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Designing and evaluating robust nature-based solutions for hydro-meteorological risk reduction

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ABSTRACT

Societies face an increasing number of challenges due to climate change – including enhanced hydro-meteorological risk (HMR). Typically, HMRs are exacerbated by rapid urban development, ecosystem degradation, and water use changes. All though data is scarce and scattered, evidence-based case studies have shown that implementing Nature-based Solutions (NBS) can reduce HMR. With further influence from anthropogenic climate change and continuing ecosystem degradation, HMH are projected to increase in frequency and severity. Consequently, NBS implemented for HMR reduction will have to be robust enough to deal with HMHs that exceed their design criteria and/or expected performance. However, currently available literature does not adequately outline processes that aid in designing and evaluating of robust NBS for HMR reduction. In response to this gap in literature, this study developed a process for designing and evaluating robust NBS for water. In the present study, robust design of a NBS for water is illustrated using an existing flood risk management system and NBS (100-year-old traditional irrigation furrows) in an agricultural area situated within the floodplain of the Chao Phraya River basin in the Pathum Thani province, Thailand. The robustness of the existing NBS for water is then evaluated through robust design and quantified through the construction of a responsive curve. Once the robustness of the existing NBS for water is quantified, an iterative process is used to enhance individual characteristics of the flood risk management system – resulting in efficient use of the flood water storage capacity offered by the existing NBS.

1. Introduction

1.1. Hydro-meteorological risk (HMR)

A naturally occurring hazard that originates from meteorological, hydrological, or oceanographic phenomena is called a hydro-meteorological hazard (HMH). Examples of HMHs are floods, storm surges, landslides, droughts, heatwaves, and forest fires [1–3]. Different areas and terrains are more prone to certain types of hazards then others, for example, coastal areas may experience mostly storm surges, mountainous terrains may experience more landslides, and riverine areas more flood events [4]. HMHs can have considerable impacts on societies, ranging from property damage and environmental degradation to disruptions of economic activities and

Abbreviations: HMH:, Hydro-meteorological Hazard; HMR:, Hydro-meteorological Risk; NBS:, Nature-based Solution.

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even death [5]. A hydro-meteorological risk (HMR) is a combination of three factors [1,6,7]: (i) the *probability of a HMH* causing damage, death, or harmful consequence (in a given period); (ii) *exposure* (i.e., presence of people and their assets during the event); and (iii) *vulnerability* (i.e., the predisposition or propensity of humans and the environment to be adversely affected when the event occurs) – as a result of a lack of adaptive or coping capacity by the socio-ecological system.

HMH have been projected to increase in frequency and severity (intensity/duration) due to further anthropogenic climate change and continued environmental degradation [1], caused by intensification of land and water use [8]. Amongst HMHs, floods are one of the most frequently occurring natural hazard [2] and the most major climate-related disaster [9]. And amongst anthropogenic climate change-induced extreme events, floods have shown the most accelerated and enhanced impact on societies because of their high frequency of occurrence - which causes many fatalities and damaging impacts, globally [10]. Increase in flood frequency and intensity is also commonly a consequence of unplanned and uncontrolled urban growth, and the subsequent land use change [11] – since within catchments, floods are aggravated by actions such as removal of vegetation, occupation of floodplains, and increased imperviousness rates [12].

1.2. Nature-based solutions (NBS)

The academic understanding of NBS is as an "umbrella concept"; a collective term for a range of innovative ecosystem-based approaches [7], that address an assortment of societal challenges, such as, food security, water security, disaster risk reduction, human health and climate change [13]. The concept of NBS describes approaches to learning from and using nature to create sustainable socio-ecological systems [14]. These existing ecosystem-based approaches have been grouped into the following categories by Cohen-Shachem et al. [13],: i) Ecosystem restoration approaches (e.g., ecological restoration, ecological engineering, forest landscape restoration)); ii) Issue-specific ecosystem-related approaches (e.g., ecosystem-based disaster risk reduction, ecosystem-based mitigation, ecosystem-based adaptation and climate adaptation services); iii) green infrastructure and natural infrastructure approaches (e.g., natural water retention measures); and iv) ecosystem-based management approaches (e.g., area-based conservation).

Compared to preceding approaches, the concept of NBS is characterised by three important innovations: i) a strong focus on developing applicable solutions; ii) incorporating a systematic approach to alleviating societal challenges and exploiting co-benefits; and iii) an inherent transdisciplinary approach of co-creating, co-developing, and co-implementing solutions to societal challenges [15]. And when comparing the concept of NBS to other ecosystem-based concept, Cohen-Shachem et al. [16], identify the following three distinguishing principles which underpin the concept of NBS and make it stand out from other approaches: i) NBS can both be implemented alone or integrated with other solutions; ii) NBS are applied at landscape scale; and iii) NBS are an integral part of the overall design of policies, measures, or actions to address societal challenges. Sowińska-Świerkosz and García [17] clarify the concept of NBS by identifying core criteria to exclude related or complementary actions that are not NBS – criteria derived from the current IUCN Global Standard for Nature-based solutions [18].

Despite ecosystems and local communities having specific characteristics, they are connected to sub-catchments and catchments level processes through climatic and hydrological cycles, along with government policies [5]. As such, Eggermont [19] proposes a typology of NBS that is based on two characteristics: i) the level of engineering of the biophysical structure involved in implementing the NBS; and ii) the level of ecosystem service delivery achievable by the NBS. A gradient along these two characteristics results in NBS being broadly classified into the following three types: Type 1 NBS, consisting of minimal or no intervention in ecosystems. This involves making better use of ecosystems to maintain or improve ecosystem service delivery. Type 2 NBS, are based on developing sustainable management approaches that result in multifunctional ecosystems within a specific landscape; and Type 3 NBS, involve managing ecosystems in intrusive ways or creating new ecosystems.

1.3. Multifunctionality of nature-based solutions (NBS)

The multifunctionality of NBS, can be understood as the capability of strategically planned blue (water-based) or green (vegetation-based) infrastructure to concurrently deliver multiple ecosystem services from ecosystem functions. That is, multifunctionality within the context of NBS is the ability of the biophysical structure and ecological processes to deliver multiple benefits through ecosystem functions [20–22]. Therefore, the multifunctionality of an NBS can be represented by the various ecosystem functions of a biophysical structure (e.g., functions of a floodplain or wetland) and ecological processes (e.g., removal of pollutants) that can promote human well-being and benefit biodiversity.

When considering the socio-ecological link, the concept of ecosystem services enables the linkage between ecosystem functions and the value of human well-being, that is, ecosystem functions can be translated into ecosystem services when humans value them. However, Termorshuizen [23] highlights that ecosystem functions can offer several ecosystem services, therefore, an ecosystem function will continue to exist (in the absence of humans), whereas ecosystem services exist because of the derived human benefit and the local value assigned to it. For example, p*lant roots and soil biota (features and qualities of the biophysical structure) fulfil the function of soil retention. People value this because soil retention (an ecosystem function), provides erosion control (an ecosystem service) that prevents damage from soil movement (valued human benefit)* [23]. The primary insight into this approach to ecosystem services is that human beings, as the valuing agents, translate the features of the biophysical structure and ecological processes into monetary or cultural value [24].

Since NBS can enhance natural processes and mechanisms, they can address societal challenges and produce multiple ecosystem services, such as soil protection and restoration or regulation of extreme climate events like floods and heat waves [25]. As such, the multifunctionality of NBS consist of utilizing the biophysical structure and ecological processes to provide ecosystem services. Ecosystem services can be considered as necessary contributions by natural or constructed ecosystems to achieving ecosystem health and human well-being [26]. The management or enhancement of preferred ecosystem services can simultaneously provide preferred economic, environmental, and social co-benefits [15]. The enhanced delivery of preferred ecosystem services that have a positive impact on human well-being can aid in achieving a reduction in risk [4].

1.4. NBS and HMR reduction

Over the last decade, policy development has been amid at advancing a resource-efficient and green economy, while protecting humans and natural ecosystems from extreme climate events. During the same period, academic research has been dominated by literature promoting and providing awareness of the benefits of natural ecosystems for human well-being and biodiversity. In light of this, NBS have been promoted as adaptive measures against the projected increase in HMHs [3]. The EU, and other entities, have begun to posit NBS as alternatives or complementary to conventional grey infrastructure (e.g., dikes, sea walls, dams, and concrete channels and pipes), when addressing societal challenges [13,27,28]. This is because NBS have shown the potential to reduce HMR while building resilience, delivering co-benefits, and fostering community wellbeing [1,2,5,7,29]. NBS can proactively manage, protect and restore ecosystems by jointly addressing varies societal challenges [13]. Therefore, NBS have been advocated as adaptive measures against the predicted increase in the frequency and serverity of HMHs. Although research shows that NBS can protect societies from climate change impacts while simultaneously providing co-benefits; their limits must be understood [14] – especially in a rapidly changing world where multifunctional landscapes and biodiversity-based resilience are key. However, understanding the operational limits of NBS is complicated by the identification of appropriate indicators for the effectiveness and efficiency of interventions to societal challenges [30].

The numerous benefits offered by NBS are often substantial enough to influence investment decisions away from conventional grey-infrastructure and towards NBS [31]. However, as compared to grey infrastructure, NBS are seldom consider as the first choice to HMR reduction. One of the reasons is the transition of NBS from an “umbrella concept” to the actual operationalisation of NBS. The other being the knowledge gap in designing NBS, which is the missing link in existing literature that makes it difficult to translate the concept of NBS into practice [3].

1.5. Designing and evaluating NBS for HMR reduction

Designing NBS may involve plans to modify the biophysical structure and ecological processes. The design of NBS also aims to encourage the involvement of stakeholders and societal actors in sustainable solutions [14]. NBS solutions are always designed and implemented to simultaneously deliver multifunctionality (e.g., flood water reduction, ground water recharge and water quality improvement). And the evaluation of specified functions of a designed NBS is usually related to indicators with quantifiable parameters (e.g., water storage volume or level), or qualitative indices for derived benefits valued by humans (e.g., an index to assess the well-being of a population) [6].

However, the design and implementation of NBS for HMR reduction faces the challenge of achieving sustainable solutions in complex environments that are impacted by climate change (and its uncertainties’) and the practical understanding of the multitude of stakeholders (their perception and their interests) when exploring the numerous types of NBS available for addressing HMR – especially in rural and natural areas [3]. Additionally, despite NBS being promoted as actions to address societal challenges, the practical application of NBS remains unclear [17] – with data of evidence-based case studies and their multiple benefits being rather scarce and highly fragmented [3,25]. There are also concerns over the reliability of NBS when compared to alternative engineering solutions. This is because NBS have not been rigorously assessed and their resilience to climate change is uncertain [30]. Additionally, There is a need to economically quantify the benefits provided by NBS to support investment decisions towards business models or business cases that promote NBS for risk reduction [27].

When considering the advancement of the NBS concept, there exists a need to identify which NBS can be implemented ubiquitously versus NBS which require site-specific characteristics [15]. This means that greater clarity and precision is required for the successful deployment of NBS [18]; and for the consolidation and dissemination of experiences and lessons learned. Therefore, good engineering design and suitable evaluation processes are required for the advancement of the operationalisation of NBS towards reducing the impacts of HMHs. This requires a balance between sustainable development of ecosystems and the exploitation of benefits from ecosystem functions. Sowińska-Świerkosz and García [17] propose framing NBS as complementary to engineering solutions and inclusive of grey infrastructure. Arguing that, in the twenty-first century, engineering solutions can no longer be associated with only concrete structures and high energy demand solutions but have advanced to also includes ecological aspects.

Cohen-shacham et al. [13] highlights the need for determining operational parameters for NBS which: i) support sound and reliable scientific knowledge that enables the defining of clear and robust criteria; ii) ensure sustained functionality; and iii) determine the effectiveness of a NBS across a range of different situations. They also highlight the need for decision-makers to be able to assess if a NBS intervention is weak and temporary or robust and sustainable, and therefore, justifying the decision to invest in an NBS. Therefore, decision-makers require a consistent process for designing and evaluating NBS implemented for the purpose of reducing the impact of extreme HMH, supporting biodiversity, and contributing to sustainable development. The process should be able to inform decision-makers on the operational parameters of a robust NBS for HMR reduction and prevent poor design and implementation – which will lead to maladaptation to anthropogenic climate change, disaster risk reduction and environmental degradation.

In this paper we propose a process for designing and evaluating robust NBS for HMR reduction. The proposed process is aimed at aiding the primary decision level of frameworks that assess the technical and physical contribution of a NBS to disaster risk reduction (e.g., the Nature Insurance Value: Assessment and Demonstration, NAIAD, framework). The process can also be used within Horizon 2020 Framework projects like RECONECT, which focus on NBS that reduce the risk of HMH that result in flood and drought risk [6]. The process proposed in this paper can: i) optimise individual parameters of a NBS to make it robust; and ii) answer questions about the level of robustness achieved by a robust NBS during an extreme HMH.

As mentioned earlier, the frequency and intensity of flood hazards is projected to increase and NBS implemented for flood risk reduction will have to be designed to adequately address these future extreme events. Therefore, this study chose to focus on NBS for water due to the projected increase in extreme flood events and because of the varying nature of floods due to anthropogenic climate change, environmental degradation, and water use changes. Additionally, evidence shows that uncertainty is pervasive within flood risk management, both in data and models used to determine how change (e.g., climate, demographics, landscapes, and water use) will influence the future [32]. Traditionally flood risk management was viewed as a civil engineering concept and a means for controlling ecosystem functions. However, this traditional engineering approach to flood risk management has gradually shifted to an integrated approach that includes water management, spatial planning, and ecology. The paradigm of controlling nature has changed and adapted to include ecological considerations [33], climate change and risk. Within this paradigm shift to flood risk management, "NBS for water" is one of the concepts that has emerged, and evolved actions and measures that focus on the creation, preservation and restoration of ecosystems [25]. Consequently, NBS for water are especially receiving attention due to their flood protection abilities [10,34] - that simultaneously provide co-benefits.

In river catchments, these NBS are generally implemented at landscape scale through Natural Flood Measures (NFM) and Natural Water Retention Measures (NWRM) [8,35,36]. In urban areas, NBS for water have mainly been developed and implemented as stormwater management measures like Low Impact Development (LID) in the United States of America, Water Sensitive Urban Design (WSUD) in Australia, Sponge City in Chain and Sustainable Drainage Systems (SuDS) in the United Kingdom [7,37,38].

2. Methodology

2.1. Defining robustness

2.1.1. Robustness within the context of flood risk management systems

The term “robust” originates from the Latin word “robustus”, which means “strong or hardy” [39]. When specifically considering flood risk management, robustness refers to the ability of a water management system to maintain essential system characteristics and functionality when subject to flood hazards that exceed their design criteria [40]. Consequently, when robustness is considered as a system characteristic, it refers to the ability of system to withstand an extreme flood hazard and can be represented by the characteristic of the flood risk management system. The robustness of a flood risk management system includes the ability of the system to respond and recover rapidly from the flood hazard, thus, limiting the impact of the flood hazard on social, environmental, and economic systems.

Therefore, robustness can be represented by the characteristics of a flood risk management system and the ability of the system to withstand the magnitude or frequency of extreme flood hazards. Within the context of water engineering, robustness can be considered as a way of designing a water management systems so that functionality and performance are ensured across a range of known but changing operating conditions – so, robustness is linked to strength and durability [39,41].

2.1.2. Designing robustness into a water management system

In water engineering, a robust design can be achieved through either robust parameter design or robust control. The goal of robust parameter design is to optimise a distinct quality (e.g., material, capacity, or durability) of a structure or an infrastructure system to ensure an accepted and predefined level of performance over its lifetime – taking into consideration the expected variations in the environment. Robust parameter design in a water management system results in “passive-robustness”.

Robust control also leads to the design of an acceptable and lasting performance over a range of known operational requirements, however, this type of robustness in a design is achieved through a combination of attenuators (e.g., storage areas), mathematical tools (e.g., models), and remote sensors (e.g., telemetry stations) that enable a technical system to maintain a predefined level of performance by adjusting to environmental variations. Robust control in a water management system leads to “active robustness” [41].

2.2. Designing a robust NBS for water

A robust NBS for water is achieved by incorporating robust design[1] into the biophysical structure and/or ecological processes – leading to robust ecosystem functions and delivery of enhanced ecosystem service. The present work defined a robust NBS for water as the “*the ability of a biophysical structure to maintain ecosystem functionality during a water-related hazards that exceeds the design criteria or expected performance, but not the tolerance limits or bearing capacity of the ecosystem*”.[2] In this paper, robust design is characterised into i) designing robust parameters, and ii) designing robust control (Fig. 1).

2.2.1. Design robust parameters

Adopting the NBS typology, suggested by Eggermont et al. [19], which characterises NBS types according to the level of engineering involved in the landscape and the level of ecosystem services delivered, provides decision-makers with an opportunity to decide on the most suitable type of NBS to implement for the identified water-related hazard – guided by site-specific characteristics that may enable or constrain the implementation of a measures. That is, during the process of designing robust parameters, decision-makers can make an intervention permanently robust through enhancing distinct or individual site-specific characteristic features or qualities of the biophysical structure and/or ecological processes – thereby, ensuring the effectiveness of an NBS to known HMH.

[1] Robust design of NBS for water has been modified from Ref. [41], who used the term in the context of designing water and wastewater engineering systems.

[2] This definition of “a robust NBS for flood risk management” is modified from [39].

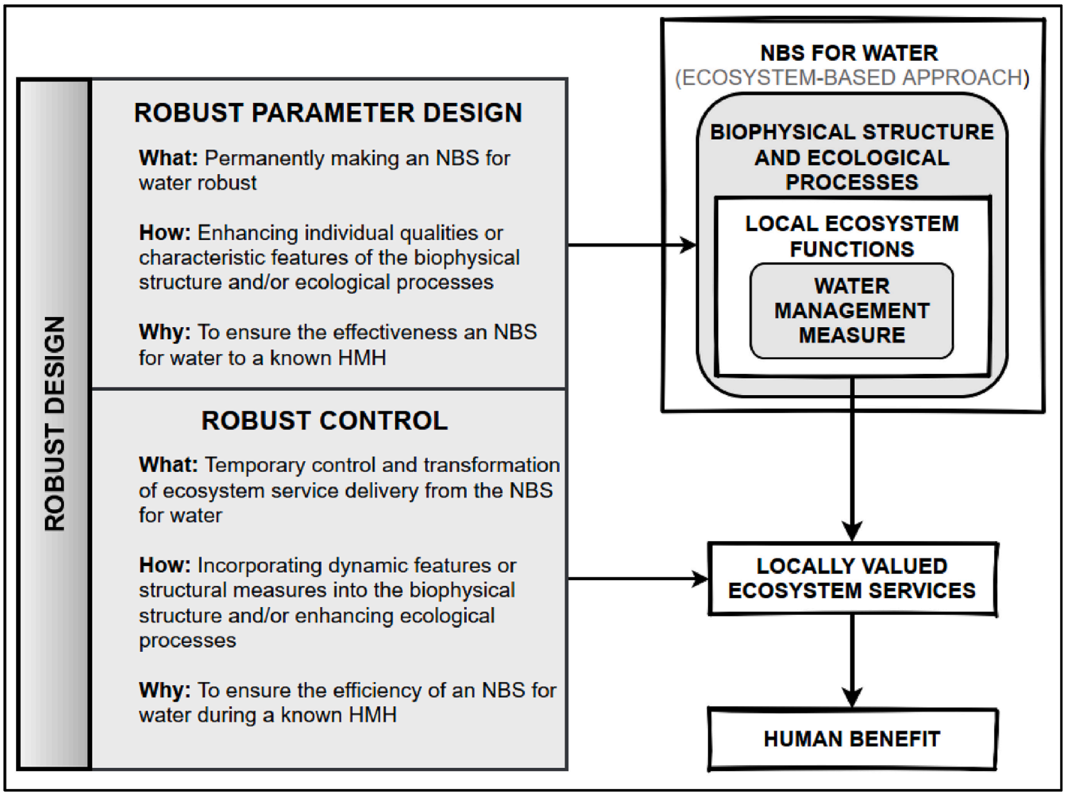

Fig. 1. Robust design of an NBS for water.

For example, during the design process of a robust NBS for water, decision-makers can either select a biophysical structure with the desired features (e.g., a floodplain or wetland) and qualities (e.g., flood tolerant vegetation) or decide to incorporate robust vegetation and grey infrastructure into the biophysical structure – thus, ensuring the effectiveness of an NBS for water. Depending on the level of engineering involved in the design of a robust NBS for water, robust parameter design also allows decision-makers to enhance ecological processes such as infiltration (e.g., through groundwater recharge measures with graded subgrade material) or water quality treatment (e.g., a constructed wetlands). Robust parameter design enhances the durability and increases the tolerance of an NBS for water to extreme HMH that exceed its design criteria or expected performance. Robust parameter design results in passive robustness in the NBS for water by permanently influencing its resistance threshold to a known HMH with varying magnitudes. That is, robust parameter design allows for the lower design limits and upper design limits of a NBS for water to be determined or established during the robust design process.

2.2.2. Designing for robust control

NBS have the potential to produce multiple ecosystem services (e.g., soil protection and restoration or regulation of extreme climate events such as floods and heat waves), through the protection and management of natural process and mechanisms [25]. Therefore, taking into consideration the established concept that ecosystem services exist because of the derived human benefit or community-based value assigned to ecosystem functions provided by the biophysical structure and ecological processes [23,24], the robust design process of NBS for water can make allowance for the enhanced delivery of preferred or locally valued ecosystem services during an extreme HMH. Therefore, designing for robust control means making allowance for *temporary* control and transformation of valued ecosystem service delivery from an NBS water by incorporating dynamic features or structural measures into the biophysical and/or enhancing ecological processes – to ensure the efficiency of an NBS for water during a known HMH.

For example, recreational parks or green spaces which are usually valued for their contribution to human wellbeing, ecosystem connectivity and biodiversity in urban areas, can be temporarily transformed into water storage areas or groundwater recharge zones during extreme flood events by allowing these areas to be flooded for acceptable short periods of time. The use of dynamic features (e.g., pumps) and grey infrastructure (e.g., flow regulators and diversion channels) within a flood risk management system can help to temporarily control flood water levels and the extent of flooding within these areas to ensure not only the effectiveness of a robust NBS, but the efficiency of robust NBS to a known HMH with varying magnitudes. A couple of examples of evidence-based case studies of robust control of the delivery of preferred ecosystem service during extreme events are the concept of Cloud Burst developed for the City of Copenhagen, Denmark [42,43] and the Room-for-the-River concept developed in the Netherlands [33].

Therefore, the design decisions that allow robust control of ecosystem service delivery, by a NBS for water during a known HMH, are catered for while designing the robust parameters of the NBS. That is, the mechanisms to further enhance the robustness of the

NBS for water, by enabling temporary control and transformation of the ecosystem services derived from ecosystem functions during a known HMH, are determined during robust parameter design. Robust control allows for the response and recover of the NBS for water to be pre-determined or established. . Robust control enables an NBS for water to shift ecosystem service delivery to better align with local values during the HMH, including an alignment to the magnitude of the HMH being experienced. Robust control results in active robustness in the NBS by influencing its response and recovery during a known HMH occurring at a given magnitude – thereby, ensuring not only the effectiveness, but also the efficiency of an NBS for water.

2.3. Evaluating a robust NBS for water

2.3.1. Quantifying robustness under uncertainty

There exists a range of equally plausible changes to the frequency and severity of HMH due to anthropogenic climate change, (rapid) urbanization and water use changes – therefore, complicating both decision-making when designing for these uncertainties and the process of evaluating robustness designed into sustainable solutions. Robust Decision Making (RDM) is a quantitative decision-making approach that supports decision making under conditions of deep uncertainty, such as those involving climate change and ecosystems responses. This approach explores future scenarios, then, uses exploratory modelling to support decision making when testing either assumptions and hypotheses or alternative decision strategies [32,44,45]. Exploratory modelling uses computational experiments to assist reasoning where the aim is to identify adaptation strategies for a system under varies future scenarios with significant uncertainty [45,46]. However, modelling tools to support strategic planning by testing the implication of adaptation strategies under deeply uncertain conditions, do not exist for water management systems [45]. And despite the utility of the RDM method and its common use in policy analysis under uncertainty [39] , it does not enable decision-makers to quantify the robustness of a water management system [47].

Although decision robustness may be beneficial to the field of flood risk management, as it represents how sensitive a specific decision is to uncertainties [39], the focus of this paper is on the robustness of NBS for water as a water management system. Therefore, robust analysis was chosen as a more suitable alternative method for quantifying robustness. This method was deemed to have the ability of aligning the quantification of robustness with the natural variability of the frequency and intensity of a HMH. Robust analysis allows for the robustness of a system to be evaluated and also enables decision makers to better understand the relationship between the magnitude of the hazard and the response of the system [47]. Robust analysis uses consolidate modelling to quantify robustness. Consolidative modelling is the use of modelling software to setup a model by consolidating know facts into a single package – which is used as a surrogate for the actual system and to predict system behaviour under different scenarios [45,46]. Additionally, robust analysis requires the development of good scenarios, which involves a combination of expert dialogue, quantified evidence, and expert judgement [32].

2.3.2. Quantifying the robustness of a NBS for water under uncertainty

Once robust design has been incorporated into a NBS for water, the robustness of the NBS needs to be quantified through an evaluation process. And the most suitable tools for evaluating NBS use performance and multi-metric indicators to enable the analysis of diverse NBS across multiple temporal and spatial scales [17]. The use of indicators simultaneously facilitates the assessment of multiple benefits offered by the NBS. Therefore, specific, and well-defined indicators should be used to assess the performance of robust NBS for water – enabling for the quantification of the robustness offered by a sustainable solution to a societal challenge.

Within the study, the robustness of an NBS for water is evaluated through robust analysis, which is a method that provides insight into how the magnitude of the HMH impacts the biophysical structure and/or ecological processes. Robust analysis involves the construction of a response curve based on the relationship between the magnitude of the HMH and the response of the robust NBS for water using selected indicators of robustness. Construction of a response curve enables for a quantifiable visualisation of the robustness offered by a robust NBS for water. In the present study, the response curve for a robust NBS for water had the following four quantitative indicators of robustness [39,40,47,48] – see Fig. 2:

1 Lower Resistance Threshold: the point when a robust NBS for water shifts from no response, after the design criteria has been exceeded, to a noticeable change in response from a known HMH. Enhancing individual qualities or characteristic features of a NBS for water through robust parameter design can influence the lower resistance threshold of a robust NBS.
2 Proportionality: the sensitivity of the response of a robust NBS for water to changes in the magnitude of the HMH, in other words, the response of the robust NBS for water with progressive increase in the magnitude of the HMH. The response and recovery of an NBS can be influenced through robust control and transformation of ecosystem service delivery during an HMH.
3 Manageability: the ability of an NBS for water to maintain a response level that is easy to recover from or is below the upper resistance threshold/recovery threshold
4 Upper Resistance Threshold: this is the point of no recovery, that is, a state where the impact of a known HMH on the robust NBS for water does not allow for it to recover. The upper resistance threshold of a robust NBS water can be influenced through robust parameter design.

2.4. Proposed process for designing and evaluating robust NBS for HMR reduction

The robust design process is focused on enhancing site-specific characteristic features or qualities of the biophysical structure and/or ecological processes. NBS are context specific, therefore, the robust design process requires an understanding of the characteristics of the HMH (e.g., magnitude and probability of occurrence), the implementation site (e.g., characteristic of the biophysical structure and ecological processes), and local value systems (e.g., local perception and interest in natural capital). Once these insights have

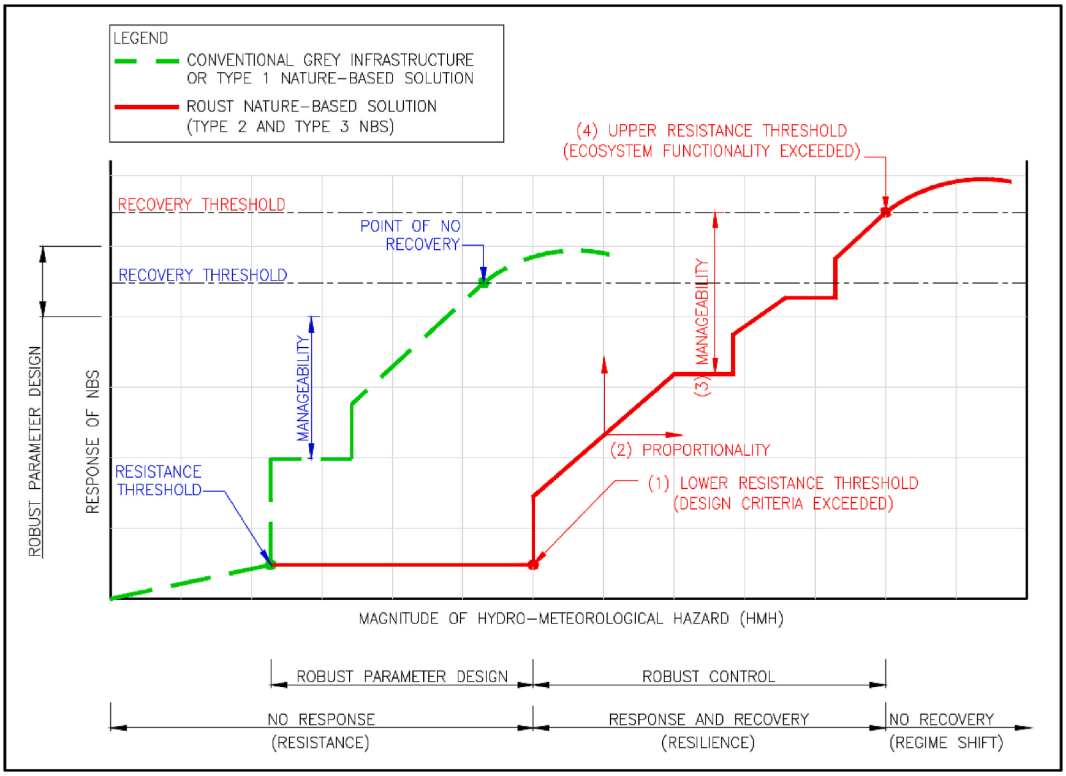

Fig. 2. Present study – response curve of a robust NBS for water (modified from [35].

been gained, a robust NBS for water can be achieved by incorporating robust design into the biophysical structure and/or ecological process to influence or enhance the delivery of preferred ecosystem services. In the present paper, robust design is characterised into [41]:

- *Robust parameter design*, which involves enhancing distinct qualities or characteristics features of the biophysical structure or ecological processes to create a permanently robust NBS to a known HMH with varying magnitudes; and
- *Robust control,* which is the temporary control of the type and level of ecosystem services delivered by a robust NBS for water during a known HMH of a given magnitude.

The evaluation process is focused on quantifying the robustness achieved through the robust design method. This is done through robust analysis [39,47], which is a method that can be used to gain insight into the relationship between the magnitude of a HMH and the response of the a robust NBS for water. Robust analysis involves the construction of a response curve that allows for a quantifiable visualisation of the robustness of an NBS for water through quantitative indicators.

The proposed process will enable decision-makers to determine key operational parameters of a robust NBS for water by enabling robustness to be designed into the NBS and for that robustness to be quantified by clearly defined indicators that are easily measured and interpreted. The systematic method of the process proposed in this paper forms a loop that allows for an iterative process in designing and evaluating a robust NBS for water. The process for designing and evaluating robust NBS for water developed in the present study is presented in Fig. 3.

3. Application of the proposed process

3.1. Case study area

Geographically, the Bangkok Municipal Region (BMR) is located in the Central Region of Thailand, forming part of the floodplain adjacent to the Gulf of Thailand – see Fig. 4. The floodwaters of the Lower Chao Phraya River Basin (Lower basin) drain through the BMR on their way to the Gulf of Thailand See Fig. 4 and Table 1 for details. The BMR plays a major role in driving the Gross Domestic Product (GDP) of Thailand. It comprises of five provinces, namely Bangkok, Samut Prakan, Nonthaburi, Samut Sakhon, Nakhon Pathom, and Pathum Thani. Bangkok province is the most populated of the 6 provinces that make up the BMR, with Samut Prakan being the second most populous province. The third most populated province is Nonthaburi, which is the major residential zone of the region, also acts as the centre for the government. Samut Sakhon and Nakhon Pathom are the least populated provinces, contributing a supporting role to the region, mostly the eastern side of the Chao Phraya River by serving as important agricultural activities and fishing areas. Pathum Thani is a complex mix of residential zones that support a populous from the Norther parts of Thailand, industrial areas, as well as being the centre of education and research for science and technology.

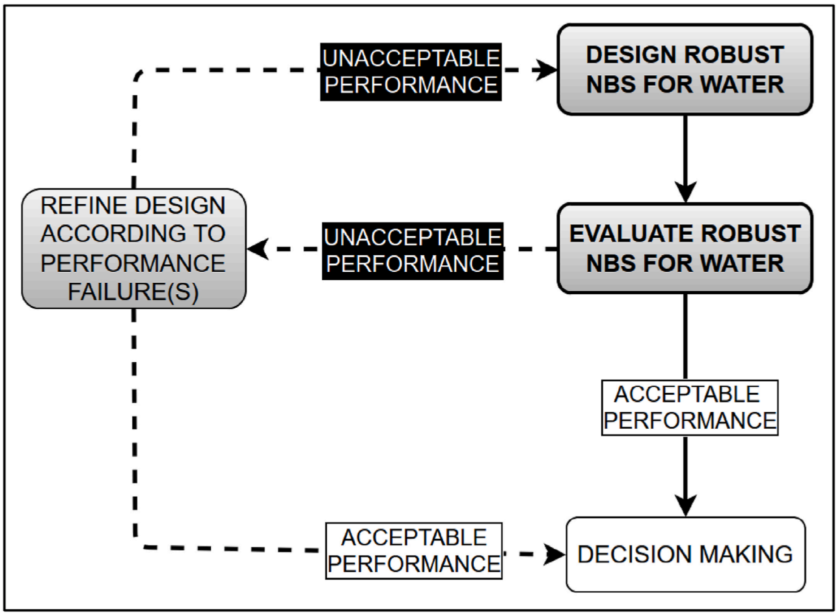

Fig. 3. Present study – process for designing and evaluating robust NBS for water.

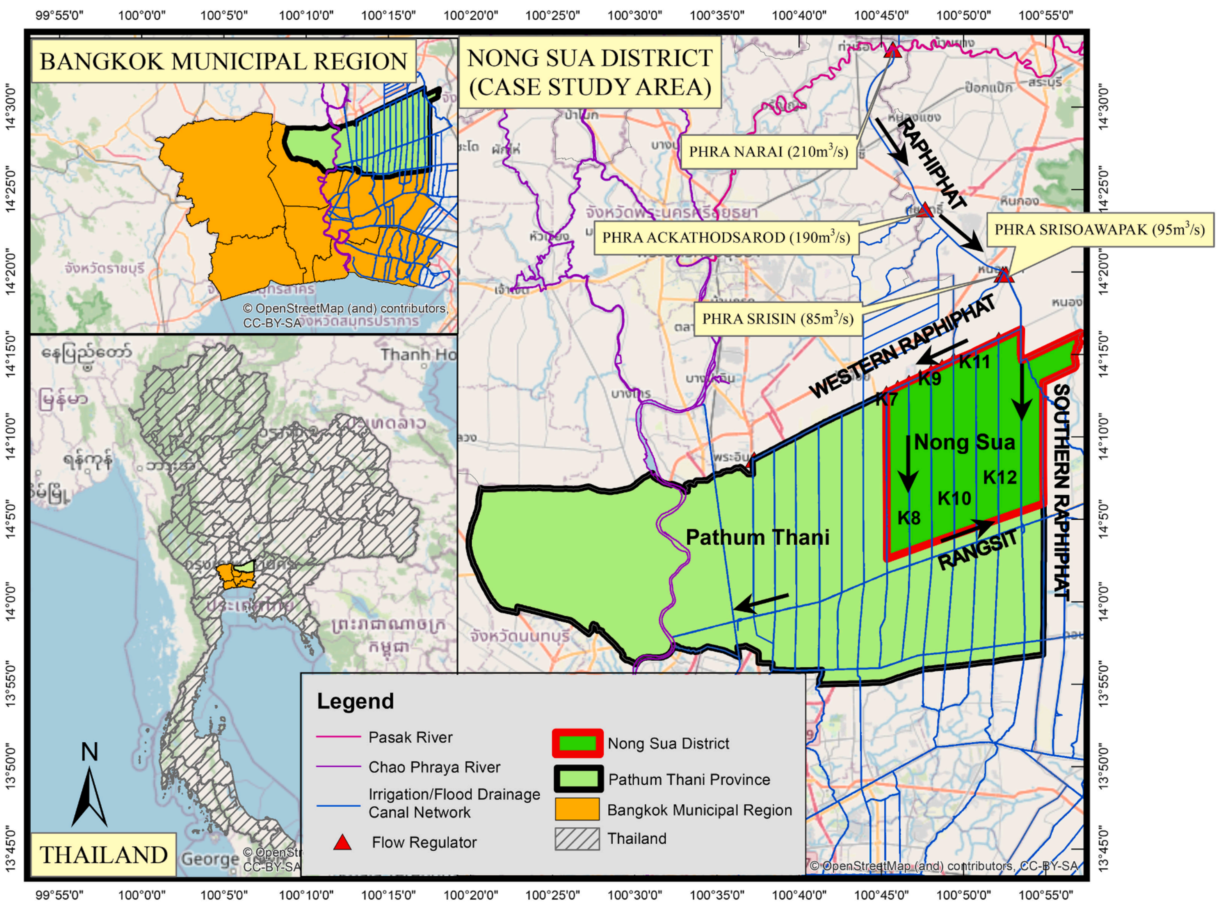

Fig. 4. Flood risk management system in case study area.

Table 1
Irrigation and drainage canals in the case study area.

Main Canal System	Maximum Discharge (m^3/s)
Raphiphat	215.00–170.00
Western Raphiphat	40.00
Southern Raphiphat	80.00
Rangsit	45.00
Sub-Canal system (Case Study Area)	Maximum Discharge (m^3/s)
Klong 7	15.00
Klong 8	15.00
Klong 9	15.00
Klong 10	30.00
Klong 11	15.00
Klong 12	15.00
Irrigation Furrows	

Over a 32-year period, from 1985 to 2016, 69 major flood events were observed in Thailand. From these floods, the ones with the most server consequences with regards to extent of affected area, deaths or displacement, and damage to assets were recorded in 1995, 1996, 2000, 2002–2007, 2010, 2011 and 2016 [49]. Historically, flood waters could overflow from the rivers onto the Lower Basin and slowly flow back into the cannel network later after the flood peak discharge had passed. Frequent floods were drained by the network of canals that criss-crossed the Lower Basin.

The effectiveness of the Lower Basin to disperse flood water and reduce the flood wave when passing through the area has been reduced by rapid land development, resulting in long-existing watercourses such as canals, ditches, and ponds to be filled in or replaced by roads, and separated by embankments. Consequently, the region is unable to drain local runoff from heavy monsoon rainfall and river overflow water discharged from the Upper Chao Phraya River Basin (Upper Basin) – leaving the area exposed to extensive riverine flooding [50,51]. Economic growth in and around Bangkok has drastically changed the landscape of the Lower Basin and with it the flood risk within the floodplain. The private sector has developed properties and placed assets of high value in flood prone areas – resulting in an urgent need for flood mitigation measures. The natural canals of the lowland areas of the Lower Basin do not have the hydraulic structures to control and retard floodwater, therefore the use of irrigation areas to store excessive flood waters has become a more feasible solution in alleviating local and downstream flooding [51].

The case study area, Nong Sua, is a district in the Province of Pathum Thani within the BMR. Nong Sua District is part of "Northern Rangsit" — an agricultural area within the floodplain of the Chao Phraya River Basin with flow regulators and traditional irrigation furrows [52] (see Fig. 5). The case study area has a total area of 54.48 km^2, of which 44.16 km^2 is used for agricultural purposes Due to being located within a floodplain, Nong Sua district has a very flat topography slope (0–3%) [53], and is braided with numerous man-made and natural canals that link major rivers to the Gulf of Thailand. A diversion dam in the Paska River (a tributary to the Chao Phraya River) diverts river water via the Phra Naria flow regulator into a gravity feed irrigation canal (Raphiphat) that further diverts into the Southern Raphiphat canal and Western Raphiphat canal at the Phra Srisoawapak and Phrasirisin flow regulators, respectively. From the Western Raphiphat canal, water drains through the case study area (Klong 7–12) and into the portion of the

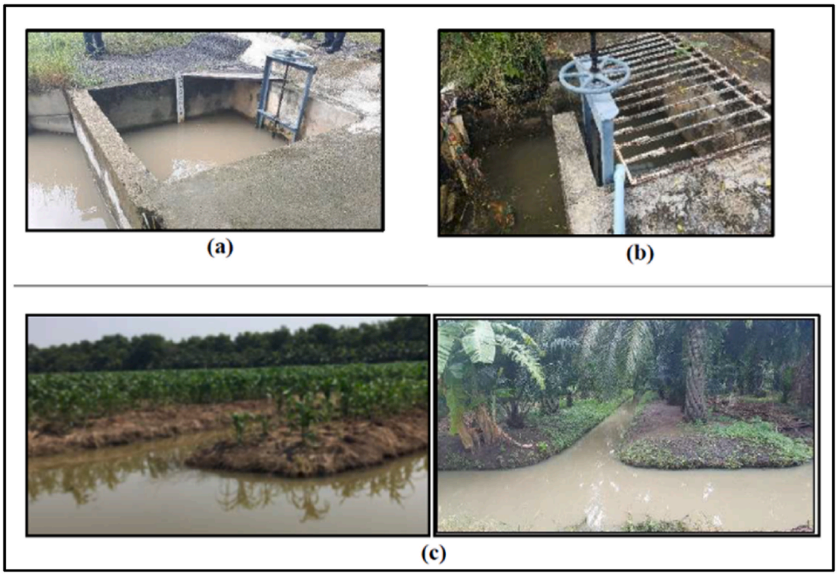

Fig. 5. (a)Flow regulator; (b) Water Gate; (c)Irrigation Furrows.

Rangsit canal draining towards the Southern Raphiphat canal. The Pasak River Dam and canal network are administrated by the Royal Irrigation Department (RID). The network of canals within the case study area are operated through the collaborative efforts of the Hydro Informatics Institute (HII) of Thailand and the Rangsit farming Community. This river water diversion system has two objectives, which are mainly: (i) to supply irrigation water to the agricultural area of Rangsit; and (ii) to mitigate flooding by diverting flood water to the Gulf of Thailand [54].

The monsoon season (wet season) in the Rangsit area usually occurs from May to October and the dry season from November to April [28]. The main canal system is used for the distribution of river water for agricultural activities from January to August. From September to December, when the runoff from the mountainous Upper Basin reaches the floodplain of the Lower Basin, the main canal system is used for flood water drainage and the sub-canal systems is used for both flood water drainage and storage. Throughout the flood season, the discharge of the flow regulators in the Raphiphat canal is increased to drain flood water from the Pasak River to the Gulf of Thailand.

After the 2011 flood, the farming community of Nong Sua district decided to increase the storage capacity of the agricultural area by expanding and deepening the network of traditional irrigation furrows. Thus, mitigating local and downstream flooding of the Bangkok Municipal Region (BMR) [28,55], while aslo exploiting the co-benefits from the stored flood water. During extreme flood events the agricultural area of Nong Sua districts is used for flood risk management through the implementation of a locally preferred water management measure known as Monkey Cheeks [56]. Monkey Cheeks (Kaem Ling) is a flood control measure that was initiated by King Bhumibol Adulyadej (King Rama IX) of Thailand, in response to the flooding in the country caused by excessive rainfall, rapid urbanization, land use changes, and insufficient drainage and flood protection systems. The king observed that monkeys stored food in their cheeks when foraging and would gradually chew and swallow the food at an appropriate time. This concept has been applied to the temporary detention of excessive floodwater during flood season and the gradual drainage of the water once the flood water level has receded. The concept of Monkey Cheeks was used in the case study area during the 2016 flood to temporary detain excessive flood water diverted from the Pasak River, and successfully prevented a flood event.

When comparing the agricultural area in the case study area and those in the south of Thailand, the existing NBS (irrigation furrows) in Nong Sua district provides social, environmental and economic benefits for the local farming community. These co-benefits are realised through the farming community in Rangsit being able to mitigate flood risk during the wet-season and exploit the benefits of flood water storage to grow crops in the dry-season. This ensures the availability of irrigative water all-year round for the farming community in Nong Sua district [28]. The network of man-made and natural canals provides connectivity within the floodplain and between the rivers and the Gulf of Thailand. Each agricultural area within Nong Sua district has distinct characteristics with regards to the type of crop, land use management, economic value of the crop and cultural values. Therefore, the agricultural practices in the case study area are diverse, with constantly changing cropping patterns [56]. This is due to the age, income, household size, distance from the market and farming experience of the local community [57].

3.2. Designing a robust NBS for flood risk management

The chosen case study area, Nong Sua District, is an existing NBS [28], and was strategically chosen to facilitate the illustration of designing a robust NBS for flood risk reduction, while simultaneous exploiting the co-benefits of flood water storage. As mentioned in Section 3.1., the NBS in Nong Sua District forms part of a pre-established flood emergency procedure by the RID. The procedure prevents the flood peak wave from the Pasak River coinciding with the flood peak wave from the Chao Phraya River during extreme rainfall periods - which happened during the 2011 flood. The diversion of flood water from the Pasak River also mitigates flooding of the ancient city of Ayutthaya, a UNESCO World Heritage site [58], Bangkok – the nation's economic hub [50], and major industrial zones [49].

The traditional irrigation furrows in the agricultural area are used for slowing and storing flood water during extreme flood events [52]. Robust design is incorporated into the existing NBS as shown in Figs. 6 and 7. As mentioned in Section 3.1., the local farming community of Nong Sua decided to deepen and expend the irrigation furrows in the case study area. Therefore, providing the existing NBS with a certain level of robustness. Integrating grey infrastructure into the biophysical structure enhances the hydraulic performance of the flood water drainage system and allows for temporary transformation of the water storage benefit derived from the ecosystem functions offered by the floodplain. Increased depth of the irrigation furrows enhances the storage capacity for flood water. The water storing ecosysetm offered by the traditional irrigation furrows is enabled by the flat topography of the floodplain and vegetation robust to flooding, such as, the previously planted orange tresses and the current oil palm trees which allow for moderate levels of inundation of the plant bed within the agricultural area without incurring crop damage. A perimeter dike around the agricultural area prevents uncontrolled flooding of the surrounding environment when controlled inundation of the agricultural area is necessary.

3.3. Evaluating a robust NBS for flood risk management

As mentioned in Section 3.1., the method used to quantify the robustness of the existing NBS to flood risk, utilises consolidative modelling to quantify the defined indicators of robustness. However, it should be mentioned that one of the critical aspects that affects the successful application of modelling software is the expertise of the users. Specifically because the user is required to conceptualise the physical world within a mathematical hydrodynamic model. Additionally, the user is required to select appropriate performance and physical structure data, to calibrate the model, in order to apply it to developed scenarios, and interpret the results sensibly [56].

Therefore, the present study modified an existing one-dimensional (1-D) hydrodynamic model, that had been setup, calibrated and validated by Ref. [52]. Within the model domain, robustness of the existing NBS (implemented as the locally preferred Monkey

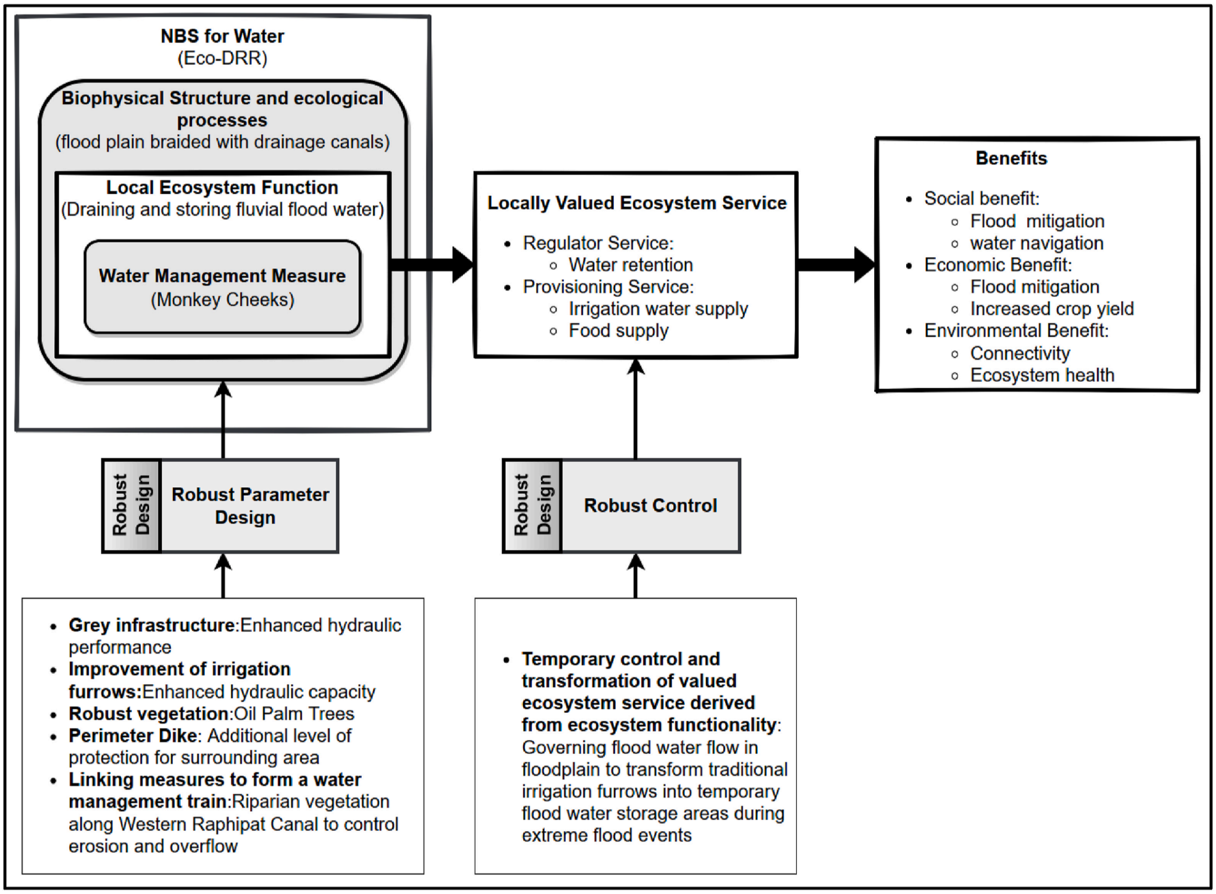

Fig. 6. Robust Design incorporated into existing NBS in Case Study Area.

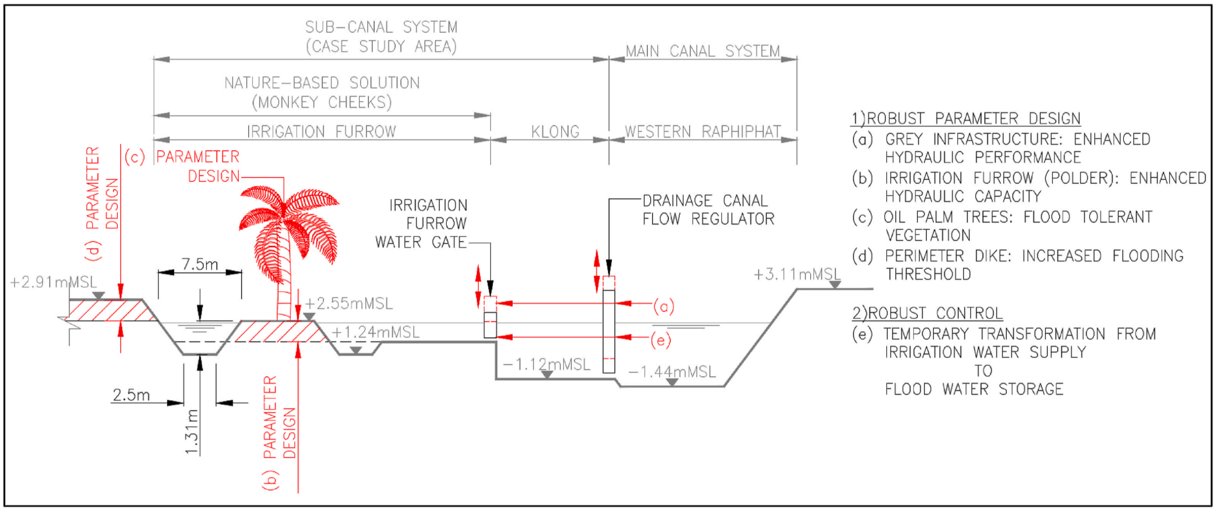

Fig. 7. Robust Design Parameters of existing NBS in Case Study Area.

Cheeks measure) was evaluated as a water management measure and as part of the flood risk management system administrated by the RID.

The robustness of the Monkey Cheeks measure in the case study area, was demonstrated using a mathematical hydrodynamic model developed by the Dansih Hydraulic Institute (DHI), MIKE Hydro River software package. The 1-D hydrodynamic model domain consisted of the following boundary conditions – see Fig. 8:

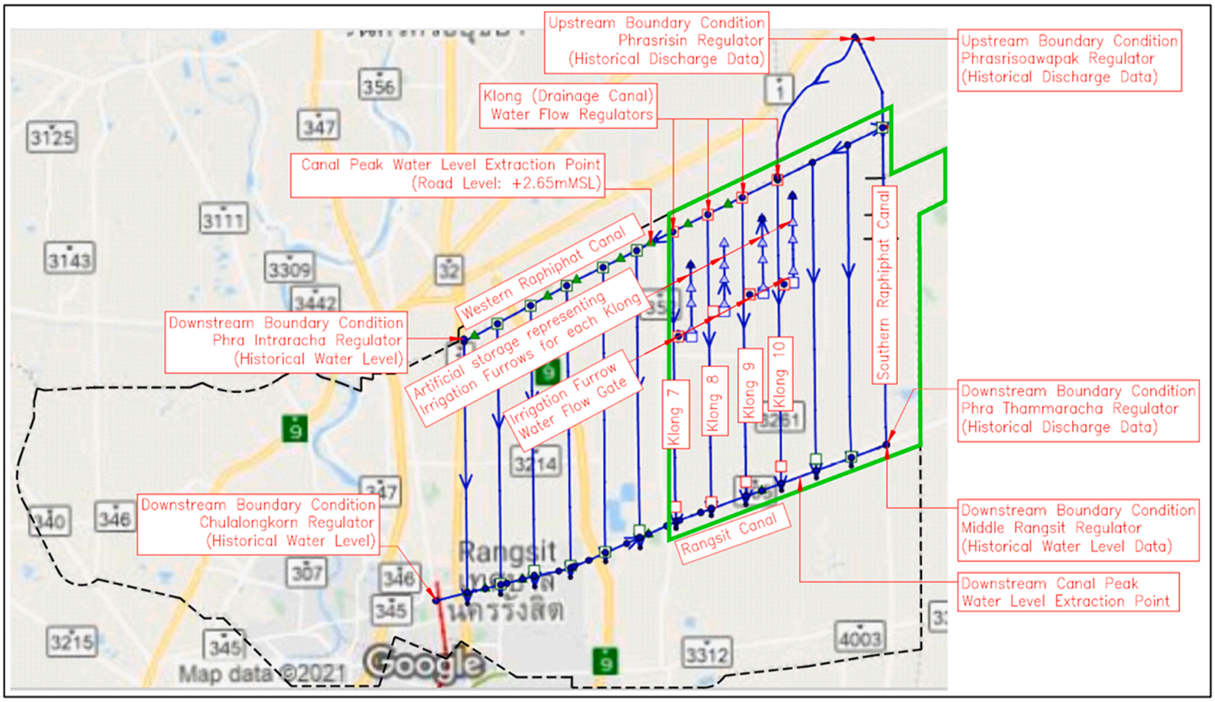

Fig. 8. Model domain and boundary conditions for case study area.

- Upstream boundary conditions at Phrasrisin regulator and Phrasrisoawapak regulator on the Raphiphat canal which were the historical flood water discharge;
- Downstream boundary conditions at Phra Intraracha regulator, Middle Rangsit regulator, Chulalongkorn regulator which were the historical water levels;
- Downstream boundary condition at Phra Thamaracha regulator which are the historical flood water discharge;
- Downstream boundary conditions for Klong 1 to Klong 12 are the Q/h relationship of the drainage canal; and
- Artificial storage areas which represent the irrigation furrows in Klong 7 to Klong 10

This present study evaluated the robustness of the existing NBS by defining the indicators of robustness for the flood drainage system and the existing NBS. This allowed for the use of the robust analysis method to quantify the robustness of the flood drainage system and the existing NBS during the 2016 flood. The same was done for the 2011 flood event that caused severe economic damage to major sectors of the country (e.g., agriculture, manufacturing, tourism, and private property). For example, the inundation of six (6) major industrial zones in the province of Pathum Thani and the neighbouring Phra Nakhon Si Ayutthaya Province between the middle of October 2011 and the month of November 2011, caused approximately 70% of the total damage recorded in the manufacturing sector [49].

Applying the robust analysis method in the construction of a response curve for the existing NBS in Nong Sua district, the present study was able to quantify and understand the relationship between the magnitude of the flood peak discharged into the Western Raphiphat canal (main drainage canal) and the flood water storage level in the irrigation furrows (sub-canal system). In the present study, the HMH was defined as the flood peak discharged into the Western Raphiphat canal during the RID emergency flood procedure. The rang of magnitude for the flood peak discharged into the Western Raphiphat canal varied from 55 m^3/s (2016 flood) to 150 m^3/s (2011 flood), which is a range that exceeds the maximum design capacity (40 m^3/s) of the Western Raphiphat canal.

Within the model domain, a peak flood discharge ranging from the 2016-Flood to the 2011-Flood events was drained from the Western Raphiphat canal via Klong 7 to Klong 10 and stored in the irrigation furrows as part of the locally preferred flood risk management strategy referred to as Monkey Cheeks. To construct the response curves for the Western Raphiphat canal it was decided to use the following indicators of robustness during robust analysis (shown in Fig. 9):

- **(1) Resistance threshold**: For the Western Raphiphat canal, this point was determined to be the incremental flood peak discharge into the Western Raphiphat canal that caused flood water level in the canal to rise above +2.65mMSL. This point was a pre-defined operational level that prevented a major roadway that crosses the canal, and had subsided due to over abstraction of groundwater, from creating a flood pathway for uncontrolled flooding of the surrounding environment.
- **(2) Proportionality:** the extent of water level rise in the Western Raphiphat canal with the incremental flood peak discharge at the Phrasrisin regulator. That is, th relationship between the flood water level in the Western Raphiphat canal and a flood peak ranging from 55 m^3/s to 160 m^3/s discharged into the canal.

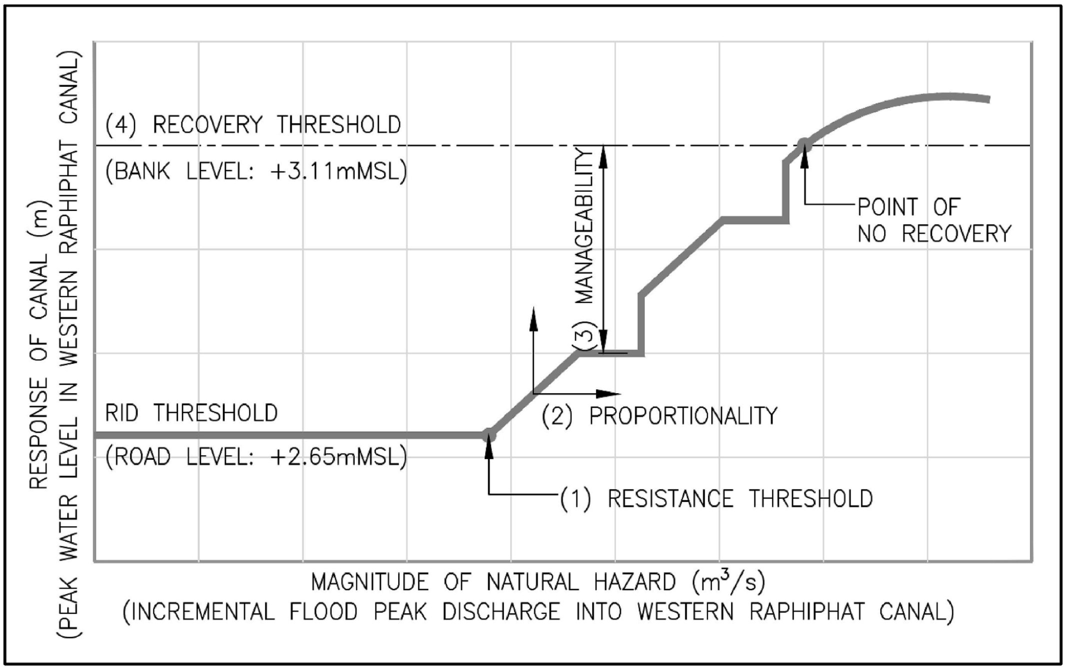

Fig. 9. Response curve for the western raphiphat canal.

- **(3) Manageability:** the ability of the flood drainage system, with and without the NBS, to maintain a flood peak water level that was below the bank level (+3.11mMSL). That is, maintaining a water level in the Western Raphiphat canal that prevents overflowing of the canal's banks with the progressive increase in the flood peak discharged at the Phrasrisin regulator.
- **(4) Recovery threshold:** a water level that exceeds the bank level (+3.11mMSL) of the Western Raphiphat canal and results in the inundation of local and downstream areas.

To construct the response curves for the existing NBS (irrigation furrows), it was pragmatical decided to use the following indicators of robustness during robust analysis (shown in Fig. 10):

- **(1) Lower Resistance Threshold**: For the irrigation furrows, this point is considered the flood water level at which there is a shift from no response to a requirement for the traditional irrigation furrows to be temporarily controlled and transformed from irrigative water use to flood water drainage and storage. Therefore, this was considered a shift from no response to a noticeable change in the flood water storage level in the traditonal irrigation furrows during the incremental flood peak discharge into the Western Raphiphat canal. This threshold was choosen as a flood water level above +1.53mMSL in the irrigation furrow. This was because water is maintained in the traditional irrigation furrows all year round to regulate soil qulaity and for navigation by mire boats designed by the local farming community.
- **(2) Proportionality:** the extent of water level rise in the irrigation furrows with the incremental flood peak, ranging from 55 m^3/s to 160 m^3/s, discharged into the West Raphihat canal at the Phrasrisin regulator. That is, the relationship between the magnitude of the flood peak discharge into the main canal system and the flood water depth in the sub-canal system (traditional irrigation furrows or existing NBS).
- **(3) Manageability: a)** the ability of the traditional irrigation furrows to maintain a flood water level that was below the economic recovery threshold during the progressive increase of the flood peak discharged into the Western Raphiphat canal. The economic recovery threshold was choosed as a water level that is below the plant bed level (+2.55mMSL). In the present study, a water level above the plant bed was assumed to result in a loss of income for the farms from the crops being damaged by flood water; and **b)** the second level of loss from flood water damage was a water level that exceeded the top of the permitter dike (+2.91mMSL). These two levels of manageability are enabled by the robust design of the existing NBS.
- **(4) Upper Resistance Threshold: a)** a water level that exceeds the plant bed level (+2.55mMSL) in the traditional irrigation furrows. **b)** A flood water level that exceeds the height of the perimeter dike wall. As was mentioned, the present study used a 1-D hydrodynamic model to evaluate the robustness of existing NBS. And as such, scenarios that explored the relationship between the upper resistance threshold of the exisitng NBS and the magnitude of the flood peak discharged into the Western Raphiphat canal could not be determined as this would require a 2-D hydrodynamic model to simulate overland flow.

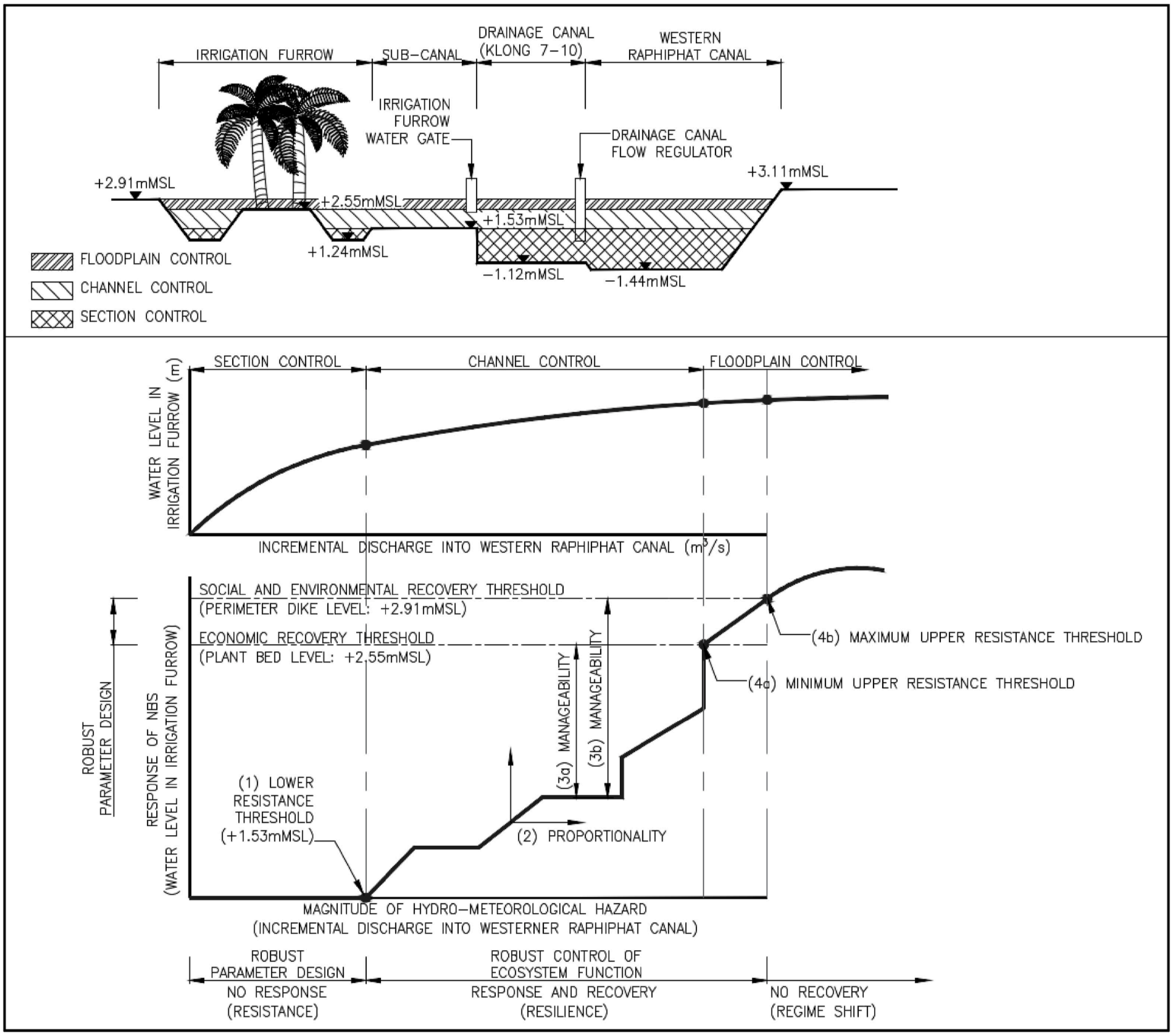

Fig. 10. Response Curve for the Irrigation furrows.

4. Results

4.1. Evaluating a NBS for flood risk management

Constructing a response curve of the Western Raphiphat canal to a flood peak discharge ranging from 55 m^3/s to 160 m^3/s, provided several insights into the relations between the main canal system and the magnitude of the HMH. The results from the evaluation of the main canal system in the Case Study Area are presented in Fig. 11. Robust analysis of the main canal system (specifically the Western Raphiphat Canal) with and without the existing NBS provided insight into the robustness offered by the Monkey Cheeks measure to the main canal system. Without the existing NBS, the water level in the main canal system exceeds the recovery threshold in the Western Raphiphat canal (+3.11mMSL) at a flood peak discharge of approximately 70 m^3/s. That is, without the existing NBS forming part of the flood risk management systems, the Western Raphihat canal would breach its banks once the flood peak discharge exceeded the design capacity (40 m^3/s) by roughly 30 m^3/s – causing local and downstream flooding. Therefore, in the present study, the flood water level in the Western Raphiphat canal is used as an indicator of robustness; it represents the ability of the existing NBS to increase the robustness of the flood risk management system to extreme flood events (e.g., a 1:100-year flood event). Incorporating the existing NBS into the flood risk management strategy established by the RID, together with the collaboratively operation of the sub-canal system by HII and the local farming community of Nong Sua, enables the Western Raphiphat canal (main canal system) to maintain functionality beyond a flood peak discharge of 160 m^3/s.

As mentioned in Section 3.3., maintaining a flood water depth that was below the level of +2.65mMSL in the Western Raphiphat canal was critical to preventing uncontrolled inundation of local and downstream urban and industrial areas during the 2016 flood. This level was chosen because it was the level of a major road that crossed the canal and had subsided due to the over abstraction of groundwater, therefore, creating an obstruction across the flow of flood water in the canal and a potential flow path to channel water

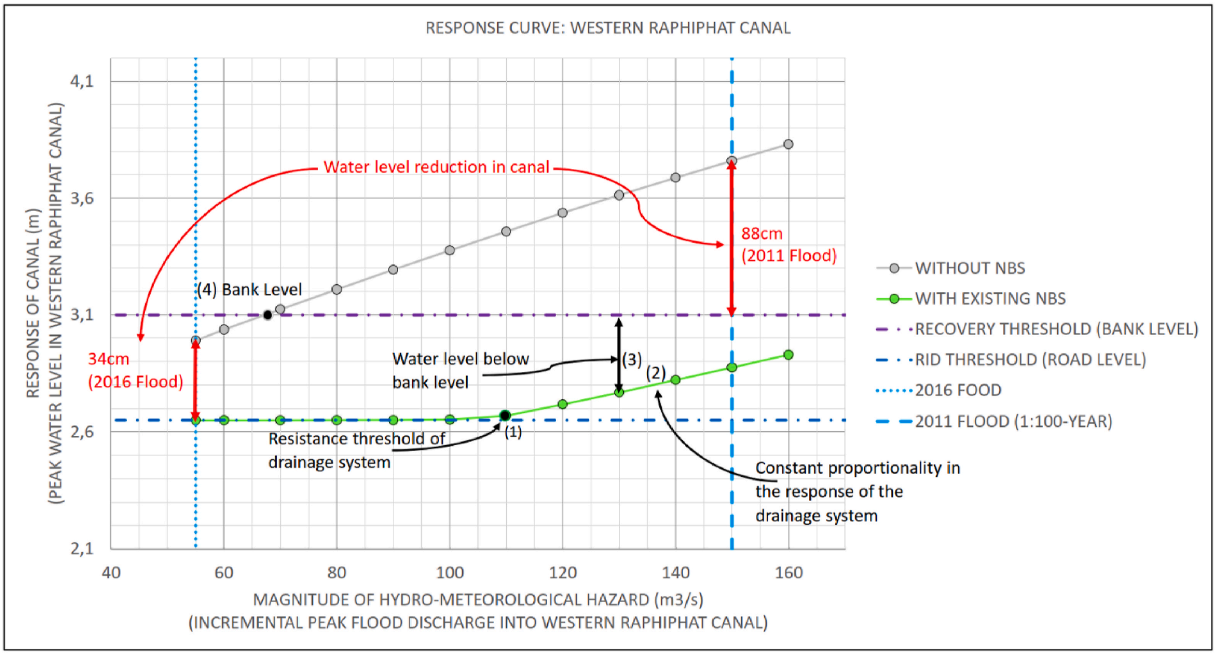

Fig. 11. Response curve for western raphiphat canal.

away from the canal. Hence, during the 2016 flood, collaborative efforts between HII and local farming community successfully achieved a water level reduction in the Western Raphiphat by diverting water into the existing NBS.

However, from Fig. 11, it can be seen that the Western Raphiphat canal is not able to maintain the expected RID water level (+2.65mMSL) beyond a flood peak discharge of 100 m^3/s. Therefore, the present study proceeded to use the proposed robust design method for NBS to optimise the efficiency of the existing NBS (sub-canal system) in order to maintain the required flood water level in the Western Raphipht Canal (main canal system) up to a flood peak discharge of 160 m^3/s – which is a flood peak greater than the 150 m^3/s flood peak that was discharged into the Western Raphiphat canal during the 1:100-year flood event in 2011. Additionally, the 2011 flood is of interest because the of the combination of factors that caused the flood event. During the rainy season of 2011, Thailand experienced five tropical storms that resulted in increased precipitation. The accumulated precipitation (1823 mm) from the monsoon season (mid-May to October) and the five (5) tropical storms between June and October resulted in a 28% increase in average rainfall (1426 mm), when compared to the previous 9 years (2002–2010) [49]. With the projected increase in the frequency and intensity of flood events due to anthropogenic climate change, a future where consecutive storms surges coincide with or occur during Thailand's monsoon season is highly plausible. Therefore, robust NBS implemented for flood risk reduction (FRR) should be able to mitigate the impact of this HMH on the physical environment and socio-economic systems.

4.2. Optimising individual parameters of an NBS for water

Using 1-D hydrodynamic modelling, the present study used robust parameter design to further enhance individual characteristics of the existing NBS to enable more efficient robust control of the NBS for water during extreme events – thereby, increasing the robustness of the existing NBS to create a "robust NBS". The robustness of the existing NBS was enhanced as detailed in Table 2 and shown in Fig. 12. Through an iterative method of trial and error the present study optimised the number of inlet structures (flow regulators) at each of the drainage canals (Klong 7 to Klong 10) to enhance the hydraulic efficiency of the existing NBS. Increasing the number of follow regulators allows for more water to be drained from the Western Raphiphat canal into the existing NBS during extreme flood events.

The present study was able to quantify the additional robustness offered to the main canal system (specifically the Western Raphiphat canal) by the robust NBS. With the robust NBS, the flood water level in the Western Raphiphat canal can be maintained at the expected RID water level (+2.65mMSL) up to and beyond the 1:100-year flood peak discharged into the canal – as shown in Fig.

Table 2
Enhancing the robustness of the Existing NBS to create a Robust NBS.

Sub-canal system	Existing NBS	Robust NBS
Klong 7	1	6
Klong 8	1	5
Klong 9	1	3
Klong 10	1	2

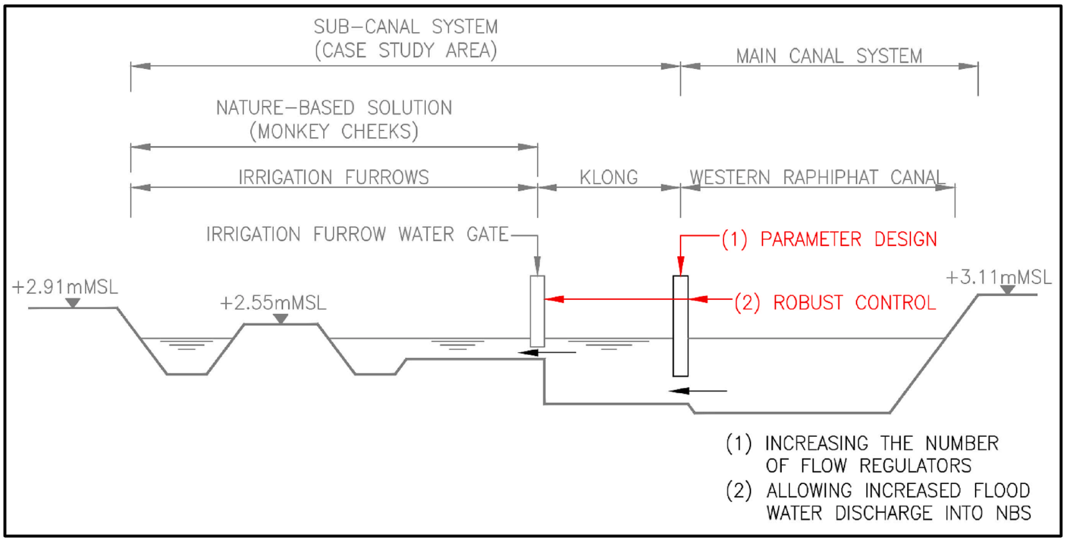

Fig. 12. Enhancing the robustness of the Existing NBS through robust design
(1) Increased the number of flow regulators/inlet structures into the drainage canals (Klong 7 to Klong 10)
(2) Increase in the number of flow regulators/inlet structure allows for more flood water to be drained into the NBS.

13. The increased flood water volume diverted into the traditional irrigation furrows, caused the water storage levels to rise within the furrows – thus increasing the efficient use of the hydraulic capacity offered by the NBS – see Figs. 14 and 15. The increase in flood water discharge into the drainage canals, Klong 7 to Klong 10, has the potential to significantly influence the water level in the Rangsit canal – which is located downstream of these drainage canals. Therefore, an investigation into the water level in the Rangsit canal showed that the incremental flood peak discharge from 55 m^3/s to 160 m^3/s into the drainage system had an insignificant influence on the water level in the Rangsit canal as shown in Fig. 16. Thus, confirming the potential robustness that could be achieved with the existing NBS through robust design..

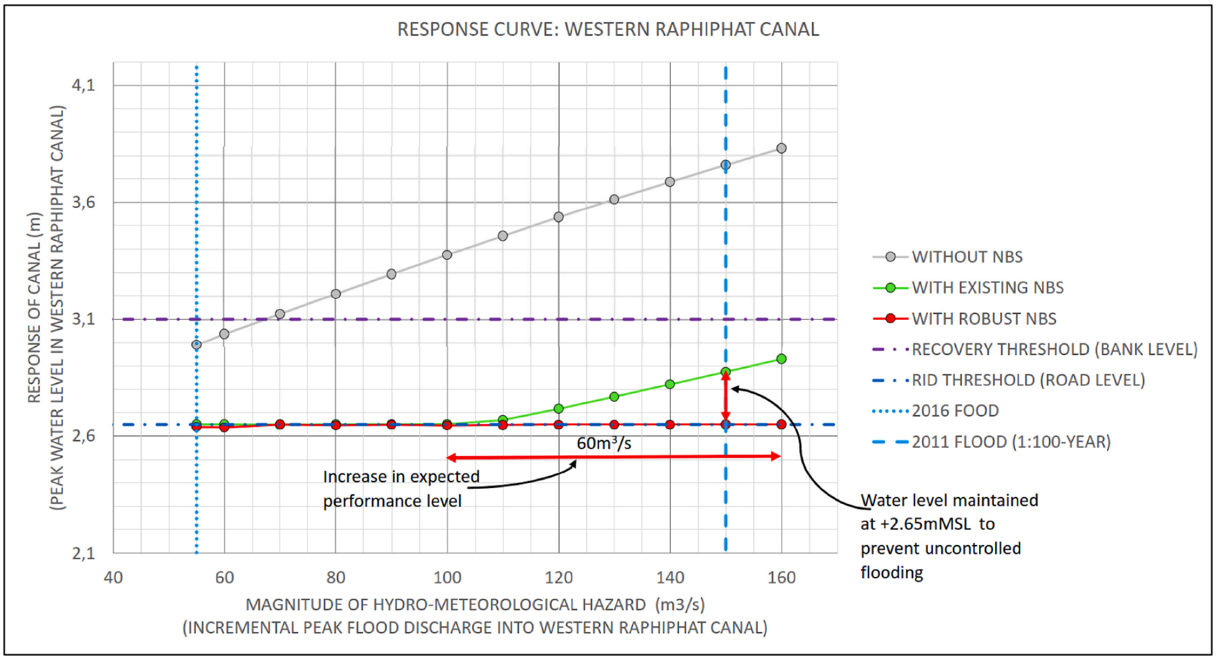

Fig. 13. Response Curve for Western Raphiphat Canal (enhanced robustness).

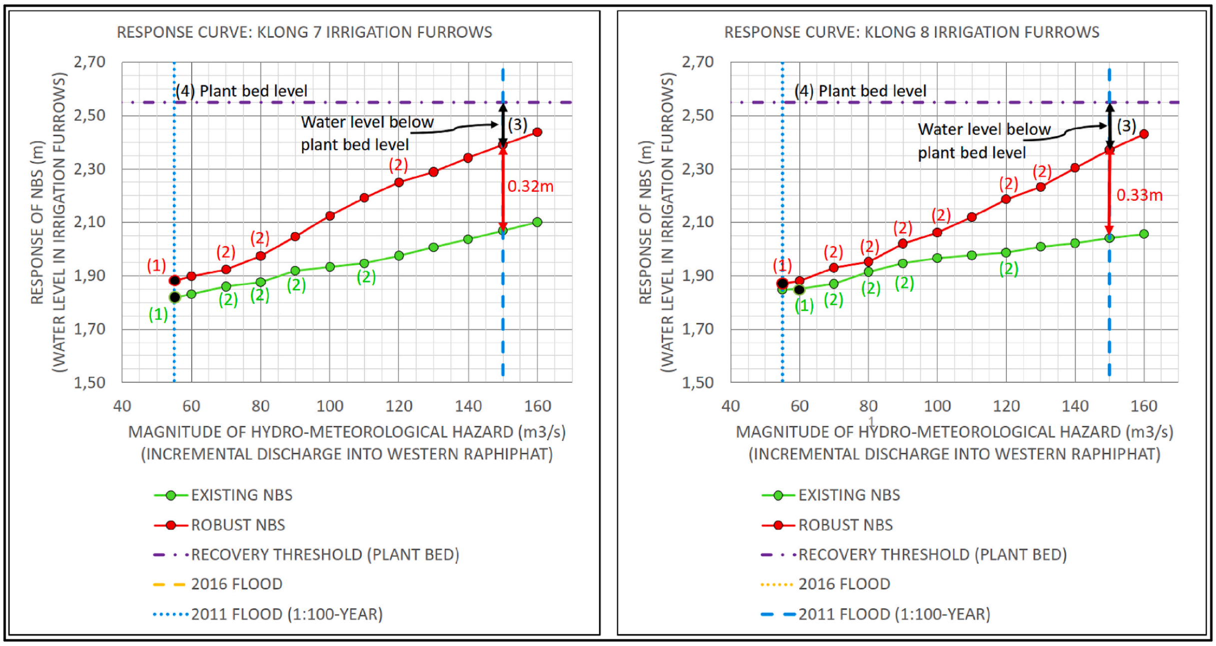

Fig. 14. Response Curve for Irrigation furrows in Klong 7 and Klong 8.

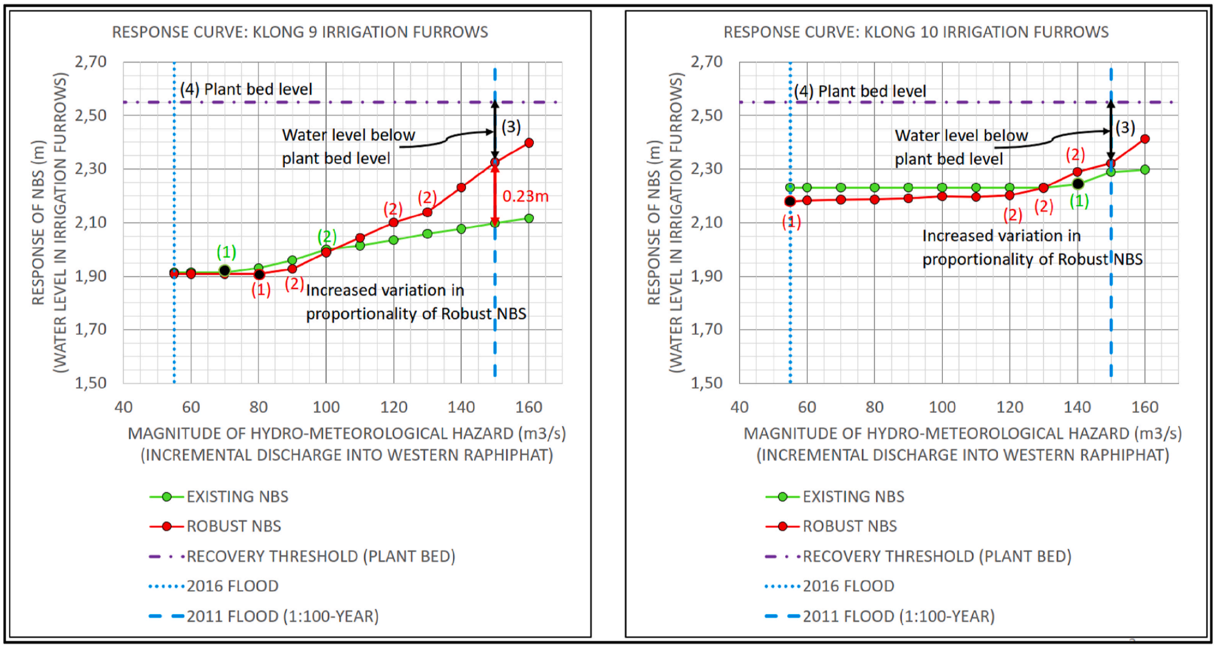

Fig. 15. Response Curve for Irrigation furrows in Klong 9 and Klong 10.

5. Discussion

NBS for water are implemented by means of measures or actions that utilise the biophysical structure and/or ecological processes to address societal challenges. These actions at the same time alter socio-ecological interactions through transformative economic, environmental, and social co-benefits [59]. When NBS for water are implemented for the purpose of addressing risk reduction, they can simultaneously provide multiple water-related benefits such as improved water quality and regulation of water quantity [31]. For example, NBS implemented for the primary benefit of addressing water-related risk caused by natural hazards (e.g., floods and droughts), can simultaneously offer co-benefits, such as irrigative water and ground water recharge.

Hence, this study proposes a systematic approach to designing robust NBS to manage, restore and create sustainable ecosystem as a solution to HMRs. The work presented in the present study, firstly demonstrated how incorporating NBS into flood risk management

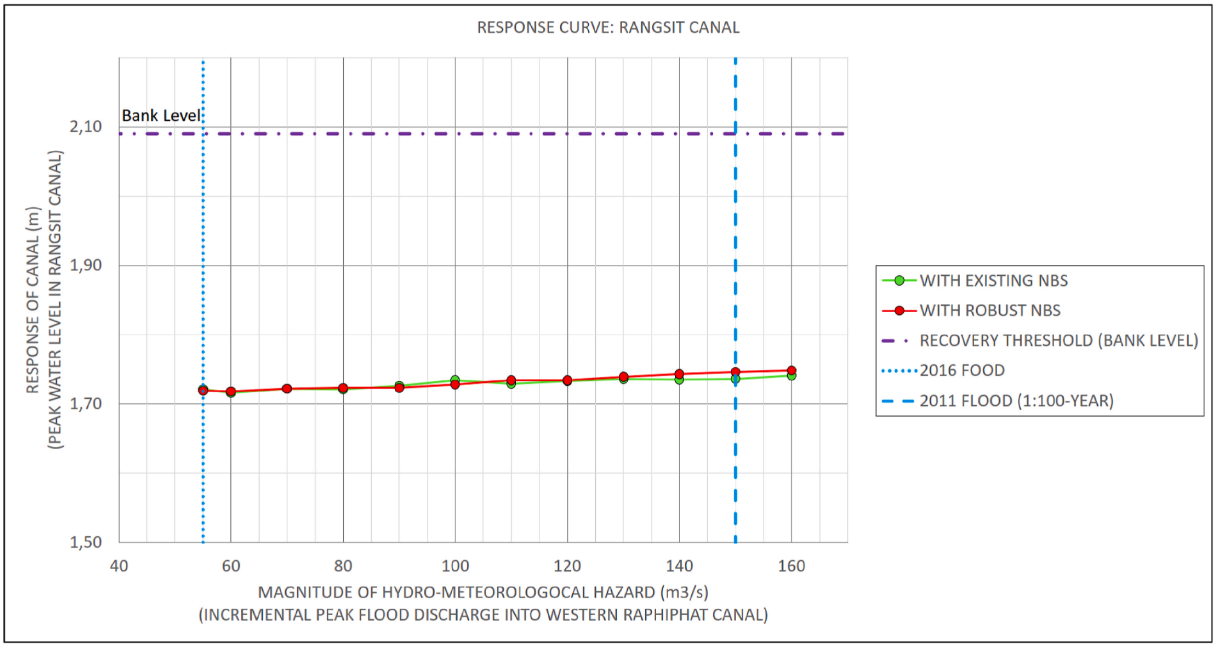

Fig. 16. Response curve for Rangist canal.

systems can increase their robustness to extreme flood events. Secondly, the study demonstrated: i) how a NBS for water can be designed to increase durability and/or tolerance to a known HMH - ensuring effectiveness; and ii) how a NBS for water can be designed to ensure efficiencientdelivery of valued or preferred ecosystem services during a known HMH. The proposed robust design process will increase the resilience of social, environmental, and economic systems and ensure they avoid disasters, while simultaneously allowing for the exploitation of co-benefit.

The main challenge in the design of NBS has been the fundamental application of the ecosystem services concept to decision-making and risk management processes [60–62]. Therefore, the present study used the cascade model, developed by Haines-Young and Potschin [63], to simplify the complex relationships that exists between ecosystems and various local communities and also as a mechanism to structure the incorporation of robust design of a NBS into the biophysical structure and ecological processes. This is because, NBS provide goods and services derived from the ecosystem functions of a biophysical structure. Therefore, the inclusion of the ecosystem services concept in the design and evaluation process of robust NBS aids in the capturing of local stakeholder values, as well as, the representatoin of those values by the selection of appropriate social, environmental, and economic indicators of the human benefits.

The ecosystem service concept creates an opportunity for decision-makers to consider site-specific ecosystem functions and the locally value assigned to those ecosystem functions. Cohen-Shacham et al. [64] also shows that applying the four main categories of ecosystem services proposed by De Groot et al. [24] helps to identify stakeholders quickly, thereby highlighting, and mitigating stakeholder problems (e.g., poor coordination and/or conflict) and stakeholder opportunities (e.g., collaboration or improved water and conservation management). Therefore, the ecosystem service concept enables for local stakeholder values to be captured in the robust design of NBS for water, and for trade-offs between often conflicting stakeholder demands, for example, nature reserve managers, local authorities, farmers, hunters, and fisherman. [64].

The present study also proposes the integration of indicators of robustness into the evaluation process of robust NBS for water. Indicators enable for the robustness of the NBS to be quantified and subsequently enhanced – where needed or when required. Therefore, the present study modified the response curve constructed during robust analysis to better suit the multifunctionality of NBS. Hence, robust analysis and the construction of a response curve (as it pertains to this study) allowed for the quantification of the robustness of the existing NBS for water and for insight to be gained into the relationship between the robustness of the NBS and the magnitude of extreme flood event. This evaluation process gives decision-makers the ability to quantify and compare the robustness of NBS to conventional grey infrastructure solutions when considering investment option into systems for reducing HMR – even within future uncertainties.

The present study developed a scenario to illustrate how a robust NBS for water can be incorporated into a flood risk management system for a river catchment to enable it to deal with an extreme flood event (1:100-year). To create a robust NBS, the presents study increased the flow regulators in Klong 7 to 10, which form part of the existing NBS, within a 1-D hydrodynamic model domain - as presented in Section 4.2. The flood water inlets in Klong 7 and 8 were increased from a single flow regulator to six (6) and five (5) flow regulators, respectively. The increase in flood water flow into the storage area allowed for an increase in the flood water being drained into the irrigation furrows for storage, during extreme flood event. Increasing the efficient use of the storage capacity offered by the features (traditonal irrigation furrows) and charateristics (flat topography) of the local biophysical structure and ecological processes (such as the low conductivity of the clay soil in the study area). During a 100-year flood, the flood water storage efficiency of the irrigation furrows for drainage canals, Klong7 and Klong 8, increased from 82% to 96% and 81% to 95%, respectively.This increase in efficiency was achieved without exceeding the recovery threshold (plant bed level) of the robust NBS.

When comparing the response curve of the existing NBS before and after the increase in flow regulators, the response curves for the irrigation furrows in Klong 9 and Klong 10, provide more insight into the relationship between the incremental flood peak discharged into the Western Raphiphat canal and the response of the NBS. The response curve of the irrigation furrows in Klong 9 shows an initial delay (resistance) in the response of the robust NBS. Indicating that the increased drainage of the flood water into the irrigation furrows for Klong 7 and 8 increased the robustness of the irrigation furrow in Klong 9. However, a comparison of the response curves for the irrigations furrows in Klong 10 shows a forward shift in the resistance threshold of the robust NBS, instead of the expected delayed shift (resistance) in response – as seen in the irrigation furrows for Klong 9. The robust analysis of these irrigation furrows shows that robust design can also enhance robustness by shifting the resistance threshold forward, that is, reducing resistance and therefore allowing the robust NBS to contribute to flood water storage at a lower flood peak discharge. This insight highlights that robust design can be used to induce or delay the resistance threshold of a robust NBS based on the design objective of the intervention.

Nong Sua is predominantly an agricultural area, and therefore the vegetation in the area would be expected to contribute to runoff reduction through infiltration, however, this anticipated co-benefit of groundwater recharge is not realised in this NBS as commonly predicted in literature. The poor drainage of this seabed sediment overlain with alluvial sediment from the Chao Phraya River and its tributaries is a site-specific characteristic that constrains/limits the expected co-benefits of infiltration. However, the clay soil found in this agricultural area enables for flood water to be stored in the irrigation furrows for extended periods. A co-benefit that is released by only the local farming community within Rangsit in Thailand.

The low conductivity of the soil in the case study area is due to the high plasticity index (30–50%) and liquid limit (60–80%) of the thick deposit (10–14 m) of marine clay known as soft Bangkok clay [65]. This deposit of soft clay is typically spread over lowlands such as floodplains – especially in river mouths. In Southeast Asia, political and economic centres are located in these areas. For example, Bangkok, Ho Chi Minh City, Yangon and Singapore. In Jakarta, the over abstraction of this soft clay caused sever land subsidence, which when coupled with a high frequency of extreme rainfall events that cause frequent flooding in this low-lying Capital City and sea level rise caused by greenhouse gasses, has resulted in the Government of Indonesia deciding to move the Capital City by 2024 [66].

Despite the obvious justifiable objectives in the selection of the case study area, there are several aspects of the concept of the robust design and evaluation of NBS that were beyond the scope of the present study. For example, from the process developed in the present study, only the relationship between a flood event with a return period of 1:100-years and the minimum upper resistance threshold of the robust NBS for water were analysed. The present study did not explore the relationship between the maximum upper resistance threshold of the robust NBS with more extreme events (e.g., 1:200- and 1:500 -year flood events). The reasons being that the present study used a 1-D hydrodynamic model for the evaluation of the flood risk management system. To investigate the inundation of the plant beds, a 2-D model would have had to be setup, calibrated and validated – which was not necessary to achieve the objectives of the study and was not possible within the stipulated timeframes of study. Hence, the limitation of the proposed design and evaluation process with regards to its application to the upper design limits of a robust NBS were not thoroughly investigated in the present study. For example, the study established that a relationship exists between upstream traditional irrigation furrows for Klong 9 and 10 and the downstream irrigation furrows for klong 7 and 8. This relationship is based on the observed influence the significant change in flow regulators in klong 7 and 8 had on the lower resistance threshold of klong 9 and 10.

6. Conclusion

Some degree of climate change is inevitable, and a certain degree of environmental degradation has already occurred, and as such, some level of risk from extreme HMH must be anticipated. Subsequently, societies should seek to build resilience by designing and implementing robust NBS that are able to mitigate and adapt to the impacts of extreme HMH. This is particularly important for natural hazards such as floods, not only because of their impact on the physical environment and socio-economic systems, but also due to the uncertainty surrounding their projected increase in frequency and intensity due to anthropogenic-driven climate change.

Considering the above, this paper developed a process for designing and evaluating robust NBS for HMR reduction. By incorporating the concept of robust design into the design process of NBS for water, the present study illustrates how individual (and site-specific) characteristics of a biophysical structure can be enhanced to ensure durability or increased tolerance to a range of external disturbances and conditions that exceed design criteria. This study further illustrates how incorporating grey infrastructure into the overall design of robust NBS, can enhance the performance of NBS - showcasing the benefit of hybrid interventions. The paper also demonstrates how incorporating robust analysis into the evaluation of a robust NBS can quantitatively capture the robustness offered by NBS implemented to address water-related risks. Incorporating robust analysis into the evaluation process of robust NBS for water provides insight into the relationship between the response of the NBS and the magnitude of the water hazard. Therefore, the design and evaluation process developed in this paper allows for decision-makers to design and also determine the effectiveness and efficiency of a robust NBS to HMH intensified by climate change.

In addressing some of the research gaps and barriers in mainstreaming the implementation of robust NBS for water to address climate change intensified HMR risk, this paper firstly, developed a process that can optimise individual parameters of an intervention. Secondly, this paper proposed the incorporation of indicators of robustness into the evaluation process of robust NBS for water to enable quantification of the robustness - which, can then be used to inform decison-makers on the effectiveness and efficiency of an NBS.

The process developed in this paper allows for an iterative method of designing and evaluating robust NBS for water, therefore, allowing for the robustness of an NBS to be better aligned to the varying magnitude of an extreme HMH. The process developed in this paper will also aid in the support of investment decision towards business models or business cases that promote robust NBS for HMR reduction. Ultimately, it is envisioned that this process will contribute in the advancement and successful implementation of the NBS concept.

Author Contribution

SM, SW, ZV, AS and MSB contributed to the study conception and design. Material preparation, data collection was performed by SM and SW. The hydrodynamic model was calibrated and validated by SD and modified by SM to perform the analysis for the present study. The first draft of the manuscript was written by SM. All authors read and approved the final manuscript.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Zoran Vojinovic reports financial support was provided by European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 776866 for the research project RECONECT. Sipho Mashiyi reports financial support was provided by Ehlobo Consulting.

Data availability

Data will be made available on request.

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