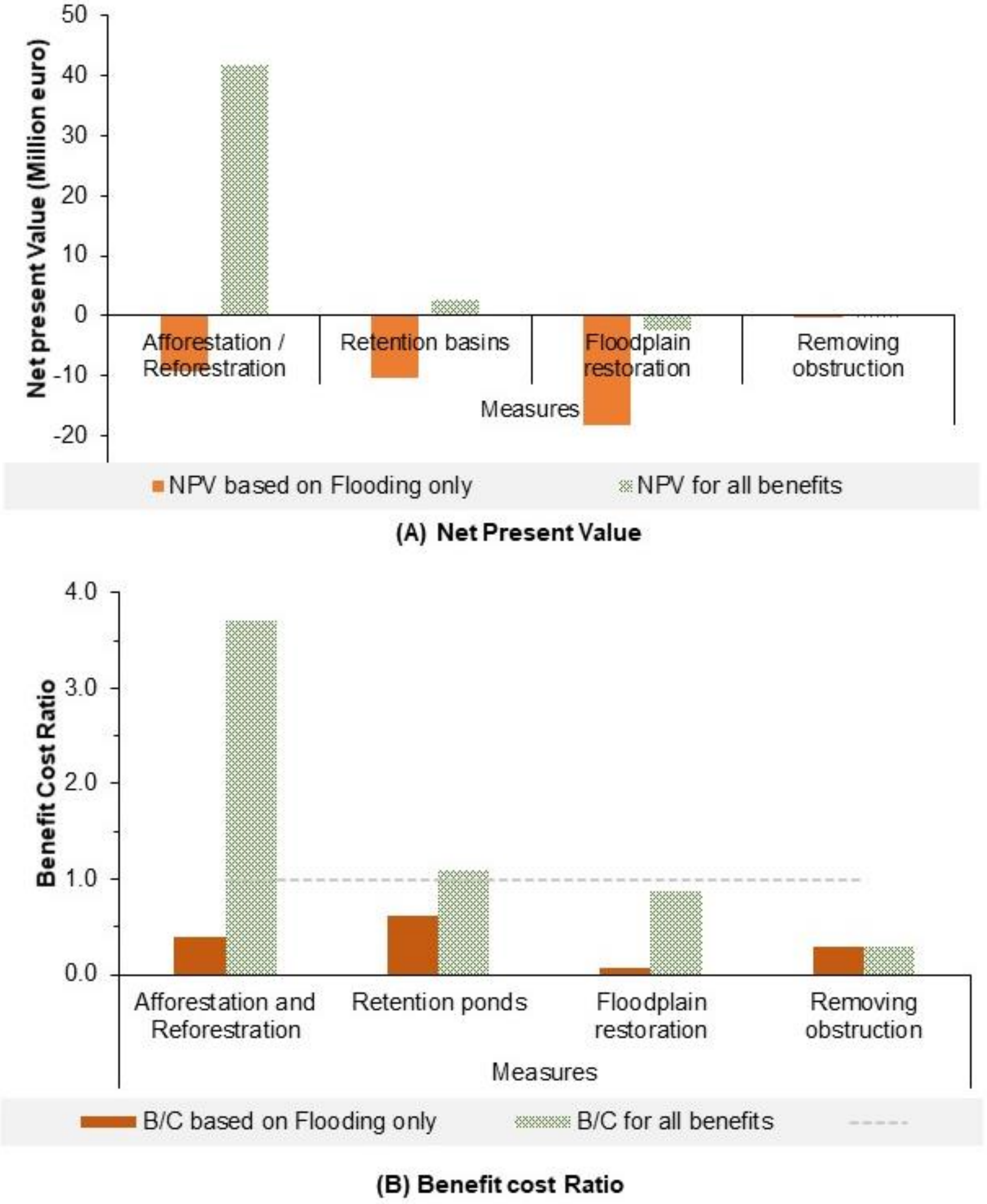


Figure 4.5 Cost-Benefits analysis results of Net Present Value (A) and Benefit Cost Ratio (B) for 30 years Life cycle with 3% discount rate

The total value of benefits was analysed by breaking it down into individual benefits (Figure 4.6). This breakdown shows the contribution of each benefits contributed to the total value, facilitating a comparison with the associated costs. Although the primary benefits of implementing afforestation/reforestation and floodplain restoration is flood risk reduction, the air pollution reduction co-benefit provides more value. However, in the case the retention basins, flood risk reduction remains the most relevant benefit. Other benefits, such as education and biological controls have relatively minor impact for all the measures.

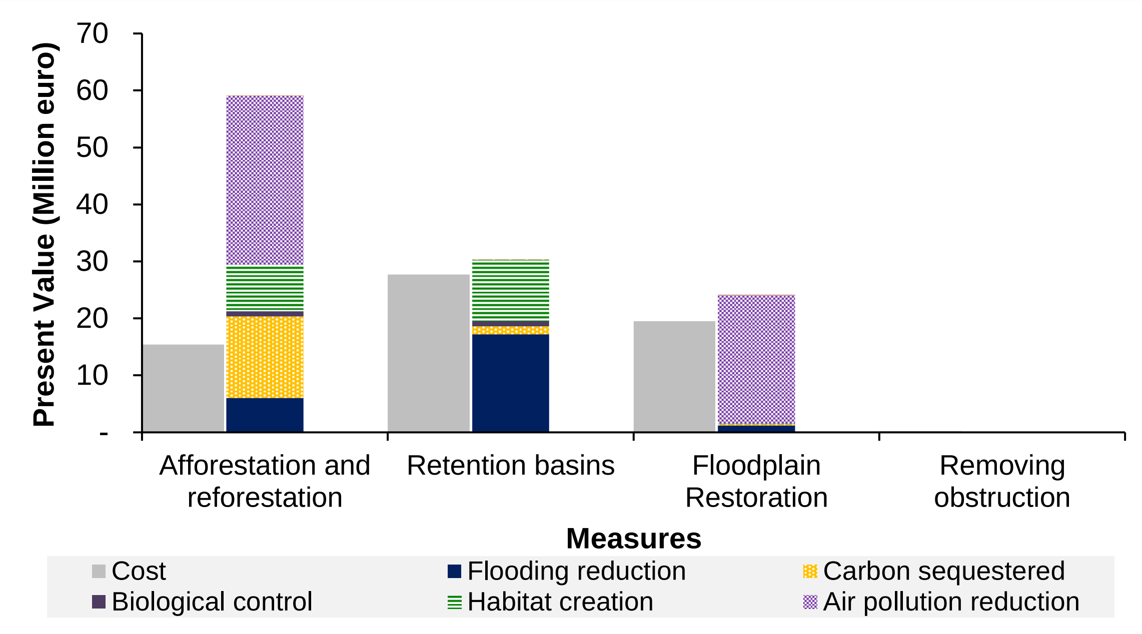
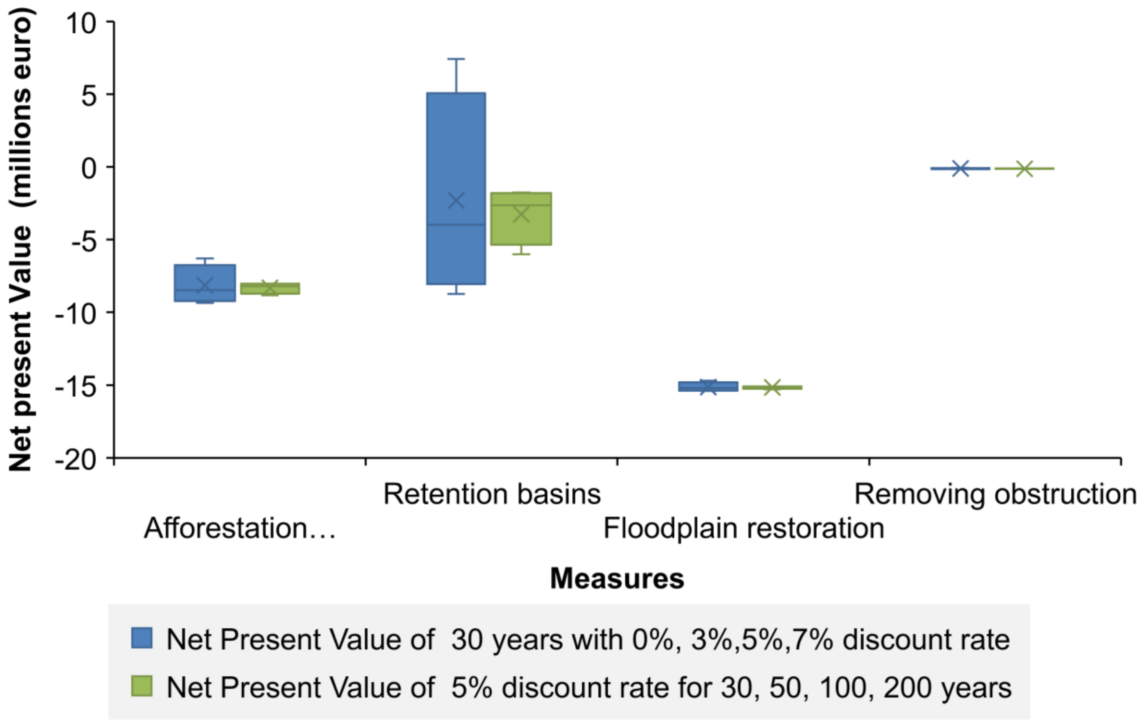


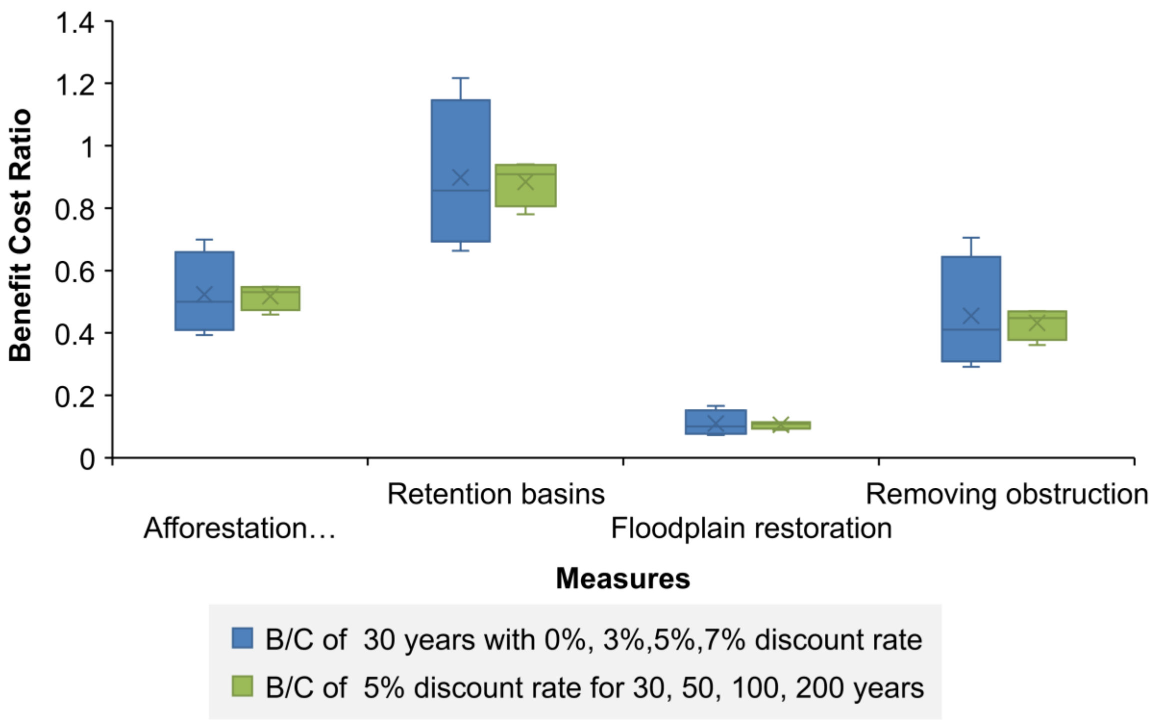
Figure 4.6. Present value of costs and relevance of individual benefits for 30 years Life cycle with 3% discount rate

4.4.5 Sensitivity analysis

A sensitivity analysis was performed to assess the impact of various parameters on NPV and BCR. This analysis involves changing discount rate and length of the life cycle to observe the corresponding changes to NPV and BCR. The results are shown in Figure 4.7A for NPV and Figure 4.7B for BCR, the lines cover the ranges in which the results move when the parameters are changed. The sensitivity analysis was carried out separately for each parameter, examining the impact of discount rates of zero, three, five, and seven, (in blue Figure 4.7) as well as life cycle durations of 30, 50, 100, and 200 years (in Grey Figure 4.7). The findings indicate that the discount rate has a higher significant impact compared to life cycle years. The NPV demonstrates lower sensitivity relative to the BCR, except in the case of Retention basins. These results highlight the importance of the parameters in evaluating the economic viability of projects, especially the discount rate.



(A) Net Present Value



(B) Benefit cost Ratio

Figure 4.7. Sensitivity analysis of Cost-Benefits analysis included Net present value (A) and Benefit Cost Ratio(B/C) (B)

4.5 DISCUSSION

The main objective of this research is to develop a methodology for assessing the economic value of NBSs at the river basin scale. The methodology is based on the CBA, incorporating NPV and BCR. To achieve this, the monetary analysis of flood risk reduction, co-benefits and the costs of NBS were estimated. The CBA plays an important role in the decision-making process as it provides a formal structure and significantly enhances transparency (Kumar et al., 2021).

The cost and co-benefits values in this study are based on a literature review and local data, while the flood risk reduction benefit was calculated using a hydraulic model and vulnerability data. Given limited local information, the study employs the value transfer method to estimate the cost and co-benefits by adjusting the value to the local contexts. Therefore, the study does not aim to provide exact costs and benefit values but rather presents a methodology that enables practitioners, researchers, and decision-makers to better understand how to assess costs associated with implementing NBS and the potential benefits derived from their implementation.

These research on focuses on four measures (afforestation/reforestation, retention basins, floodplain restoration, and removing obstruction) and four co-benefits (carbon sequestration, biological control, habitat creation, air pollution, and education). The reason for only selecting these measures is that not all benefits for all the measures can be monetarised using valuation approaches for CBA (Van Zanten et al., 2023).

In terms of flood risk reduction, the results show that measures implemented at the upstream of the catchment, such as afforestation and reforestation, and retention basins, have a higher potential for avoiding flood damage. On the other hand, local measures like floodplain restoration and removing obstruction show minor difference in damage costs compared to the baseline scenario. One reason for this could be that damage calculation in this research encompasses for the whole catchment, while rebuilding bridge or floodplain restoration are localised measures implemented at only one section of the river. Therefore, looking at the impact at the local scale may have more significant impact for rebuilding bridge or many of these measures should be implement across the catchment.

Regarding co-benefit evaluation, floodplain restoration is significantly lower compared to afforestation and reforestation and retention basins. This disparity can be attributed to the smaller area involved in floodplain restoration projects. As floodplain restoration focuses on restoring specific areas of floodplains, the coverage is limited compared to the broader scale of afforestation and reforestation initiatives. Consequently, the smaller area impacted by floodplain restoration results in a reduced contribution to the overall co-benefits.

The CBA results indicate that when considering flood risk reduction alone, all the measures have a higher cost than benefit from flood damage reduction. However, when incorporating the co-benefits into the analysis, afforestation/reforestation, and retention basins have positive NPV values and BCR, indicating potential financial gains and cost-effectiveness. Therefore, it is important to include co-benefits as it enhances the economic efficiency of NBS. Similar results have been obtained previously by Alves et al., (2019) and Ossa-Moreno et al., (2017). Moreover, the evaluation of NBS when co-benefits are included can be seen as an evidence to help to improve the confidence and competence associated with the practicality of NBS. Similar conclusions were also found by Kumar et al., (2020).

The breakdown of the total value of benefits and the cost in Figure 4.6 helps in understanding the contribution of NBS benefits, which can be used to inform decision-making processes and help prioritize NBS measures based on their potential benefits and costs. Moreover, the sensitivity analysis performed in the study highlights the importance of discount rates in evaluating the economic viability of projects. The findings indicate that the higher discount rate lead to a lower economic impact.

In this study, only individual measures were considered for cost-benefit analysis as the aim of the research is to develop a methodology to include both flood risk reduction and co-benefits into the cost-benefits analysis. It is important to first have a methodology to assess the economic value for each measure. Future work should aim to compare NBS measures with traditional flood management measures and also optimise the combination of NBS measures or combination of NBS measures with traditional flood managements measures, in order to identify the most cost-effective scenarios. By analysing the potential synergies and interactions between different NBS measures, it is possible to identify optimal combinations that provide the greatest overall benefits and cost-effectiveness. Such an approach would enhance the practicality and applicability of NBS in real-world river basin management and decision-making processes.

4.6 CONCLUSION

This work provides a methodology for economic assessment of NBSs by incorporating the monetary analysis of co-benefits in addition to the flood risk reduction. The assessment is carried out using life-cycle Cost-Benefits Analysis (CBA) with the Net Present Value (NPV) and Benefit Cost Ratio (BCR) as key indicators.

In addition, this research introduces a conceptual framework for monetarily assessing co-benefits of NBS and a methodology to enhance the accuracy of the economic assessment by adjusting differences between the study site and the policy site. Standardisation techniques are employed to ensure comparability, including adjusting general price levels and currency exchange rates.

The methodology is applied to a case study; the Tamnava river basin in Serbia, where cost and benefits are analysed with and without co-benefits. The findings show that when considering only primary benefit (flood risk reduction), the project is expected to result in more costs than flood damage reduction. However, when the flood reduction is combined with co-benefits, certain measures can generate a positive financial impact.

These results emphasise the importance of incorporating co-benefits into the economic assessment to achieve economically viable implementations of NBS. Although the numerical results are context-specific to this case study, it is proposed that that the insights derived from the integration of co-benefits into economic assessments have broader and more generalizable implications. In essence, our research suggests that the integration of co-benefits into economic assessments has the capacity to significantly enhance the overall economic efficiency and viability of NBSs. The most important strength of the developed methodology is its potential for replication in other regions. It offers a systematic approach to evaluate NBS and therefore serves as a valuable tool for practitioners, researchers, and planners, enabling them to effectively integrate co-benefits into the economic assessment of flood risk reduction measures during the decision-making process. By utilising this methodology, decision-makers can make informed choices that maximise economic efficiency while addressing the multifaceted challenges of flood risk.

5

BENEFITS ASSESSMENT OF IMPLEMENTED NATURE-BASED SOLUTIONS[5]

Nature-based solutions (NBS) are solutions that can protect, sustainably manage, and restore natural or modified ecosystems in urban and rural areas, while providing many benefits and co-benefits. Many stakeholders lack knowledge of the capabilities and benefits of NBS, and as a result, they continue to rely on grey infrastructure in their projects. When information is made available on the benefits and how they can be quantitatively measured, it is hoped that NBS will be promoted to a mainstream infrastructure choice. A valuable way to quantify and highlight the benefits of NBS is by using an evaluation framework. This article presents an evaluation framework that aims to quantify the benefits and co-benefits of implemented NBS. The outcome of the framework is a single numerical grade that reflects the benefit functioning for an NBS site and values for each performance indicator. This information may be used by decision makers to determine their budget allocations to expand or construct a new NBS site, to update maintenance plans that will improve the benefits of that site, to set up programs to monitor the NBS benefits and co-benefits over time, and to schedule labour and resources for other NBS projects. The framework was tested and validated on a case study of NBS in Thailand.

[5] This chapter is based on: Watkin, L.J., Ruangpan, L., Vojinovic, Z., Weesakul, S., Torres, A.S., 2019. A Framework for Assessing Benefits of Implemented Nature-Based Solutions. Sustainability 11, 6788. https://doi.org/https://doi.org/10.3390/su11236788

5.1 Introduction

Extreme weather events affected 60 million people worldwide in 2018; floods were responsible for 35.4 million deaths, storms traumatized 12.8 million people, wildfires caused billions of dollars in damage and were responsible for many deaths, landslides had detrimental impacts on 54,908 people, and droughts affected 9.3 million people (EM-DAT, 2018). It is no longer sufficient to respond to such disasters by implementing grey infrastructure alone.

Grey infrastructure options, such as pipes, are capable of conveying runoff from storms up to a specific size, for example, for a 1 in 10-year storm. Such rigid designs are not adaptable in an uncertain future climate. Furthermore, grey infrastructure removes stormwater from where it falls, making it inaccessible to the environment.

Nature-based solutions (NBS) are showing great potential in mitigating the effects of extreme weather events. NBS can slow and store stormwater which reduces downstream flooding; they are flexible and adaptable solutions to hydro-meteorological risk, and have the added potential to provide a range of benefits and co-benefits (Alves et al., 2018a; European Environment Agency, 2017). NBS can also be used in combination with grey infrastructure, which are often referred to as hybrid measures (Alves et al., 2016; Vojinovic et al., 2017). Such measures can provide a wealth of benefits for people, the environment, and the economy.

Small-scale NBS, such as infiltration trenches and rain gardens, can benefit stormwater management by reducing runoff, flooding, and transport of pollutants (Zhao et al., 2018). Vegetated swales can slow the runoff and mitigate erosion and sediment transport processes (Keesstra et al., 2012; Martínez et al., 2018). NBS that incorporate ponds or wetlands can provide benefits of infiltration, water storage and reuse, evapotranspiration, and groundwater recharge (GWR) (Roy et al., 2008).

Room for the river (RFR) project implemented several large-scale NBS measures along four rivers in the Netherlands. These solutions included floodplain creation, lowering of dikes, widening and deepening of rivers, and construction of high-water channels to make room for excess river water in rural areas thus preventing flooding in urban areas. The main benefits of the RFR were flood mitigation, increase of recreation potential, and enhancement of the environment and aesthetics along the rivers. There were also numerous co-benefits as a result of this project, including increased biodiversity, habitat, accessibility, and water storage.

NBS that incorporate vegetation like grasses, shrubs, and trees are capable of reducing heat, noise, water, soil, and air pollution; they reduce waterborne illnesses, respiratory diseases, and stress for people who have access to them. NBS are more adaptable to different storm events and can save millions of dollars when compared to implementation of grey infrastructure alone (Lawson et al., 2014). NBS with water storage and reuse capabilities can increase agriculture production and incomes in farming communities (World Bank, 2017; Zhang et al., 2018).

Overall, the benefits and co-benefits of implemented NBS can be observed in different domains and contexts, but systematic evaluation frameworks that can assess their full potential (as well as their possible side effects) are still lacking (Ruangpan et al., 2020a). Such frameworks are needed in order to quantify the benefits so that decision makers have a better understanding of their advantages and disadvantages. There are several existing frameworks that can be found in the literature, most of them aim to evaluate potential benefits of future NBS, like the World Bank principles and implementation guidance framework (World Bank, 2017). Others focus on hydro-meteorological (Alves et al., 2019); there are a few frameworks that address the evaluation of implemented NBS, but these provide only qualitative assessments (Raymond et al., 2017b). Hence, a framework for quantitative evaluation of implemented NBS is needed and this paper provides a contribution in this direction.

A recent review of NBS research revealed many gaps in the existing knowledge base (World Bank, 2017). The findings show that more investigations are required on the assessment of large scale NBS, hybrid measures that combine large and small scale NBS, and catchment scale NBS. Many methods were identified that are used to assess the benefits of NBS; these are hydrological and hydraulic modelling, water balance, rainfall runoff estimates, cost-benefit analysis, life cycle costing, and multi-criteria analysis. It is recommended that these methods be combined with interviews and fieldwork so that qualitative and quantitative benefits may be assessed (World Bank, 2017).

Many stakeholders are uncertain about the performance and reliability of NBS (Thorne et al., 2018), the present paper fills some of these gaps in the NBS knowledge base. The framework can be applied to urban and rural, large and small scale, hybrid, and catchment scale NBS, and it proposes a combination of several methods to assess both qualitative and quantitative benefits while integrating stakeholder’s preferences.

The present framework assigns a grade to an existing NBS by assessing each individual benefit through various methods and stakeholder input. It aims to provide a systematic evaluation of the benefits and their relative effectiveness in comparison to the same situation without NBS. The output shows where improvements are possible and can help farmers to improve their resilience to climate change, their livelihoods, and the quality of life for their communities. The framework output also provides valuable information about NBS benefits and co-benefits as well as their advantages to support academics, water managers, and planners when studying, promoting, and implementing NBS technologies. The framework was applied to an NBS case study in the Rangsit canal area of Thailand.

5.2 Proposed Framework Overview

The framework proposed here was developed from other relevant frameworks, the current knowledge base of different NBS technologies, their benefits and co-benefits, performance indicators, and practical experiences. It also reflects on some important discussions with the key stakeholders in the case study area. The following sections describe the framework steps and its application.

5.2.1 Overall Framework

The framework proposed here takes the approach of the RECONECT (Ruangpan and Vojinovic, 2022) project which builds from the challenges of the EC-funded EKLIPSE (Raymond et al., 2017b) project; these are combined into three categories, namely water, nature, and people, and form the foundation for evaluating and comparing sites with and without NBS. It is important to note that the two sites compared should be alike in most aspects except for the presence of the NBS so that a meaningful comparison can be made. For example, the sites should have the same water, nature, and people related features such as climate, rainfall, water supply, rivers, land use type, culture, etc. If the sites are alike then the differences in the benefits are assumed to be the result of the NBS performance. The schematic layout of the proposed framework is shown in Figure 5.1. After determining the requirements of the stakeholders and becoming familiar with the case study area, the five steps in the framework can be followed to determine the performance and benefits of NBS.

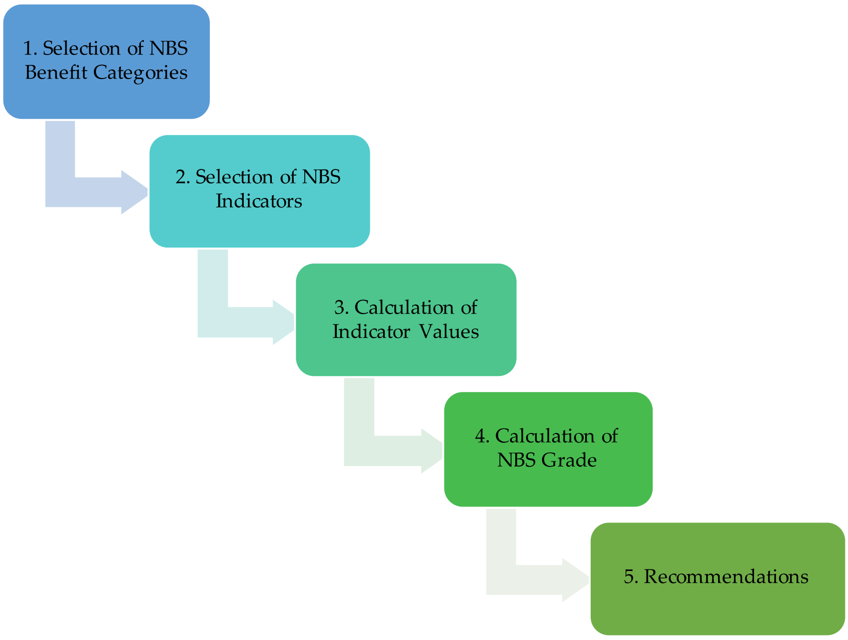


Figure 5.1. An overview of a Framework for assessing implemented Nature-Based Solutions.

5.2.2 Step 1: Selection of Benefit challenges

The benefits of NBS are categorized to three challenges as water (W), nature (N), or people (P) related. This classification was adopted from the RECONECT project, where the main focus is on hydro-meteorological, or weather-related water benefits (Ruangpan and Vojinovic, 2022). The water related benefits are directly associated with water, and include flood mitigation, drought and flood resilience, water storage and reuse, and groundwater and surface water quality. The nature related benefits are associated with the environmental features of soil, air, and vegetation, and include infiltration, biodiversity, and soil quality. The people related benefits include cultural, education, recreation, and economics.

Depending on the needs of stakeholders, and the relevance to the case study NBS, one, two, or all three of the categories may be selected for further analysis.

5.2.3 Step 2: Selection of Indicators

Selection of indicators is accomplished through stakeholder conversations and for each benefit category, select the indicators of interest and relevance. Every benefit in different categories is represented by an indicator. Certainly, not all indicators can be applicable to each case.

5.2.4 Step 3: Calculation of Indicator Values

For each indicator selected in Step 2, a numerical value will be calculated to determine its performance. Equations can be found for indicators in Supplementary Materials; every equation requires data specific to each indicator. The data may be collected through interviews, literature searches, field investigation and measurements, numerical modelling, remote sensing, etc. The benefits can be either qualitative or quantitative and the final result is expressed in a numerical value.

The equations provided in Supplementary Materials aim to compare the variables of Area A (the case study area with the NBS) with those of Area B (the comparison area without NBS or the case study area before implementation of the NBS). For example, the variable for the indicator biodiversity is the number of species in the area.

Indicators may have a positive effect on the environment, such as biodiversity (number of species), or a negative effect, like water quality (or increased level of pollution). For the biodiversity indicator to have a high value, the number of species in Area A must be much higher than in Area B, and this is referred to as a positive effect (Equation 5-1). For the water quality indicator to have a high value, the level of pollution must be much higher in Area B than in Area A and this is referred to as a negative effect (Equation 5-2). Indicator values that are close or the same for Area A and Area B imply that there are no differences in indicators, or NBS benefits.

Equations should be tested with hypothetical numbers to see if they result in the appropriate values. The difference between Area A and Area B parameters must be large to produce a high value and small to produce a low value. The higher the value of each indicator, the more pronounced the benefit will be in that area.

The equations used to determine the value for each indicator may be of the following types:

For positive effect, indicator: $X = 100 \times (A - B) \div A$ *Equation 5-1*

For negative effect, indicator: $X = 100 \times (B - A) \div B$ *Equation 5-2*

where X is the percentage of change, A is the case study area with the NBS, B is the area without NBS or the case study area before implementation of the NBS. Percent change equation: the difference between Area A and Area B for indicator X.

As the difference between A and B increases, the value of indicator X approaches 100, which is a high score, meaning that the benefit is very pronounced. Conversely, as the difference between A and B approaches 0, which is a low score, the value of indicator X approaches 0, meaning that there is little or no difference in the benefit between the two areas.

Some indicator equations must be developed on an individual basis. These indicators may be evaluated by comparison between the NBS variable (A) and expected values, literature, other case study areas, and other methods. Equations may be altered to suit the specific benefits of NBS. The data collected for each indicator is used as input for its corresponding equation; the output is a value for each indicator that quantifies how the benefit is causing an impact on the area with the NBS. Table 5.1 shows the types of equations that may be used to calculate the values of indicators.

Table 5.1. Indicators and equations types used for each.

Type of Equation	**Related Indicators**	
Equation (1): positive effects	Connectivity GWR Biodiversity Habitat provision Carbon storage Cultural and spiritual	Community interaction and development Aesthetics/property value Agriculture Economic Green jobs
Equation (2): negative effects	Historical flood mitigation Coastal flood mitigation Resilience to drought	Air quality Water quality Climate control Landslide risk reduction Noise quality

Type of Equation	**Related Indicators**	
	Resilience to flood Irrigation costs	
Equation: comparison of indicator values with the literature or case studies	Research Infiltration Recreational	Education Quality of life Social safety

5.2.5 Step 4: Calculation of NBS Grade

Next, each indicator value from step 3 is converted to a score using Table 5.2. Indicator values show the percentage difference. For example, a value of 75 with a corresponding score of 4 implies that the performance of the benefit in Area A is 75% more pronounced than in Area B. Scores less than 2 indicate that there is little or no difference between the benefit in Area A and Area B. Furthermore, they may imply that the data was not collected or analysed correctly or that the benefit is not relevant to the case study. A negative value indicates that the benefit in Area A may be inferior to Area B. When the indicator score is less than 2, the relevance, data collection, and analysis method should be re-evaluated before including it in the grade calculation.

Table 5.2. Indicator values and scores.

Indicator Value	Score
<20	1
20–40	2
40–60	3
60–80	4
>80	5

The grade for the NBS is determined by taking the average of all the indicator scores. An optional step may be to assign weights to the indicator scores if the stakeholders find some to be more important than the others. Weighted criteria should be defined by stakeholders depending on the level of importance for each indicator's benefit to the community. After all the scores have been weighted, they will be averaged, added, and will result in a single number; this is the NBS grade that incorporates all the benefits assessed.

The NBS grade, specific to the case study, will be the outcome of the assessment and the grades range from 1, indicating no benefits of NBS, to Table 5.3.

Table 5.3 Nature-based solutions (NBS) grades

NBS Grade	Description	Grade Number
Very poor	The NBS do not provide any benefits; re-evaluation is necessary.	0–1
Poor	The NBS are providing very few benefits; improvements may be required; re-evaluation may be necessary.	1–2
Good	The NBS are providing some added benefits; some improvements may be required.	2–3
Very good	The NBS are providing added benefits; minor improvements may be required.	3–4
Excellent	The NBS are adding at least 80% more benefits; continue with regular maintenance.	4–5

5.2.6 Step 5: Recommendations

The final step in the framework is to make recommendations for all indicators, or only those with low scores. Recommendations can include guidance on how to better involve stakeholders in every step of the framework, how to better measure, collect, and analyse data, and how to maintain the NBS to maximize benefits. Furthermore, this step may provide advice on how to monitor the benefits of NBS to ensure they remain positive into the future, as well as how to plan for better balance between biodiversity, habitat and agricultural output, how to reduce expenses through efficient irrigation, solar powered pumping, alternate fuel and fertilizer sources, and upscaling of the particular NBS site.

5.3 FRAMEWORK APPLICATION: RANGSIT, THAILAND

5.3.1 Case Study Areas

The case study areas used in the present work are located in the Rangsit area, in the eastern part of the Chao Phraya valley in central Thailand. Rangsit is located between the Western Raphiphat and the Rangsit canals. The case study includes two areas—Area A in Pathum Thani province (Bueng Cham O (BCO) and Noppharat (NP) sub-districts), and Area B in Saraburi province (Nong Rong (NR) sub-district), shown in the upper right-hand corner of Figure 5.2. The type of NBS addressed in the case study work are furrows which are located in Area A only.

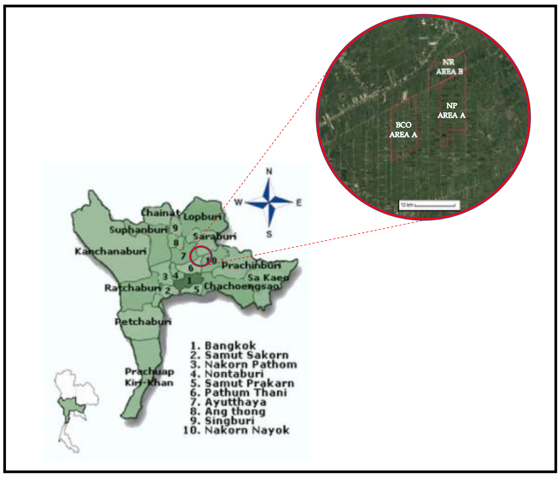


Figure 5.2. Central Thailand provinces and study area locations.

Furrows represent a unique rural NBS that exist in the Rangsit area of Thailand. These are small canals in agriculture fields connected to the sub-canals through locks with gates; they are similar to the RFR concept used for high-water channel. Furrows were first built to store water for irrigation purposes, but they can also provide several other benefits including flood protection by controlling and channelling flows. Figure 5.3 shows typical furrows in the Rangsit area.

Figure 5.3. A typical Rangsit furrow (Ditthabumrung et al., 2018).

Most of the farmland in BCO and NP sub-districts (Area A, Figure 5.2) were converted from rice paddies to orange orchards in 1984, but in 1991 a citrus disease destroyed most of the trees. The Ministry of Agriculture approached farmers to consider growing palm oil trees, which were only grown in southern Thailand at the time. As a result of that, many farmers turned to palm oil production, which became profitable. However, the farmers were faced with water shortages, poorly maintained shallow canals, and flooding. The 2011 floods caused extensive bank erosion and other damages. Hence, the farmers decided to expand and deepen the network of furrows on their land. The use of furrows for water storage boosted palm production as well as many other crops, such as bananas and vegetables during dry seasons.

Due to water availability throughout the year, Rangsit farmers harvested almost double of the palm oil yield from southern Thai farmers. Approximately 13,000 palm oil trees were planted along 72.8 km of canal banks to prevent erosion and also to stop illegal construction. Palm oil production resulted in higher yields than the farms in southern Thailand which did not have furrows (Carr, 2011).

Although it is not necessary to irrigate palm oil trees, a study in Thailand found that during the dry season, by providing up to 450 L/tree/day there will be an increase in fruit yield of up to 50% (Carr, 2011).

Figure 5.4 shows the average October rainfall from 1991 to 2016 in Thailand; two of the worst, most recent floods occurred in 2011 and 2016 (198.4 mm and 195.9 mm respectively), shown in red were used to assess the values of W1, W2, and W3. Dry season in Rangsit usually occurs from 1 November to 30 April and the monsoon season is from 1 May to 31 October each year.

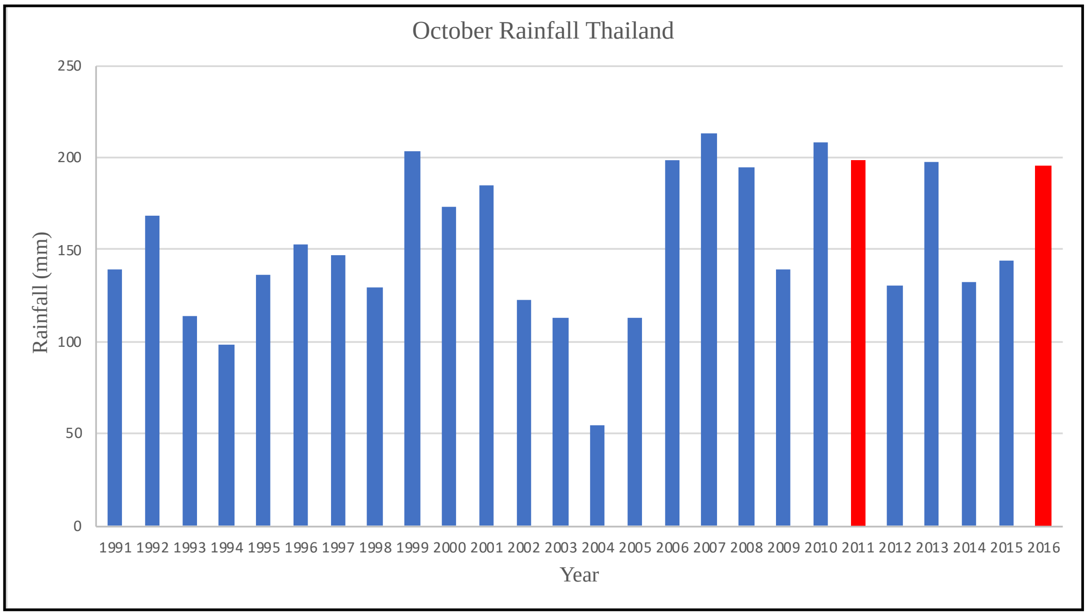


Figure 5.4. October rainfall in Thailand. 2011 and 2016 floods shown in red.

It is estimated that the Rangsit area can store up to 137 million cubic meters of water (including canals, sub-canals, and furrows), which is sufficient to supply farmers throughout the year. Furrows are approximately 2 m in depth, 2.5 m wide, and the network of 129 km provides 4600 m3/ha of water storage. There were four Area A farms included in the analysis: A-1, A-2, A-3, and A-4. All farms were used for water quality measurements, and A-3 and A-4 farmers were interviewed; A-1 and A-2 farmers were not available for interviews. The average size of farms in Area A and Area B is 18 Rai (2.88 ha); approximately 20%–25% of the land surface in Area A farms is occupied by furrows.

In the neighbouring sub-district of NR (Area B), the farmers did not convert their rice paddies to furrows. They were reluctant to change from rice to other crops due to the high initial investment costs involved in creating furrows. Presently, the most common crop in NR is still rice. There were four Area B farms used in the analysis: B-1, B-2, B-3, and B-4. Farmers in all four farms were interviewed.

5.3.2 Framework Application to Rangsit Case Study Areas

Involvement of Stakeholders

Ten stakeholders were involved in the development and testing of the framework. Six farmers were interviewed to collect information about expenses, incomes, irrigation use, floods, droughts, crops, key indicators, and fertilizer use. A Thai translator was present during all the interviews; the questions were written ahead of time to ensure the correct information was gathered (farmer interview questions are available in Appendix B).

Two local municipality personnel were separately interviewed to gather knowledge about water use, crop, flood, drought, recreation, education, key indicators, area history, and culture information. Two government experts provided information concerning total area irrigation volume, groundwater usage, and groundwater well level data for the case study areas.

Time and budget resources were limited in the application and testing of the framework. For future application of the framework, it is recommended that larger sample sizes are used, and that focus group discussions with stakeholders are included.

Step 1: Selection of Benefit Categories

Rangsit stakeholders were interested in all three benefit challenges (water, nature, and people) and they wanted to see how the benefits of flooding and drought resilience, water storage, GWR, biodiversity of crops, water quality, farmer incomes, and farm productivity were performing in their respective communities.

Step 2: Selection of Indicators

Through discussions with stakeholders on what indicators were applicable to the case study areas and important to the community, the list in Table 5.4 was produced. The selection process involved choosing relevant indicators and eliminating those that were irrelevant. For each selected indicator, the reason for selection and data source are shown in Table 5.4

Table 5.4. Rangsit indicator selection.

Indicator	Reasons for Selection	Data Source
W1: Local flood mitigation W2: Downstream flood mitigation	Occurrence of past flood event (2016). Hydrodynamic model for Rangsit was available.	World Bank database (rainfall)
W3: Historical flood mitigation	Occurrence of past flood event (2011).	2011 Flood map
W4: Water storage and reuse	Dimensions of the furrows, storage capacity, and furrow water use information were available.	Previous research [22] Farmer interviews
W5: Irrigation cost	Irrigation costs were available.	Farmer and government expert (irrigation department) interviews
W6: Resiliency to drought	Incomes in drought and non-drought years were available.	Farmer interviews
W7: Connectivity	Aerial images were available.	Google Earth
W8: GWR	Rainfall data and groundwater monitoring well level data were available. Declining groundwater level was a concern in Thailand.	World Bank database (rainfall) Government expert interview
W9: Water quality	Water sampling locations, and TSS and turbidity measuring equipment were available.	In-situ sampling
N1: Infiltration	Test locations and infiltration rings were available.	In-situ sampling
N2: Biodiversity	Species information was available.	Farmer and municipality interviews
N3: Soil quality	Soil sampling locations and a testing laboratory were available.	In-situ sampling
N4: Fertilizer reduction N5: Air quality	Fertilizer use and carbon emission information were available.	Farmer interviews
P1: Cultural and spiritual P2: Education and research	Number of events were available.	Farmer and municipality interviews
P3: Economic P4: Agricultural	Annual incomes and expenses information were available.	Farmer interviews

Step 3: Calculation of Indicator Values

The following section describes how the data was collected and analysed and how the equations were applied.

(1) Water related indicators

The nine water related indicators in Table 5.4 were analysed for the Rangsit case study areas and the details are provided below.

MIKE HYDRO River one-dimensional hydrodynamic modelling software, developed by the Danish Hydraulic Institute (DHI), was used for flood analysis in the Area A canals using October 2016 flood data. It used unsteady, nonuniform flow to simulate flows from different sub-catchment areas; which resulted in changes in water levels and discharges at five cross-sections along Klong 10 and five along Klong 1 (Klong is the Thai word for canal). The NBS storage was represented as artificial storage within the network and a weir with storage was introduced to represent the furrows.

The model used upstream and downstream flow regulators and downstream Q/h relationships for the boundary conditions (Ditthabumrung et al., 2018). Figure 5.5 shows the MIKE HYDRO River model network of the Rangsit area. Area A (marked with orange colour) is located in the upper right-hand corner. October 2016 flood data was first simulated in the case study area without storage and then again with the NBS storage; refer to Figure 5.5 for the storage location on Klong 10 (K10). The model was used to determine values for indicators W1 and W2; W1 measured Area A flooding at K10 cross-sections and W2 measured downstream flooding at Klong one cross-section.

W1: Local flood mitigation

The furrow storage was estimated at one million cubic meters; flood water levels (heights above the canal bank elevations) were recorded at five cross sections upstream and downstream of the storage location at K10 with and without the storage (see Table 5.5 for water height levels).

To understand the significance of the furrow storage, the flood level reduction was compared to the water level at which maximum damage occurs in typical Asian agriculture (obtained from a depth-damage curve) (Huizinga et al., 2017). The maximum damage occurred in agriculture at 4.8 m of flood water; mid-range damage occurred at 1.4 m; the steepest slope, or highest rate of damage occurred between 0.5 and 1.0 m of flood water. Agricultural damage is the lost output when crops are destroyed by flooding. The maximum average agricultural damage in Asia was 0.022 USD/m2 of land (2010 prices) (Huizinga et al., 2017). Using a flood depth of 0.5 m (above which most damage occurs), the ability of the furrows to reduce this value was assessed. This indicator provided an estimate of how furrows affected local flooding in the rural area around K10 in Area A., the result for W1 local flood mitigation is 43% (Table 5.5).

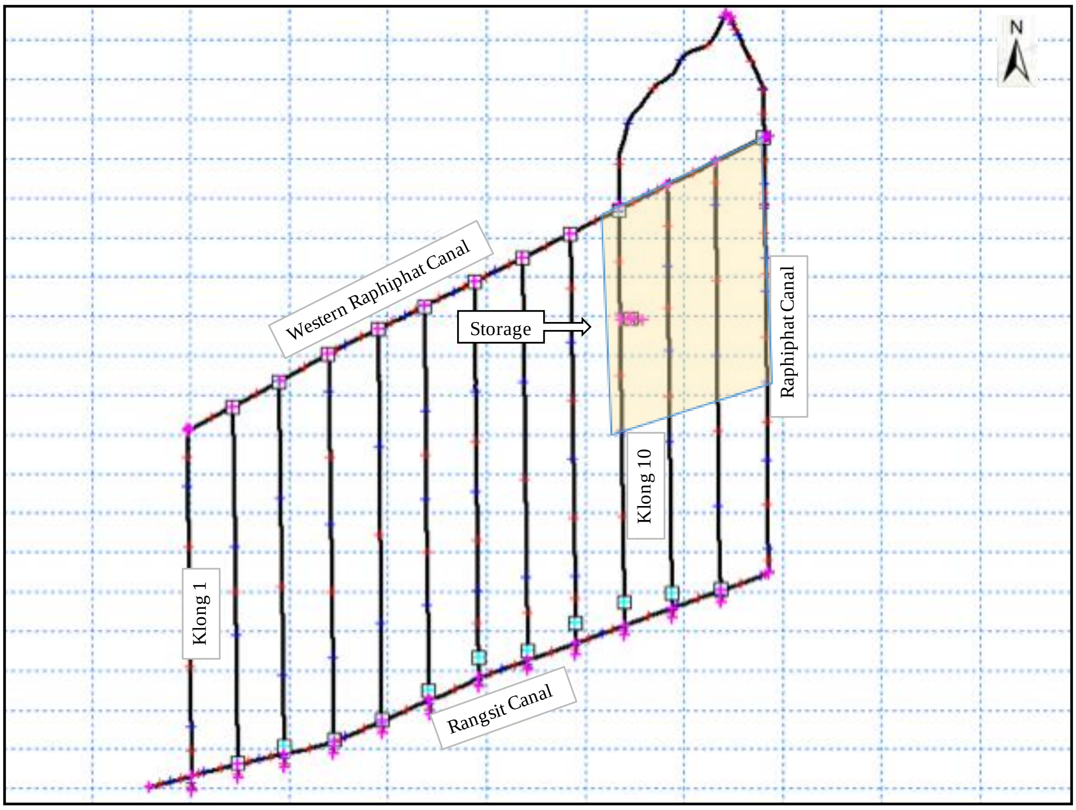


Figure 5.5. MIKE HYDRO River model network showing NBS storage location (Area A is indicated in orange)

Table 5.5. Water depths in K10 canal with and without furrow

Cross-Section	A. Top Canal Bank (m)	B. Max Water Level (No furrow) (m)	C. Height Difference (m) A–B	D. Max Water Level (with furrow) (m)	E. Height Difference (m) A–D	Flood Height Reduction (m) C–E
K10-1	3.828	5.246	−1.418 *	5.03	−1.203 *	0.215
K10-2	3.593	5.246	−1.653 *	5.03	−1.437 *	0.216
K10-3	3.6	5.246	−1.646 *	5.03	−1.43 *	0.216
K10-4	3.767	5.246	−1.479 *	5.03	−1.263 *	0.216
K10-5	3.136	5.246	−2.11 *	5.03	−1.894 *	0.216
Average flood height reduction due to the addition of storage:						0.216
D (height of maximum damage from depth-damage curve) = 0.5 m						
H_{st} (flood height reduction with NBS storage) = 0.216 m						
$W1 = 100 [1 - (D - H_{st}) \div D] = 100 [1 - (0.5 - 0.216) \div 0.5] = 43\%$						

Remark * Negative values in columns C and E indicate flooding.

W2: Downstream flood mitigation

Indicator W2 measured the potential flood mitigation potential of the furrow storage in Area A at a downstream commercial location, Klong 1 (K1).

The same model and method were used for indicators W1 and W2; for W2 the flood water levels were recorded at five cross-sections along K1. To understand the significance of the furrow storage, the flood level reduction was also compared to the height at which maximum damage occurred in commercial areas in Asia. After comparing, there was no downstream flood mitigation reduction.

W3: Historical flood mitigation

This indicator compared flooded areas in Area A and Area B for the 2011 flood event. Figure 5.6 shows a 2011 flood map that was used to estimate the areas of flooding. Purple indicates flooding and light blue indicates dry land; Area A and Area B are shown in the northeast corner. Since the 2011 flood map shows only a portion of Area B, the same sized area in Area A was used for comparison. Approximately 35.6% of Area A and 63.8% of Area B were flooded during the 2011 flood event. Therefore, the flood reduction based on the historical flood (W3) in 2011 is 44%.

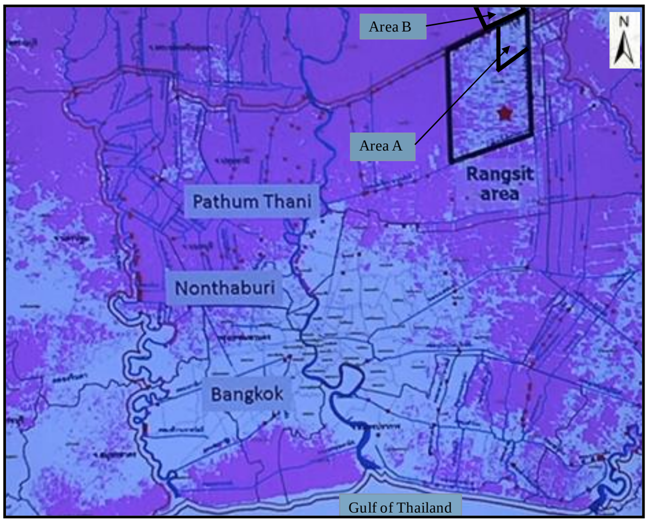


Figure 5.6. Case study areas; 2011 flood map.

W4: Water storage and reuse

The water storage and reuse potential of the furrows in Area A were evaluated based on the percentage of time that the farmers had adequate irrigation water. Information was gathered during interviews with farmers in the NP sub-district. Area B was not used for comparison since there were no furrow water storage and reuse potentials in this sub-district. Farmers in Area A were able to use furrow water for irrigation 85% of the year; the resulting value for W4 was 85.

W5: Irrigation cost

The cost (Baht/year/Rai) for all sources of irrigation (furrows, canals, and groundwater) was compared in Area A and Area B. During interviews, the farmers provided the total yearly irrigation cost for their farm; this included electricity, equipment, fuel, labour, and all operation costs; refer to Table 5.6 for details of irrigation costs (2016). Groundwater use was rare. Irrigation cost W5 for NBS was 75% higher than the area without NBS.

Table 5.6. Irrigation costs

Farm	Irrigation Cost and Units	Farm Size (Rai)	Irrigation Cost (Baht/year/Rai)
A-3	350 Baht/week	18	1011
A-4	1750 Baht/month	18	1167
	Average Area A farms (A):		1089
B-1	12000 Baht/year	36	333
B-2	12000 Baht/year	9	1333
B-3	24000 Baht/year	36	670
B-4	1250 Baht/year	8.3	150
	Average Area B farms (B):		622
W5 = 100 [(B − A) ÷ B] = 100 [(622 − 1089) ÷ 622] = −75%			

W6: Resilience to drought

This indicator compared lost farm income between a non-drought year (2016) and drought year (2015). During interviews, farmers provided their annual incomes for 2015 and 2016. Thailand experienced a drought in 2015, when dam levels dropped below 10%, and 30% of the country was on water restrictions. The rainy season, usually beginning in May did not start until August; refer to Table 5.7 for details of farm incomes. Loss of farmer income from the drought for NBS area is -150% of the area without NBS.

Table 5.7. Loss of farm income (2015 to 2016)

Farm	Loss of Income (%)
A-3	0
A-4	30
Average Area A farms (A): 15	
B-1	50
B-2	20
B-3	20
B-4	−67 (gain)
Average Area B farms (B): 6	
W6 = 100 [(B − A) ÷ B] = 100 [(6 − 15) ÷ 6] = −150%	

W7: Connectivity

The lengths of water channels (canals and furrows) in Area A and Area B were compared and lengths were estimated using Google Earth; refer to Table 5.8 for details. This indicator showed how furrows may have contributed to the distribution of sediment, organisms, and nutrients in the water systems. The higher the water connectivity was, the easier it would have been for these elements to move in the environment (Couto et al., 2018). Using Equation (1) the result for W7 was 72.

Table 5.8. Total length of canals and furrows in case study areas

Area	(1) Length of Canals (km)	(2) Length of Furrows (km)	(3) Area of Sub-District (km2)	Total Length Per Area (km/km2) [(1) + (2)] ÷ (3)
A	51.12	254.80	66.1	4.63 (A)
B	34.3	0	26.7	1.28 (B)
W7 = 100 [(A − B) ÷ A] = 100 [(4.63 − 1.28) ÷ 4.63] = 72%				

W8: GWR

According to the literature, Area A had an estimated rate of GWR of between 5% and 14% of anual rainfall (Fornés and Pirarai, 2014). The average annual rainfall (2001 to 2017) for the Thai province of Pathum Thani was 1497.8 mm/year; therefore, the anticipated GWR was between 75 mm/year (5%) and 210 mm/year (14%).

Both the Water Table Fluctuation (WTF) method and groundwater monitoring well records could not be used to estimate GWR due to the presence of confined aquifers below the case study area; water that infiltrated did not necessarily recharge aquifers directly below.

However, infiltration will be higher in the areas with furrows; infiltration is directly related to GWR, even if the GWR is occurring in other sub-districts. This indicator compared the surface area of water in Area A and Area B. The areas were estimated using Google Earth; the area was 22.2% for Area A and 4.7% for Area B. The resulting value for W8, using Equation 5-1, was 79.

W9: Water quality

Primary treatment of water removes the larger solid particles such as grit, sediment, and floating debris. Water that entered the NBS carried sediment and pollutants from other water bodies or from runoff. Without this process, the pollutants would have remained in the sub-canals and canals; therefore, the water quality in the canals was improved.

If the Area A furrows provided some primary water treatment for the main canal, the sediment in the furrows would have been higher than in the canals. Sediment was represented by measuring levels of total dissolved solids (TDS) and turbidity; total suspended solids (TSS) may also be used, but this test was unavailable. Furrow water samples from Area A farms (A) were tested onsite with a portable TDS probe and a portable turbidity meter, as well as Klong 12 (K) where the water originated; refer to Table 5.9 for test results. Using Equation (3) the result for W9 was 45.

Table 5.9. TDS and turbidity for Area A furrows and Klong 12

Parameter	**Furrows A-1 to A-4 (A)**	**K12 Canal (K)**	**[(Wi,K − Wi,A) ÷ Wi,K]**
Average TDS (ppm)	453	291	**0.36**
Average turbidity (NTU)	86	39	**0.55**
W9 = average [(Wi,K − Wi,A) ÷ Wi,K] 100 = average (0.36, 0.55) 100 = 45%			

Remark: The symbol i represents the different parameters; in this case there are two: TDS and turbidity.

(2) Nature related indicators

The five nature related indicators in Table 4 were analysed for the Rangsit case study areas; the details are provided below.

N1: Infiltration

Infiltration is an indication of healthy soil. A soil that is porous, drains well, and helps prevent runoff and erosion is considered healthy. The locations in Area A with furrows would have experienced infiltration. How the furrows contributed to infiltration was of interest; since there are no furrows in Area B, they were not used for comparison. Instead, infiltration rates, measured beside the furrows were compared to the literature rates for the same soil type. Infiltration rates were measured at farms A-3 and A-4 using double stainless-steel infiltration rings (30 cm inner ring and 60 cm outer ring).

In-situ measurements of infiltration measured in the field (A) were compared to the literature infiltration rates (L) for the area without NBS that has similar conditions. The infiltration in area A was 69% higher.

N2: Biodiversity

Biodiversity, in terms of variety of plant and animal species, in Area A and Area B was compared by determining the number of different crops; this information was collected during interviews with farmers and municipal staff. Area A had 20 species and Area B had 5. The resulting value for N2 is 75, which means that the biodiversity in area with NBS 75% is higher than area without NBS.

N3: Soil quality

This indicator was added at the request of stakeholders; it was specific to Area A. Farmers dredged sediment from the furrows once or twice per year and applied it to their land. Many farmers felt that the sediment was rich in nutrients, since it originated from the canals that contained agricultural runoff. This indicator compared the nutrients (nitrogen (N), phosphorus (P), and potassium(K)) of the furrow sediment (S) to nutrients in the native soil (N) at farms in Area A; samples were collected from two farms in Area A and analysed at Central Laboratory Co. in Bangkok; refer to Table 5.10.

for test results. Central Laboratory used an in-house method TE-CH-211 based on AOAC (2012) 993.13 for total nitrogen analysis, in-house method TE-CH-183 based on AOAC (2012) 958.01 for total phosphorus, and manual on fertilizer analysis, APSRDO.DOA; 4/2551 for total potassium analysis. The result for N3 was 17.

Table 5.10. Sediment and soil sample testing results

Farm	**Sample type**	**Total Nitrogen (%)**	**Total Phosphorus (%)**	**Total Potassium (%)**
A-3	Sediment (S)	0.5	0.5	0.25
	Soil (N)	not detected	0.6	0.22
A-4	Sediment (S)	0.5	0.5	0.19
	Soil (N)	0.5	0.5	0.22
Average sediment (S):		0.5	0.5	0.22
Average soil (N):		0.25	0.5	0.22
[(Zi,S − Zi,N) ÷ Zi,S]:		50	0	0
N3 = average [(Zi,S − Zi,N) ÷ Zi,S]: average (50,0,0) = 17%				

N4: Fertilizer reduction

Soil quality can also be estimated based on the quantity of fertilizer that was applied; the less fertilizer required, the better the quality of the soil. This indicator was added at the request of stakeholders, and was specific to Area A. Many farmers believed that by spreading sediment from the furrows onto the land, they required less fertilizer. This indicator compared the mass of fertilizer used in Area A to Area B in 2016, and information was collected from farmers during interviews; refer to Table 5.11 for fertilizer usage details. Area A with NBS using less fertiliser for 5% comparing to Area B without NBS.

Table 5.11. Farm fertilizer use

Farm	**Farm Area (Rai)**	**Baht/Year**	**Kg Fertilizer/Year**	**Kg Fertilizer/Year/Rai**
A-3	18	5000	250	14
A-4	18	30,000	1500	83
Average Area A farms (A): 49				
B-1	36	28,800	1440	40
B-2	9	13,400	670	74
B-3	36	32,000	1600	44
B-4	8.3	7470	374	45
Average Area B farms (B): 51				
N4 = 100 (B − A) ÷ B = 100 (51 − 49) ÷ 52 = 5%				

N5: Air quality

Lal (2004) conducted a review of research on the conversion of energy used by farm operations into its carbon equivalent (CE). It was estimated that for every kilogram of fertilizer used, 1.70 kg of CE were produced [36]. Since the difference in fertilizer use in Area A and Area B was insignificant (see N4) this method was not used.

Air pollution may also be quantified by measuring emissions such as carbon and nitrogen dioxide in the air. This indicator evaluated air quality using a remote sensing database for nitrogen dioxide levels between 10 July 2018 and 28 January 2019 [37]. The differences in emissions in Area A and Area B; the NO2 concentrations were 0.054 mmole/m2 for Area A and 0.059 mmole/m2 for Area B. The resulting value for N5 is 8.5.

(3) People related indicators

The four people related indicators in Table 4 were analysed for the Rangsit case study areas; the details are provided below.

P1: Cultural and spiritual

This indicator compared the number of cultural and spiritual events in Area A and Area B in the same year. During interviews, farmers and municipal staff were unable to identify any cultural or spiritual events that took place in Area A or Area B in 2017, as a result, the value for P1, using Equation (1) is 0.

P2: Education and research

The number of people that attended education and research events in Area A were identified through interviews with municipal staff. Over 900 people visited Area A in 2016 to study the furrows (students, communities, and government officials. If this area has no furrow, this visit would not be possible, thus the resulting value for P2, using Equation (3) was 100.

P3: Economic

The incomes (Baht/year/Rai) of farmers in Area A and Area B were compared for this indicator. During interviews, farmers from farms A-3, A-4, and B-1 to B-4 provided annual farm incomes for 2016; refer to

Table 5.12 for details. The result shows that Famer in the Area A has 77% income higher than the Area B.

Table 5.12. Farm incomes for Farms A-3, A-4, and B-1 to B-4 (2016)

Farm	Income (Baht/Year/km^2)
A-3	27,778
A-4	22,222
Average Area A farms (A): 25,000	
B-1	4089
B-2	12,222
B-3	6667
B-4	361
Average Area B farms (B): 5835	
P3 = 100 (A − B) ÷ A = 100 (25,000 − 5835) ÷ 25,000 = 77%	

P4: Agriculture

This indicator compared the productivity in Area A to Area B. The productivity was calculated as agriculture outputs divided by inputs ($/$); the higher the productivity, the more profitable the farm was. Farm output and input for 2016 were collected during interviews with farmers. Agriculture outputs included profits made through the sale of crops (Baht/year); agriculture inputs included costs of seeds, pesticides, fertilizers, packaging, tools, equipment, gas and oil, and labour (Baht/year); investment costs were not included; refer to Table 5.13 for productivity details The results shows that the farm productivity (Net income) in area A is 70% higher compare to area B.

Table 5.13. Farm productivity (2016)

Location	Income (Baht/Year/km2)	Expenses (Baht/Year/km2)	Productivity (Income/Expenses)
A-3	27,778	1667	
A-4	22,222	5556	25,000/3611 = 6.9
Average A:	25,000	3611	
B-1	4089	4000	
B-2	12,222	4444	
B-3	6667	2778	5835/2848 = 2.0
B-4	361	169	
Average B:	5835	2848	
P4 = 100 (A − B) ÷ A = 100 (6.9 − 2.0) ÷ 6.9 = 70%			

3.2.5. Step 4: Calculation of NBS Grade

Weights were applied to the indicator scores. Stakeholders ranked the benefits in order of importance using four categories: safety, income, environmental improvement and pastime; weights were assigned accordingly as shown in Table 5.14.

Table 5.14. Weight criteria for Rangsit indicators

Category	Indicators	Weight
Safety	Local flood mitigation Downstream flood mitigation Historical flood mitigation	0.45
Income	Economic Agricultural Irrigation cost Resiliency to flood	0.30
Environmental improvement	Water storage and reuse Connectivity Infiltration GWR Biodiversity Soil quality Fertilizer reduction Air quality Water quality	0.15
Pastime	Cultural/spiritual Education and research	0.10

Remark: Weights must add to 1.0.

The next step converted the indicator values into scores using Table 5.2. If the score for any indicator was less than two, that indicator may not have been relevant to the NBS or a different method of assessment may have been required. Indicators that required further assessment are shown in brackets in Table 5.15. Weights were applied to the average score in each weight category by multiplying the average score by the weight (see the last column in Table 5.15), the sum of the weighted average scores became the furrow grade; refer to Table 5.15 for grade calculation details.

The furrow grade was 3.65, referring to Table 5.3, this grade corresponds to very good: the furrows are providing added benefits; minor improvements may be required. The next step involved making recommendations for improving the performance of each indicator.

Table 5.15. Furrow grade calculation

Indicator	**Name**	**Calculated Value**	**Score (Using Table 2)**	**Average Score**	**Weight**	**Weighted Average Score (Average Score x Weight)**
W1	Local flood mitigation	43	3	3	0.45	1.35
W2	{Downstream flood mitigation}	{0}	{0}			
W3	Historical flood mitigation	44	3			
P3	Economic	77	4	4	0.3	1.2
P4	Agricultural	70	4			
W5	{Irrigation cost}	{−75}	{1}			
W6	{Resiliency to flood}	{−150}	{1}			
W4	Water storage and reuse	85	5	4	0.15	0.6
W7	Connectivity	72	4			
N1	Infiltration	69	4			
W8	GWR	79	4			
N2	Biodiversity	75	4			
N3	{Soil quality}	{17}	{1}			
N4	{Fertilizer reduction}	{5}	{1}			
N5	{Air quality}	{8.5}	{1}			
W9	Water quality	45	3			
P1	{Cultural/spiritual}	{0}	{0}	5	0.1	0.5
P2	Education and research	100	5			
Furrow grade (sum of weighted scores):						**3.65**

Remark: Terms within brackets were not used in the furrow grade calculation.

3.2.6. Step 5: Recommendations

The final step in the framework was to provide recommendations on how to improve or better quantify the benefits of the furrows; this information may be helpful in project management, budget, maintenance, and labour resource planning for decision makers. Recommendations for each indicator are shown in Table 5.16Table 5.16 for the case study area; decision makers may choose to follow all, or only those that are important to the community and within their budget.

Table 5.16. Recommendations for Rangsit indicators.

Indicator	Recommendations
W1 Flood mitigation: local, rural	• Flood preparedness • improve communication between flood forecasting and local communities • improve emergency plan • Educate other agricultural communities and governments on furrows • Implement furrows in other areas
W2 Flood mitigation: downstream, urban	• Increase water storage capacity • add more furrows or NBS • maintain canals regularly to minimize sediment build-up
W3 Flood mitigation: historical	• Improve flood water storage capacity • extend or deepen furrow network • dredge sediment from canals and furrows regularly • keep gates well maintained
W4 Water storage and reuse	• Increase the storage capacity • increase furrow networks • widen or deepen furrows • maintain furrows regularly to prevent sediment build-up • fill furrows more before the dry season • Plant drought-resistant crops during dry season • Use more efficient irrigation methods
W5 Irrigation cost	• Reduce irrigation costs • plant more drought resistant crops • use efficient irrigation methods • consider more solar pumping systems
W6 Resiliency	• Increase drought resiliency • use drought resistant crops during dry season • increase water storage • use more efficient irrigation methods
W7 Connectivity	• Improve water connectivity • create more furrows • remove man-made barriers in water channels • connect and restore wetlands
W8 GWR	• Improve GWR • improve infiltration (see N1) • reduce groundwater pumping
W9 Water quality	• Improve water quality • increase flow of sub-canal water into furrows • increase suctioning frequency of sediment from the furrows • look at benefits of using furrow sediment in more areas

Indicator	Recommendations
	• decrease upstream pollution
N1 Infiltration	• Increase infiltration • employ methods of tilling/aerating soil • add more porous soils • decreasing impervious area • add organic residues like groundnut stover, tamarind or rice straw to improve soil quality [34]
N2 Biodiversity	• Increase biodiversity • plant a variety of crops and trees • increase areas with water • Obtain the services of a professional biologist for a more thorough analysis
N3 Soil quality: nutrients	• Improve soil quality • increase suctioning frequency of furrows • reduce upstream pollution
N4 Soil quality: fertilizer use	• Reduce fertilizer use • understand specific plant fertilizer requirements • improve soil quality by adding organics • avoid burning crop waste; leave it on land and till into soil
N5 Air quality	• Reduce pollutants • use crop species that have high carbon sequestration capabilities • reduce fertilizer use • avoid burning crop waste • use renewable energy sources for pumping and other farm equipment operation
P1 Cultural and spiritual	• Discuss the benefits of furrows with community members
P2 Education and research	• Continue to promote the use of furrows to others
P3 Economic: Incomes	• Improve crop yield • use crops suited to the local conditions • optimize conditions for planting, watering, fertilizing, and harvesting
P4 Agricultural productivity	• Improve productivity • study cultivation and rainfall patterns to optimize crop growth • plant more drought resistant crops in dry season and crops that consume less water • reduce expenses

5.4 Discussion

A framework for assessing implemented NBS was developed and tested on the Rangsit case study. The work to date suggests that the framework may be used to gain better understanding of benefits and co-benefits of NBS and to promote their implementation. The five-step quantitative post-implementation assessment framework can be seen as a valuable tool that may be used by stakeholders to evaluate the performance and potential advantages of their NBS.

Many of the Rangsit indicators provided an appropriate assessment of the NBS benefits. The calculated values of the 18 case study indicators are presented in Figure 5.7.

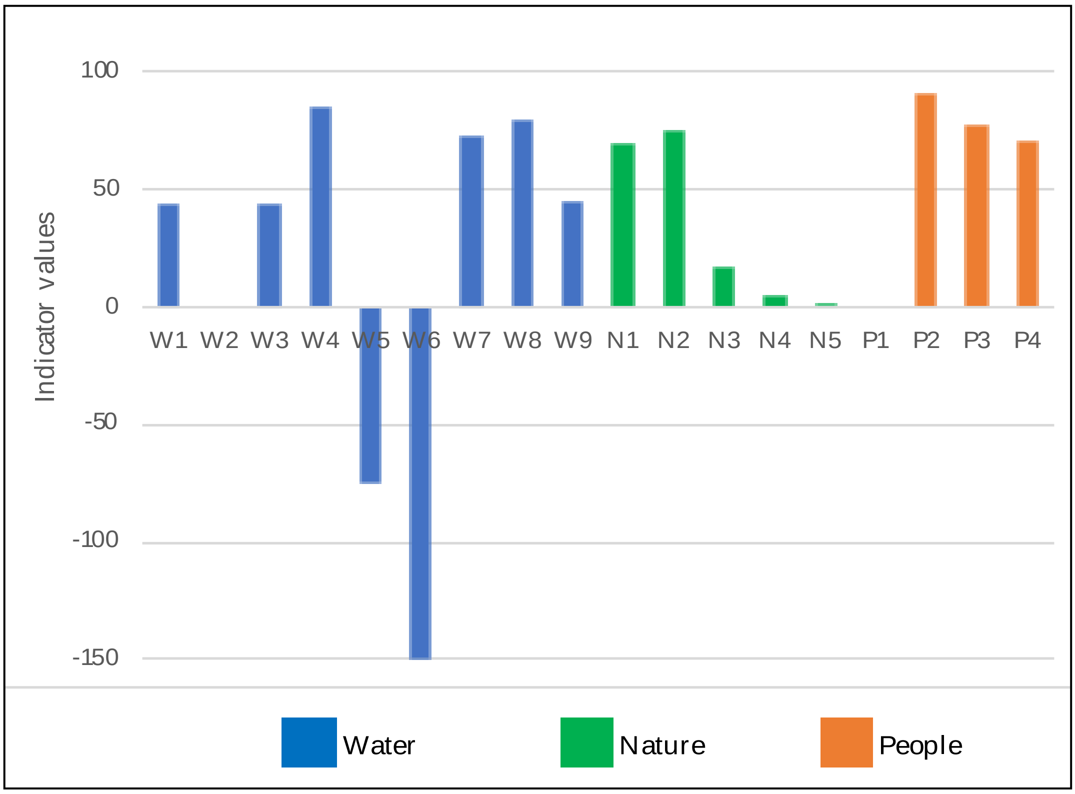


Figure 5.7. Values for each indicator

The indicators with the best performance were water storage and reuse (W4) and education and research (P2). This is due to the extensive network of furrows in the area and the widespread communication with other communities about the benefits of furrows. The indicators with low performance were local flood mitigation (W1), historical flood mitigation (W3), and water quality (W9). These indicators show that if improvements are made, such as more frequent dredging of canals and furrows, their scores will likely improve.

Seven indicators with scores less than 2 were excluded from the final score, these were W2, W5, W6, N3, N4, N5, and P1. To understand downstream flood mitigation (W2) capabilities of the NBS more accurately, the total furrow storage volume of the entire district should be used and not just from Area A. To get a more accurate value for irrigation costs (W5), resiliency to drought (W6), and soil quality (N3), larger sample sizes are required. The indicators of fertilizer use (N4) and air quality (N5) are relevant to the case study but a different way to measure them is required; comparing fertilizer use in Area A to Area B, where the crops had completely different needs, was an incorrect way to assess these indicators; a better method may be to determine the carbon sequestration capabilities of the plant species. The cultural (P1) indicator was not applicable in this agricultural setting.

The final grade for the Rangsit furrows was 3.65 which is assessed to be very good. This grade indicates that the benefits due to the NBS in Area A are greater than in Area B which does not have an NBS. The sample sizes in the research were small due to limited time and budget. The Rangsit municipality contacted farmers in the areas to set up interviews; unfortunately, only two farmers in Area A and four in Area B were available for interviews. The average of the data collected from the Area A and Area B farms was used to calculate indicator values. For a more in-depth analysis of the benefits, it is recommended to increase the samples sizes, gather more data, and to hold more workshops and interviews with the stakeholders.

The outcome of the framework application demonstrates the extent of advantages of NBS, how each benefit is performing, and where improvements can be made. The framework can be repeated numerous times over a span of several years to ensure the performance of the NBS is maintained. Furthermore, a monitoring program may provide insights into how NBS and their benefits change over time.

The framework can be found valuable for: researchers who want to study the impacts from NBS on climate change; water managers and planners who wish to promote, upscale, and implement NBS; decision makers who may want to allocate budget for NBS construction, expansion, maintenance, and monitoring; farmers who may want to improve, maintain, and expand their NBS to optimize the economic benefits; and all stakeholders who would like to understand the full benefits of NBS.

Incorporating NBS in communities may improve their resilience to climate change; NBS can diminish the effects of drought, landslides, pollution, illness, poverty, and flooding. Figure 7 depicts the impacts that furrows had on the Rangsit area during the 2011 flood event. NBS are becoming more important as the climate worsens, the knowledge of their capabilities should be spread to all stakeholders and the framework presented here offers a method to accomplish such objective.

The framework fills several gaps in the existing knowledge base related to NBS evaluations. The framework can be applied to urban and rural, large and small scale, hybrid, and catchment scale NBS, and it suggests several methods to assess both qualitative and quantitative benefits while integrating stakeholder’s preferences.

5.5 CONCLUSIONS

There are many examples of NBS around the world that have proven their potential in providing benefits to water management, nature, and people. Hence, it is important to quantify and document the performance of their benefits so that the others can gain better understanding of their potential and significance. There are several frameworks that are proposed to date, but none of them can be used to assess the full potential of implemented NBS. The present paper proposes a framework that can be applied to any implemented NBS and it was tested on and adapted to a case study area in Thailand. The framework addresses both qualitative and quantitative benefits while integrating stakeholder's preferences.

The framework presented here evaluates how implemented NBS are performing and provides information of how they may be improved or sustained. The framework consists of five main steps: selection of NBS benefit categories, selection of NBS indicators, calculation of indicator values, calculation of NBS grade, and making recommendations for each indicator. Most importantly, the framework offers a tangible way for decision makers to understand the benefits, giving NBS more credibility, and hopefully elevating them to a mainstream infrastructure choice.

Application of the framework involved ten stakeholders who provided the necessary information for each step; it was revealed that the NBS were providing a wide variety of benefits, some were performing well, and others required improvements. The work undertaken in Thailand demonstrated that NBS such as furrows in agricultural land are beneficial for flood mitigation as well as for several other co-benefits. This information can be used by the farmers to improve their livelihoods, resilience to climate change, and their communities. The framework output also provides valuable information to support academics, water managers, and planners when studying, promoting, and implementing NBS.

The framework presented here did not include the calculation of benefits in monetary terms. By translating the indicator values into economic benefits, stakeholders are more likely to see the value and incorporate NBS in their projects. Therefore, in our future work we will attempt to further develop the framework to include a methodology for assigning monetary values to a variety of benefits and co-benefits.

6

FEASIBILITY ASSESSMENT OF REAL-TIME CONTROL TECHNOLOGY[6]

The intensity and frequency of hydro-meteorological hazards have increased due to fast-growing urbanisation activities and climate change. Hybrid approaches that combine grey infrastructure and Nature-Based Solutions (NBSs) have been applied as an adaptive and resilient strategy to cope with climate change uncertainties and incorporate other co-benefits. This research aims to investigate the feasibility of Real-Time Control (RTC) for NBS operation in order to reduce flooding and improve their effectiveness. The study area is the irrigation and drainage system of the Rangsit Area in Thailand. The results show that during the normal flood events, the RTC system effectively reduces water level at the Western Raphiphat Canal Station compared to the system without RTC or with additional storage. These findings highlight the potential of using RTC to improve the irrigation and drainage system operation as well as NBS implementation to reduce flooding. The RTC system can also assists in equitable water distribution between Klongs and retention areas, while also increasing the water storage in the retention areas. This additional water storage can be utilized for agricultural purposes, providing further benefits. These results represent an essential starting point for the development of Smart Solutions and Digital Twins in utilizing Real-Time Control for flood reduction and water allocation in the Rangsit Area in Thailand.

[6] This chapter is based on Ruangpan, L., Mahgoub, M., Abebe, Y.A., Vojinovic, Z., Boonya-aroonnet, S., Torres, A.S., Weesakul, S., 2023. Real time control of nature-based solutions: Towards Smart Solutions and Digital Twins in Rangsit Area, Thailand. J. Environ. Manage. 344, 118389. https://doi.org/10.1016/j.jenvman.2023.118389

6.1 INTRODUCTION

Floods affect more people than any other natural hazards, with 1.65 billion people affected between 2000 and 2019 (United Nations, 2020). Furthermore, floods are also the most frequent natural hazard, constituting 44% of the natural hazard events that occurred during the same period.

Grey infrastructure such as dams, dikes, canals, sewers, and tunnels have been the traditional approach for flood protection and mitigation. In most cases, this approach is considered as a single objective, high-cost solution. Several studies indicate that such an approach only reduce the impact in the considered areas, and may not be flexible enough to provide adequate protection against the increased intensity and frequency of extreme flood events (Brink et al., 2016b). Nature-based Solutions (NBSs) often provide a resilient and sustainable approach that incorporates co-benefits (e.g., recreation, habitat creation, carbon sequestration, air pollution reduction) to flood risk reduction, but still might not be enough to completely mitigate extreme hydro-meteorological events (Kabisch et al., 2016a). Therefore, NBSs are often connected to grey infrastructure in so-called 'hybrid measures'. This can provide an adaptive and resilient strategy to cope with climate change uncertainties, incorporate co-benefits that enhance environmental sustainability and biodiversity, and improve socio-economic activities and water security (Alves et al., 2020b; Dorst et al., 2019; Vojinovic et al., 2021; Watkin et al., 2019). Their functioning can be further improved by the use of online modelling, monitoring and system control technologies which together deliver a 'Smart Solution' with efficient performance, reduced maintenance costs, and faster decision making. Furthermore, when placed within the wider context of data and model integration, i.e. *Digital Twins*, such solutions offer improved opportunities in the management and operation of water systems (Figure 6.1). Nowadays, digital twins are increasingly becoming valuable to water professionals (Karmous-Edwards et al., 2019). Digital twins combine models with heterogeneous data sources to interpret and predict the behaviour of a real system, and technologies such as Telemetry, Supervisory Control And Data Acquisition (SCADA) systems and Internet of Things (IoT) are invaluable for this purpose. In the case of NBS, the application of such technologies can deliver ecosystem services more efficiently and help respond to climate change effects (Arts et al., 2015; Goddard et al., 2021; Gulsrud et al., 2018; Li and Nassauer, 2021; Nigro et al., 2014; Nitoslawski et al., 2019).

Although there are many studies on smart technologies for water systems, none of the above studies focus on the potential benefit of implementing RTC for improving the capacity of NBS or hybrid measures to reduce flooding. Therefore, Smart NBSs in this research will focus on the effectiveness of RTC in reducing flooding and increasing the capacity of NBSs.

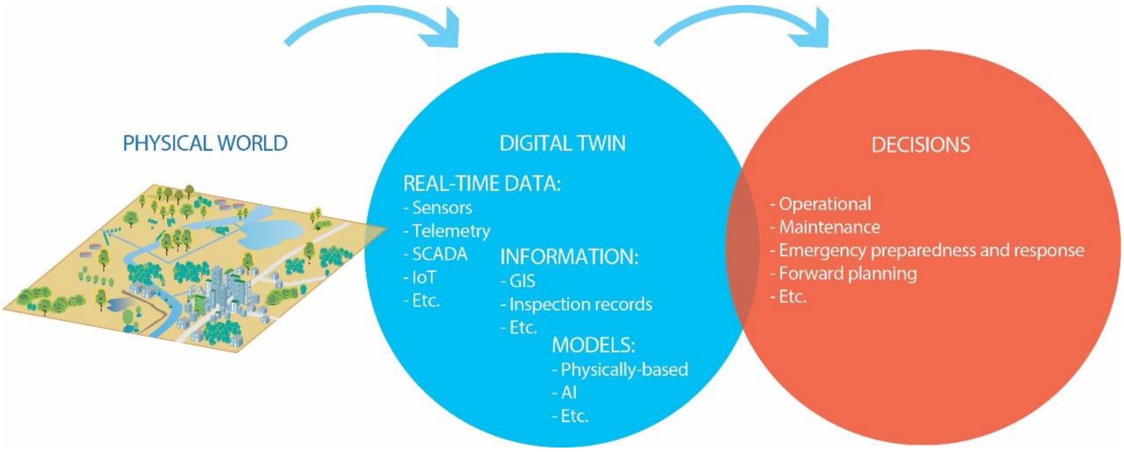


Figure 6.1. Smart technologies and Digital Twins in the management and operation of water systems.

RTC techniques can be used to automatically control structures in real-time according to pre-established rules and/or weather and hydraulic conditions (Bilodeau et al., 2018). Some of the advantages that RTC can provide include improvements to water storage management, flood prevention, system operation, operational costs, optimisation of the retention time, and system capacity (Marsalek, 2000; Wahlin, 2002). By using RTC for NBS, grey infrastructure such as pumping stations, weirs, sluices, inlets, and outlets are needed to regulate water system issues.

This research investigates the feasibility of upgrading an existing passively-controlled NBS system to a Smart-NBS by introducing (active) RTC and eventually developing a Digital Twin for the Rangsit case. To do so, the control is performed through the simplest and most common controllers called the proportional-integral-derivative (PID controllers) (Malaterre, 1995) in a supervisory feedback control scheme. The application is carried out in the irrigation and drainage system of the Rangsit Area in Thailand, in order to reduce flood risk and achieve equitability in water distribution between retention areas. The currently implemented NBS in the area is furrows, which connect the irrigation and drainage systems.

This article is organised as follows. Section 6.2 introduces the theoretical background for developing RTC. Section 6.3 provides general information about the case study along with available modelling and data. Section 6.4 explains the methodology proposed and used in this research to develop RTC and evaluate its performance. Section 6.5 presents the results of the application, which demonstrate the utility of RTC in terms of flood reduction and equitability in water distribution between retention areas. Section 6.6 discusses the impact of using RTC. Finally, in section 6.7, some conclusions are drawn, and suggestions for further research are made.

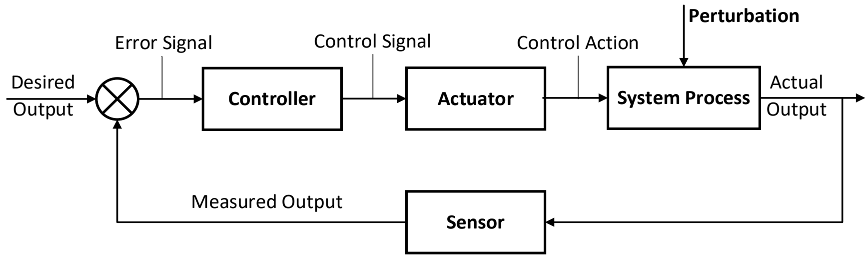
6.2 THEORETICAL BACKGROUND

6.2.1 Feedback control scheme

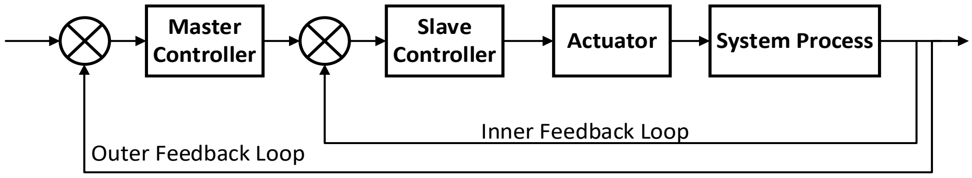
A feedback control scheme is a closed loop scheme, which means that any deviation of the system output from the set point in the current control step will be used in the subsequent control step to generate a corrective control action which aims to return the system output back to its desired value.

The advantage of a feedback control scheme is that all kinds of perturbations are indirectly considered, as their effect is included in the determined system output. A feedback control scheme is reactive, which means the control action is only taken when a deviation from the set point happens (Malaterre et al., 1998; Van Overloop, 2006). Figure 6.2A shows a general schematisation of a feedback control scheme. The scheme consists of the measuring element (sensor), the comparator, the controller, and the actuator. The comparator is where the desired output (i.e., setpoint or target value for a variable) and the actual output of the controlled process are compared. The resulting output from this component represents the current control system error, indicating the deviation between the actual output and the desired output. Typically, the desired output is entered into the system by a user, while the sensor measures the actual output of the system. The controller is responsible for executing control commands, with the objective of reducing its input (i.e., the system signal) to zero. The actuator is used to physically influence the process to receive the controller's control signal. Through mechanisms such as adjusting valves or gates, the actuator acts upon the system to bring the actual output closer to the desired output. The system's response is continuously monitored through the sensor, and the feedback loop enables iterative control adjustments. The actuator's role is crucial in effectively implementing the control signals and driving the system towards producing the desired output.

However, in addition to the controllers of the gates, Schuurmans et al., (1999) suggested that a master controller and a slave controller can be effectively applied to the control of water levels in irrigation and drainage canals. A master controller is used to determine the additional discharge that should be directed to the canals during flood situations. The role of a master controller is to determine the setpoint of the slave controller. So, the master controller is not directly connected to the actuator. Figure 6.2B shows the concept of a Schematisation feedback control with master and slave controllers.



A



B

Figure 6.2. Schematisation of Feedback Control Scheme (A) and Feedback Control with master and slave controller (B)

6.2.2 Proportional-Integral-Differential Controller (PID controller)

The role of the PID controller is to preserve desired values of the controlled variables using three tuning parameters, which are P: proportional, I: integral, and D: derivative. The proportional gain (P) is used to determine the value of the control action in proportion to the difference between the measured control variable and its desired setpoint. Using the proportional gain (P) alone would lead to steady-state offset errors, so the integral (I) parameter is used to eliminate this error. The derivative (D) parameter is used to reduce overshooting and oscillations (Wahlin, 2002). The PID controller was developed in 1936 and is the controller that is most often applied in control engineering. Equation 6-1 shows the mathematical formulation of the PID controller action.

$$u(t) = K_p e(t) + K_i \int_0^t e(T)dT + K_d \frac{de(t)}{dt} \qquad \text{Equation 6-1}$$

where, $u(t)$: the control action, $e(t)$: the deviation from the setpoint (e(t)= y_{ref} – y(t)). K_p, K_i, K_d : the proportional, integral, and derivative gain parameters, respectively.

The behaviour and response of the PID controller can be adjusted by tuning the K_p, K_i, and K_d parameters in order to stabilise the control system. The control system sensitivity mainly depends on the proportional gain, so increasing K_p will make the system more oscillatory and less stable. On the other hand, increasing the K_i parameter will increase the amplitude of the oscillations. For the Derivative term, increasing the K_d parameter will reduce the time of dampening out and make the response faster, but it can also amplify the noise (Romero et al., 2012).

6.2.3 Controlled Variables and Control Actions

There are two types of open channel controls that are based on the position of the control gate in relation to the controlled variable: upstream control and downstream control. In upstream control, the control structure is located in the downstream end of the canal reach and is used to control the flow upstream of it. Here, the control variable is usually the upstream water level. For the downstream control, the control structure is located at the upstream end of the canal reach and is used to control the flow downstream of it. Here, the control variable can be the water level downstream the gate or the discharge passing through the gate. In both control types, the control action taken to bring the controlled variables to their setpoints can be changing the gate level or the gate width, but usually, the gate level is adjusted. Figure 6.3 shows a sketch of an underflow gate with its possible controlled variables.

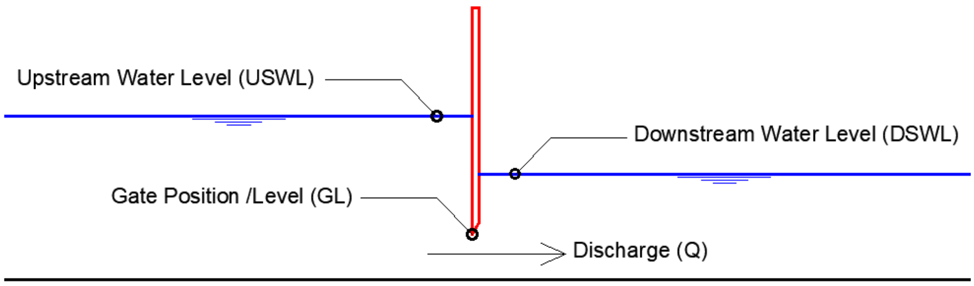


Figure 6.3 Sketch of an Underflow Gate

6.3 Description of the Case Study and Available Data

The case study area is the irrigation and drainage system of Rangsit Area, which is located in Pathum Thani Province, the eastern part of the Chao Phraya valley, central Thailand. The system consists of Raphiphat canal (i.e., main Raphiphat canal, Western Raphiphat canal, Southern Raphiphat, Hokwa-sai-bon canals), Rangsit canal, 12 main irrigation canals or so-called “Klongs” in Thai (K1 to K12), Klong control structures, and farms and furrows as shown in Figure 6.4. Klongs are used for both irrigation and drainage. Klongs are fed by water from the Western Raphiphat Canal and drained into the Rangsit Canal. At the beginning of each Klong a gate is used to control the discharge, and at the end of each Klong another gate is used to control the water level. Klongs also supply water to the farms, where water is stored in furrows.

Furrows are used as a NBS to store part of the diverted excess flood water and prevent overtopping of the irrigation and drainage system canals in Rangsit Area (Ditthabumrung and Weesakul, 2019; Mashiyi, 2021; Watkin et al., 2019). Although these furrows occupy 20 to 25% of the palm oil farms area, the water availability they provide throughout the year means that production has doubled (Watkin et al., 2019). According to the Hydro Informatics Institute (HII) in Thailand, a field with furrows can store up to 1.875 m^3 of water per m^2 of the farm area during floods. Under normal conditions, 0.4375 m^3 per m^2 of the farm area should be preserved in the furrows in order to have enough water for farm production.

Previous studies show the potential of the furrows in the Rangsit area in reducing flood risk (Ditthabumrung and Weesakul, 2019; Mashiyi, 2021), in addition to providing environmental and social co-benefits (Watkin et al., 2019). As Klong 7 and 8 have the most extensive storage areas (2.58 km^2 and 8.41 km^2), this research focuses on applying RTC to these canals (See Figure 6.4).

Currently, this system is operated manually by the Royal Irrigation Department (RID) to divert the excess flood water of the Pasak River to the Gulf of Thailand and to supply and distribute water for agriculture in the area. For example, in October 2016, flood water was diverted into the Raphiphat Canal as part of the pre-established flood emergency procedure by the RID. This emergency operation was to prevent the flood peak wave from the Pasak River coinciding with the flood peak wave from the Chao Phraya River and causing flood downstream at Ayutthaya (a UNESCO World Heritage site) and the Bangkok Metropolitan Region.

A MIKE 11 hydrodynamic model is available from the study of Ditthabumrung and Weesakul, (2019). This model was built for modelling the irrigation and drainage system of Rangsit Area and it has been calibrated and validated. The model includes the irrigation network layout, the Klongs’ cross sections, information on the Klongs’ gates, as well as boundary condition discharges and water levels of the main regulators. The MIKE 11 model layout of the Rangsit Irrigation and Drainage System is shown in Figure 6.4.

6.4 METHODS

6.4.1 Hydro-dynamic model

The MIKE 11 model developed and calibrated by Ditthabumrung and Weesakul, (2019) was converted to MIKE Hydro River as it provides more options for simulating control rules of hydraulic structures. To simulate the NBS furrows, the same approach that had been used by Ditthabumrung and Weesakul, (2019), Watkin et al., (2019), and Mashiyi (2021) was followed. Since multiple furrows are connected to one Klong, the approach is to sum up the spatially distributed NBS furrows into schematised retention areas with the equivalent total capacity for each Klong (Figure 6.5). The RTC system in this research is applied up to the level of Klongs, not to the level of fields. Therefore, the approximation of NBS furrows into one retention area of each Klong is also applicable. The simplification of modelling each furrow connected to the klongs as one retention area is considered acceptable because in the proposed control system, the gates connecting furrows to a Klong would only have two states: all open or all closed.

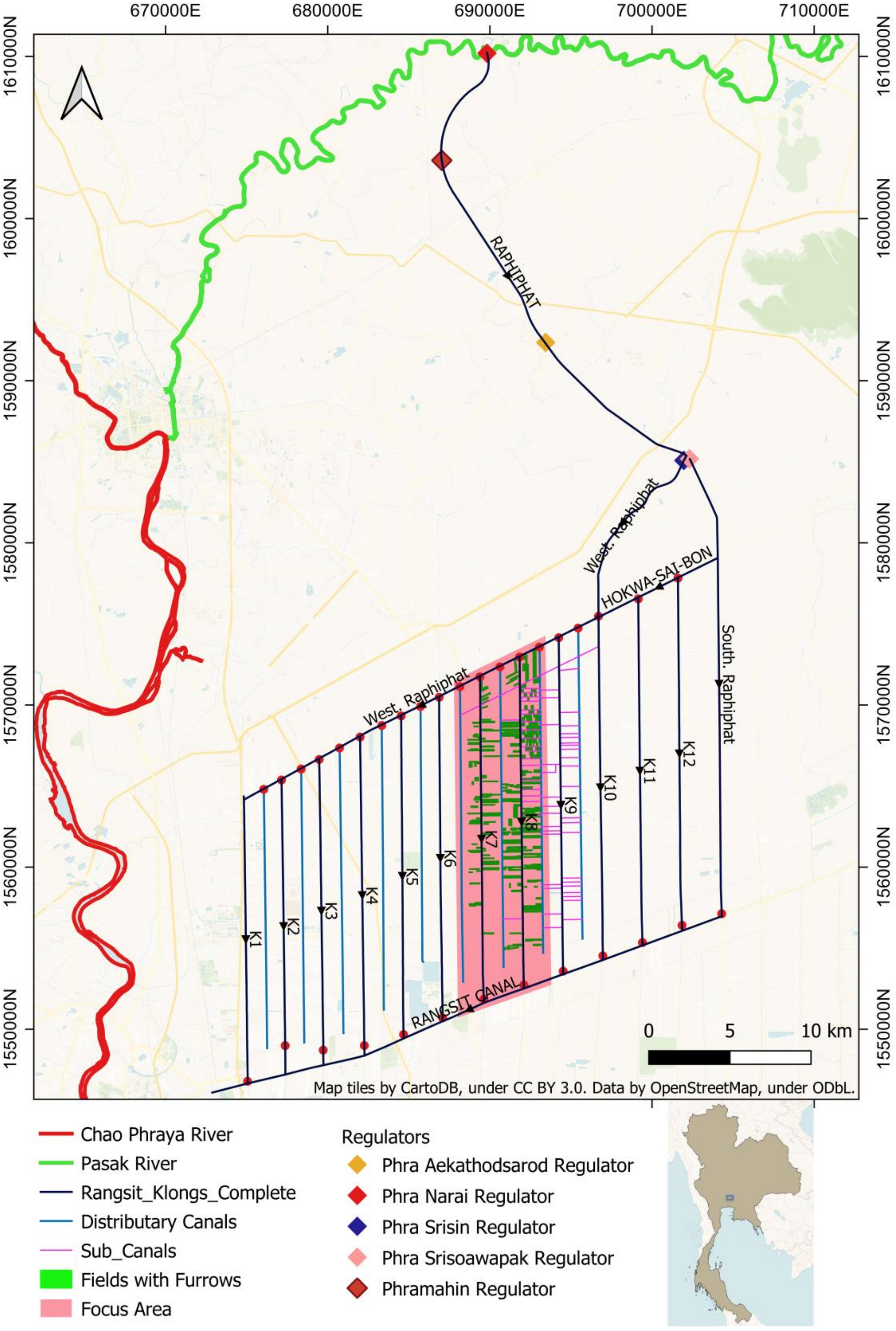


Figure 6.4 Rangsit Irrigation and Drainage System Components and Layout

To simulate the NBS furrows of Klong 7 and Klong 8, the farms containing furrows related to these Klongs were calculated. However, all the furrows cannot be included directly in the MIKE Hydro River model as it will be too complex and cause instabilities. Therefore, schematised retentions are used as NBS furrows to store water. Two schematised retention areas (A7 and A8) are calculated from the digitised farms. The areas of A7 and A8 are 2.58 km^2 and 8.41 km^2, respectively. A7 and A8 retention areas were connected to Klong 7 and Klong 8 using aggregated canals (Figure 6.5). These aggregated canals are used to add an underflow gate to regulate the flow from Klong 7 and Klong 8 to the retention areas.

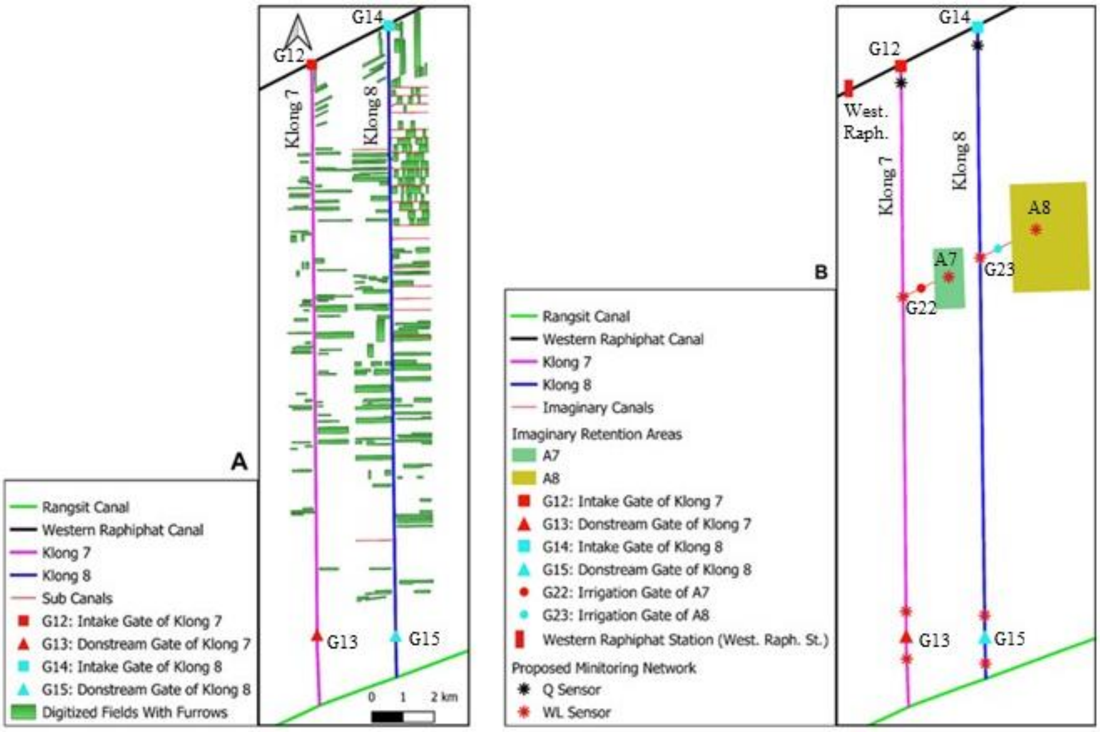


Figure 6.5. Layout Klongs 7 and 8 with the digitised farms including furrows (A) and with the aggregated retention areas simulated in the model (B)

To add retention areas (A7 and A8) to the MIKE Hydro River Model, there are three options available, namely: a side structure with storage, an elevation-area relationship, and adding a storage area to the downstream cross-section. However, with the first option no observation points can be used in the model to monitor water storage or water level in the retention area. The last option is to add the storage area to the downstream cross-section of each aggregated canal by setting a closed boundary at the end of these canals. This, as well as the elevation-area relationship, are the two best are the best retention area methods, as suggested by Ditthabumrung and Weesakul (2019).

The methods for simulating retention area were investigated by comparing the water level increase and inflow discharge in the retention area. The resulted water levels in the retention areas and their inflow discharges using both approaches are shown in Figure 6.6. Based on the analysis, adding a storage area to the downstream cross-section method is selected for this research as it is the most suitable method to simulate retention areas.

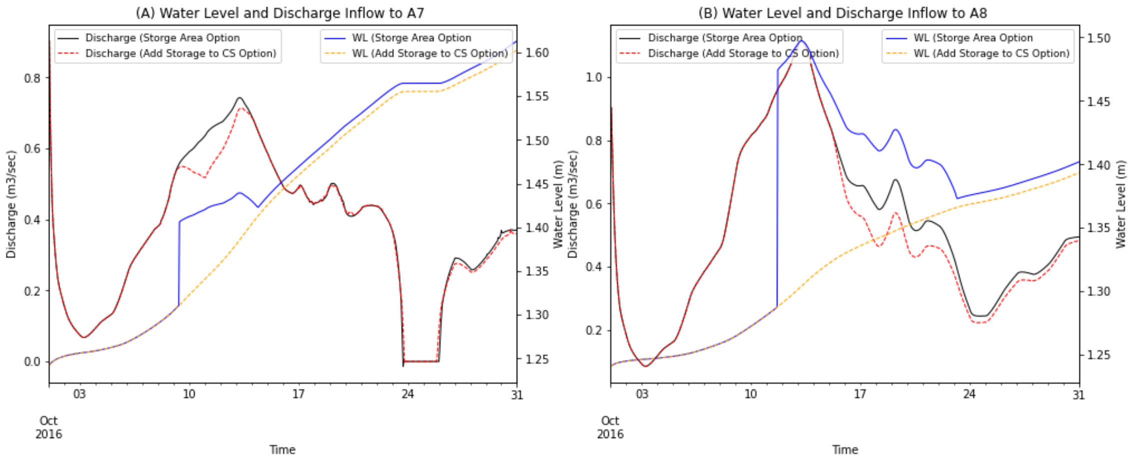


Figure 6.6. Water Level and Discharge Inflow to A7 (A) and A8 (B) using Storage Area option and the Adding the Area to Cross Section option

In the case of the Storage Area option, it can be observed that there is a sudden increase in the water level of A7 (Figure 6.6A) and A8 (Figure 6.6B) around the 10th October, even though there is no sudden increase in the inflow discharge to the two retention areas. Similarly, decreases in the water levels can also be noticed in both retention areas, despite no negative discharges causing these water level decreases. The reason could be a numerical error in the exchange between the canal and the storage area as the governing equation for both are different.

For the Add Storage Area to a Cross Section method, the relation between the water level and the discharge is the simple reservoir routing equation in which the rate of change of water stored in the reservoir is equal to the difference between the inflow and outflow discharges. From the results, it can be concluded that the Add the Storage Area to a Cross Section method is more suitable for this research to simulate retention areas.

6.4.2 Feedback control strategy

Proposed control Structures and Monitoring Network

The proposed control strategy would necessitate implementation of telemetry and SCADA technologies, which could then be coupled with the model and used for the RTC operation of NBS. The structures that will be controlled are the intake gates of Klong 7 and Klong 8 (G12 and G14), the irrigation gates of the aggregated retention areas A7 and A8 (G22 and G23), and the downstream gates of Klong 7 and Klong 8 (G13, and G15). A direct feedback control scheme (Figure 6.2A) is used with an “Open/Close” controllers for G22 and G23, and PID controllers for G13 and G15. While for G12 and G14 a supervisory feedback control scheme (Figure 6.2B) is used with a master controller to determine the discharge setpoint for both gates, and a slave PID controller for each gate to achieve its setpoint. In addition to the existing water level gauging station on Western Raphiphat Canal, the proposed monitoring network would require discharge measurement sensors for G12 and G14, water level sensors upstream and downstream G13 and G15, and water level sensors upstream and Downstream G22 and G23 (Figure 6.5).

The operational rules for G12 and G14 are based on discharge control and distribution between Klong 7 and Klong 8 depending on the water level data at the Western Raphiphat station and in the retention areas (A7 and A8). So, the controlled variables of G12 and G14 are the discharges passing through them. For G13 and G15, the objective is to stabilise the water level in Klong 7 and Klong 8, as well as to prevent overtopping, so their controlled variables are the water levels upstream of each of them. For G22 and G23, the objective is to (as fast as possible) achieve the minimum water demand during normal conditions, and to drain excess water to the retention areas in case of floods. Therefore, these gates have only two states: fully open or fully closed.

Feedback Control Strategy Development

A feedback control strategy is developed to investigate the feasibility of applying an RTC system to improve the operation and fulfil its irrigation and drainage goals, considering the capacity limitations of the NBS furrows. The flowchart of the developed feedback strategy is presented in Figure 6.7. The objective of the developed strategy can be summarised as follows: 1) reduce flooding by reducing the water level in the Western Raphiphat Canal below a threshold (2.3 m +MSL); 2) achieve equitability in water distribution between the retention areas; 3) maintain minimum water storage in the furrows; 4) prevent overtopping in Klong 7 and Klong 8.

The first feedback control strategy is to reduce flooding. The maximum water level threshold at the Western Raphiphat Canal station is 2.3 +MSL, based on the observed level during the 2016 flood. So, in this study, the flood situation is defined when the water level at the Western Raphiphat Station exceeds 2.3 +MSL. During flood situations, the proposed action in the developed strategy is to increase the discharge passing through G12 and G14 and distribute it with equity according to the available capacity of the retention areas related to each Klong.

The second objective of the strategy is in relation to water distribution. The discharge distribution factors are related to the deficit volumes of the retention areas and need to be calculated. The factors are developed for two situations; no flooding and flooding. For the no flooding situation, the total discharge supply (Q_s) for both Klongs is assumed to be the same as total discharge as without control, while the way it is distributed depends on the water volumes in the retention areas (A7 and A8). The distribution factors for the discharge between Klong 7 and Klong 8 ($R7_{nf}$ and $R8_{nf}$) in the no flood situation are calculated as per Equation 6-2 and Equation 6-3. In the case of flooding situation, a master controller is used to determine the additional discharge that should be abstracted from the Western Raphiphat Canal and directed to Klong 7 and 8, in order to keep the water level below the flood threshold. The distribution factor used to distribute discharge between Klong 7, and Klong 8 are $R7_f$ and $R8_f$ (Equation 6-4 and Equation 6-5)

$$R7_{nf} = \frac{(WD_{min} - WD_{A7}) \times A7_{area}}{[((WD_{min} - WD_{A7}) \times A7_{area}) + ((WD_{min} - WD_{A8}) \times A8_{area})]} \qquad \textit{Equation 6-2}$$

$$R8_{nf} = \frac{(WD_{min} - WD_{A8}) \times A8_{area}}{[((WD_{min} - WD_{A7}) \times A7_{area}) + ((WD_{min} - WD_{A8}) \times A8_{area})]} \qquad \textit{Equation 6-3}$$

$$R7_{f} = \frac{(WD_{max} - WD_{A7}) \times A7_{area}}{[((WD_{max} - WD_{A7}) \times A7_{area}) + ((WD_{max} - WD_{A8}) \times A8_{area})]} \qquad \textit{Equation 6-4}$$

$$R8_{f} = \frac{(WD_{max} - WD_{A8}) \times A8_{area}}{[((WD_{max} - WD_{A7}) \times A7_{area}) + ((WD_{max} - WD_{A8}) \times A8_{area})]} \qquad \textit{Equation 6-5}$$

where $R7_{nf}$ and $R8_{nf}$ are the distribution factors of the total discharge in Klong 7 and Klong 8 in case of no flood situation; $R7_f$ and $R8_f$ are the distribution factors of the total discharge in Klong 7 and Klong 8 during the flood situation; WD_{min} is the minimum water depth (0.45 m) that should be kept in the retention areas (A7 and A8); WD_{max} is the max water depth (1.88 m) in the retention areas; WD_{A7} and WD_{A8} are the water depths (m) in the retention areas (A7 and A8); $A7_{area}$ and $A8_{area}$ are the areas (m^2) of the retention areas A7 and A8.

Another objective is to maintain minimum water storage in the furrows. The minimum water storage needed in the furrows is 0.45 m^3 per m^2 of the furrow fields, and its maximum capacity is 1.88 m^3 per m^2. Thus, the minimum water depth to be achieved is 0.45 m, and the maximum water depth that can be utilised (but not exceeded) during floods is 1.88 m for both retention areas.

The final objective of the strategy is to prevent overtopping in Klong 7 and Klong 8. Two water levels setpoint are defined for each downstream gate on Klong 7 and Klong 8. The first one is used during the flood situation to utilise the whole capacity of the Klongs to store water and make the process of draining water to the retention areas faster, but without overtopping the banks of the two klongs. The second setpoint is less than the first one and is used during the normal situation. For the downstream gates of Klong 7 (G13) and Klong 8, (G15), there are two different setpoints for each gate, which are used during the no flood situation and the flood situation. These setpoints are 1.7, and 2.0 +MSL for G13; and 1.5 and 1.8 m +MSL for G15. These thresholds were selected according to the bank's levels of Klong 7 and Klong 8.

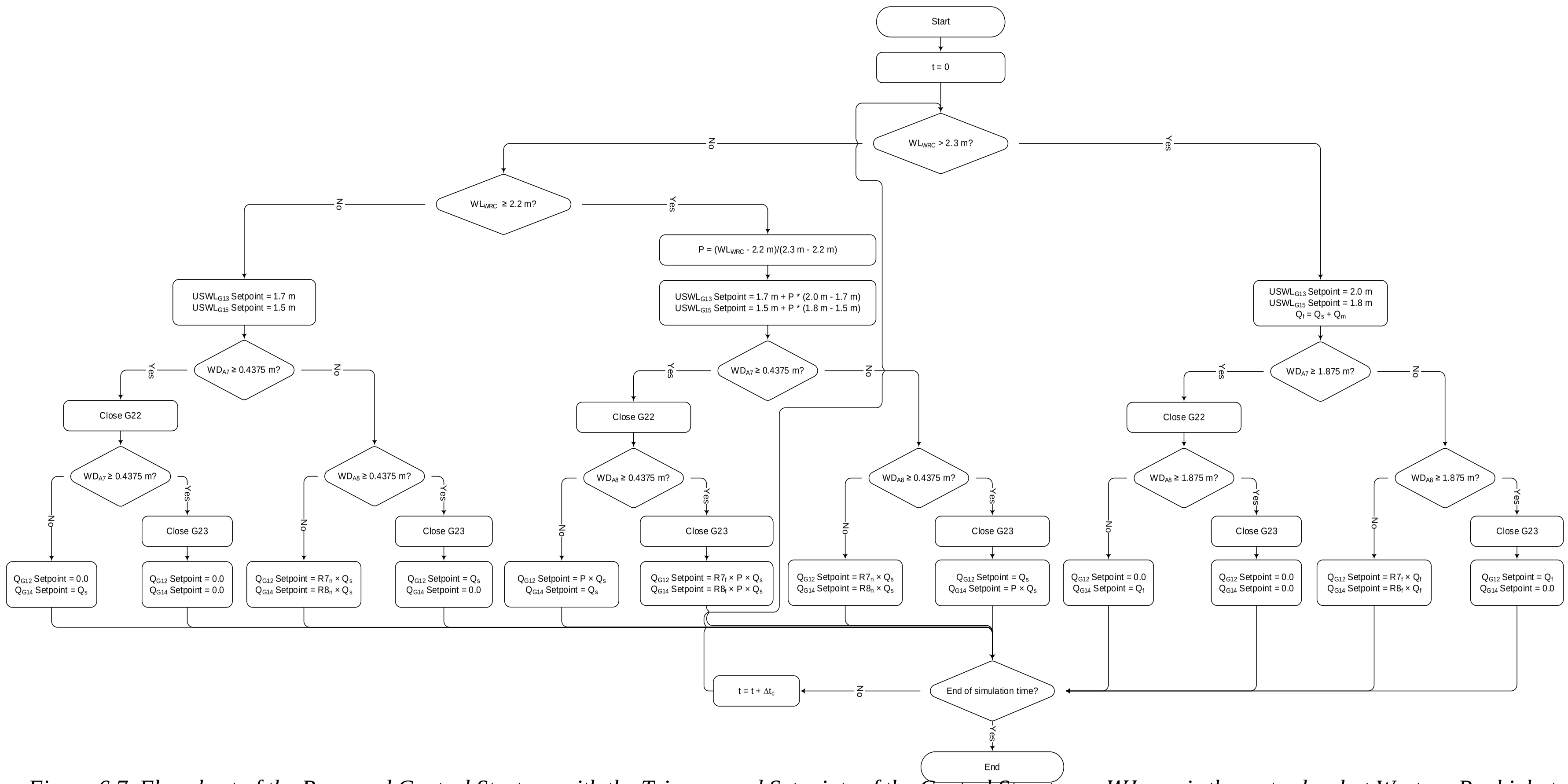


Figure 6.7. Flowchart of the Proposed Control Strategy with the Triggers and Setpoints of the Control Structures, WL_{WRC} is the water level at Western Raphiphat Canal station; $USWL_{G13}$ and $USWL_{G15}$ are the water levels upstream G13 and G15; Q_{G12} and Q_{G14} are the discharges passing through G12 and G14; WD_{A7} and WD_{A8} are the water depths in the retention areas A7 and A8; Q_f is the total discharge to be distributed between Klong 7 and Klong 8 during flood; Q_s is the scheduled discharge to be distributed between Klong 7 and Klong 8 during normal situation; Q_m is the dishcarge that should be diverted from the Western Raphiphat Canal during flood to reduce water level and is calculated by the master controller; Δt_c is the control time step; P is the percentage used for the gradual change of the setpoints within the transition zone

The developed strategy is based on local controllers that regulate variables close to the control structures of Klong 7 and Klong 8 (i.e., G12 and G14 for controlling discharge at the upstream; and G13 and G15 for controlling water levels at the downstream). However, the setpoints of the controlled variables are dependent on the information coming from remote locations (water level at the Western Raphiphat Station, and the water levels in the NBS retention areas). To avoid the sudden changes of the setpoints when switching between the flood situation and the normal situation, a transition zone is used in the control strategy. The transition zone is the situation when the water level at the Western Raphiphat Canal station is between 2.0 and 2.3 +MSL. For this zone, the setpoints are not constants but are gradually varied based on the measured water level at the Western Raphiphat Canal station.

6.4.3 Tuning of PID Controllers Parameters

The tuning process is to determine the best values of the PID controllers' parameters in order to have a stable control response while achieving the required setpoints with minimum deviations. In this study, we have investigated four different methods by using the data of the October 2016 event with constant setpoints. The set points used in the tuning process are shown in Table 6.1.

Based on the analysis of tuning PID controllers' parameters, two different methods were employed for this research. A combined simulation was conducted to examine the disturbance effect between gates in the same canal reach. The first method uses the MIKE Hydro River default values for Gate 13 and 15 as the controller achieved the upstream water levels setpoints. The second method is the individual tuning method for G12 and G14. The parameters for PID controllers are shown in Table 6.2

Table 6.1. Setpoints used in the tuning process

Gate	**Controlled Variable**	**Setpoint**
G12	Discharge Passing Through the Gate	3.0 (m^3/sec)
G13	Upstream Water Level	1.7 m (+MSL)
G14	Discharge Passing Through the Gate	5.0 (m^3/sec)
G15	Upstream Water Level	1.5 m (+MSL)

Table 6.2. MIKE Hydro River PID parameters values (used for G13 and G15), and the PID parameters values resulted from the individual tuning (used for G12 and G14)

Gate	$T_i\ (hrs)$	$T_d\ (hrs)$	$K_p\ (Unitless)$	α_1	α_2	α_3
G12 and G14	0.1	0.1	0.01	1.0	1.0	1.0
G13 and G15	0.083333	0.000222	-1.0	1.0	1.0	1.0

6.4.4 Operational scenarios and RTC performance evaluation

The developed strategy was evaluated based on the control objectives defined in Section 6.4.2. The criteria used to evaluate the performance of RTC are: 1) reduce flooding by reducing the water level in the Western Raphiphat Canal; 2) increasing water that will be stored and achieving the minimum water storage in the retention areas; 3) achieving equitability in water distribution between the retention areas; and 4) preventing overtopping in Klong 7 and Klong 8.

The evaluation is based on comparing two scenarios: baseline system (without RTC system) and with RTC system. The baseline system is based on the current operating rule in the study area, which is without an RTC system. The 'With RTC system' scenario assumes the feedback control rules and PID controllers from the developed strategy are implemented. For evaluating flood reduction, an extra storage with the area of 27.2 ha is also included in the evaluation as the stakeholders in the area are planning to implement this retention area.

The strategy is evaluated for two events. The normal flood event is based on the flood event of 2016. The extreme flood event is based on the flood event of 2011.

6.5 RESULTS

6.5.1 PID Parameters Tuning

The tuning of PID parameters for controllers G12, G13, G14, and G15 was performed. The controlled discharges of G12 and G14 using the PID parameters values resulted from the individual tuning method, and the controlled upstream water levels of G13 and G15 using the MIKE Hydro River default values of the PID parameters are presented in Figure 6.8.

With the PID parameters from the individual tuning method, the controller was able to achieve the discharge setpoints for G12 and G14, as shown in Figure 6.8A. Similarly, the upstream water level setpoints of G13 and G15 were achieved by the controller for the default values of the PID parameters as shown in Figure 6.8B. However, for G13, the upstream water level could not be brought to the setpoint within periods from 2^{nd} to 5^{th} October. This is not because of the controller performance, as the gate was totally closed (Figure 6.8D), but because of the incoming zero discharge from G12 (Figure 6.8A).

Using suitable values of the PID parameters for each gate did not only improve the stability of the gate itself and its controlled variable, but also the stability of the other gate in the same canal. Figure 6.8A, and Figure 6.8B show the stability of the controllers of the upstream gates G12 and G14. This also eliminated the oscillations and improved the stability of the controlled water levels of the downstream gates G13 and G15 (Figure 6.8B and 6.8D) compared to other methods.

Therefore, the stability of the controller of each gate is not only dependent on the PID parameters for the controllers, but also the stability of the other gates located in the same reach, especially in a canal network with a flat topography like in the Rangsit Area.

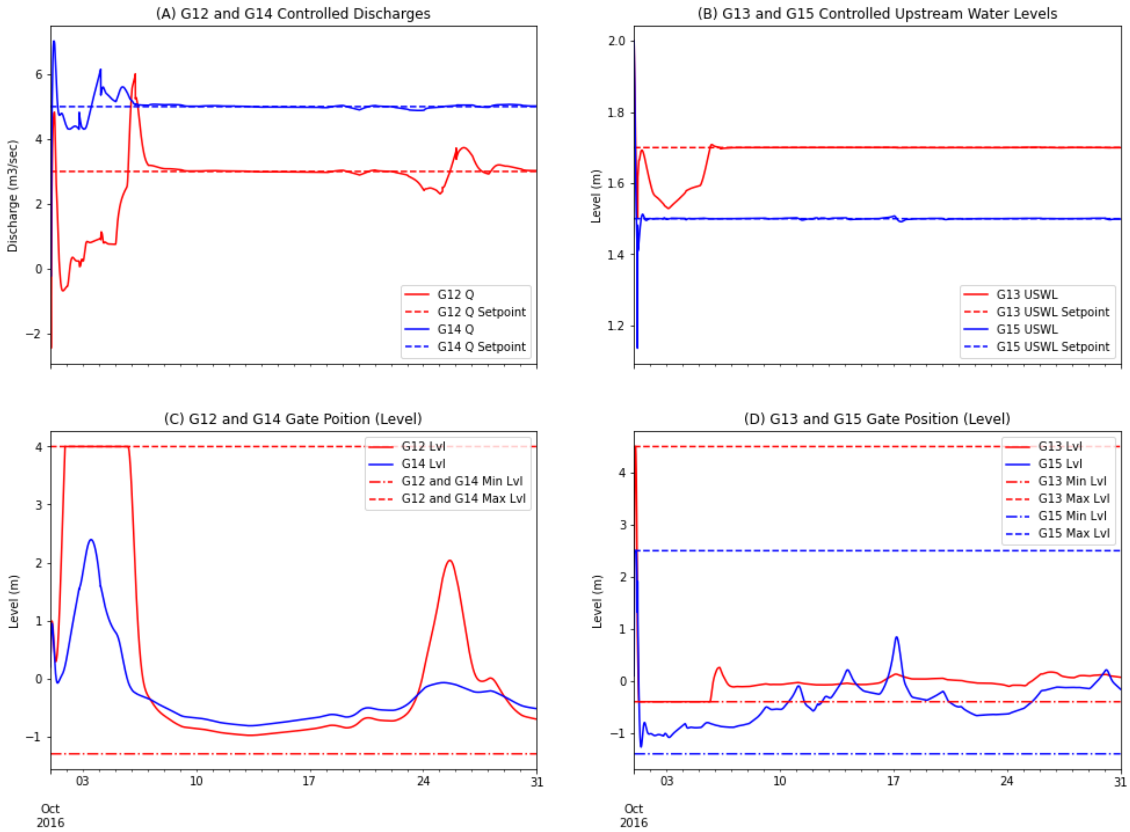


Figure 6.8. Results of the controlled discharges of G12 and G14 (A) with their gate levels (C) using PID parameters from the individual tuning method; and the controlled upstream water levels of G13, and G15 (B) with their gate levels (D) using PID parameters from the MIKE Hydro River default

6.5.2 Evaluating RTC performance

Flood reduction in the Western Raphiphat Canal

This section shows the flood reduction results in the Western Raphiphat Canal with and without RTC and with extra storage scenarios for a normal flood event (Figure 6.9A) and an extreme flood event (Figure 6.9B). For the normal flood event, the RTC system was able to reduce the water level at the Western Raphiphat Canal Station by about 0.25 meters compared to the system without RTC and with extra storage (Figure 6.9A). However, it is still about 0.05 meters water level above the flood threshold.

From Figure 6.9B, it can be seen that the proposed control system was not able to keep the water level at the Western Raphiphat Canal Station around the flood threshold during the extreme flood event. However, compared to the options without RTC and extra storage, the water level was reduced by about 0.5 meters. Thus, RTC may be able to help to reduce the impact of flooding at the downstream.

We can also see that the water level increased after the flood peak in the case with RTC for both scenarios. This is due to closing the upstream gates G12 and G14 in the normal situation as soon as the required minimum water volumes had been achieved, as per the proposed strategy.

From both events, the results for the baseline scenario and the extra storage scenario have the same water level. The reason for that is the extra storage that stakeholders would like to implement is very small compared the amount of water from flooding.

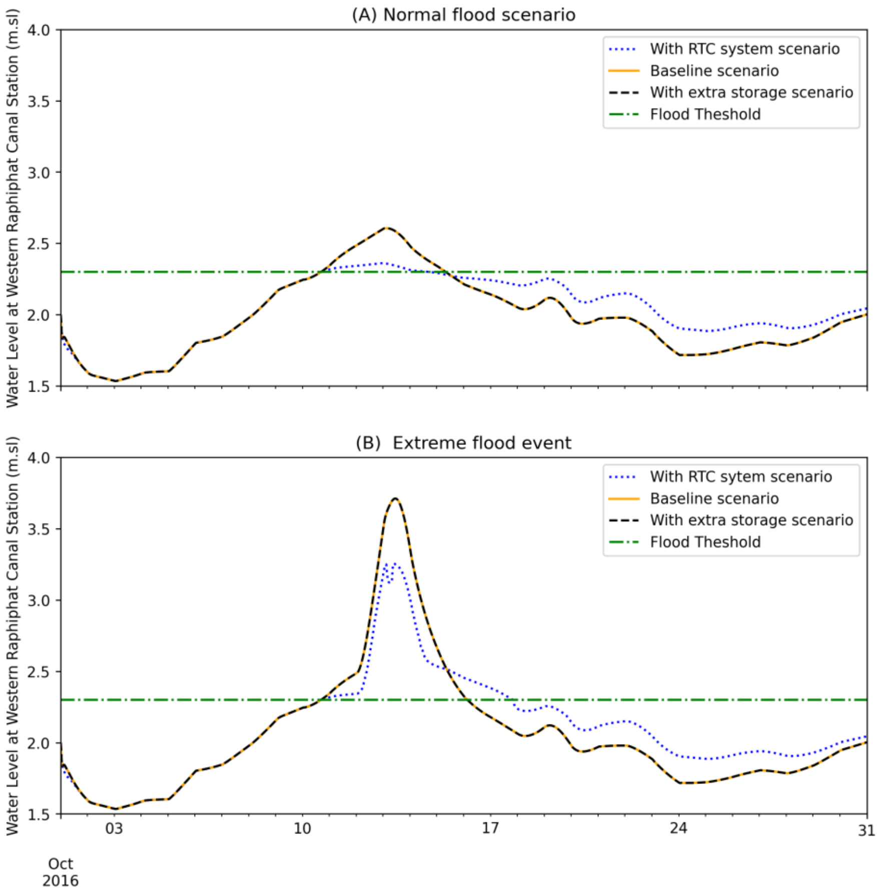


Figure 6.9. Water level in the Western Raphiphat Canal of baseline, with RTC system and with extra storage scenarios for normal flood event (A) and extreme flood event (B)

Water storage in the retention areas

The results of water volume in retention areas with and without the RTC system for flood and extreme flood scenarios in Klong 7 and Klong 8 are shown in Figure 6.10A and Figure 6.10B, respectively. From the results, it can be seen that the minimum water volumes were achieved for both retention areas during the normal flood scenario and the extreme flood scenario. For the system without RTC, the retention areas were only opened by the local framers starting from the 13th October (close to the flood peak), while in the system with RTC, the water begins to fill in the retention at the beginning of the events. As a result, the RTC scenario (green dash-dotted and blue dotted line) can store more water in the retentions during the events compared to without the RTC strategy (orange and red lines).

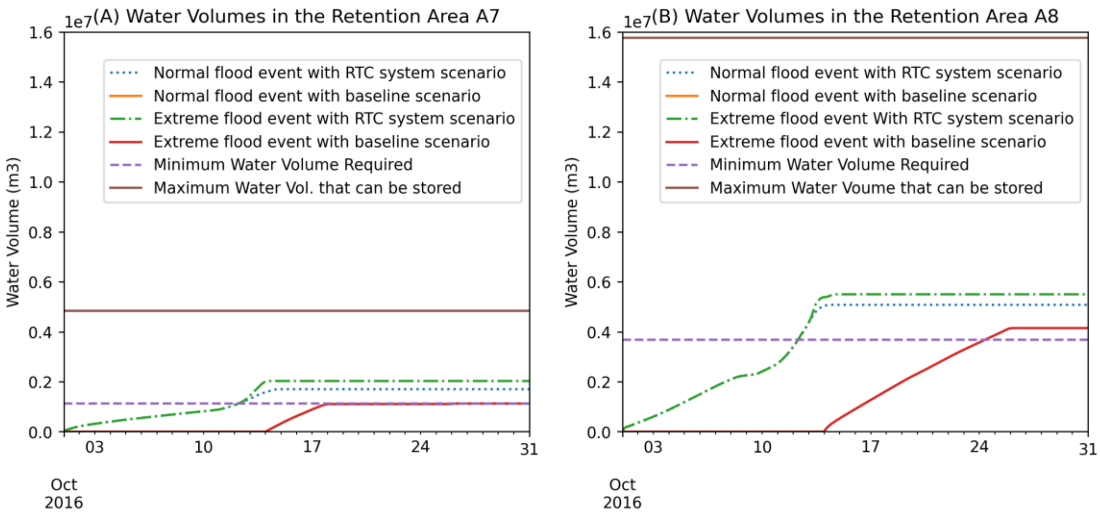


Figure 6.10. Water volume of flood and extreme flood events with RTC system and baseline scenarios in the retention area A7 (A) and A8 (B)

Equitability in water distribution

Regarding water distribution, the main criteria applied in this research was to achieve equitability. The water discharge is distributed to Klong 7 and Klong 8 in no flood situation (water level at Western Raphiphat Canal < 2.3 m) according to the relative water volumes required to achieve the required minimum water depth in the retention areas A7 and A8. While during flood situations (water level at Western Raphiphat Canal > 2.3 m) the water is distributed according to the relative available volumes until the maximum capacity of A7 and A8. Applying the proposed strategy, equitability was achieved as shown in Figure 6.11. The percentages of the diverted water discharged to Klong 7 and Kong 8 are very similar to the percentages of the required water volumes for the retention area A7 and A8 based on the relative water needs. However, deviations between the applied water discharges percentage and the required water volumes percentage can be seen between the 14th and 19th October. This is due to the smooth transition rules that were used for the setpoints of the controlled gates, in order to improve the control system stability.

For the without RTC system, even though water distributes to Klong 7 and Klong8 equally by around 50 percent, it does not meet the required water volume for both Klongs as Klong 8 has an irrigation area three times larger than Klong 7.

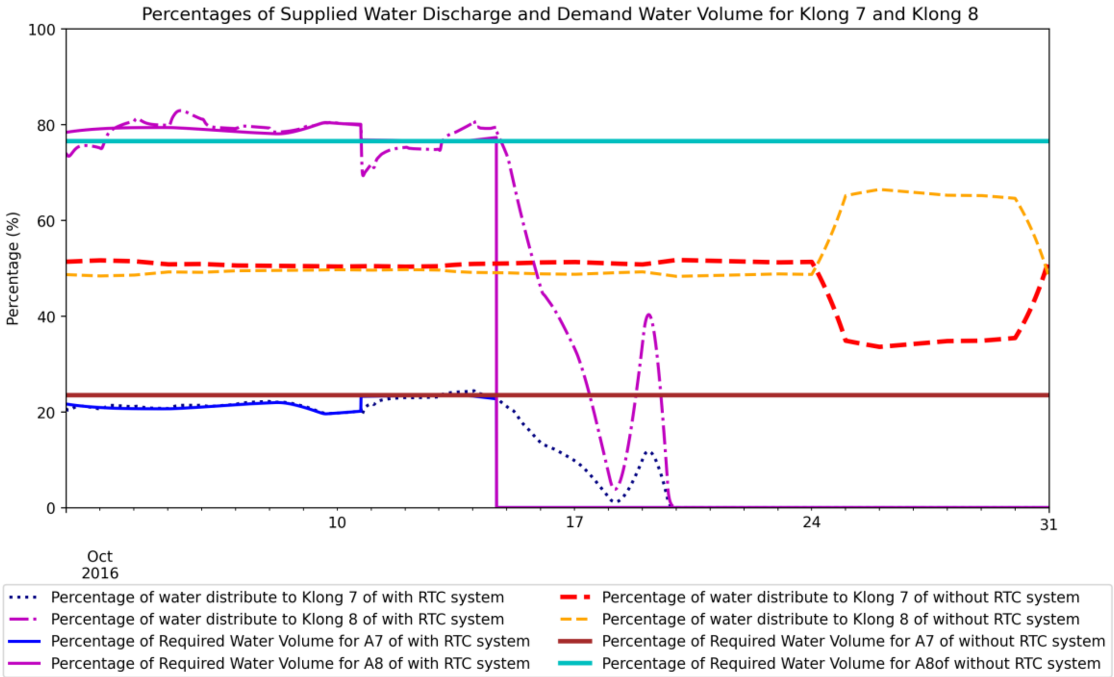


Figure 6.11. Percentage of supplied water to Klong 7 and Klong 8 and the percentage of required water volumes in the retention areas A7 and A8 for the normal flood scenario

Preventing overtopping

Figure 6.12 shows the result of overtopping of the system for the scenarios with and without RTC for both normal flood and extreme flood scenarios in Klong 7 (A) and Klong 8 (B). From the results, it can be seen that there was no overtopping of either klong during both scenarios, except at the end of Klong 8 at the end of the extreme flood (Figure 6.12B). This is because the maximum water level in the scenario with the RTC system is higher than without the RTC system, due to the increased discharges directed to both klongs during the flood.

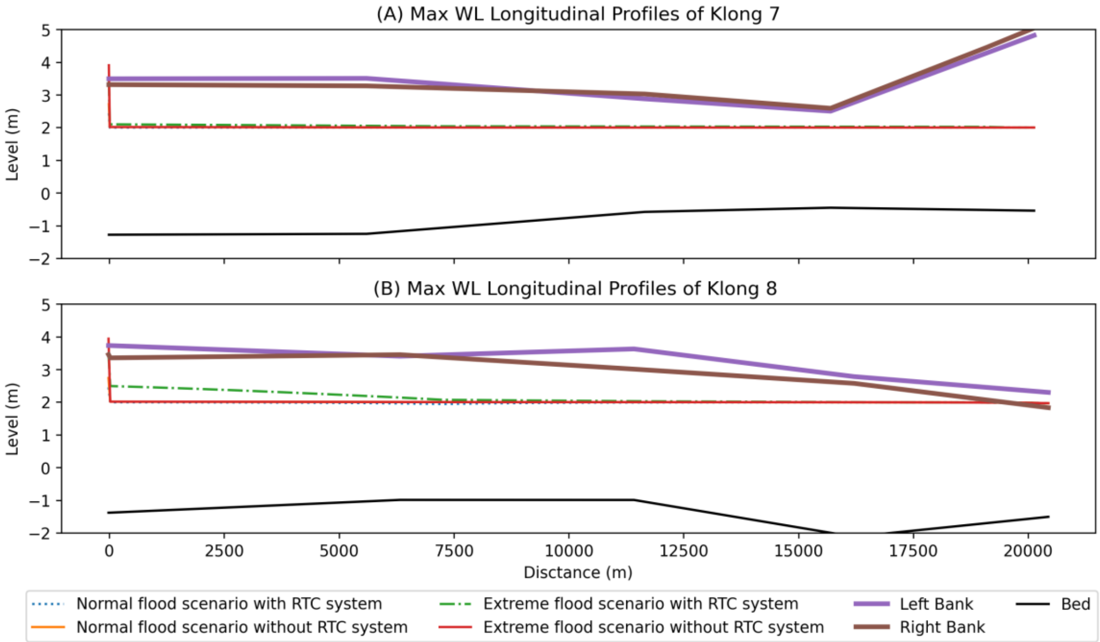


Figure 6.12. Maximum water level of RTC system and without RTC for the normal food and extreme flood scenarios on longitudinal profiles in Klong 7 (A) and Klong 8 on (B)

6.6 Discussion

This study focused on the implementation of SMART NBSs by using RTC to control and operate water in the irrigation and drainage system of the Rangsit Area, Thailand. A classical feedback control is used in this study. The developed strategy for the irrigation and drainage system of the Rangsit area shows the potential of PID feedback control for achieving the control objectives with stable performance without oscillations during flood events with discharge similar to the 2016 flood. There are also some general advantages of the feedback PID control, such as the simplicity and easy applicability. However, to apply the feedback control, it is important to tune PID control parameters to define the most suitable parameter for the case study. This is the main disadvantage, as it is difficult to tune PID parameters that are suitable for different flow regimes. Another disadvantage of a completely automated system is that instabilities in one gate can lead to undesirable control of another downstream.

In RTC evaluation scenarios, four control objectives were considered which are: 1) reduce flood risk by reducing the water level in the Western Raphiphat Canal below a threshold (2.3 m +MSL); 2) achieve equitability in water distribution between the retention areas; 3) maintain minimum water storage in the retention areas; and 4) prevent overtopping in Klong 7 and Klong 8. From the above results, it can be seen that the RTC system can help achieve the minimum required volume and increase the volume in the retentions.

Moreover, The RTC system can also be used to automatically operate the system before the flood peak without any overtopping in the Klongs. This can help reduce the flood downstream as the water has been diverted and stored in the retention areas.

However, for extreme flood scenarios, it can be seen that even RTC cannot help to keep the water level at around the flood threshold. This could be because the developed feedback control strategy in this study included only two Klongs, which underestimate the potential of the control system for reducing the water level in the Western Raphiphat canal during the extreme flood scenario. Therefore, future studies may include all the furrows of the other Klongs to investigate the maximum capacity of the RTC.

As mentioned above, one of the limitations in this study is that NBS furrows cannot be included individually into the hydrodynamic model as it is too complex and causes instabilities. Therefore, the furrow areas have to sum up all the NBS furrow area into schematised retention areas with the same total capacity as the total capacity of the furrows. This approach was also used in Ditthabumrung and Weesakul (2019), Watkin et al., (2019) and Mashiyi et al., (2023). Our future work will proceed in the direction of developing a full Digital Twin for the Rangsit area, in Thailand.

6.7 CONCLUSION

Effective water resources operation and control is a crucial task in reducing flood risks and providing water supply. This research has investigated the feasibility and the benefits of using SMART-NBS focusing on RTC to reduce floods and increase water storage of NBS measures for agriculture. The work presented here is part of a wider effort to develop a Digital Twin that combines various data and models to achieve better operational efficiency in the case study area. The case study area is an irrigation and drainage system in Rangsit area, Thailand. The NBS is comprised of furrows which are used to store part of the diverted excess flood water and prevent overtopping of the irrigation and drainage system canals. Currently, this system is operated manually by the Royal Irrigation Department (RID) to divert the excess flood water of the Pasak River to the Gulf of Thailand and to supply and distribute water for agriculture in the area. The control strategy was developed and tested with two operational scenarios; a baseline system (a passive system without RTC) and the system with RTC, for the 2016 and 2011 flood events. The feedback control strategy with PID parameters was used for the RTC scenario. The simulation for controlling rules of hydraulic structures was performed by using MIKE Hydro River.

The results indicate that (i) RTC has potential in improving the operation of the hybrid irrigation and drainage system during flood events; (ii) RTC can help to distribute the water between Klongs and retention equally; and (iii) RTC can help to increase the water storage in the retention areas, which can be used for agriculture. The methods presented in this study thus represent an important starting point towards Smart-NBSs by means of Real-Time Control for flood reduction and water allocation. In future research, we aim to investigate the potential of model predictive control with real-time data for operating the irrigation and drainage system.

7

Reflection and Outlook

7.1 INTRODUCTION

The previous chapter offer insights into the evaluation of Nature-Based Solutions for both before and after implementation. This chapter summarises and reflects the outcomes of the previous chapters in relation to the research objectives and questions presented in Chapter 1. This includes their strengths and limitations, and critical reflections about the outcomes of this work. These are the personal reflections of the researcher regarding topics such as NBS. Finally, this chapter provides an outlook on the topic, identifying further opportunities for improvement which should be included in future research efforts.

7.2 REFLECTIONS

7.2.1 Ex-ante Evaluation of NBS

Ex-ante evaluation aims to provide decision-makers with the necessary information to make informed choices about whether to proceed with the proposed solutions or make modifications to improve its viability. This evaluation is based on the local knowledge, scientific knowledge, and technical means. The research objective related to ex-ante evaluation of NBS is *to develop methodologies for ex-ante Evaluation of NBS that can be used at different scales and contexts in relation to flood risk reduction and enhancement of environment and social benefits.* This thesis proposes two phases for ex-ante evaluation of NBS; selection and assessment of potential NBS and economic assessment of nature-based solutions for flood risk reduction and co-benefits. The proposed works are presented in Chapter 3 and 4.

Selection and assessment of potential NBS is still a challenge due to specific local constraints and social-economic conditions. The research question related to selecting potential NBS measures is *What methodology would be applicable and feasible for the selection and assessment of potential NBS?*

This research question is answered in Chapters 2 and 3. A systematic review was done in Chapter 2 to understand different context of NBS. The framework presented in Chapter 3 offers a holistic approach that integrates a preliminary selection tool within the MCA framework to select potential NBS measures. The preliminary selection process can help eliminate measures that are not relevant to the problem, location or characteristics of the area. This process is important in identifying NBSs that are suitable to the project beforehand, thus reducing unnecessary time spent on the analysis.

The MCA Framework allows stakeholders' preferences to be incorporated in assessing selection criteria and potential measures. It considers not only the primary goal of risk reduction but also related co-benefits such as water quality, ecosystem services, socio-economic aspects, human well-being, and economic factors. Including all these benefits in the framework can help stakeholders and decision makers recognise trade-offs associated with NBS. As a result, these projects often involve diverse stakeholders, including local community members, government agencies, environmental organizations, and industry stakeholders, among others. Considering stakeholders' preferences is a crucial step in any decision-making process, particularly when it comes to planning large-scale NBS.

By integrating stakeholders' preferences into this framework, decision-makers can ensure that the planning process reflects the values, needs, and aspirations of the communities and individuals affected by the project. This transparency in decision-making enhances stakeholders' understanding of how their preferences influence the selection of measures. Consequently, it builds trust and credibility, increasing the acceptability of NBS implementation as stakeholders can see the consideration and value given to their input.

However, it is important to acknowledgement that incorporating stakeholders' preferences into a multi-criteria framework can be challenging. Stakeholders often have diverse and sometimes conflicting perspectives, which can introduce biases or uncertainties into the decision process. These biases may arise from stakeholders' professional backgrounds, where different priorities and values are given to various results. For example, risk managers may give a higher weight to risk than environmental and social benefits, while environmental authorities may think that environmental benefits are more important than risk and social benefits. To address these challenges, establishing effective communication channels, fostering mutual understanding, and employing facilitation techniques are necessary to ensure fair representation and meaningful engagement. Unfortunately, in this particular research, the limitations imposed by global pandemic, specifically COVID-19, prevented face-to-face workshops and direct interactions with stakeholders. As a result, the collection of stakeholders' preferences was limited to an online questionnaire, which might have restricted the depth of insight and information that could have been obtained through more interactive methods.

Following the development of this methodology, a missing step was identified in between the preliminary selection process and MCA framework, namely the suitability analysis. This step is needed as the preliminary selection does not account for local characteristics in detail. A suitability analysis allows the stakeholders to define which measures are suitable to implement in the specific case study, leveraging their local knowledge. The final set of suitable measures is then used in MCA Framework to analyse the ranking of measures. This additional step can help to shorten the analysis in MCA framework. The improved methodology has been reapplied to two case studies mentioned in Chapter 3 as well as applied to other cases in EU-funded RECONECT project such as Kamchai river basin in Bulgaria, Pilica River Basin in Poland, Bregana River basin in Croatia, ChaoPhraya river basin in Thailand, and Lili and Melendez River basins in Colombia. Furthermore, a preliminary selection tool has now been implemented on the web-based platform (https://www.webscada.nl/reconect/measures/#!/measures) as 'RECONECT Selector measure tool', providing a use-friendly interface for the users.

Economic assessment of nature-based solutions for flood risk reduction and co-benefits is another challenge in assessing the effectiveness of NBS, especially the value of co-benefits. The research questions for this stage of research related to economic assessment of NBS is: *How can the cost, flood risk reduction and co-benefits of NBS be integrated in economic assessment of NBS?*

We have addressed this question in Chapter 4 by developing a methodology for assessing the economic value of NBSs at river basin scale. This methodology incorporates the monetary analysis of co-benefits in addition to the flood risk reduction. The economic assessment is based on the CBA, incorporating NPV and BCR as key indicators. The finding shows that when considering flood risk reduction alone, the cost of implementing NBS measures outweighs the benefits of flood damage reduction. However, when the co-benefits are incorporated into the analysis, some measures show potential financial gains and cost-effectiveness. Therefore, it is important to include co-benefits in economic assessment as it enhances the economic efficiency of NBS.

The developed methodology serves as a valuable tool to effectively integrate co-benefits into the economic assessment of flood risk reduction measures during the decision-making process. One of the strengths of this methodology is its adaptability to local contexts, achieved through the use of value transfer methods that adjust values to the specific study area. This enables the assessment to capture the local nuances and make the results more relevant to the specific case.

However, it is important to note that the cost and co-benefit values applied and presented in this study are based on a literature review and limited local data. While this methodology provides a systematic approach for assessing the economic value of NBS, it also introduces assumptions from other case studies and value simplification. As a result, it may not fully represent the potential costs, benefits, or uncertainties related to the specific NBS project and may introduce inaccuracies or biases in the economic evaluation.

The research focused on the CBA of individual measures, as the aim was to develop a methodology to include both flood risk reduction and co-benefits into the CBA. However, it is important to note that a comprehensive evaluation of NBS performance requires considering the implementation of multiple measures and their interactions.

In this research, only five co-benefits for four NBS measures were considered in the co-benefit estimation. While this provides a detailed assessment monetary value of co-benefits, it is important to recognise that it may not capture the full range of benefits and impacts associated with NBS. This is one of the limitations in assessing the performance of NBSs by using economic value, as it is difficult to quantify and assign monetary values to all benefits. Therefore, economic considerations should not be the only one aspect of the overall decision-making process but other aspects that influence the success of implementing NBS project, such as technical feasibility, environmental impact, and social acceptability, should also be considered.

The flood risk analysis conducted in this research focused only on different flood return periods under the current situation and did not consider climate change scenarios. This decision was made due to the high uncertainty associated with available climate models for the specific case study. Including climate change scenarios in the analysis could introduce additional complexities and uncertainties, potentially leading to confusion in the interpretation of the results. While acknowledging the importance of considering climate change impacts in flood risk assessments, it was deemed more appropriate in this study to focus on the general economic assessment that incorporates flood risk reduction and co-benefits with cost analysis. By doing so, the methodology can provide valuable insights into the financial implications and benefits associated with implementing NBS measures for flood risk reduction. The same economic assessment methodology can still be applied when climate change scenarios are considered.

Finally, the CBA involves discounting, which is the process of converting the value of all future benefits into present terms. The sensitivity analysis conducted in the study highlights the influence of discount rates on the economic viability of projects. The results demonstrate that higher discount rates lead to lower economic impacts. This finding emphasizes the need to carefully consider discounting when evaluating the long-term viability of NBS projects.

7.2.2 Ex-post evaluation of NBS

Ex-post evaluation provides insights into the actual outcomes and impacts of the implementation of NBS, identifies lessons learned, and informs future decision-making by highlighting successful practices or areas for improvement. The research objective on the ex-post evaluation is *to develop methodologies that can be used for Ex-Post evaluation of NBS in relation to hydro-meteorological risk reduction and co-benefits enhancemen*t. This includes benefits assessment of implemented NBS and using real-time control to improve the performance of NBS. The proposed works to achieve this are presented in Chapter 4 and 5.

Benefits assessment of implemented nature-based solutions can help to gain better understanding of benefits and co-benefits of NBS, which is very important for promoting their implementation. The research question regarding assessing the benefits of implemented NBS is *How can the performance of implemented NBS be evaluated?*

This research question is addressed in Chapter 5, in which a framework for assessing implemented NBS is proposed. The Framework considers both qualitative and quantitative benefits while integrating stakeholder’s preferences. It provides a five-step quantitative post-implementation assessment framework that serves as a valuable tool for stakeholders, decision-makers and technicians to evaluate the performance and potential benefits of their NBS projects.

The framework can be repeated periodically over several years to ensure ongoing performance monitoring of the NBS. The framework is applicable to various scales of NBS, including urban and rural settings, large and small-scale projects, hybrid systems, and catchment scale NBS. Moreover, this framework can also be used for ex-ante evaluation to estimate the benefits of NBS.

Different methods such as farmer and municipality interviews, in-situ sampling, modelling, and data analysis, were employed to assess the indicators of NBS. These methods can be used as an example of how to assess such benefits.

However, it is important to acknowledge some limitations from this research. The development, testing and application of the framework involved ten stakeholders, including six farmers (two farmers in an area with the NBS and four in an area without NBS), two municipality workers, and two government experts. While these stakeholders provided valuable information for each step of the framework, they may not represent the entire community or capture the full diversity of perspectives. The calculation of some indicators relied on the average of the data collected from the area with NBS and area without NBS. Unfortunately, the data from areas with NBS were limited compared to those without NBS.

Furthermore, the framework primarily focuses on quantifying the benefits and co-benefits of NBS. While this provides valuable insights, it may not capture the full range of impacts or considerations associated with NBS implementation, such as social equity, cultural values, or long-term resilience. The weights in this research was only collected based on benefit categories, which helps to simplify the process for stakeholders. However, this simplification may not accurately represent the importance of individual indicators. Moreover, the calculated average score was only based on scores higher than two. The reason for this is that it was assumed that if any indicator has a score less than two, the indicators may not relevant to the NBS or that a different assessment method was required. However, this approach may lead to confusion and limit the understanding of the overall average scores. Including all scores, regardless of their magnitude, could offer valuable insights into the variations among different indicators and provide a more comprehensive understanding of their contributions.

Despite these limitations, the framework offers a tangible way for decision makers to understand the benefits of NBS, enhancing their credibility and potentially making them a mainstream infrastructure choice. The work undertaken in Thailand demonstrated that NBS such as furrows in agricultural land are beneficial for flood mitigation as well as for several other co-benefits. This information can be used by the farmers to improve their production, resilience to climate change, and their communities. The framework output also provides valuable information to support academics, water managers, and planners when studying, promoting, and implementing NBS.

Feasibility assessment of real-time control technology offers the potential to enhance the effectiveness of NBSs by transforming an existing passively-controlled NBS system into a more active and responsive Smart NBS. The question for this stage of the research is *Can methods such as RTC technology improve the performance of implemented NBS?*

The chapter 6 provides insights into the feasibility and the benefits of using Smart Solutions and Digital Twins in utilizing Real-Time Control for flood reduction and water allocation in the Rangsit Area in Thailand. The evaluation of RTC in Rangsit area was based on historical time series data rather than real-time sensor data. The aim was first to assess the feasibility of existing passively-controlled NBS system to a Smart NBS by introducing (active) RTC for the Rangsit case. The integration of digital twins further enhances the capabilities of RTC by providing virtual representations of NBS. Digital twins enable decision-makers to visualize and simulate different scenarios, test strategies, and evaluate the impacts of proposed changes before implementing them in the real world. However, the work presented here is only part of a wider effort to develop a Digital Twin that combines various data and models that can achieve better operational efficiency in the case study area.

The results showed that the RTC system can help achieve to increase the volume in the retentions. Moreover, The RTC system can also be used to automatically operate the system before the flood peak without any overtopping in the Klongs. This can help reduce the flood downstream as the water is diverted and stored in the retention areas. The methods presented in this study thus represent an important starting point towards Smart NBSs by means of RTC for flood reduction and water allocation.

The RTC simulation and modelling was developed within MIKE Hydro river, which has some limitations. Firstly, there is no option for simulating master controllers or selecting a control time step different than the computational time step which is chosen based on the numerical stability of the model. This constraint can restrict the flexibility of the control system. Additionally, NBS furrows was not able to include individually in the hydrodynamic model due to complexity and stability concerns. Instead, the furrow areas were aggregated into schematized retention areas with equivalent total capacity for each Klong. While this approach aligns with previous studies, it may not fully capture the dynamics of individual furrows.

In extreme flood scenarios, it was observed that RTC alone cannot effectively maintain the water level around the flood threshold. This limitation could due to the fact that the RTC system in this study only focused on two klongs, which underestimated the potential of the control system for reducing the water level in the Western Raphiphat canal during the extreme flood scenario modelled.

Finally, it is important to consider socio-economic implications of implementing RTC such as cost of implementation, maintenance, security for expensive monitoring equipment. While RTC may be an effective approach in operating NBS, it is essential to recognize that local individuals who are currently involved in manually operating gates may lose their jobs and income as automation takes over. This aspect needs careful consideration to ensure that the implementation of RTC does not adversely impact the livelihoods of the local community.

7.3 OUTLOOK

This thesis proposes a methodology for evaluating NBS for both before and after implementation. In the previous section, we identified many of the existing limitations and challenges associated with this proposed methodology. Despite these challenges, we can foresee various opportunities to implement the methodology and adapt it for specific projects in various locations and settings. Therefore, to further advance the field of NBS and promote sustainable solutions for addressing hydro-meteorological risk reduction, proposals for future improvement opportunities based on these challenges are provided below.

With respect to the selection and assessment of potential NBS: due to the uncertainties around weights, we recommend decision making and policy management studies use a larger and more varied group of stakeholders to minimise uncertainties. Moreover, future research should also include an analysis of the sensitivity of the final ranking of the measures to the weights assigned by the stakeholders. It would be particularly important to compare responses of different groups of stakeholders, such as local authorities, civil protection or academia. In addition, the scoring (i.e., the performance of NBS) that is used in this research was only based on the literature review. Future researcher and decision makers can change this value by using the real data from their case study.

With respect to the economic assessment: although the methodology presented in this research is a valuable contribution to the field of economic assessment for NBS, to further enhance the accuracy and applicability of economic evaluations, future research should focus on collecting more local data and conducting site-specific assessments. Furthermore, future work should aim to combine and optimise the NBS measures to identify the most cost-effective scenarios by applying the proposed methodology in assessing economic value. The optimisation can help to recognise the potential synergies and trad-offs between different NBS measures. Moreover, future research should aim to incorporate climate change projection scenarios into risk assessments as this will enable a comprehensive evaluation of the potential impacts of climate change on risk, then adaptive strategies to mitigate future risks effectively can be developed. Finally, we also recommend that CBA should be complimented with other methods, including non-monetary value, qualitative assessment, and stakeholder engagement. These non-monetary values, such as cultural heritage preservation, community cohesion, and ecological conservation, significantly contribute to the overall impact of NBS on society and the environment. These additional approaches can help capture the broader range of benefits and ensure a more comprehensive evaluation of NBS effectiveness.

*With respect to the benefits assessment of implemented NBS: f*or a more in-depth analysis of benefits, it is recommended to increase the samples sizes, gather more data, and to hold more workshops and interviews with the stakeholders than what was performed in the present research. The knowledge of capabilities of NBS should be spread to all stakeholders and the framework presented here offers a method to accomplish such objective. Moreover, future work should focus on gaining attention to deeper understanding of NBS benefits for human well-being as well as conducting long–term monitoring and evaluation of ecosystem performance and function.

With respect to Smart NBS: future research should aim to investigate the potential of model predictive control with real-time data for operating irrigation and drainage system. For solving the problem of using control time step different than the computational time step, a separate RTC model (RTC Tools) can be used and coupled with the hydrodynamic MIKE Hydro River model, and defining the time step of the exchange between the models to be equal to the required control time step. Moreover, future studies should consider increasing the scope of the RTC system to include all the furrows in other Klongs, so as to investigate the maximum capacity of NBS using RTC.

Finally, these improvements will lead to increased recognition and integration of NBS into policies and planning processes. Advancements in technology, such as the use of sensors and real-time data, will enhance the effectiveness and efficiency of NBS implementation. Furthermore, knowledge exchange among stakeholders and sharing of best practices will foster learning and innovation in the field of NBS. As a result, there is great potential for scaling up NBS interventions, replicating successful approaches in different contexts, and achieving widespread adoption of nature-based solutions for a more sustainable and resilient future.

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APPENDIX A

APPENDIX A.1 QUESTIONNAIRE FOR COLLECTING LOCAL INFORMATION TO USE AS AN INPUT FOR PRELIMINARY MEASURE SELECTION

H2020 project "Regenarating ECOsystems with Nature-based solutions for hydro-meteorological risk rEduCTion (RECONECT)"

RECONECT

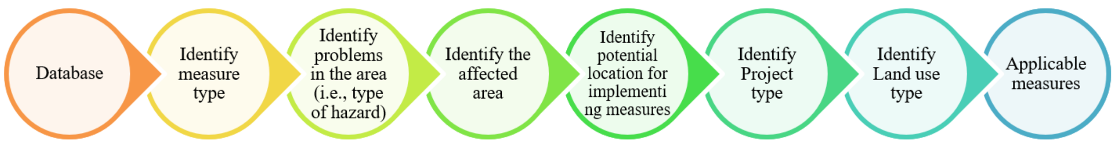
Introduction to the project

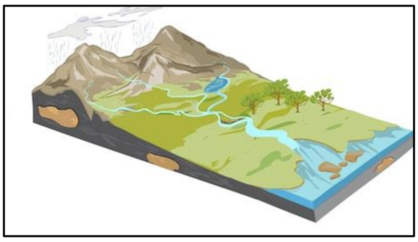
The **RECONECT project** aims to develop a framework that can help affected people and involved stakeholders to find suitable and sustainable solutions for their area. The project focusses in selectin and evaluating measures that are known as **'Nature-based solutions' (NBS)**. NBS have been proven in many cases that they are beneficial in terms of flood risk reduction and other types of hazards. In comparison to the traditional grey infrastructure, NBS can give the opportunity not only to fulfil one single purpose (e.g. reducing the flood risk) but also to provide valuable co-benefits to the ecosystem and human well-being as well as climate resilience. More information about the project can be found on the website (**www.reconect.eu**).

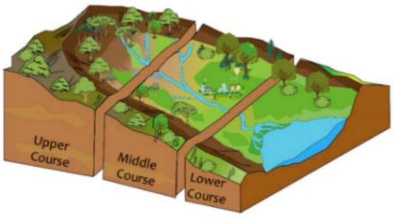
Survey description

Since not all measures are suitable for all locations and all hazard types, six filters are used in this process to narrow down the list of measures. Therefore, this survey is conducted in order to collect valuable data for these six filters, which will contribute to **Preliminary selection measure** process (See Figure below). The outcome will be seen as suitable measures for a specific situation.

6 filters that are used to narrow down the list of measures that have potential to reduce the local hazards in the particular affected area are described below. The criteria area; **measure type, hazard type, affected area, potential location for implementation of measures, type of project, and land surface type.**



1. **Measure type**	
Please select type of measures that you wish to implement in order to reduce local risk (you can select more than one)	
☐ Nature-Based Solutions	☐ Grey infrastructures
2. Hazard type	
Select hazards that your area have been experienced (you can select more than one)	
 ☐ Pluvial flooding	 ☐ Fluvial flooding
 ☐ Flash Flooding	 ☐ Coastal flooding/storm surge
 ☐ Landslides	 ☐ Drought
3. Affected area	
Please select **the area** that have been **affected** by the hazard (you can select more than one)	
 ☐ Urban area	 ☒ Non-urban area

4. Potential location for implementing measures	
If your area is **urban area** please select	☐
If your area is **non-urban area** please select below (you can select more than one);	
Moutainous area	☐
Coastal area	☐
River basin	
 Upper Course (Mountainous)	☐
Middle course (Middle of river)	☐
Lower course (floodplain and Delta area)	☐

5. type of project
Please select **type of project** that you wish to implement in order to reduce local risk (you can select more than one)
☐ Implementation of new measures
☐ Improvement or expansion of existing measures

6. Land surface type
Please select **Land surface type** that you wish to implement in order to reduce local risk (you can select more than one)
☐ Artificial surface
☐ Agriculture area
☐ Forest and semi-nature areas
☐ Wetlands
☐ Water bodies

APPENDIX A.2 LIST OF SUB-GOALS AND THEIR INDICATORS THAT USED TO ASSESS THE PERFORMANCE

Sub-Goals	Indicators that used to assess the performance of sub-goals
Flood risk reduction	Surface run-off reduction
	Slowing and storing runoff
	Flood hazard
	Vulnerability
	Delay time to peak
	Flood peak reduction
Improve water quality in rivers/watercourses, lakes/ponds	Change in water pollution caused by wastewater (point sources)
	Reduced pollutants coming from land to water (non-point sources)
	Attenuation of heavy metals and nutrients contamination in surface water
	Sediment deposition
Improve coastal water quality	Reduction of pollution in coastal waters
	Coastal water pollutants in shellfish
Improve groundwater quality	Attenuation of pollution in groundwater
	Change in soil quality
	Seawater intrusion
Increase habitat area (quantity)	Changes in riparian habitat
	Changes in aquatic habitat
	Change in wetland habitat
	Changes in terrestrial habitat
	Increase green area
Habitat provision and distribution (quality)	Distribution of public green space
	Connectivity/fragmentation of habitat structural
	Change in location of habitat boundaries
To reflects ecological status and physical structure of habitats	Change in vegetation along watercourses
	Conservation status of habitats
	Shoreline characteristics and erosion protection
Land use type	Low impact space
	Diversity of land use in the agricultural area
	Change in land cover
	Change in land use
To maintain and enhance biodiversity	Restricted-range species
	Species richness and composition in respect to indigenous vegetation and local/national biodiversity targets
	Number and type of protected species
	Density of Species
	Diversity of species
	Type, density of native species
Reduce disturbance to ecosystems	Number, area, location, of non-native/mitigated animal and planted species
	Number, area, location, of invasive non-native animal and planted species that are threatening to ecosystem, habitats or species
Increase recreational opportunities	Increasing recreational opportunities of NBS area
	Number and value of people visit or spend free time in NBS area
	Number of people engaging in alternative livelihood activities in the NBS area

Sub-Goals	Indicators that used to assess the performance of sub-goals
	Number of tourists
Education and awareness about NBS	Provision of NBS sites for education and research
Maintain and if possible enhance cultural values	Loss of cultural heritage due to hydro-metrological events/due to land take
	Food production
	Number of cultural events in NBS area
Accessibility	Accessible NBS area per capita
	Footpath network recover through erosion reduction and improvement of path smoothness
	Average journey time for people by foot to NBS area or average distance from home/public transportation to NBS area
Improve Community Cohesion	The number of people communicate with neighbourhood in the NBS area
	Cognitive and social development in children and young people
	Community development and cohesion
Encourage new business models and other community benefits provided by NBS	Number of subsidies or tax reductions applied for (private) NBS
	Number of new businesses attracted from NBS
	Number of green jobs created
	Enhancing attractiveness of places for living and working, and to visit
	Gross value added per employees based on full-time equivalent jobs in the green sector.
	Finances and willingness to pay
	Increased competitive advantage for cities applying NBS
Stimulate/increase economic benefits	Reduced/avoided damage cost from hydro-meteorological risk reduction
	Economic benefit from the reduction of stormwater that typically needs to be treated in a public sewerage system
	Energy and carbon savings from reduced building energy consumption (heating and cooling)
	Reduce cost of health impacts of air and noise pollution
	Value of reduced CO2 emission and carbon sequestration
	Reduced need for management and maintenance
	Change in land and/or property values
Direct health and wellbeing impacts	Mental well-being
	Physical health/activities
	General self-rated health
	Reduction in chronic stress and stress-related diseases
	Reduction in number of cardiovascular morbidity and mortality events Episodes of water-borne diseases
Indirect health and wellbeing impacts	Urban heat island effect mitigation
	Increase in pathogen vector habitat
	Change in heavy metal emission
	Avoided greenhouse gas emissions [should this be in Nature section? very long-term indirect relationship to human health and wellbeing]
	Air pollution improvement through capture/removal by vegetation
	Noise pollution attenuation

APPENDIX A.3 QUESTIONNAIRE FOR COLLECTING STAKEHOLDERS' PREFERENCES ON GOALS AND SUB-GOALS

H2020 project "Regenarating ECOsystems with Nature-based solutions for hydro-meteorological risk rEduCTion (RECONECT)"

RECONECT

INTRODUCTION

Introduction to the project
The **RECONECT project** aims to develop a framework that can help affected people and involved stakeholders to find suitable and sustainable solutions for their area. The project focusses in selectin and evaluating measures that are known as **'Nature-based solutions' (NBS)**. NBS have been proven in many cases that they are beneficial in terms of flood risk reduction and other types of hazards. In comparison to the traditional grey infrastructure, NBS can give the opportunity not only to fulfil one single purpose (e.g. reducing the flood risk) but also to provide valuable co-benefits to the ecosystem and human well-being as well as climate resilience. More information about the project can be found on the website (**www.reconect.eu**).
Survey description
This survey is conducted in order to collect valuable data, which will contribute to the of the **feasibility selection process of NBS measure**. Collected inputs will be used for a **Multi-criteria Analysis (MCA)**. The outcome will be seen as feasible measures to discuss possible solution opportunities for the existing problems in the area. This process is done with **multiple stakeholders** in order to reflect on all involved stakeholder opinions and to form a conclusion based on expert knowledge, local opinions, and knowledge from involved people in the area.
Filling in Weights for Goals/Sub-goals
In the next section (**Weighting of Goals & Sub-goals**), you will find the Goals & Sub-goals that are included in the NBS selection and evaluation process. You are asked to give weight on those Goals & Sub-goals based on your knowledge of the area and **your opinion of the importance to address the specific Goal or Sub-goal**. Description of Goals & Sub-goals can also be found in the next section.

Select the group of stakeholders that best describes your position	
☐ Authorities	Name of organization …………………………………
☐ Political Representatives	Name of organization …………………………………
☐ Civil Society Commercial	Name of organization …………………………………
☐ Sector Academia / Research	Name of organization …………………………………
☐ Media	Name of organization …………………………………
☐ International and	Name of organization …………………………………
☐ Utilities	Name of organization …………………………………

Explanation
The six main goals that are part of the NBS evaluation process are described below: **Hydro-meteorological Risk, Water quality, Habitat structure, Biodiversity, Socio-economic and human well-being**. Furthermore, these goals are divided into sub-goals, which are also described below. The provided information of the goal/sub-goal description can be used as a basis to give a reasonable weight for the chosen category. Please fill in weight for each category to show the importance of addressing the related issue in the area. Weights should be given by choosing a value from **0 to 10**, where a value of **0** represents **not important,** and a value of **10** means the **most importance**. Also, please give a short explanation of why do you give a certain weight (e.g., drought risk has very low value because this risk is barely present in the area).

Main goals

1. **Hydro-meteorological Risk**
This goal represents the hydro-meteorological risk that is present in the chosen area and reflects the need for reducing it. What importance do you place on reducing the hydro-meteorological risk in the area? **Put Weight here (0-10):** **Give an explanation of the given weight:**
2. **Water Quality**
This goal indicates the importance of improving the overall water quality, including surface and groundwater bodies in the investigated area. Water quality is an essential factor since it interrelates with other factors such as ecosystems and human health. What importance do you place on improving the water quality in the area? **Put Weight here (0-10):** **Give an explanation of the given weight:**
3. **Habitat structure**
The habitat structure category determines the main aspects related to habitat quantity and quality in the area. This includes the importance of increasing habitat area, habitat provision and distribution, ecological status and physical structure of habitats and land use type. What importance do you place on improving habitat conditions in the area? **Put Weight here (0-10):** **Give an explanation of the given weight:**
4. **Biodiversity**
The biodiversity refers to the variety of life on earth at all its levels, from genes to the ecosystem. It presents the status of ecosystems and enhances local biodiversity in order to create conditions where various species can thrive in abundance and live without disturbance. What importance do you place on improving biodiversity in the area? **Put Weight here (0-10):** **Give an explanation of the given weight:**
5. **Social-Economic**
This category relates to the people living in the chosen area or those affected by current developments. This category reflects on the need or the present opportunities that are needed to increase socio-economic development in the area. What importance do you place on improving livelihood conditions of involved people and local citizens in the area? **Put Weight here (0-10):** **Give an explanation of the given weight:**

6. Human well-being

This category relates to the enhancement of human well-being benefit in the area from implementing NBS. The importance of this category reflects on health and well-being such as mental well-being, physical activities/health, urban heat island effect mitigation, air pollution improvement through capture/removal by vegetation etc.
What importance do you place on improving human well-being of involved people and local citizens in the area?
Put Weight here (0-10):
Give an explanation of the given weight:

Sub-goals

1.1 Flood risk reduction in urban areas and around rivers, lakes, watercourses, etc.

This sub-goal considers the importance of flood risk reduction in the area. This includes urban areas, rivers, lakes and watercourses. It also means to reduce flood vulnerabilities, reduce flood hazards, reduce flood peaks, slow down runoffs and delay flood peaks.
What importance do you place on reducing the flood risk in the area?
Put Weight here (0-10):
Give an explanation of the given weight:

2.1 Improve water quality in rivers/watercourses, lakes/ponds

This sub-goal indicates whether the improvement of water quality in surface water bodies like rivers and lakes is required. Change in water pollution (i.e., both point sauces and non-point sources), heavy metals, nutrient contamination and sediment deposition, are important key indicators, which can lead towards problems for ecological and human health.
What importance do you place on improving the water quality in surface waters in the area?
Put Weight here (0-10):
Give an explanation of the given weight:

2.2 Improve coastal water quality

This sub-goal reflects on the water quality in coastal areas. The main key factor here is the pollution level of coastal waters. Most ocean pollution is influenced by the land, either along the coastline or coming from the. It causes dangerous conditions for marine life.
What importance do you place on water quality of coastal waters in the area?
Put Weight here (0-10):
Give an explanation of the given weight:

2.3 Improve groundwater quality

Groundwater is a very important source in terms of drinking water supply in many nations. Groundwater quality is less prone to contamination than surface water but can also be affected by various pollution sources and infiltration through the soil. The indicators can be attenuation of pollution in groundwater, change in soil quality or seawater intrusion.
What importance do you place on improving the groundwater quality in the area?
Put Weight here (0-10):
Give an explanation of the given weight:

3.1 Increase habitat area (quantity)

This sub-goal focuses on the importance of increasing the habitat area (i.e., change in riparian, aquatic, wetland and terrestrial habitats for local species). The size of the habitat has significant effects on reproduction and population persistence for various species. Increasing green space can improve population growth and reduce the risk of species extinction.
What importance do you place on increasing room for habitat in the area?
Put Weight here (0-10):
Give an explanation of the given weight:

3.2 Habitat provision and distribution (quality)
Habitat provision and distribution refers to the quality state of a habitat. This can be seen in the distribution of green space in the area and whether habitat structures are showing good connectivity with each other. Better connectivity of habitat structures leads to a higher ecosystem function where higher diversity of animal and plant species can be found, leading to better overall ecosystem health. What importance do you place on improving the quality of habitat in the area, such as habitat connectivity? **Put Weight here (0-10):** **Give an explanation of the given weight:**
3.3 To reflect the ecological status and physical structure of habitats
This sub-goal indicates the significance of carrying out conservation and protection strategies to reflect on the ecological status and physical habitat structure of the area. This can be done by monitoring changes of vegetation, erosion protection and the overall conservation status and by looking at possible trends and future projections. What importance do you place on reflecting the ecological status and physical habitat structure in the area? **Put Weight here (0-10):** **Give an explanation of the given weight:**
3.4 Land use type
This sub-goal relates to the type of land that could potentially be used or changed to implement a possible NBS. A low impact space (e.g. rooftop) can be used to increase its values of ecosystem services and functions. Often compromises are needed to prevent conflicts in those areas and provide sustainable solutions. What importance do you place on choosing the right land-use type for possible implementation in the area? **Put Weight here (0-10):** **Give an explanation of the given weight:**
4.1 To maintain and enhance biodiversity
This sub-goal relates to the importance of maintaining and enhancing biodiversity, which means improving number and types of protected species, native species and their density and diversity in general. What importance do you place on the maintenance and enhancement of biodiversity in the area? **Put Weight here (0-10):** **Give an explanation of the given weight:**
4.2 Reduce disturbance to ecosystems
Reducing the disturbance to the ecosystem, in this case, means to decrease stressing ecological factors in the area such as specific amounts of non-native/migrated and invasive species that could be a threat to the local ecosystem or local species. What importance do you place on reducing the disturbance to ecosystems in the area ? **Put Weight here (0-10):** **Give an explanation of the given weight:**

5.1 Increase recreational opportunities
Increased recreation opportunities mean providing recreational space, giving the possibility to people to spend their free time in the area, engaging livelihood activities and increasing number of tourists. These can be beneficial for human well-being from both biological and psychological aspects. What importance do you place on increasing recreational opportunities in the area? **Put Weight here (0-10):** **Give an explanation of the given weight:**
5.2 Education and awareness
A site can be seen as an opportunity to provide knowledge and awareness about connected key aspects such as the reduction of major risks (e.g. flooding) in the area as well as supporting ecosystems. What importance do you place on increasing or improving educational/awareness opportunities through NBS in the area? **Put Weight here (0-10):** **Give an explanation of the given weight:**
5.3 Maintain and if possible enhance cultural values
Maintaining and (if possible) enhancing cultural values present in the area includes reducing the risk of losing cultural heritage during extreme weather events. Also, it means to improve working environments for local food production and to maintain or increase numbers of cultural events. What importance do you place on maintaining or enhancing cultural values in the area? **Put Weight here (0-10):** **Give an explanation of the given weight:**
5.4 Accessibility
Accessibility reflects on the factor of how easy it is to reach/ access the NBS site. It includes free space of the area and connection between area and surrounded homes. What importance do you place on the accessibility to an NBS in the area? **Put Weight here (0-10):** **Give an explanation of the given weight:**
5.6 Improve Community Cohesion
Improve community cohesion is enhanced when the people are engaged in an activity which connects them. This also includes the number of people who communicate with the neighbourhood in the NBS area and cognitive and social development in children and young. What importance do you place on improving community cohesion in the area? **Put Weight here (0-10):** **Give an explanation of the given weight:**

5.7 Stimulate/increase economic benefits
This sub-goal shows the significance of increasing or stimulating economic growth in the area. This includes factors such as avoided future damage costs and reduced costs from energy and carbon saving through NBS (e.g. reduced energy consumption of buildings). Also, factors can be seen in reducing the costs of negative health impacts and an increase in property values. What importance do you place on stimulating/increasing economic benefits in the area? **Put Weight here (0-10):** **Give an explanation of the given weight:**
5.8 Encourage new business models and other community benefits provided by NBS
This sub-goal refers to the opportunity of encouraging new business models and community benefits to arrive through a NBS. Due to increasing attractiveness of the area, new businesses could be interested in settling, also through the improvement of living and working conditions. Furthermore, this could mean an increase in created green jobs in the area. What importance do you place on encouraging new business opportunities and benefits to the community in the area? **Put Weight here (0-10):** **Give an explanation of the given weight:**
6.1 Direct health and well-being impacts
Direct health benefits can be considered in terms of mental and physical well-being. One of the main reasons why an NBS could improve human health can be seen in the fact that it allows increasing physical activity to the people who live or visit the area, spending more time outside and being more engaged within the community. What importance do you place on improving direct health impacts in the area? **Put Weight here (0-10):** **Give an explanation of the given weight:**
6.2 Indirect health and well-being impacts
Indirect health impact can be seen due to improving air quality (e.g. removing pollution with planted vegetation), less noise pollution, possible reduction of heavy metal contents in the environment and the mitigation to the urban heat island effect. NBS can reduce the exposure level of toxic substances towards humans and can be beneficial in terms of human health. What importance do you place on indirect health impacts in the area? **Put Weight here (0-10):** **Give an explanation of the given weight:**

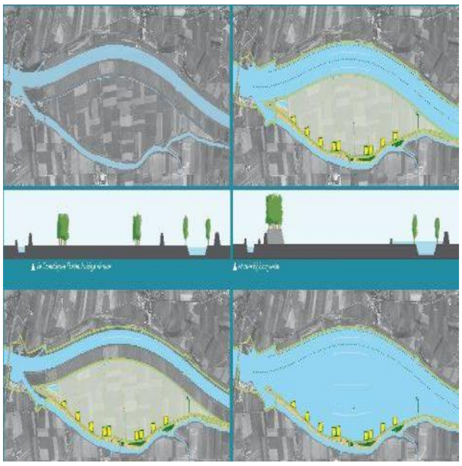
APPENDIX A.4 QUESTIONNAIRE FOR COLLECTING STAKEHOLDERS' PREFERENCES ON APPLICABLE/SUITABILITY OF MEASURES

An explanation

This section provides some information about NBS measures. Definition, primary function and co-benefits are given for each NBS measure, with a picture that should give a better understanding of how the measure would look like in reality.

Weights should be given with **values from 0 to 10** in order to show the suitability to address the present issues and developments in the area. A value of **0** represents **inapplicable/unsuitability**, whereas **10** means that the measure is **very suitable**.

1. Floodplain excavation/enlargement/restoration



A floodplain is an area bordering a river that naturally provides space for the retention of floods and rainwater. Floodplains have often been drained, and in many places, they have been separated from the river by structures.
The floodplain can be enlarged by lowering the level or/and increasing the width of the floodplain area. An area of the floodplain increases will create more room for the river during high flow by increasing the discharge capacity and provide upstream retention.
The associated changes in land use and reduction in surface-runoff can lead to higher recharge of water into the ground. Increased organic matter content can increase soil water retention, while removal of sediment improves soil permeability.
Co-Benefit: The floodplain excavation creates opportunities for nature and recreational development. With a significant change of land cover, it can reduce pollution by activating filtration by vegetation and soil. Floodplain restoration enables recovery of natural erosion and sedimentation processes, therefore reducing sediment transport downstream. Floodplain contributes to creating terrestrial, aquatic and riparian habitats, increasing fish populations, improving biodiversity and providing natural biomass. Floodplains are likely to contribute to climate change adaptation through the fixation of carbon dioxide by photosynthesis and C-burial. They also provide recreational opportunities and aesthetic value.
Put Weight here (0-10):
Give an explanation of the given weight:

2. Depoldering

The dike on the riverside of a polder is relocated land-inwards, which return the polder to the river. This way, the river has more room for flooding due to the water can flow into the area at high water levels.
A new dike is built further inland. Breaches are created in the old dikes, allowing the tides to flow in and out of the area. This is how tidal nature, with mudflats and marshes, develops in the depoldered area. At the same time, the force that the water exerts on the dikes is tempered, reducing the likelihood of floods further inland.

Co-Benefit: Depoldering creates opportunities for nature habitat developments as well as improve aesthetic value in the area. It also offers opportunities for recreation activities and economic activity.

Put Weight here (0-10):

Give an explanation of the given weight:

3. Widening of water bodies

The river width is an activity which aims to increase the conveyances characteristics of the river though widening by excavating the embankment. The widening rivers provide more space in the river. By enlarging the cross-sectional area, it increases the bank discharge of the river along with its hydraulic radius. This will increase the velocity of the river and reduce the chances of it flooding in the immediate area by moving the floodwater further on downstream.

Co-Benefit: Channel migration and braiding are enabled within the widened reach, leading to greater structural, hydraulic, and habitat heterogeneity. The exchange between the water column and channel bed and river banks (vertical and lateral linkages) can affect water quality because these are biogeochemically active areas where organic matter decomposition and nitrogen removal occurs.

Put Weight here (0-10):

Give an explanation of the given weight:

4. Deepening water bodies

The water body bed is deepened by excavating the surface layer of bed to increase the depth of water bodies such as rivers, canals or ponds. The deepened water body bed provides more room for the water.

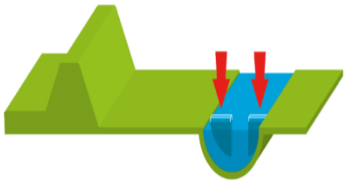
Increasing the depth of water bodies is also increasing the storage volume. The amount of water which can be stored in this way can become available when water is scarce. The water bodies are refilled when water is abundant during wet periods. Deepened water bodies help to reduce flood risk as rivers can transport a larger amount of water to downstream and ponds and lakes have a larger retention capacity.

Co-Benefit: Deepening water bodies contributes to improving the status of Physico-chemical and hydro-morphology quality elements. Diversifying water depth contributes to improving the diversity of habitats offered by the river and to create new habitats. Deepening water body also fosters the development of riparian habitats on river banks. This leads to enhanced natural biomass production and helps to create and preserve biodiversity. The measure also contributes to better management of fish stocks and helps to improve the status of biology quality elements and prevent surface water deterioration.

Put Weight here (0-10):

Give an explanation of the given weight:

5. Lowering groynes



Groynes stabilise the location of the river and ensure that the river remains at the correct depth. However, at high water levels groynes can form an obstruction to the flow of water in the river. Lowering groynes increases the flow rate of the water in the river.

. A perpendicular groyne is constructed at a right angle to the flow of the river. These groynes will be lowered or removed. By lowering the groynes in the river and building parallel barriers, the river will be able to drain excess water easier

Co-Benefit: Lowering the groynes are more navigable depth for shipping and wet banks at low water levels during dry periods. In the side stream of lowering groynes, development of flora and fauna is expected to improve along the river banks.

Put Weight here (0-10):

Give an explanation of the given weight:

6. Bypass/diversion channels

Bypass channels divert river flows at a point upstream of an area. These diverted flows can be discharged back to the same river (Bypass channel), or into another natural drainage system nearby (Diversion channel). Gates usually use to regulate flows into bypass and diversion channels. The measure implies 'giving back' floodplain area to the river. It is a separate channel into which floodwaters are directed to lessen the impact of flooding on the main river system.

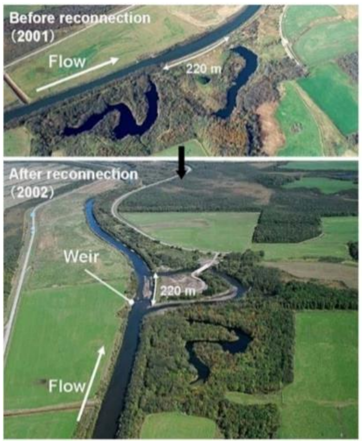
Co-Benefit: Apart from enhancing the rivers' capacity, many secondary benefits are produced such as increasing groundwater infiltration, improving water quality, restoring natural floodplain forming processes (e.g., sediment transport and deposition) and improving fish and wildlife habitats. With reduced flows in the main stem of the river, streamside vegetation can encroach into the river channel, thereby changing its physical and biological characteristics and restoring the natural floodplain ecosystem. The in-stream habitat component is providing good elements of abundant cover, clean substrates and high base flows, which assures a stable water supply with adequate depths and flow during droughts. Recreational opportunities can best be enhanced by developing additional access facilities on the diversion channel to relieve current crowded conditions.

Put Weight here (0-10):

Give an explanation of the given weight:

7. Reconnection of oxbow lakes and Re-meandering

Oxbow lakes are former meanders that have been cut off from the river, thus creating a small lake with a U form. Oxbow lakes occur naturally, but may also occur due to artificial river straightening. Reconnecting an oxbow lake/re-meandering involves removing terrestrial lands between both water bodies, therefore favouring the overall functioning of the river by restoring lateral connectivity, diversifying flows and cleaning the river section of the present oxbow, and thereby providing better water retention during floods.



Co-Benefit: Oxbow lakes and reconnected side arms may play an important role in creating habitats, but care should be paid not to destroy pre-existing oxbow lake habitats. Often these habitats are used for spawning places by fish and other aquatic groups so that fish stocks can increase. That, in turn, contributes to improving the status of biology quality elements. Bank vegetation often expands after reconnection because of improved water regime, and populations of water birds, amphibians, reptilian and mammal species can increase. Restoration of natural green areas significantly contributes to the 2020 Biodiversity Strategy and provides aesthetic and cultural value.

Put Weight here (0-10):

Give explanation of the given weight:

8. Retention basins

Retention basins are ponds designed with additional storage capacity to attenuate surface runoff during rainfall events. Ponds are created by using an existing natural depression, by excavating a new depression, or by constructing embankments. Increasing storage can be applied on different scales. Retention basins reduce peak runoff through storage and controlled outflow and reduce the risk of surface flooding in conjunction. Reduction of discharge causes lower water levels downstream of the site of the measures.

Co-Benefit: Retention basin also help to prevent downstream erosion, and improve water quality in an adjacent river, stream, lake or bay thought vegetation. Sometimes they act as a replacement for the natural absorption of a forest, or other natural proves that was lost when an area is developed. Retention basins can be effective at pollutant removal. They are also highly effective at intercepting sediment. Through reducing diffuse pollution, retention basins play a role in preserving and improving surface water quality. Creation of ponds will create new aquatic and riparian habitat, therefore increasing natural biomass production and contributing to biodiversity preservation. Retention basins can contribute to more sustainable agricultural practices. Retention basins also increase the aesthetic/cultural value of the landscape.

Put Weight here (0-10):

Give an explanation of the given weight:

9. Detention basins

A detention basin is a free space from water in dry weather. It designs to store runoff for temporary during high flow then releasing it slowly to downstream or a nearby watercourse, using an outlet control structure to control the flow rate.

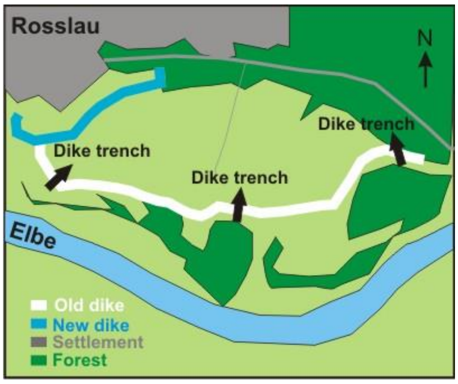
Detention basins are vegetated depressions designed to hold runoff from impermeable surfaces and allow the settling of sediments and associated pollutants. They are not designed to allow infiltration. The storage capacity is dependent on the design of the basin, which can be sized to accommodate any size of the rainfall event. Detention basins can reduce the risk of surface flooding in conjunction with other NBS features, and in doing so, contribute to climate change adaptation.

Co-Benefit: Detention ponds and basins can be effective at capturing sediment in urban or rural runoff and at pollutant removal, as a result of the settling of particulate pollutants and uptake by vegetation. Therefore, they have the potential to improve water quality in receiving water bodies by addressing diffuse urban pollution and reducing chemical pollution.
Detention basins may provide minor biodiversity benefits (although unlikely to provide significant habitat improvements). Where used to intercept and store runoff from low permeability surfaces in agricultural areas, detention basins can contribute to more sustainable agricultural practices. By creating green areas, they provide aesthetic and recreational benefits.

Put Weight here (0-10):

Give an explanation of the given weight:

10. Dike removal/relocation



Relocating a dike land-inwards increase the width of the floodplains and provide more room for the river. This entails exposing land that once had been protected by the dyke to high water in order to expand the river's winter bed. Relocating dikes increase conveyance in the floodway by enabling floodwaters to spread out and slow down. This reduces the height of floodwaters, reduces peak flows in receiving watercourses, and consequently reduce flood risk and erosion. Moreover, it reduces the pressure on the dike itself.

Co-benefit: Dike relocation creates new retention area, which can give more room for the river by opening former floodplains. This will also benefit in improving dynamics and functions of ecosystem and biodiversity. Reduced flows also contribute to the filtration of pollutants, potentially improving surface water qualitative status and preventing surface and groundwater status deterioration. Moreover, this will enhance in creating recreational opportunities. If the new construction of dike includes hiking or biking, this will be able to provide both a recreation opportunity for neighbouring communities and accessibility to the restored floodplain and riparian habitats.

Put Weight here (0-10):

Give an explanation of the given weight:

11. Removing obstacles

Removing or modifying obstacles, such as bridge, abutments, factories on mounds, involves the removal of man-made elevations which disturb the free flow of the river. Removing or modifying obstacles can increase the flow rate of the water in the river and reduce the water levels upstream of the measure.

The removal of hydraulic obstacles in the floodplain is another way to increase its discharge capacity without increasing its water level.

Co-Benefit: Removing obstacles add sheer surface area to the floodplain and reduce the visible remains of human activity (artefacts). This enhances the naturalness of the area and the diversity of natural habitats.

Put Weight here (0-10):

Give explanation of the given weight:

12. Wetland restoration/enhancement

A wetland is an area of marsh, fen, peatland or water for whether temporary or permanent. Wetlands restoration can store water and slowly release water. Wetlands often dense vegetation and are usually flat area, which contributes to slowing runoff by reducing peak flow and reduce stream discharge. Therefore, it reduces flood risks as well as in coastal areas can support protection against seat storms and storm surges.

Co-benefits: Wetland provides a wide range of socio-economic co-benefits. Wetlands contribute to water quality through their natural ability to filter effluents and absorb pollutants. Microorganisms in the sediment and vegetation in the soil help to break down many types of waste, eliminate pathogens and reduce the level of nutrients and pollution in the water
They create aquatic and riparian habitat. It is potentially providing large areas of natural habitat that is valuable for recreation activities, livelihood opportunities and education opportunities.

Put Weight here (0-10):

Give an explanation of the given weight:

13. Lake restoration

A lake is a natural water retention facility. In passing through the lake, river water is not only slowed down but also has its physics-chemical characteristics altered/ regulated. These mechanisms contribute to reducing peak flows in receiving watercourses, effectively maintaining the natural flood risk management capacity of a catchment. Protection against floods can be improved through an integrated strategy considering all water uses.

Co-benefits: A lake can store water (for flood control) and provide water for many purposes such as water supply, irrigation, fisheries, tourism, etc. Besides, it serves as a sink for carbon storage and provides important habitats for numerous species of plants and animals, including waders. Lake restoration has the potential to improve water quality in receiving water bodies. It also preserves aquatic habitats and can increase species diversity. Along with the benefits to temperature and water quality, this can contribute to increase fish stocks. Restoration of the lake and their surroundings can also benefit riparian vegetation and species, and provide an overall increase in biomass production. As a result of improving the production of phytoplankton and zooplankton, creates optimum conditions for aquatic and terrestrial ecosystems. Lake restoration is thus a key measure for reaching good water ecological status. Lake can have recreational and cultural benefits, becoming popular areas to visit.

Put Weight here (0-10):

Give an explanation of the given weight:

14. Buffer strips

Riparian forest buffers can have more significant in holding water than cutover or non-forest covered areas. Riparian buffers serve to slow water as it moves off the land. Because of their rougher ground surface, they can slow runoff more effectively than bare ground. However, riparian forest buffers have a limited ability to store and slow terrestrial runoff due to their relatively small breadth.

Co-benefits: By preserving a relatively undisturbed area adjacent to open water, riparian buffers can serve several functions related to water quality and flow moderation. The trees in riparian areas can efficiently take up excess nutrients and may also serve to increase infiltration. Forest riparian buffers can play an important role in biodiversity preservation, both by direct provision of riparian habitat and by providing habitat "corridors". They contribute to the creation of aquatic habitat by moderating the stream temperature regime and by acting as a source of coarse woody debris. Riparian buffers also increase the recreational value of the area.

Put Weight here (0-10):

Give an explanation of the given weight:

15. Afforestation/Forests and naturally vegetated land

Afforestation is the process of planting trees, or sowing seeds, in areas that have ever been forested to create a forest. Forests can help to reduce public costs for stormwater management, flood control, transportation, and other forms of built infrastructure. Trees (as well as other vegetation covers in the catchment), intercept rainfall and increase infiltration thus moderating both the runoff into the river system and the storage of water in the soil. The ability of soils in forest areas to store water and release it through seepage, transpiration and evaporation helps in regulating the water supply in the catchment. Forests and areas with good vegetation cover can moderate extreme events by reducing the likelihood (or frequency) of floods, landslides, mudflows and avalanches, which can cause extensive damage to infrastructure and inhabited areas.

Co-benefits: Afforestation play a pretty important role when it comes to decreasing the greenhouse effects. We all know that greenhouse gases represent a contributing factor that triggers climate change all around the globe. Forests can also protect biological diversity and preserve essential ecological functions while serving as a place for recreation and civic engagement.

Some afforestation might be developed by companies to grow trees and improve the production of charcoal and timber. Furthermore, afforestation also constitutes more job opportunities. It also helps local businesses to increase the supply of its products while also benefiting the local economy.

Put Weight here (0-10):

Give an explanation of the given weight:

16. Reforestation and forest conservation

Reforestation is the restoration of forests in areas where forests were removed or destroyed. Forest growth prevents water runoff. That is because the forested area will release its water to the mainstream later than water running off pastureland. The water then seeps into the soil and recharges groundwater. This will increase the water supply for both animals and people. Trees and other plants also enrich the soil and increase its quality, they prevent the process of soil erosion and landslide, also provide better water-retention.

Co-benefits: Reforestation can be used for both as mitigation and adaptation measures for climate change. It can cause dramatic and rapid accumulation of carbon in tree biomass as trees can capture and store carbon dioxide from the atmosphere during photosynthesis, and convert it into oxygen and carbohydrates. Thus, this helps mitigate global warming by reducing the growth of carbon emissions to the atmosphere. Reforestation can also be used to improve the quality of air by removing air pollutants such as sulphur dioxide, ammonia and nitrogen dioxide from the air. The tree roots also prevent erosion that can wash away good soil. Trees also help to rebuild ecosystems and habitats as trees provide homes for animals and birds.

Put Weight here (0-10):

Give an explanation of the given weight:

17. Upper watershed restoration

Upper watershed restoration aims to improve infiltration; thus, precipitation can infiltrate to the ground without flowing as runoff. Watershed restoration often uses bio-engineering techniques. Bio-engineering combines living plants with dead plants or non-living material to produce a living system that resists erosion. Selective planting on a hillside is an example of bioengineering. When properly completed, the bioengineered solution can produce an environment that stabilises the land, controls flooding and even takes part in the treatment of water.

Co-benefits: Restoration of a watershed can help the ecosystem to return as close as possible of original. The restorative process includes the remediation of the water quality, repairing the source of the water damage, and repopulating the watershed with plant and animal species. In some cases, it is sufficient to make the restored habitat attractive to native species and to allow natural repopulation. Restoring watersheds is important to species health, which is part of the ecosystem and to the communities that depend on the watershed for their drinking water.

Put Weight here (0-10):

Give an explanation of the given weight:

18. Natural bank stabilisation

Natural bank stabilisation involves recovering its ecological components, thus reversing such damages and allowing the bank to be stabilised, as well as allowing the river to move more freely. Riverbank renaturation consists in recovering its ecological components, thus reversing such damages and especially allowing the bank to be stabilised, as well as rivers to move more freely.

Common techniques of natural bank stabilisation are bank-re-vegetation and bio-engineering. Bank re-vegetation is very effective in mitigating the erosive effects of overland flood flows eroding down the banks as waters recede. Bio-engineering techniques for bank stabilisation incorporate the use of riparian vegetation and wood cuttings that are installed in the bank to provide structural stability.

Co-Benefit: An increased surface area of natural materials allows for increased natural filtration and biological pollutant decomposition, which contributes to increasing the capacity of the river to purify the water naturally. Stabilising banks prevents river flow from eroding the river banks, although activating the typical hydro-morphological processes can lead to small scale erosion and sedimentation and the development of a broad and gently sloping bank profile.

By slowing down the flow and giving back its natural features to the river, natural bank stabilisation creates aquatic and riparian habitats, thus potentially increasing fish populations and natural biomass production, improving the status of biology quality elements and preserving biodiversity. Replacing concrete banks with natural materials and vegetation also improves the aesthetic value of the area.

Put Weight here (0-10):

Give an explanation of the given weight:

APPENDIX B

Farmer interview questionnaires

AREA A: NONG SUEA (district) – Noppharat (sub-district) Farmers. DATE:

Name:

Email:

Phone Number:

Address:

1. History of farm

2. Estimate the percentage o irrigation water is from furrows (vs. canals):

3. What are annual irrigation costs (equipment, pumping, fuel, etc.)?

4. What was the decrease in annual income in 2015 due to drought? (from 2017)

5. List of crops, animals, insects, birds etc.

6. Type of fertilizer:

amount used: kg/km2/year:

cost (Baht/year):

where is it used:

7. Farmer income: (Baht/year.)

8. Size of farm:

9. Productivity: outputs/inputs (Baht/Baht) (expenses: fuel, equipment, seeds, labour, fertilizer etc):

AREA B: NONG KHAE (district) Nong Rong (sub-district) Farmers. DATE:

Name:

Email:

Phone Number:

Address:

1. History of farm:

2. What are annual irrigation costs (equipment, pumping, fuel, etc.)?

3. What was the decrease in annual income in 2015 due to drought? (from 2017)

4. List of crops, animals, insects, birds etc.

5. Type of fertilizer:

amount used: kg/km2/year:

cost (Baht/year):

where is it used:

6. Farmer income: (Baht/year.):

7. Size of farm:

8. Productivity: outputs/inputs (Baht/Baht) (expenses: fuel, equipment, seeds, labour, fertilizer etc)

List of Acronyms

AMS	Adaptive metropolis search
AST	Adaptation Support Tool
BeST	Benefits of SUDs Tool
BCR	Benefits-cost ratio
BGI	Blue-Green Infrastructure
BMPDSS	Best Management Practice Decision Support
BMPs	Best Management Practices
CBA	Cost-benefit analyses
CBD	Convention on Biological Diversity
CCA	Climate change adaptation
CEM	Commission on Ecosystem Management
DE	Differential evolution
DRR	Disaster risk reduction
EbA	Ecosystem-based Adaptation
Eco-DRR	Ecosystem-based Disaster Risk Reduction
EC	European Commission
FrASH	Framework for Adaptive Socio-Hydrology
GI	Green Infrastructure
IIED	International Institute for Environment and Development
IUCN	International Union for Conservation of Nature
LCC	Life cycle costing
LID	Low Impact Development
MAUT	Multiattribute utility theory
MCA	Multi-criteria analysis
MLSOP	Multilevel spatial optimization
MOEA	Most popular multiobjective evolutionary algorithms
MOO	Multi-Objective Optimal

MOPSO	Multi-objective particle swarm optimisation
MOUSE	Model of Urban Sewers
MUSIC	Model for Urban Stormwater Improvement Conceptualization
NBS	Nature-Based Solutions
NPV	Net Present Value
NSGA-II	Non-dominated Sorting Genetic Algorithm II
PSO	Particle swarm optimisation
RECONECT	Regenerating ECOsystems with Nature-based solutions for hydro-meteorological risk rEduCTion
ROI	Return on Investment
RPE	Relative Performance Evaluation
RTC	Real-Time Control
SA	Simulated Annealing
SCADA	Supervisory Control and Data Acquisition
SCP	Sponge City Programme
SDGs	Sustainable Development Goals
SEI	Stockholm Environment Institute
SFDRR	Sendai Framework for Disaster Risk reduction
SUDs	Sustainable Urban Drainage Systems
SUSTAIN	System for Urban Stormwater Treatment and Analysis IntegratioN
SWAT	Soil and Water Assessment
SWMM	Storm Water Management Model
UN	United Nations
UNFCCC	UN Framework Convention on Climate Change
US EPA	United States Environmental Protection Agency
UWOT	Urban Water Optioneering Tool
WCPA	World Commission on Protected Areas
WSUD	Water Sensitive Urban Design

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ABOUT THE AUTHOR

Laddaporn Ruangpan, also known by her nickname “Milk” originates from the southern region of Thailand. In 2015, she received a bachelor of Engineering in an international program of Civil Engineering at King Mongkut’s University of Technology Thonburi (KMUTT) in Bangkok, Thailand. During her under graduation years, she received scholarship to participate in a student exchange programme at Water Resource University in Hanoi, Vietnam for six months. She also spent another six months at Windesheim University of Applied Sciences, Netherlands to complete her bachelor’s graduation project. After that she commenced her career as a water resources engineer at PANYA CONSULTANTS CO. LTD in Thailand for a year.

In October 2016, she moved to the Netherlands to study Master of Water science and engineering, specilised in Hydroinformatics - Modelling and Information Systems for Water Management at UNECO-IHE institute for water Education in Delft thanks to the support of Rotary scholarship. She successfully obtained her MSc degree in April 2018.

In the same year, she decided to stay within academic. This decision led ger to start her PhD research, focusing on Evaluation of Nature-Based Solutions for hydro-meteorological risk reduction. This research is part of EU-funded RECONECT project and is carried out at IHE Delft, Institute for Water Education and Delft university of technology. Her contributions extended to practical applications within the RECONECT project.

In addition to academic endeavours, Laddaporn embraced personal milestones during her PhD journey. She got married with Alex Neil Curran, and a few months later, she welcomed her daughter, Muireann Anne Curran, into the world.

At the end of 2021, alongside her PhD, she established her consulting company named “Climate Adapt” focused on climate change adaptation. Notably, she has been collaborating with diverse clients, including a Norwegian company named Mitigrate and World Wildlife Fund (WWF). She has received the certificate to become a trainer for the Natural and Nature-Based Flood Management Green Guide Training from WWF.

In 2022, the summary of her thesis was selected as one of 12 finalists to be published in compendium essays of the Allianz Climate Risk Award.

Upon completing her PhD, she continues to contribute to the RECONECT project, being employed by IHE as a project management assistant.

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Delft, 4th of December 2023

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The SENSE Research School declares that **Laddaporn Ruangpan** has successfully fulfilled all requirements of the educational PhD programme of SENSE with a work load of 44.8 EC, including the following activities:

SENSE PhD Courses

- Environmental research in context (2018)
- Research in context activity: Organizing Symposium in IHE 2019 on 10-11 October 2019'

Other PhD and Advanced MSc Courses

- Research design, TU Delft (2019)
- How to make a questionnaire and conduct an interview, TU Delft (2019)
- Nature based solutions for urban and rural applications, Agricultural University of Iceland, Iceland (2022)

External training at a foreign research institute

- Ur field lab: Chiang Mai urban flooding, World Bank, Thailand (2019)
- Nature-based Solutions for Disaster and Climate Resilience, UNEP (2021)
- Natural and Nature-Based Flood Management Green Guide Training of Trainers course WWF (2022)

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- Supervising three MSc students with thesis (2018-2021)
- Member of IHE PhD Academic board (2019-2021)

Oral Presentations

- *Involvement of stakeholders in the selection and implementation of Nature-Based Solutions for hydro-meteorological risk reduction.* EGU, Online (2020)
- *Stakeholders' opinions on enhancing benefits of Nature-based Solutions.* IHE PhD Symposium, Delft, The Netherlands (2020)
- *A framework for evaluating performance of large scale nature based solutions to reduce hydro-metereological risks and enhance co-benefits.* SIMHydro2021, Sophia Antipolis, France (2020)
- *Assessing benefits of nature-based solutions for flood risk reduction*. IHE PhD Symposium, Delft, The Netherlands (2021)

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There is growing evidence that hydro-meteorological events, and particularly floods, are the most frequent cause of disasters for many places around the world. Nature-Based Solutions (NBS) have been introduced to address these growing risks and they have a potential to be more effective than traditional grey infrastructure. NBS offer a way forward, enabling us to adapt to anticipated changes in climate and society while achieving multiple benefits for ecosystem services and functions. However, scientists and decision-makers require holistic perspectives and frameworks to help understand, evaluate and design NBS in such a way that can reduce social, economic and environmental impacts, increase resilience to hydro-meteorological events and enhance the co-benefits. This book presents a methodological framework for the evaluation of Nature-Based Solutions for hydro-meteorological risk reduction and co-benefits enhancement. The evaluation framework consists of two main evaluation processes, which are ex-ante evaluation and ex-post evaluation. The ex-ante evaluation was applied to the Tamnava river basin, Serbia, while the ex-post evaluation was conducted in the Rangsit area, Thailand. The results of this research contribute to the improvement of decision-making and NBS evaluation processes, both before and after NBS implementation. They offer valuable insights for practitioners and researchers to enhance the effectiveness and credibility of NBS, considering their risk reduction benefits and co-benefits.

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