Ecological engineering solutions for the Day River

Case study around the Day Dam

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By

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Abstract

This bachelor thesis proposes a combination of ecological engineering measures that can improve the ecological and hydrological issues in a research area that is located upstream in the Day River Catchment, about 25 km from Hanoi, Vietnam.
The most urgent issues in the research area are low water quality and quantity, as well as an ecosystem that has deviated far from its original state. The final design of this research includes eight different measures that are targeted at agricultural areas, as well as water bodies and their surroundings. By shaping the ecosystem and its functions, the stated issues can be addressed in a novel and environmentally friendly way.

Further research should identify ecosystem-based approaches that can introduce more freshwater into the area, since it currently mainly depends on precipitation inputs into a small catchment measuring about 27 km^2. Research should also analyze the economic feasibility of the proposed measures.

If it is decided to implement ecological engineering measures in the research area, the interaction between the government, local institutions and citizens will be determining their success to a large extent.

Preface

This Bachelor thesis was written in the framework of the MK27-project, which is part of the CGIAR Research program on Water, Land and Ecosystems.
TU Delft is the leading institution in the Vietnam-focused project ‘MK27: Inclusive development paths for healthy Red River landscapes based on ecosystem services’, which is aimed at “developing pathways for the land and water resources of the Red River basin that maximize social and environmental benefits over the next decades” (MK27, 2014). The research program consists of three work packages. The case study in the MK27-project is the Day River Catchment, a distributary of the Red River located close to Hanoi, and part of the Day/Nhue sub-basin. Hanoi University for Natural Resources and Environment (HUNRE) is one of the important research partners in this collaboration due to the specific knowledge, combined with geographical nearness.

The specific topic of ecological engineering evolved from my personal interest in water management in combination with ecology and sustainability aspects. In my opinion, ecological engineering is a concept that can contribute to solving many of the problems humanity is facing now and will face in the future in an environmentally-friendly and ethically responsible way.

Acknowledgements

I would like to thank my supervisor **Dr. ir. Martine Rutten** for making this thesis possible and supervising me throughout these interesting and challenging 9 weeks. She was very open towards my ideas to work on this topic and gave me the chance to do this for the Day River within the framework of the MK27-project.

Special thanks also go to **Thi Van Le Khoa** from HUNRE for the information provided throughout Skype sessions and contact via mail. This was very helpful in order to understand the Day River and larger context of this research.

Maarten Duijnisveld
Delft, 15 June 2015

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1. Introduction

1.1 The Red River and the Day/Nhue sub basin

The 1200 km long Red River (Song Hong) originates in the southwest Chinese province of Yunnan and runs through northern Vietnam on its last 500 km (figure 1). Above Hanoi, it enters a low-lying area, the Red River Delta, where it confluences with other large rivers, and also bifurcates forming several sub-basins (Eisenschmid, 2008).

One of these sub-basins is the Day/Nhue sub-basin in the southeast of the Red River Delta (figure 2). The wet-hot monsoon tropical climate consists of dry-cold winters and a rainy-hot wet season (June-October) (ICEM, 2007). The average annual rainfall in is 1500-2200 mm, with peak rainfall occurring in the Ba Vi Mountains in the upper catchment of the Tich River. The wet season contributes to 80% of total annual flow in the sub-basin (ICEM, 2007). It is composed of eight main tributaries and four main distributaries. The basin is also densely populated with 1,136 inhabitants per km^2, which is four time higher than the national average (ICEM, 2007).

Vietnam is one of the most water abundant countries in the world. The Red River itself has historically had high variations in the amount of water carried (Bloschl, 2003). Consequently, the lower Red River basin has been subject to flooding throughout history (Bloschl, 2003), especially during the monsoonal rains in the wet season (Dijkman, Eversdijk, Lindenberg, & Stefess, 1996). Hydraulic engineering interventions throughout the whole Red River basin during the 20th century have led to a highly altered hydrology in the Day/Nhue sub basin. Purpose of these interventions was flood protection, irrigation or hydropower generation (ICEM, 2007). The total length of river dikes in the Red River Delta is 3000 km (Dijkman et al., 1996). Next to that, an extensive infrastructure of estuary and sea dikes, as well as dams and reservoirs exist throughout the whole tributary of the Red River (Hagedooren & Keyzer, 2015).

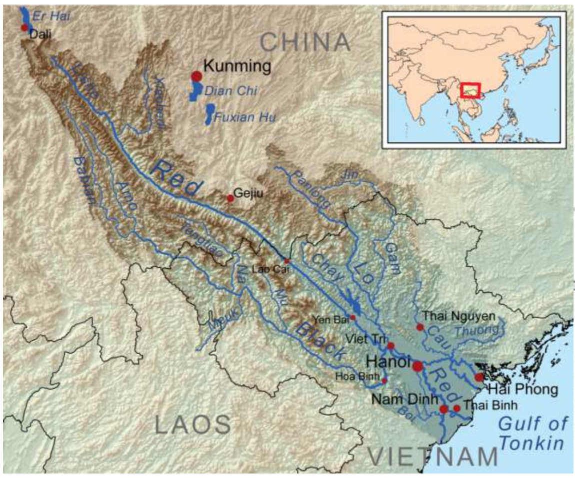


Figure 1: Red River basin (Hagedooren & Keyzer, 2015)

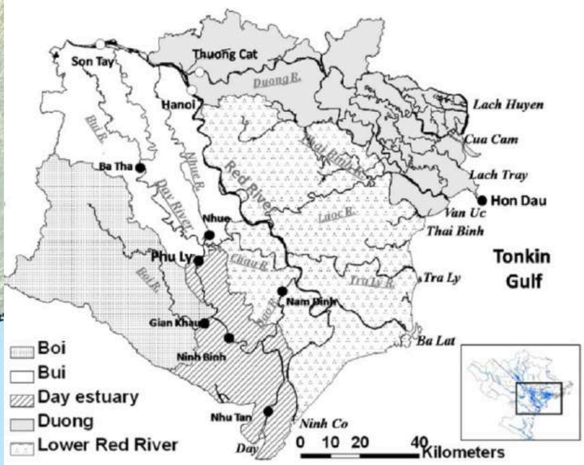


Figure 2: Day/Nhue River basin within the Red River Delta (Hagedooren & Keyzer, 2015)

1.2 The Day River

A very suited example for these hydrological alterations is the Day River (Sông Đáy). This river used to be a regular distributary of the Red River, diverting water off the Red River at Hat Mon (Figure 3), about 25 km upstream of Hanoi.

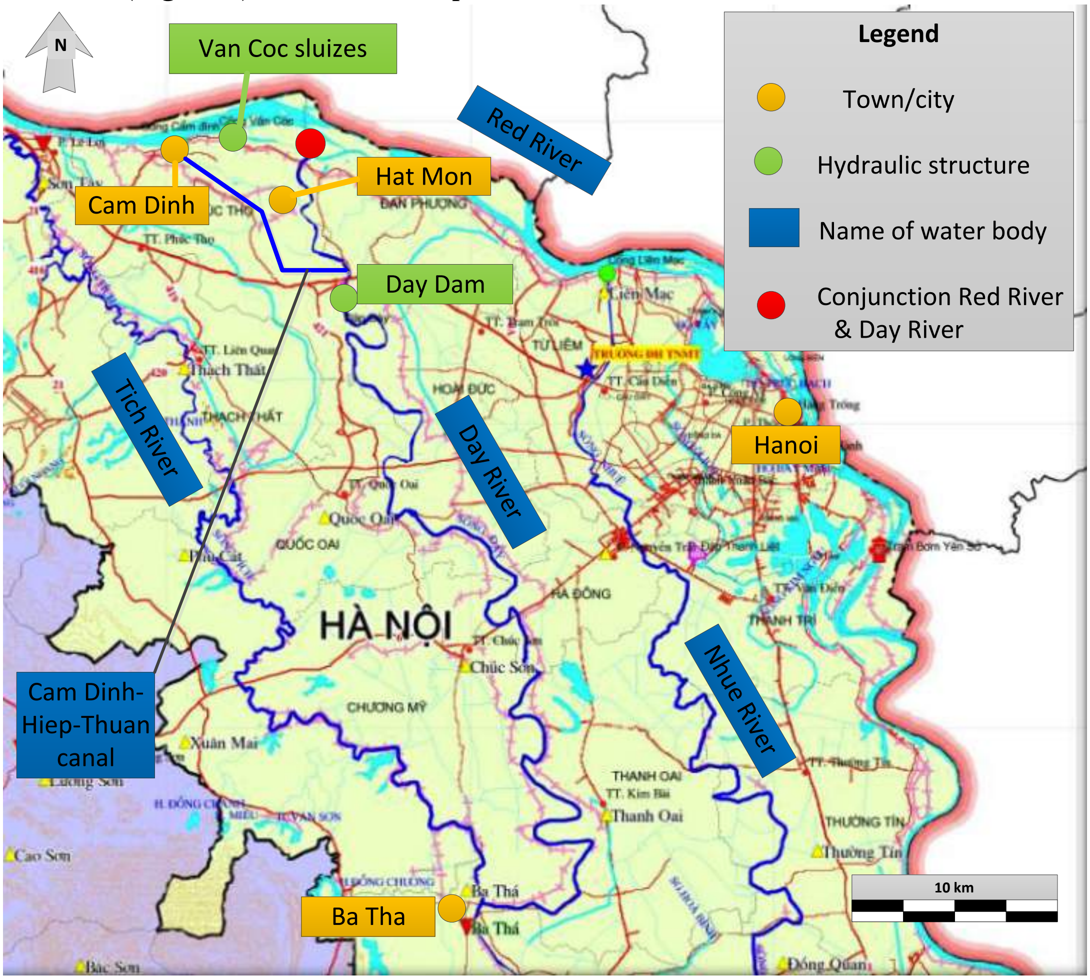


Figure 3: Overview on the Nhue/Day basin (self-made map; original map from (Hagedooren & Keyzer, 2015)

Agriculture is one of the main activities of the local population around the Day. For instance in the community of Hat Mon (see figure 3), just land inward from the conjunction with the Red River, where Bloschl (2003) found that agricultural land makes up 77% of the area, and 38% of the population is accounting for 85% of agricultural labor in the community.

Throughout history, the area around the Day had been prone to flooding (Dijkman et al., 1996), and local inhabitants and their living and farming practices were adapted to the yearly floods (Bloschl, 2003). In 1937, the Day Dam was constructed. It is located about 10 km downstream from the conjunction with the Red River, and built with the purpose to divert flood waters (which would have then already flooded the upstream area between the Dam and Red River) from the River in a controlled manner. This should protect the city of Hanoi from floods and the connected damages to human lives and the built environment (Dijkman et al., 1996) (Hagedooren & Keyzer, 2015).
After construction of this diversion dam, the mentioned upstream area between the Red River and Day Dam was still prone to flooding with the worst flood in 1945 recording a floodwater level of 4,5 m in Hat Mon (Bloschl, 2003). In order to hydrologically control this upstream area as well, the Van Coc sluices were constructed in 1966, right by the conjunction of the

Day with the Red River. These sluices function as an inlet structure for water in case of extreme floods, and divert it towards Day Dam (Dijkman et al., 1996).

The result of these engineering works was a well-functioning system in which the whole Day River area was flood safe, and flood waters could be diverted to the area if necessary, with the government compensating the farmers for lost yields (Bloschl, 2003). Flood water levels in Hanoi could effectively be reduced by 0.5 m by the use of these structures (Dijkman et al., 1996). In fact, after 1966 flooding only happened during a dike break in 1986, and with floods in 1969 and 1971 (Bloschl, 2003). This 1971 flood also represents the last time the Day Dam was opened (Hagedooren & Keyzer, 2015). This reduction in flood events happened due to three main reasons.
On one hand, flood water levels in the Red River Delta reduced drastically during the 20th century. This happened due to the construction of dams and reservoirs in the upstream area of the Red River (ICEM, 2007). Next to that, human and natural morphological alterations like dredging operations and riverbed erosion lowered the level of the river bed, also reducing water levels in the Red River on average (Khoa, 2015). Accordingly, Hanoi has been less threatened by flooding in the recent past (ICEM, 2007).
The steadily growing population of over a half a million of inhabitants around the bed of the Day and related human activity have reduced the discharge capacity of the river since 1971. Already in 1996, 25 years after the last flooding of the Day area, the maximum water level reduction at Hanoi was estimated to be only around 0.2 m (less than half the design capacity) (Dijkman et al., 1996).
Furthermore, flooding would nowadays mean the evacuation of many inhabitants and lead to great damage and economic losses (Dijkman et al., 1996).

In 2015, one of the six floodgates of the Day Dam is broken. However, the flow passing through the dam is almost negligible (Hagedooren & Keyzer, 2015). The Day Dam has basically lost its function and has become more of an industrial remnant than a hydraulic structure.

The benefit of this flood-safe, highly engineered area thus led to the situation that the Day River between the Red River and Ba Tha turned into a 'Dead river'. Riverbed siltation and agricultural transgression have led to a negligible flow in the river. Water is abundant in the wet season, but there is water shortage in the dry season (Khoa, 2015).
This shortage also has a negative impact on the water quality. In Hagedooren & Keyzer (2015), a visit to the area around Day Dam in late 2014 (during dry season) describes the bad water quality as "easy to notice (…) by the amount of garbage in and around the river and the disgusting odor".

At Ba Tha, the Dead segment of the Day ends. The Day joins in with the water coming from the Tich tributaries, resulting in an annual average discharge in the Day of 42.8 m^3/s at this conjunction (ICEM, 2007). Further downstream, the Bui and Dao tributaries feed the Day as well. Finally, it discharges into the sea at Day Estuary (Figure 2). The total length of the Day is 240 km, whereas the Dead river is the segment from 0 km up to approximately 71 km (ICEM, 2007).

The Cam Dinh-Hiep-Thuan canal is a canal from Cam Dinh, joining the Day just upstream Day Dam (see figure 3). It was constructed in 2004 and aimed at delivering freshwater into the Day (Hagedooren & Keyzer, 2015). However, this canal is not functioning at all due the mentioned reduction in water level of the Red River (Khoa, 2015). Another government program that is aimed at channelizing part of the original path of the Day has been initiated, but at this point put on full stop (Khoa, 2015).

1.3 Ecosystem-based approaches

One way to solve the problems of the dead river segment of the Day is planning measures according to ecosystem-based approaches.
Ecosystem-based approaches are integrated solutions for the management of land, water and resources (CBD, 2015). In environmental sciences, there are several ecosystem-based approaches that can contribute to biosphere sustainability (Zalewski, 2013). Distinction can be made between Conservation, Restoration, Ecological Engineering and Ecohydrology. Which of these approaches is fitting, is determined by the goal of the intervention and boundary conditions at the location (Palmer, Filosoc, Hills, & Fanelli, 2014). Palmer et al. (2014) argues that ecological engineering can be one of the main driving forces in improving one or the full suite of ecosystem services at a location.

Ecological engineering is an emerging field that is aimed to address two objectives at the same time: provide engineered solutions contributing to human welfare, while protecting the natural environment and its ecosystem services (Bergen, Bolton, & Fridley, 2001). This is achieved by shaping the function of ecosystems in a way that the offer benefits to nature and mankind at the same time (Zalewski, 2013). Ecological engineering combines the fields of engineering (designed solutions) and ecology (self-organizing and regulating systems) into one discipline (Odum & Odum, 2013). Humans provide an initial input in the form of energy and resources, but once the ecosystem is set-up, it should function autonomously without much human maintenance, fulfilling the purposes it was designed for (Bergen et al., 2001).

1.4 Problem statement and knowledge gaps

There is a negligible flow of water into the Dead river and very little freshwater entering the catchment during dry season, since water input is mainly depending on precipitation (Khoa, 2015). The water quantity in the Dead River is low during dry season and the water quality decreases to undesired levels (Hagedooren & Keyzer, 2015). Next to that, human-initiated actions like land-use changes, urbanization and domestic wastewater discharge put additional pressure on the quantitative and qualitative water status and lead to ecosystem degradation (MK27, 2014; ICEM, 2007).

Vietnam is among the five countries in the world, which are most vulnerable to climate change (IPONRE, 2009). Climate change will yield altered precipitation patterns, which is expected to put additional stress onto the hydrological system (Trenberth, 2010). For the case of the Day, the increased risk for extreme droughts could worsen the water quality and quantity problems. Climate change is also linked to the extinction of biodiversity, which is expected to have negative impact on the ecosystem and the services derived it (IPONRE, 2009).

Literature clearly suggests that previous solutions in the Red River basin have purely focused on flood and water control, leaving other aspects like ecology behind (Bloschl, 2003). In the Greater Mekong Subregion, interventions have mainly been aimed at hard engineering measures to address environmental problems (GMS, 2013). Zalewski (2013) argues that these “traditional over-engineered water management measures (…) usually degrade the biological

structure and function of ecosystems" (Zalewski, 2013, p. 9) . In the Nhue/Day-basin, the amount and scale of these measures have led to a highly altered hydrological system, which has resulted in urgent environmental and hydrological problems like for the case of the Dead river segment of the Day (Khoa, 2015; Hagedooren & Keyzer, 2015).
Furthermore, no engineering works can be expected to improve the situation in the near future, since most existing structures and canals are not functioning or lost their purpose, and future projects have stagnated or been cancelled due to financial and organizational reasons (Khoa, 2015).

Research in the GMS EOC has shown that large cost reductions can be achieved when using ecosystem-based approaches instead of hard infrastructure measures in coastal areas: for adapting to a 12-centimeter sea level rise by 2020, costs were estimated to be 1.7 million Viet Nam dong per capita for coastal reforestation and forest conservation versus 38.8 million Viet Nam dong per capita for an engineered sea dike system (GMS, 2013, p. 5). GMS (2013) states that ecosystem-based (ES-based) approaches have so far strongly focused on biodiversity landscapes. Novel landscapes like the surroundings of Hanoi, for instance the Day basin, have not been subject of many studies on ES-based approaches (GMS, 2013). Zalewski (2013) underlines that the process-oriented approach of ecological engineering should be considered in many novel landscapes, because ecological restoration efforts are "not realistic due to demographic and economic dynamics" (Zalewski, 2013, p. 98). This is supported by the fact that the agricultural activities that take place in such landscapes have a negative impact on biodiversity and reduce the variety and levels of Ecosystem services (ESS) (Barral, Benayas, Meli, & Maceira, 2015), which are the goods and services that nature provides to humans (MEA, 2005).

Ecological engineering involves strongly ecosystem-based interventions and leads to improving the provision of certain ESS, yielding benefits to the human environment (Zalewski, 2013). Restoring ESS in areas where large parts of the population work in agriculture or resource-based activities is "critical to survival" (Rao et al., 2013), since people living in these areas strongly depend on these services for their livelihood. Linkages between ecosystem-based interventions like ecological engineering and the provision of ESS are still poorly understood (Trabucchi, O'Farrell, Notivol, & Comin, 2014).

Literature on the history of the Dead river segment is readily available in English, but no studies in English have been found to properly outline the hydrology, ecology and land use characteristics for this specific part of the Day. Bloschl (2003) suggests that "Research on changes in agricultural ecology and vegetation'' should be carried out in order to better understand the processes and main drivers in the area.

2. Goals of this research

The objective is to identify ecological engineering measures, which can contribute to solving the existing problems in a chosen research area in the dead segment of the Day.

First of all, it is aimed to understand the research area by analysing the hydrological setting and land use patterns.
As a second step, the research should identify ecological engineering solutions that can address the following issues present in the dead segment of the Day:
-Low water quantity and freshwater input
-Low water quality due to domestic and agricultural discharges
-The ecosystem has degraded far from its original state

A final design of a combination of suited alternatives is the desired outcome.
The effect of these selected alternatives on the environment and human well-being should be understood by linking them to the provision of ecosystem services.

3. Research questions

3.1 Main question:

Which combination of ecological engineering measures can address the problems that are present in the research area in the Dead river segment of the Day River?

3.2 Sub-questions:

SQ1: Which part of the Day is appropriate as the case study's research area?
Methods: Literature study, personal communication
SQ2: What are the hydrological characteristics and land use patterns of the research area?
Methods: Literature study, mapping
SQ3: Which different ecological engineering measures are suited for the research area?
Methods: Literature study
SQ4: What is the effect of the suited solutions on ecosystem services?
Methods: Literature study, evaluation of measures

4. Methods and procedure

4.1 Literature study

A literature study is conducted to gain knowledge on the research area, ecological engineering, ecosystem services and other relevant information.

4.2 Mapping

Mapping is used in order to find the research area and get an understanding of it in terms of land use and hydrological setting. For a detailed description of programs and datasets used, as well as mapping procedures, consult appendix A.
The mapping can be split up into three parts A, B and C:

A) Understanding the research area in a static way, purely based on satellite images
Program used: Google Earth Pro 7.1.4

B) Get a better understanding of the hydrological system by mapping the watersheds and watershed characteristics in and around the research area
Program used: QGIS 2.8.2 Wien

C) Understanding the hydrological components of the research area in a dynamic way, based on results from (A) and (B)

4.3 Evaluation of measures

After identifying suited alternatives, the alternatives are evaluated with respect to their effect on ecosystem services.
Finally, a design, most likely a combination of alternatives, will be proposed based on findings in the evaluation.

4.4 Personal communication

This includes mail contact, Skype calls and interviews with relevant stakeholders, since there are several knowledge gaps in the literature that can be filled by talking to these parties.

5. Mapping the research area

(A) Mapping in Google Earth

(A1) The Day River from Red River conjunction to Ba Tha

The total length of the Day River up to Ba Tha is measured to be 70.8 km. As has been stated in the intro, it is not a regular flowing river. Studying the radar images supports this: the visual appearance of the river varies intensely on those 70.8 km (Figure 4).

A distinction of four types of appearance of the Day River can be made:

-Creek

Official definition: "A small stream or tributary to a river" (dictionary.reference.com, 2015)

Definition for this paragraph: water body with a width of less than 20m.

-River

Official definition: "Large natural stream of fresh water flowing along a definite course, usually into the sea, being fed by tributary streams" (dictionary.reference.com, 2015)

Definition for this paragraph: water body with a width of more than 20m and no large flow obstructions.

-Vegetated zone

Definition for this paragraph: Water body, which is mainly covered with vegetative surface.

-Terraces/ponds:

Definition for this paragraph: Sections where the Day consists of ponds or terrace-like structures, which are divided by dams, perpendicular to the flow direction

Note that the term "flowing" is not used to define river and creek in this research, since it cannot be observed to what extend this is the case from the satellite images.

However, studying the images it can be concluded that there seems to be no constant flow in the river: especially the dammed, terrace or pond-like structures look like they only allow for negligible flow. These ponds are most likely used for irrigation purposes. For a visual impression of the appearance types, see appendix B.

Table 1: Different appearances of the Day (Google Earth, 2014)

Appearance type	Number of sections on Dead River	Total length of section (km)	Percentage of total length
Creek	4	14.1	19.9 %
River	9	32.7	46.2 %
Terraces/ponds	2	8.8	12.4 %
Vegetated zone	7	15.2	21.5 %
Total	**22**	**70.8**	**100 %**

Table 1 provides an overview of the different appearances of the Day from the conjunction with the Red River up to Ba Tha. Figure 4 supports this graphically.

Less than half of the Day's length up to Bha Ta actually has river characteristics, which underlines the fact that this river has deviated far from its original state and carries a negligible flow. From figure 4 it can also be concluded that the characteristics of the river are not constant, supported by the total of 22 different sections on the Day up to Ba Tha (Table 1).

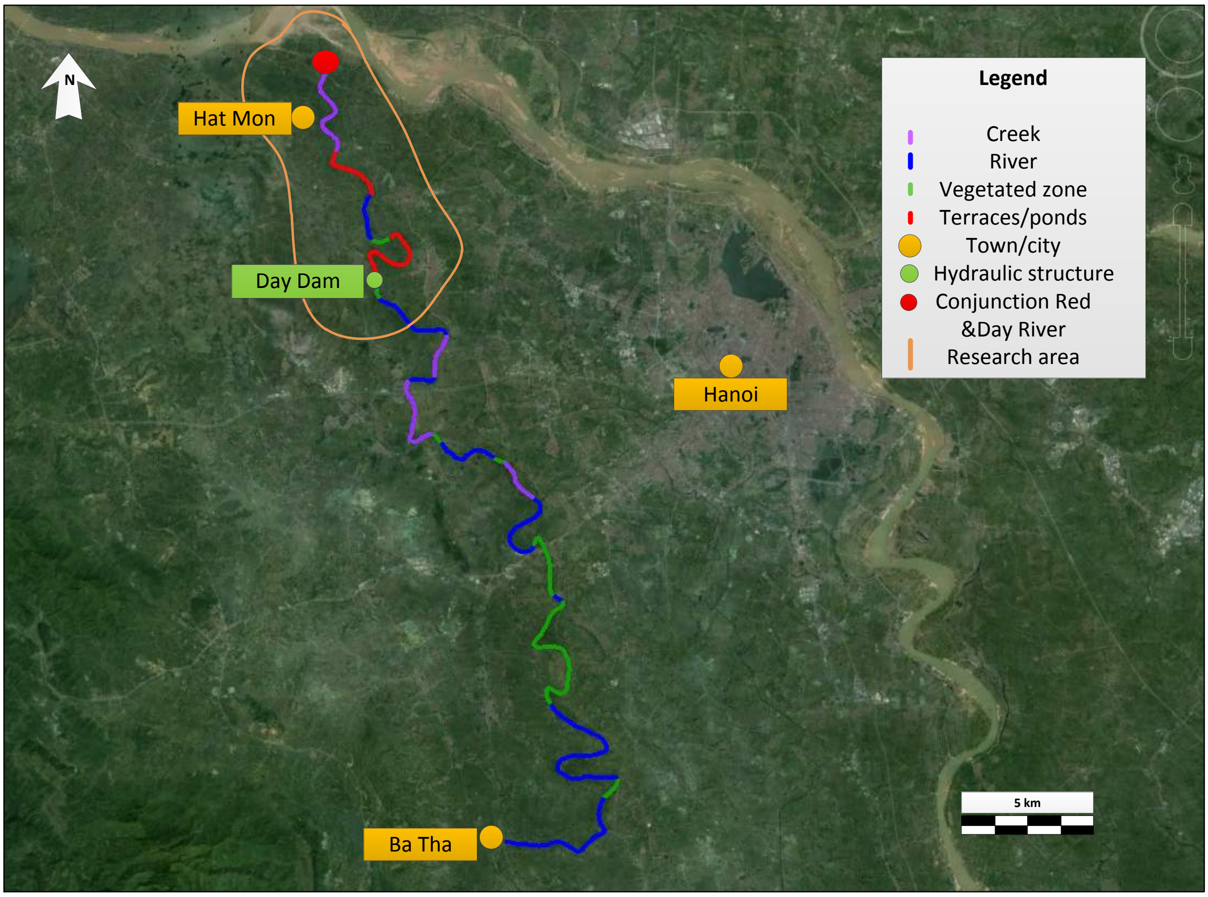


Figure 4: Path of Day up to Ba Tha with different appearances and location of research area indicated (Google Earth, 2014)

(A2) Identify research area and map the land uses

After talking to Thi Van Le Khoa, lecturer at HUNRE, it was decided to study the area from the conjunction with the Red River until downstream Day Dam, due to the following reasons:
-This area has been subject to hydrological alterations (Day Dam and the Van Coc sluices are located in this area),
-The area is close to the Red River, which is a potential source of freshwater intake
-The issues stated in the research goals are clearly present in this area

It was chosen to make the Day Dam the center of the research area, since it is a clear landmark. The Day Dam is located 8.5 km downstream from Hat Mon, thus the total length for the research area along the Day was chosen to be 17 km along the Day.
Its shape was determined by several considerations that can be found in the appendix B. The location of the research area is depicted in Figure 4.

In order to answer sub-question 2, the land uses in the area have been mapped using Google Earth. Detailed data on these land uses can be found in Table 2.

Table 2: land uses in the research area

Land Use Type	Area (ha)	Fraction of total area
Agriculture	6275.9	71.3 %
Built environment	1950.3	22.1 %
Open water bodies	403.2	4.6 %
Ponds and reservoirs	134.9	1.5 %
Industry/storage	43.7	0.5 %
Total	**8808.0**	**100 %**

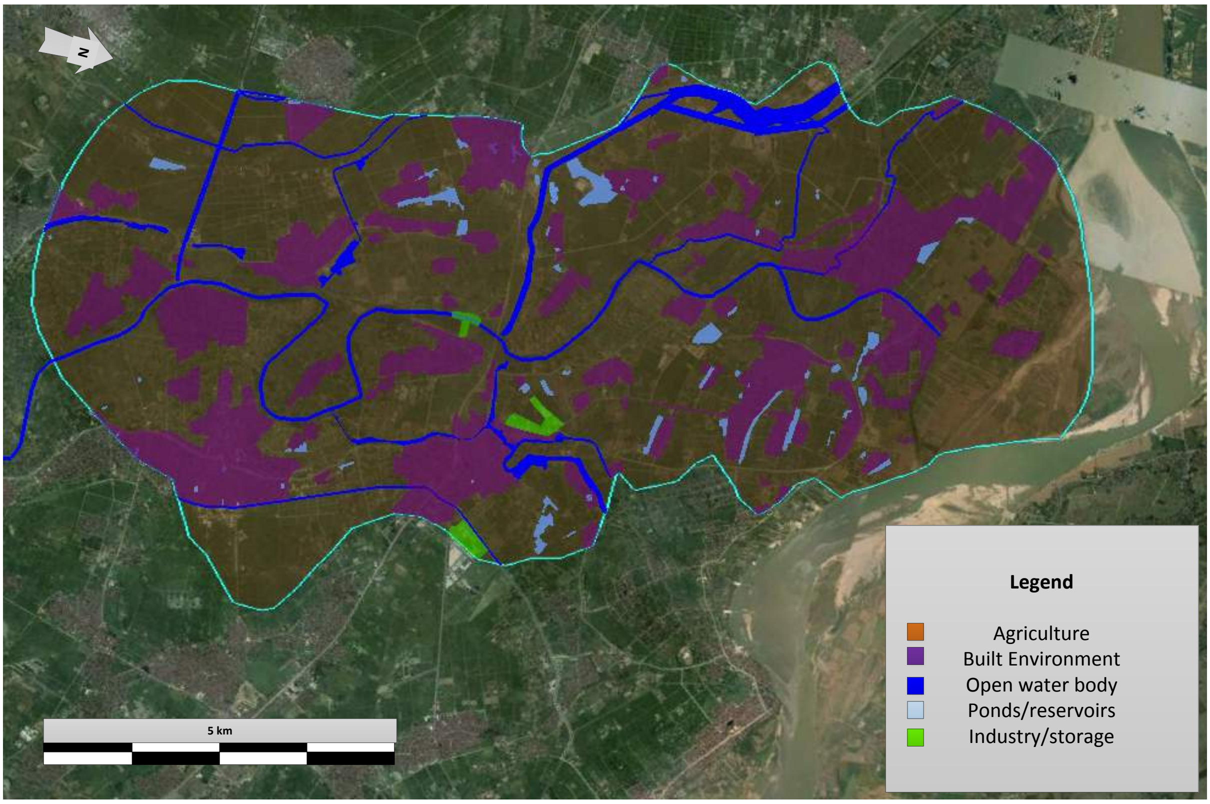


Figure 5: Land uses in Research area (image from Google Earth)

Agricultural land use makes up 71.3 % of the area. Fields occur in many different shapes and have different vegetative appearance, varying from grass green to brown (see appendix B). Another point to note is that some farmers are practicing mixed agriculture consisting of fields and trees, which seem to be agroforestry.

The built environment accounts for 22.1 % of the total research area. It is clearly dominated by residential buildings, but also includes public spaces and roads. There are lots of trees in between the buildings.

Water bodies can be distinguished from space and have been split up into open water bodies (canals and water bodies with negligible flow, 4.5 %) and water bodies, which look like ponds and reservoirs (1.5 %).

	
Built environment with ponds (marked in light blue)	Built environment with open water body (marked in dark blue)

Figure 6: Land uses in Research area (Google Earth, 2014)

The ponds seem to be man-made, since they are usually located around residential areas and have clearly defined and straight edges (Figure 6, image 1).

(A3) Mapping the hydrology in and around the research area

The hydrology around the research area was mapped along 30 km of the Day, bounded in west and east by respectively the Tich and Nhue Rivers. For a detailed description of this procedure, consult appendix A.

The Main components of this hydrological system are:
-Rivers: Tich, Day, Red and Nhue
-Canals: man-made, mainly straight canals, which are transporting water through the system and are mostly used for transport and irrigation (Khoa, 2015).
-Open surface water bodies: like described in the previous paragraph, these water bodies are part of the hydrological infrastructure, but they only allow for negligible flow due to their terrace/pond-like structure.
-Trenches and ditches: due to the highly engineered water infrastructure, there are numerous trenches and ditches, which are used for irrigation purposes
-Hydraulic structures: intake stations at the Red River and pumping stations within the system.

(B) Mapping watersheds in QGIS

The obtained watershed map analysed in step (C) was obtained using the GRASS-function ‘watersheds’ in QGIS with 25.000 cells per basin (for details on the mapping procedure in QGIS and selection of watershed map, consult the appendix).

(C) Understand the hydrology of the research area in a dynamic way

Analysing the obtained watershed map, stream segments and flow accumulation, it can be concluded that only a very small stroke around the Day drains directly into it. This watershed is from now on called the Day watershed and depicted in figure 7. It has an area of 26.6 km^2.
The Day watershed itself drains into a watershed to the east, at a point by the southern boundary of the research area.
The watersheds around the Day watershed create stream segments, which drain into other basins than the Day watershed, generally into southern direction (this matches with the general drainage direction/gradient of the Day/Nhue sub-basin, see paragraph 1.2).

Next, the canals that are running through the research area or are potentially contributing to the Day watershed have been mapped in order to find out if these are flowing into or out of the Day. Only the main canal infrastructure has been mapped (see figure 7). All the canals run across drainage divides and three of them are directly connected to the Day. They have been mapped in and outside of the research area, from their point of inflow up to where they connect to another water body, and numbered 1-5.

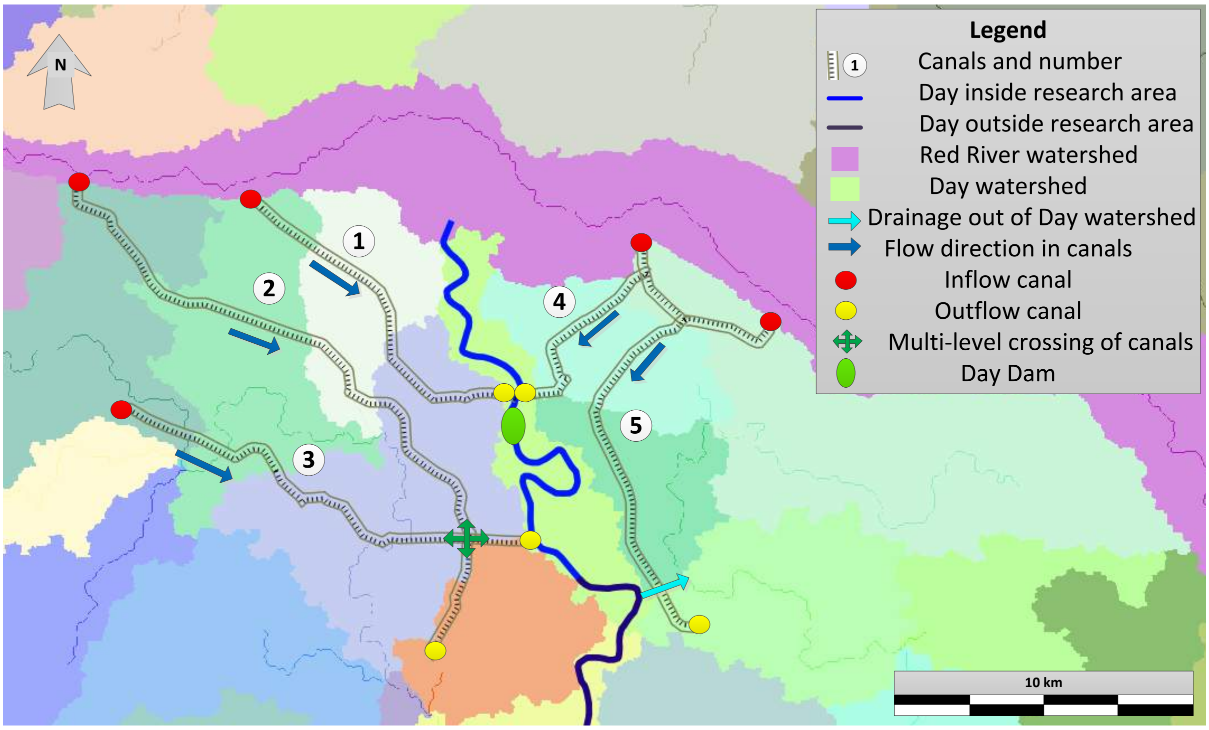


Figure 7: Watersheds (coloured patches) and stream segments (thin coloured lines) mapped with GRASS in QGIS; Day river and canal infrastructure layers with flow directions have been added, and drainage out of the Day watershed has been visualized clearly (self-made map; original map obtained with QGIS)

Based on the following two observations, the flows in the canals have been derived.
-All stations along the Red River take water in from the Red River (ICEM, 2007)
-The stream segments created in the area below the Red River flow in southern directions, thus the general direction of the hydraulic gradient is north to south

-Canal 1: This is the Cam Dinh-Hiep-Thuan canal, which was built to deliver water to the Day, but is not functioning (see paragraph 1.2).

-Canal 2: Intake from Red River, outflow into another canal

-Canal 3: Intake from Tich River, outflow into Day

-Canal 4: Intake from Red River, outflow into Day

-Canal 5: Intake from Red River, outflow into canal that is connected to Nhue River

Conclusion: Canals 1, 3 and 4 flow into the Day.

Exact inflow data could not be retrieved, but the following information is available:
-Inflow from canal 1 is negligible (Khoa, 2015)
-Canal 4 has dammed, pond like-structures in it (see paragraph 5.A1), flow is most likely negligible too

Concluding, the Day is depending on inflow from canal 3. Since the conjunction of canal 3 with the Day is 15 km downstream from the Red River, the whole area upstream is solely dependent on input from precipitation, which is too low for a healthy water environment in the dry season (Khoa, 2015).

6. Ecological engineering alternatives and final design

6.1 Ecosystem services classification

This paragraph will give a brief introduction on ESS and describe, which ESS will be investigated in this research. Then the process of finding the alternatives is quickly explained. Afterwards, basic underlying processes that appear throughout this paragraph will be explained. Thirdly, the selected alternatives and their main benefits are presented, as well as the effects in table-form.
The paragraph concludes with a final design for the research area.

ESS are the goods and services that people obtain from ecosystems (MEA, 2005). The way in which ecosystems and biodiversity can contribute to human well-being is illustrated in the ESS cascade model (see figure 9). Research on ESS has exponentially grown since the beginning of the 21st century, especially after the Millennium Ecosystem Assessment (MEA) in 2005 (Liquete et al, 2013). ESS have been categorized differently in the scientific world, depending on the context and type of research executed (Liquete et al., 2013) (see appendix D for details)

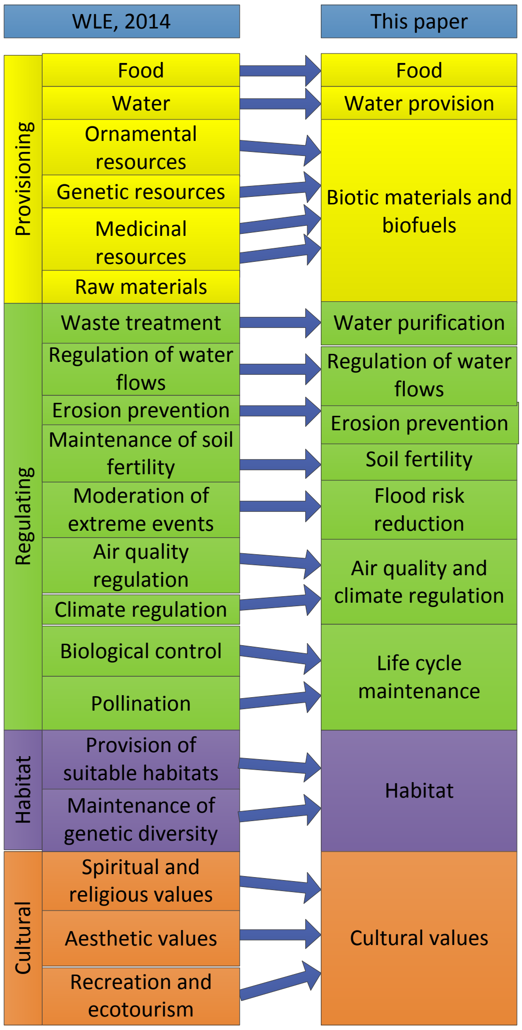


Figure 8: Ecosystem services classification for this research and how it has been derived from WLE (2014)

This research will use its own categorization of ESS (see figure 8), derived from the Ecosystem and Resilience Framework categorization (WLE, 2014). An individual classification is derived due to practical reasons and in order to be able to make a good evaluation of the alternatives' effects on different ESS. The WLE classification is also used throughout the MK27-research project (see preface) and thus seems the most logical framework to derive a classification for this research from, since it is aimed at contributing to MK27. For a description of how this classification was derived, as well as definitions of the classified ecosystem services, consult appendix D.

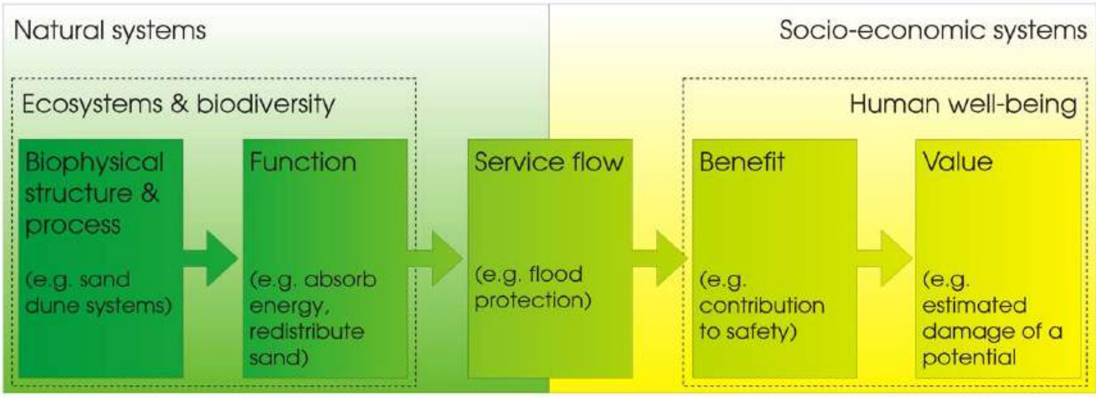


Figure 9: The ecosystem services cascade model (Liquete et al., 2013)

6.2 Finding suited alternatives

From numerous available possible measures, a selection has been made based on the following criteria:
-Does the measure have the potential of solving the issues presented in the research objectives (paragraph 2)?
-Does it match with the ecological engineering principles?
-Is it suited for the research area's land uses, topography and climate?

Figure 10 depicts the selection of alternatives and which measures were excluded.

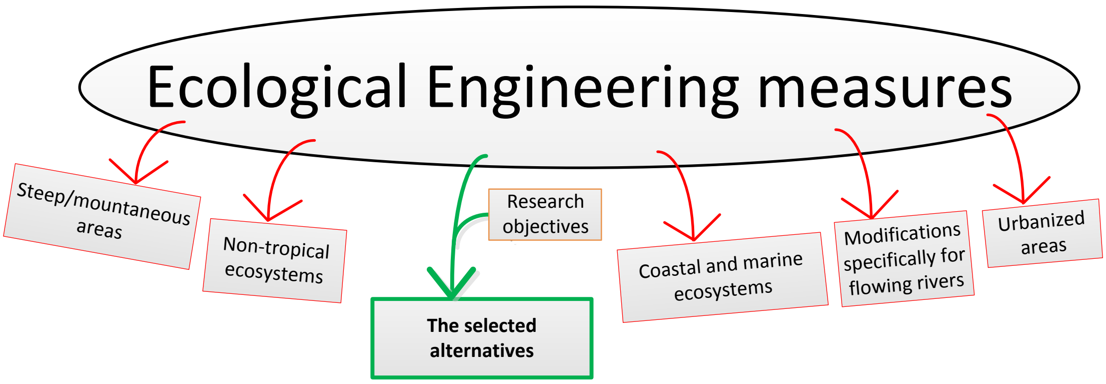


Figure 10: Procedure for selecting the ecological engineering measures for the research area

6.3 Basic processes

Before focusing on the different alternatives, a few basic underlying processes that appear throughout this chapter will be highlighted.

Water retention

Water retention, or the increase of water that is stored in surface waters or underground, is an alteration of the hydrological cycle and has a positive effect on the regulation of water flows in the system (Kedziora, Negussie, Asres, & Zalewski, 2011). It can be achieved by various measures presented in this paper.

Vegetation can change the microclimatic conditions, which alternate water balances and can decrease potential evaporation. Surface waters can store, infiltrate or divert water. Soil water retention can be achieved by changing the soil structure through plant roots or with soil conditioners (Farrell, Ang, & Rayner, 2013).

Water purification

A healthy soil with vegetation rooted in it can generally promote water purification through chemical losses. Clusters or strips of vegetation form so-called "biogeochemical barriers" (Kedziora, 2010, p. 12), which can control chemical losses in landscapes. The main mechanisms are uptake by plant roots, as well as the retention in the soil by sorption processes. For nitrogen, which is a crucial nutrient in agricultural landscapes next to phosphorous, release into the atmosphere is another way of chemical loss (Kedziora, 2010).

Erosion control

Vegetation provides protection again erosion by wind and water through several mechanisms. It provides soil cover, and increases stability of the soil through its roots, which makes it less vulnerable to erosion (NWRM, 2014). Vegetation also slows down wind speeds, as well as speed of water run-off, which reduces the amount of sediment that can be eroded. Furthermore, soil particles from wind can be trapped by the vegetation (Wolfe & Nickling, 1993).

6.4 The selected alternatives

In this chapter, the different measures, which have been selected according to chapter 6.2, will be presented. It has been chosen do to this in a purely qualitative manner. However, much quantitative data on the different alternatives can be found in appendix F.

Vegetative buffers

This incorporates measures that are aimed at creating areas and strips with natural vegetative cover, which can be grassland, bushes, hedgerows or trees. They can be implemented in between or at the boundaries of agricultural fields, as well as in riparian zones around water bodies. (Vought, Pinay, Fuglsang, & Ruffinoni, 1995)

Processes that are taking place in the soil and root zone of the plants retain nutrients as nitrogen and phosphorous effectively, playing an important role in reducing agricultural runoff and related pollution of receiving water bodies (NWRM, 2014) (see appendix E for a model of nitrogen cycling). This water treatment functions works especially well in lowland areas like the Red River Delta, since the removal efficiency is highest with low groundwater flow velocities (Kedziora et al., 2011).

The hydraulic roughness created by buffer zones reduces surface flow velocities. This can minimize the erosion from agricultural land as well as related losses in nutrients and sediment. Sediment can be the major pathway for nutrient loads in certain watersheds, so its retention can be of importance for maintaining good water quality (Vought et al., 1995).

By providing vegetated cover for the soil and changing the soil structure through its roots, buffer zones generally promote the water retention capacity and increase soil moisture (Leung, Garg, & Wang Wai Ng, 2015).

Figure 11: Tea farm in Argentina with large vegetative buffers around it (Tea for two, 2014)

Next to these water treatment and erosion control functions, vegetative buffers can have several microclimatic impacts, especially large vegetation like bushes and trees. They act as carbon sinks (Koseoglu & Moran, 2014) and provide shade, which regulates the temperature around the vegetation and decreases wind speed. The buffers also affect the evapotranspiration of the surrounding land, which yields positive effects on the water economy in agricultural landscapes (Kedziora, 2010). Furthermore, they enable dew formation and catch precipitation, which contributes to the mentioned water retention functions (Vought et al., 1995).
Another important aspect is the stimulation of biodiversity by introducing different plants in an often monocultural landscape (Vought et al., 1995). Furthermore, these buffers provide habitat for different animal species (see also beetle banks in the next section) and increase the aesthetic value of a landscape (NWRM, 2014).
Implementing buffer strips means changing land uses and making areas non-arable. However, these areas do not have to be large, since they are strip-shaped and run along fields or water bodies.

As stated above, these vegetative buffers can appear at various locations. Which specific functions are provided to which degree strongly depends on the location's soil type and the type of vegetation that is used. Generally, water treatment capacity increases with the size of the vegetation: while grasslands provide basic water treatment, zones vegetated with bushes or trees have can have a larger impact on the water quality (NWRM, 2014). Vought et al. (1995) identified Riparian vegetation along water bodies as the "ultimate buffer for surface and subsurface runoff" (Vought et al., 1995, p. 6), because of favourable conditions of vegetation type and soil moisture.

Beetle banks

This ecological engineering measure includes the creation of uncultivated strips of land, within or at the boundaries of agricultural fields (Koseoglu & Moran, 2014). The strips are at most a few meters wide, and consist of nectar-rich plants. These attract predators of natural pests, like for the example of Vietnam the brown planthopper, which has devastated rice harvests throughout the country in the past (DW, 2014).

The measures directly enhance biodiversity and provide habitat for species (NWRM, 2014), while having indirect effect on pollution. Since pests are controlled in a natural manner, pesticide inputs on fields decrease drastically. In Vietnam, pesticide sprays are often misused due to poor equipment and knowledge, which results in too high application rates (Heong, Escalada, Chien, & Cuong, 2014). In a field study in Vietnam (part of the "Eco-Eng-initiative"), beetle banks around rice fields without any pesticide application had significantly lower pest populations than control fields (DW, 2014). Latter ones were sprayed with pesticides 2 to 3 times a day, while the ecologically controlled fields were purely regulated by the species diversity. These fields also recorded a significantly higher population of predators (DW, 2014).

Next to their main function, beetle banks also contribute to the prevention of erosion and pollution in a similar way as vegetative buffers do. However, the impacts are smaller since the banks usually consist of small flowers. (NWRM, 2014)

Figure 12: Flowers on boundaries of a rice field in Vietnam (Vice Minister launches Ecological Engineering Initiative, 2015)

Crop practices

A way of increasing the resilience of an agricultural area is by growing several crops in one area, instead of a monoculture (NWRM, 2014). Biodiversity is stimulated and the biological system is kept more dynamic through the different species in one area. Soil structure is altered, for instance by combining deep- and shallow rooted plants.
Crop rotation, strip cropping and intercropping are the mechanism presented in this paper. They differ in execution, but the effects of these measures are very similar. Yields are

increased when implemented in a correct way (Koseoglu & Moran, 2014). The soil fertility and water infiltration capacity improves, while erosion risks are reduced (Oisat, 2015). Furthermore, these practices provide a great service in preventing crop diseases, pests and weed build-up (NWRM, 2014). This indirectly reduces the application of fertilizers, pesticides and herbicides, which reduces water pollution.

Figure 13: Intercropping in a mustard field in India (Intercropping with mustard, 2015)

Crop rotation alternates different crops on the same field in succeeding seasons (NWRM, 2014). Attention has to be paid to which crops are combined in this rotation, and what the rotational schedule is (Britannica, 2014). Rice can also be included in crop rotation practices, as long as special attention is paid to the effect of drying the rice patties for cultivating other crops (Thomson, 2015).

Strip cropping involves strips of different crops, sown close to each other. It should be noted that it has an especially positive effect on soil fertility, since the thin strips improve the nutrient dynamics between the different crops (Koseoglu & Moran, 2014; NWRM, 2014).

Intercropping is a method of growing two or more crops in the same fields. The proximity of the crops provides benefits by enabling resource sharing and the provision of shade (NWRM, 2014). A combination of strip cropping and intercropping is alley cropping/ agroforestry. This technique introduces woody tree species into crop production system, which yields green manure for soil maintenance (Kang, 2015).

Tillage variation

Tillage is the modification of the soil in agricultural areas by mechanical means (NWRM, 2014). No- and low-till farming are the tillage practices presented in this paper. These are methods aimed at minimizing the disturbance of the soil. While no-till farming involves no ploughing of the soil at all, low-till farming makes use of minor surface work on the soil (NWRM, 2014). Sowing happens with special devices that minimize soil disturbance (Huggins & Reganold, 2007). Soil residues are partly left on the fields, which protects the soil from erosion and improves productivity and nutrient cycling (Huggins & Reganold, 2007). Other connected benefits are water conservation and soil carbon sequestration (Lal, 2007). The functioning of this technique is strongly determined by the amount of crop residue and dung/manure that is applied, and this can be a limiting factor (Lal, 2007). It should also be noted that next to various benefits, the presented low- and no-till practices impose the risk of lower yields (Huggins & Reganold, 2007).

Through the use of organic residue, these techniques generally reduce the amount of chemical input in agriculture (Macilwain, 2004). In combination with organic farming, which is not presented as an ecological engineering measure in this paper, benefits from low or no-tillage practices can be improved further (Trewavas.A., 2004). Organic farming, next to several other benefits, enhances the positive effects on the environment by eliminating chemical inputs from fertilizer, herbicide and pesticides into the agricultural system (Macilwain, 2004).

Water retention additives

These conditioners are added to the soil in order to change the soil characteristics. The two main additives available are hydrophilic polymers (also called hydrogels) and silicate-based granulates (Farrell et al., 2013).
So-called Hydrogels have the ability to "absorb and store up to 500 times their own weight when saturated" (Farrell et al., 2013, p. 1). An environmentally friendly option that is presented in this paper is biopolymers (microbial polysaccharides). They increase the inter-particle-cohesion and soil porosity under dry conditions, which is specifically beneficial for erosion prevention (Chang, Prasidhi, Im, Shin, & Cho, 2015). A schematization of the erosion control effect of biopolymers can be found in the appendix E.
Silicate-based granulates contain natural silicate-based stone powders, carbon compounds and cellulose that attach to soil particles and increase the surface area available for nutrient and water absorption (Farrell et al., 2013).

Both additives generally increase the plant available water and water retention (Farrell et al., 2013). They have the potential to reduce irrigation frequency and are beneficial for vegetation growth, especially in dry areas (Chang et al., 2015). While biopolymers have a positive effect in early vegetation stages like germination (enhancing it by up to 300% (Chang et al., 2015)) and sprout growth, silicates have been found to be more beneficial for mature plant establishment (Farrell et al., 2013). However, general conclusions should be handled with care, since the soil type strongly influences the performance of the applied conditioner (Farrell et al., 2013).

The application of these additives is however quite costly, especially when it is applied on large areas like it would be the case in agricultural landscapes (Duijnisveld, 2015).

Basins and ponds

Basins and ponds can appear in agricultural areas, as well as in the built environment. Their general functions can be described as runoff management, increased water storage/infiltration and water treatment (Kedziora et al., 2011).

So-called detention basins can be free from water under dry weather conditions (NWRM, 2014). They manage runoff by retaining the water and slowly draining it into receiving water bodies. Since they are partly dry, they can fulfil cultural functions (e.g. recreation) and provide possibilities for vegetative zones and thus the provision of habitat (Kedziora et al., 2011).


Figure 14: A restored irrigation pond in Thailand (Suutari & Conran, 2015)

Infiltration basins are very similar to detention basins. However, instead of having the main purpose of slowing run-off and diverting it elsewhere, they are designed to increase groundwater recharge while at the same time improving the water quality. This is achieved by physical filtration through sediment trapping and removal of solids from the water, biochemical degradation of pollutants, or adsorption into surrounding soils (NWRM, 2014; Koseoglu & Moran, 2014).

Ponds permanently have a certain amount of water stored in them, which makes them a different ecological feature than detention basins. Aquatic life and vegetation can evolve in a more complex way, offering habitat and water treatment functions to a larger extend than in dry detention basins (NWRM, 2014). Sedimentation of particles and chemicals can take place, improving the water quality. This sediment can be used as fertilizer, as long as it does not contain any heavy metals (Kedziora et al., 2011).
Just like detention basins, they have additional water storage capacity, which enables runoff attenuation (NWRM, 2014). Ponds fulfil an important functions in agricultural areas storing water for small scale irrigation (Kedziora et al., 2011).

A special modification of a pond system are wastewater stabilisation ponds (van Lier & de Kreuk, 2014). These consist of a series of linked ponds that treat wastewater based on natural re-aeration processes and symbiosis between algae and bacteria. This system is often applied in developing countries, due to low cost input and self-regulation, as well as efficient pathogen removal (van Lier & de Kreuk, 2014). A schematization of such a system is given in appendix E. However, this systems is only suited in rural areas, since it requires a relatively large area and is often accompanied with odour nuisance (van Lier & de Kreuk, 2014).

Constructed wetlands

Wetlands are transitional areas between terrestrial and aquatic systems, in which water is the main driver for developing soil and connected biological communities (Sundaravadivel & Vigneswaran, 2012). They can appear in salt- and freshwater environments. While mangroves are a well-known example of saltwater wetlands, this paper exclusively focuses on freshwater wetlands, since the designated research area is located in a freshwater environment.

Generally, wetland ecosystems consist out of four main components (Sundaravadivel & Vigneswaran, 2012):
-Wetland vegetation
-Media or substrate supporting vegetation
-Water column that maintains wet soils
-Living organisms

Wetlands usually have oscillating water levels (Mitsch, Zhang, Waletzko, & Bernal, 2014), and the diverse vegetation can be submerged, emergent or floating in the water (Zapater-Pereyra, Ilyas, Lavrnic, van Bruggen, & Lens, 2015). They can appear at different scales, from constructed small-scale household treatment units, to whole landscapes which are natural wetlands (NWRM, 2014).

Wetlands function as efficient carbon sinks by sequestering it into plant biomass, and storing carbon in the soil (Mitsch et al., 2014). They also fulfil water treatment functions, which get specific attention in the following paragraph. Through the creation or restoration of wetlands, biologically diverse habitats for plant and animals can be provided (Mitsch et al., 2014). Furthermore, they can effectively recharge groundwater and thus influence the hydrological cycle in a positive way (Sundaravadivel & Vigneswaran, 2012).

Constructed wetlands are human-made wetlands that are aimed to imitate the specific functions that occur in natural wetlands ecosystem. Nowadays, this imitation works well and can be executed in a controlled manner (Vyzamal, 2010). Since the research area does not seem to include working wetland ecosystems, there are two types of constructed wetlands, which will be presented as suitable alternatives to address the problems in the research area:
-Constructed treatment wetland
-Constructed flood control wetlands

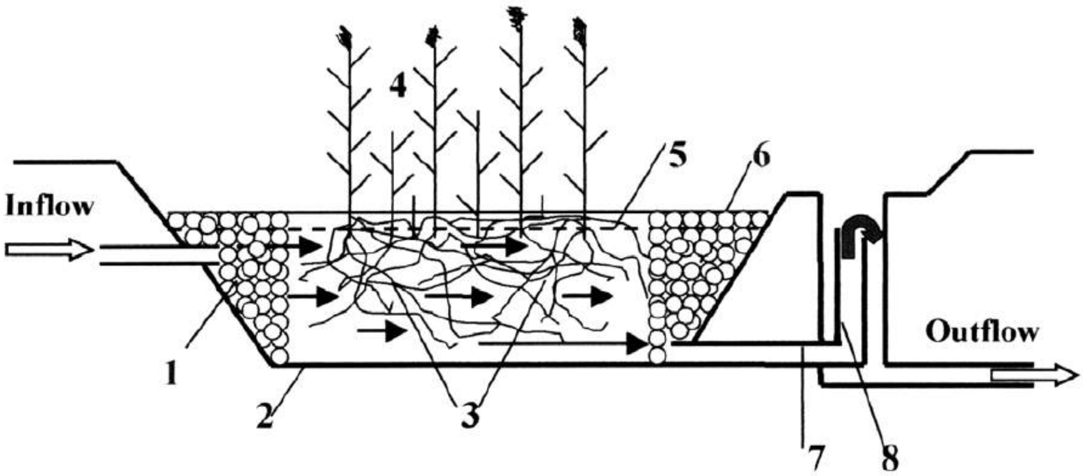


Figure 15: Schematic layout of a constructed wetland with horizontal subsurface flow. (1) inflow distribution zone filled with large stones; (2) impermeable layer; (3) filtration material; (4) vegetation; (5) water level in the bed; (6) outflow collection zone; (7) drainage pipe; (8) outflow structure with water level adjustment (Vyzamal, 2010)

Constructed treatment wetlands

Constructed treatment wetlands are special types of wetlands which are designed to treat wastewater through the natural processes of a wetland (Rai, Upadhyay, Singh, Dwivedi, & Tripathi, 2015). Major processes area taking place through the vegetation, while the supporting media stores the biotic and abiotic components of a wetland and provides the basis for vegetative growth (Sundaravadivel & Vigneswaran, 2012).
Water treatment through the vegetation occurs in several ways. The biomass of the vegetation slows down the pathways of the wastewater, which stimulates sedimentation of solids. Next to that, the root system takes up some pollutants from the wastewater as nutrients (Sundaravadivel & Vigneswaran, 2012). The roots also provide a large surface area, which (1) filters larger particles like suspended solids and debris and (2) enables the growth of microorganisms, which transform pollutants. Furthermore, diffusion of oxygen through the roots creates aerobic conditions for the treatment of pollutants (Sundaravadivel & Vigneswaran, 2012).

There are many designs for constructed treatment wetlands, which will not be discussed in detail since they all serve a similar purpose. However, it can be mentioned that the scale, type of vegetation and soil, water level in relation to surface, and direction of flow are the main characteristics that differ in the different designs (Vyzamal, 2010)

Figure 16: Example of a small-scale constructed wetland (IEES, 2007)

Sundaravadivel & Vigneswaran (2012) and Rai et al. (2015) both argue that constructed treatment wetlands in developing countries have been established as a suited measure, since they are natural measures that involve relatively low costs. Furthermore, they function very well in a tropical climate (Murdiyarso, Kauffman, Warren, Pramova, & Hergoualc'h, 2012), making them a suited alternative for the research area.
Constructed treatment wetlands require large areas than water treatment plants, which rather makes them feasible for smaller communities than for urban areas (Sehar, Naeem, Perveen, Ali, & Safia, 2015). For the research area, this alternative is suitable in terms of space, as is underlined by calculations in appendix F.

Figure 17: Large-scale example of a constructed wetland: the Olentangy River Wetland Research Park in Ohio, USA (Mitsch et al., 2014)

Floodplain restoration and wetlands

Floodplains are areas adjacent to a river that provide water retention functions for flood- and rainwater. These areas have in many cases been dammed off and used for agricultural purposes, since land is fertile in those areas (NWRM, 2014). Floodplain restoration is also aimed at restoring those areas as self-sustaining ecosystems, minimizing any engineering interventions (SNRE, 2015).

The creation of floodplains can be combined with the construction of flood control wetlands, since the conditions in a flood plain are very favourable for wetland plants (SNRE, 2015). These wetlands provide only basic water treatment due to fluctuations in water levels (SNRE, 2015), but have several positive impacts on the hydrological system. Next to providing a hydraulic buffer capacity for floods and runoff, they can enhance water storage, groundwater recharge and soil water retention, as well as provide water for human purposes (Koseoglu & Moran, 2014).

Figure 18: Floodplain area under water in Lenzen, Germany (NWRM, 2014)

Stream re-naturalization

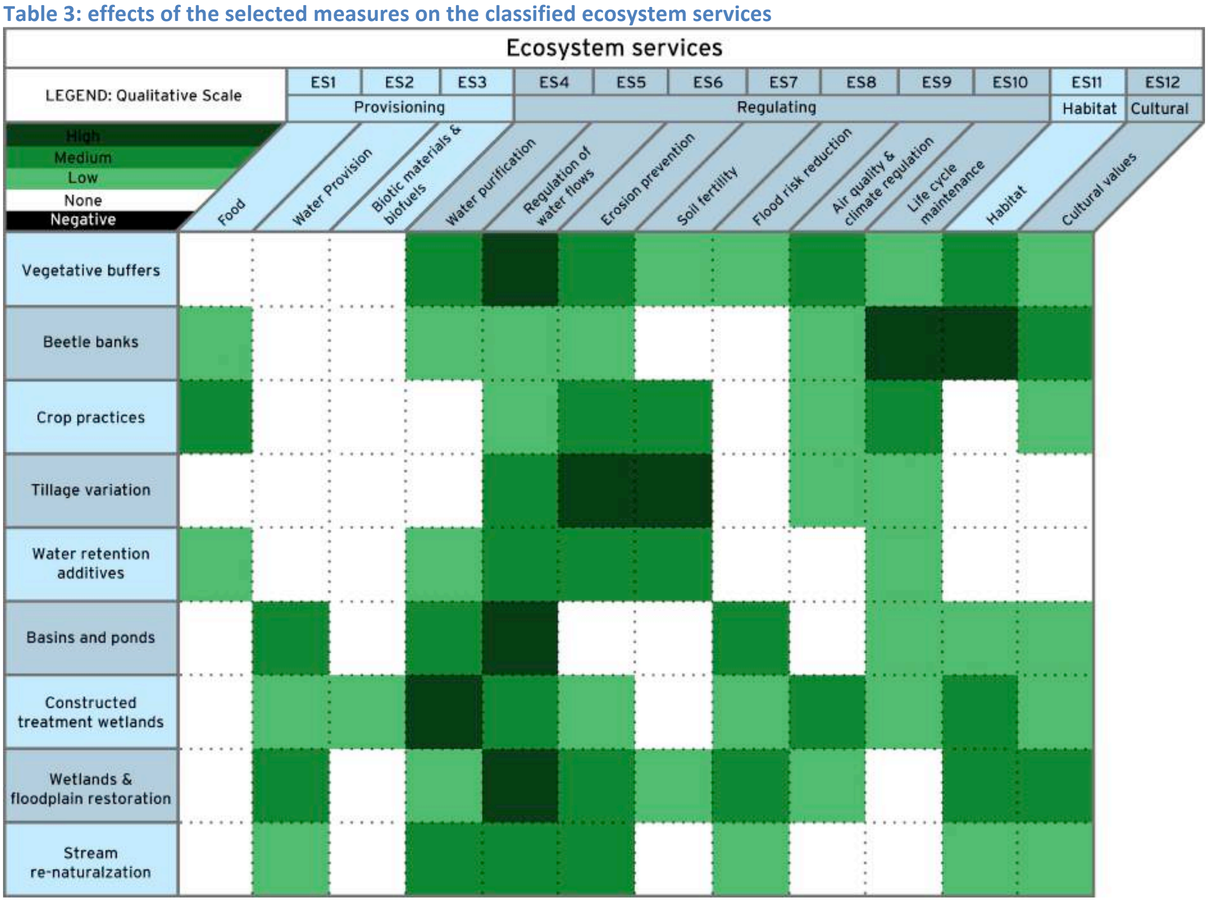
This measure is aimed at giving streams and rivers a more natural character. It incorporates the modification of riverbeds that are constructed out of concrete or large stone. These constructions are partly or completely removed, and replaced with natural structures that can fulfil the same function, and reconnect the stream to its surroundings (NWRM, 2014). The replacing structures are usually composed of stone, soil and vegetative features that provide natural bank stabilization (Chandrashekhara, 2015).
Runoff speed is decreased, which controls erosion. The stream is also naturally connected to the surrounding groundwater, which, in combination with vegetation along the stream, provides natural water purification functions that were not or merely existing before. The connection to the surrounding landscape also increases the retention of water (NWRM, 2014). Furthermore, aesthetic value is created by removing the hard infrastructure and replacing it with natural features (NWRM, 2014).

Figure 19: Restoring the riverbed of the Kallang River, Singapore. Pictures before (left) and after the restoration (right). (Chandrashekhara, 2015)

6.5 Ecosystem services effect table

An overview of all the selected alternatives and their effects on the classified ecosystem services is displayed below:

Table 3: effects of the selected measures on the classified ecosystem services



6.6 Final design for the research area

As table 3 shows, each alternative has a characteristic effect on the provision of the ecosystem services. Other conclusions regarding this table are:

-No negative effects on the provision of ecosystem services can be observed
-All the alternatives contribute to the regulation of water flows
-With nearly all alternatives, positive impacts can be achieved for the ecosystem services water purification, erosion prevention, soil fertility, air quality and climate regulation, life cycle maintenance, habitat, cultural values.

Furthermore, the alternatives involve very different types of measures that can differ in scale (small field up to landscape) and in target area (agricultural area, water, or built environment).

Due to the added value of each alternative, the final design for the research area that is proposed involves all the measures presented. The measures are very different, but can all be confirmed to contribute to solve the three issues stated in the research objectives:

-Low water quantity and freshwater input
-Low water quality due to domestic and agricultural discharges
-An ecosystem that has degraded far from its original state

The selected alternatives can be implemented in the research area in the following ways (for a visual impression see figure 20):

1) Vegetative buffers:

Either located with or at the boundaries of fields, as well as along water bodies, they can provide basic treatment of the water flows in the research area, as well as several other regulating services. Especially along the Day, vegetative buffers in the form of riparian vegetation could help to reduce the pollution with domestic wastewater, since people living along the Day discharge it directly onto the river (Khoa, 2015).

2) *Beetle banks:*

This biological control measure can reduce chemical pollution of water resources in the agricultural landscape throughout the research area, while raising biodiversity levels.

3) Crop practices and tillage variation

These agricultural practices can increase the resilience and productivity of farming systems, while reducing negative inputs to the environment.

4) Water retention additives

This is a measure that can have a positive effect on the water conservation in the research area. Farmers could benefit from the improved soil characteristics and water retention, especially in the dry season. This measure might however be too expensive to be implemented.

5) Basins and ponds

Many ponds are located around the built environment in the research area (see section 5.A.2). These could be restored through relatively small alterations in soil or vegetation in and around the ponds, aimed at providing basic water treatment functions and other related benefits. This would increase the water quality in these ponds, and since they are used for irrigation, it would have a positive effect on the water quality in the surroundings too. Furthermore, it could restore the ecological regime of those water bodies.
If wastewater treatment functions are the desired function, it can be considered to design a system of wastewater stabilisation ponds from the existing ponds. However, due to the odour nuisance accompanying these ponds, constructed treatment wetlands might be the better option around the built environment.

6) Constructed treatment wetlands

This option should seriously be considered to treat domestic wastewater, since it will reduce input of wastewater into the Day and other water bodies, and improve overall water quality. It is realistic for the research area, which is underlined by calculations done in appendix F. Constructed treatment wetlands could be deployed at two different scales:

6a) Small scale: for one or several households by converting agricultural fields into constructed treatment wetlands. Waki, Yasuda, Suzuki, Komada, & Abe (2015) has demonstrated that constructed treatment wetlands function in transformed rice paddies, a feature which makes up 70% of the agricultural area in the Day/Nhue sub-basin (ICEM, 2007).

6b) Large scale: a constructed treatment wetland along the Day riverbed, which could improve the water quality of the river. However, for this option to work, freshwater supply to the Day needs to be more reliable. Two suited locations are proposed, at points where connected canals could deliver the required amounts of fresh water to create such a wetland (see figure 20).

7) Floodplain restoration and wetlands

The only suited location is the former floodplain at the conjunction of the Red River and the Day. Dijkman et al. (1996), even though a somewhat outdated source, already recommended restoration of this former floodplain in their report. This option would yield several positive impacts, of which water provision and the benefits from the creation of wetlands are highlighted. Feasibility strongly depends on hydraulics, due to lowered water levels in the Red River (see Introduction), the connected costs of resettling inhabitants, as well as the political dimension.

8) Stream re-naturalization

These measures could provide benefits regarding the highly channelized infrastructure around the Day. Many canals will not be suited for this measure, since it incorporates the removal of parts of the concrete channel, which would destroy the functioning of the canal. However, since canals/ smaller open water bodies have been identified that have negligible flow in them (see results from section mapping), these could be the targets of such measures.

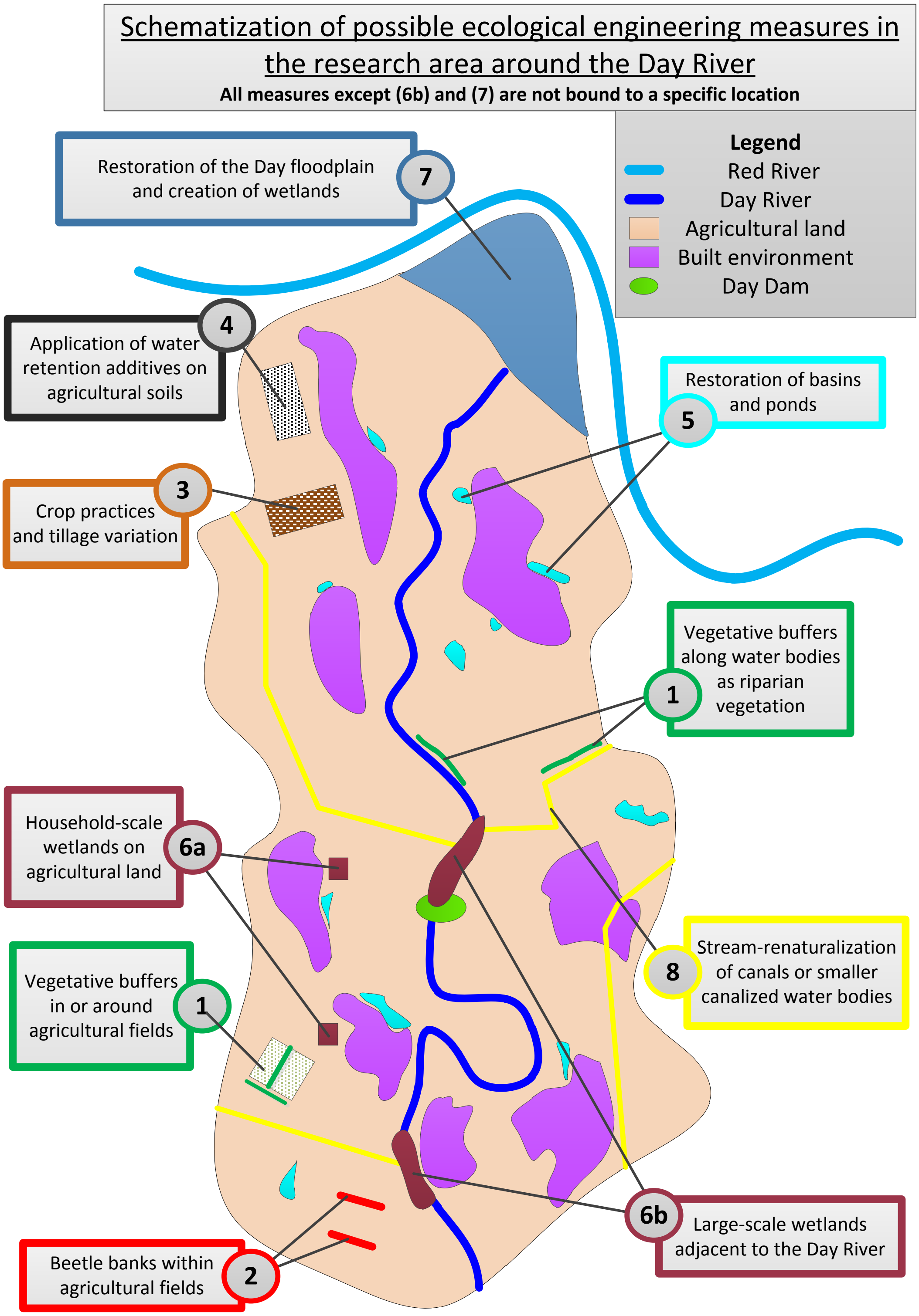


Figure 20: schematization of the implementation of the selected measures in the research area (self-made map)

For a more detailed impression of the locations that could be suited for these measures, the land use map in chapter 5.A2 can be consulted, which depicts agricultural areas, different water bodies, and the built environment in detail.

7. Conclusion

This thesis has compiled a diverse combination of ecological engineering measures, and has shown that these could address the ecological and hydrological issues present in the research area by evaluating their effect on the provision of ecosystem services.
The measures can partly be implemented by individuals (e.g. farmers) and partly require larger projects being set up including multilevel stakeholder involvement. Independent of scale and type, each measure should be evaluated by the relevant stakeholders before it is decided to implement it. Since ecological engineering is a novel approach for addressing the issues in the research area, pilot projects could be a good starting point for testing the concepts' performance and cultural acceptance on a smaller scale.
Local institutions and governments play the central role in creating momentum for initiating such innovative projects. Since the proposed interventions directly affect and shape the citizen's environment, their acceptance and participation is another central element determining the success of the presented measures. Farmers' awareness about the added value of implementing ecological engineering concepts into their farming practices needs to be raised through education and citizen science campaigns. They could also be stimulated through creating incentives for farmers that use these environmentally friendly techniques.

While most of the presented measures address water quantity issues by improving water flows and water conservation, they do not have the capacity to solve the issue of freshwater shortage in the dry season. Freshwater input to the Day needs to be increased in order to restore a healthy hydrological and ecological regime. Solutions to these problems can certainly involve ecological engineering principles (for instance the creation of a floodplain, as presented in this paper), but will most likely also require traditional hydraulic engineering to some degree due to the modified hydrology in the research area. Further research should investigate how more freshwater can be introduced to the area by working with nature to the highest degree possible.
Another important aspect that has not been subject to this paper is the economics of implementing ecological engineering measures. Even though literature suggests that economic benefits can be achieved through switching to ecosystem-based measures, the economic feasibility of such interventions need to be researched in detail.

The developed concepts also have potential for areas outside of the research area, since similar ecological or hydrological issues play a role in many agricultural landscapes in developing countries. Like for this case study, the measures should be tested on feasibility and performance at location before they are initiated on a larger scale.

This paper ultimately shows that ecological engineering can be a good alternative to traditional engineering for certain applications. Humans have shaped ecosystem since the beginning of time, and using natural principles to do so is an approach that deserves attention in the engineering world. This is especially valid in the context of treating the resources of planet earth in a responsible and sustainable way. However, applying ecological engineering principles does not simply guarantee the planned outcomes. Since ecosystems are dynamic living organisms and less predictable than engineered structures, measures that are taken need to be well thought trough and executed properly with the knowledge needed in the context of the intervention.

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Appendix A: Detailed procedure of the mapping, steps A, B, C

A1) Map the whole Dead River segment and find research area

Program used:

Google Earth Pro 7.1.4

Objectives:
-Get an impression of the appearance of the Dead River from satellite images and categorize them
-Choose the research area within the Dead River

A2) Analyse land uses and hydrological system in the research area

Program used:

Google Earth Pro 7.1.4

Objectives:
-Map and quantify the different land uses in the area
-Map the hydrological system and categorize its components

Procedure for step (B):

This part of the mapping aims at understanding the dynamics of the hydrological system by mapping the watersheds around the research area. This can be combined with the "static" picture of the hydrological components obtained in step 2).

B1) First of all, the Hydrosheds data is analyzed. In this dataset, watersheds have already been constructed and thus purely need to be evaluated.

B2) As next step, watersheds are created using QGIS. The GRASS-plugin in QGIS is used, since it can construct watersheds purely based on digital-elevation-models (DEM). First, DEM models are downloaded from the corresponding sources and loaded into QGIS, and then added to a new mapset in the GRASS plugin. A so-called GRASS-region is chosen; this is the region, which GRASS should create watersheds in. Via the "r.watershed" function, GRASS creates 4 outputs:
-Accumulation: showing the areas where the flow accumulates
-Drainage direction: depicting the direction into which each individual cell drains

-Stream segments: the streams that are created based in the previous two layers
-Basins raster map: depicting the watersheds that have been constructed (from now on referred to as watershed map)

The basins raster map is of main interest for this research, since it depicts the watersheds. The amount of watersheds that GRASS creates is based on the following user input: the amount of cells that one watershed should contain. This means: the higher the number of cells per watershed, the large the watershed, meaning the lower the number of watersheds that are constructed in the GRASS-region).

The research area is located in a Delta region, where the topography is flat. When using the DEM-model as input, is relatively hard to derive watershed boundaries in flat regions, compared to for instance mountainous regions. It was chosen to use two different DEM-datasets for the construction of the watersheds to have a higher chance of yielding a useful watershed map.

The objective of step B is to find a suited watershed map that can be used to understand the dynamics of the hydrological system. This watershed map will be chosen on the following criterions:
-Watersheds should not be too big, or too small
-A watershed map, which depicts the path Day River the best on its path within the research area
-A watershed map that depicts the basin of the Red River well in the area around Hanoi

This last criterion is a good way to verify the basin map: in satellite images and maps, it is very clear where the Red River path is located, so a watershed map that depicts the Red River watershed well is also assumed to be useful for analysing the rest of the area.

B1) Map the watersheds in QGIS

Program used:

-QGIS 2.8.2 Wien

Material used:

-Hydrosheds

B2) Map the watersheds in QGIS and GRASS

Program used:

QGIS 2.8.2 Wien
GRASS plugin for QGIS

Table 4: the DEM models used in B2):

Name	Void-filled DEM from USGS	Aster GDEM Version 2
Data format	Raster	Raster
Ellipsoid	WGS84	WGS84
Release date	March 2007	October 2011
Resolution	3 arc-second	1 arc-second
Source	(USGS, 2007)	(USGS, 2011)

C) Understand the hydrology of the research area in a dynamic way

Combining observations from steps B1 and B2, conclusions are drawn regarding the watershed of the Day itself and around it, especially with regards to water inputs into the Day.

Appendix B: Mapping step A, intermediate results

5.A.1 Dead river appearance

Creek		**River**	

Vegetated zone		**Terraces/ ponds**	

Figure 21: Appearances of Dead river segment (Google Earth, 2014)

5.A.2 Defining a research area

First, it was aimed at using a watershed shape for the research area as can be seen in Figure 5. However, in all available satellite images provided by Google Earth, there is an about 4 km wide stroke of images missing, which is running in latitudinal direction, east of Day River. This stroke is at some point at about 3,3 km longitudinal distance from the river path. Due to this, the area looked at has been limited to a 6 km wide stroke (3 km on each side of the Day), which follows the river path (Figure 5)

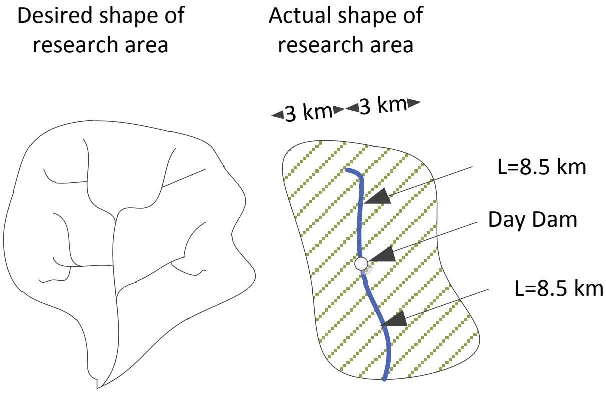

Figure 22: schematization of research area (self-made)

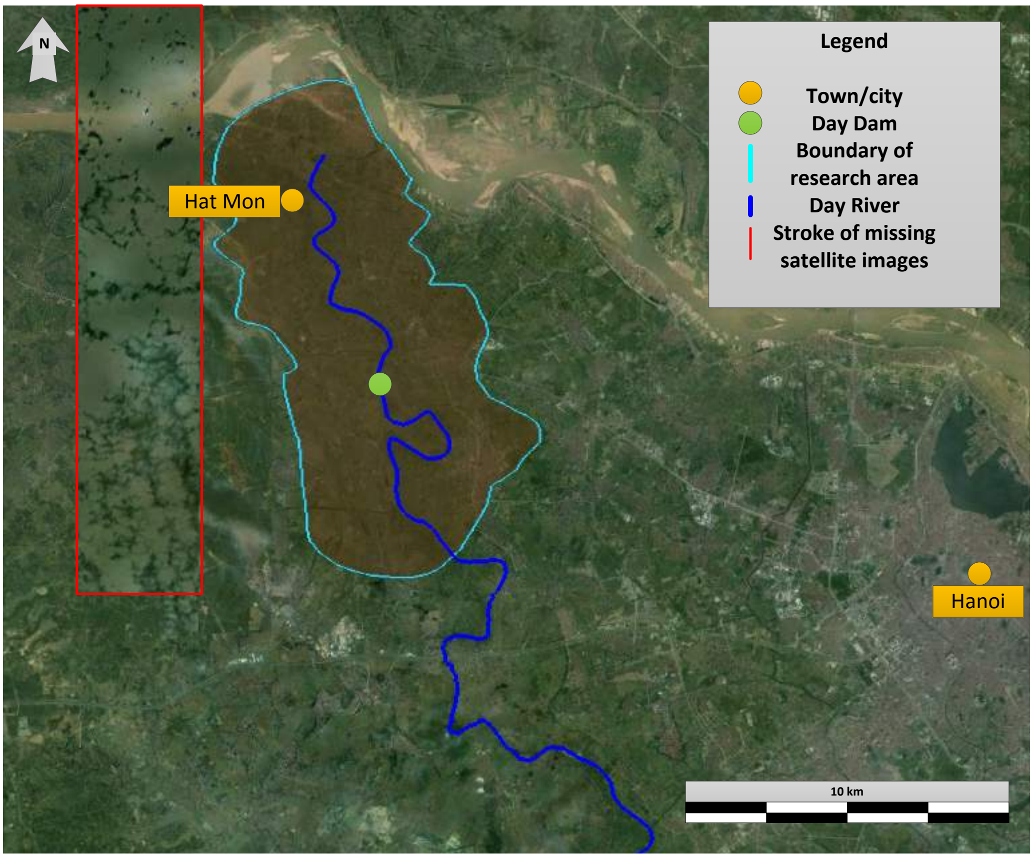

Figure 23: overview research area (Google Earth, 2014)

Mapping land uses

Long rectangular patches of land with farms

Large grassland agricultural land use

Mixed agroforestry agriculture (different ground colors very well visible)

Small patches, irrigation trenches clearly visible (satellite image is from a different image recording, which manifests in color tone)

Figure 24: images of agricultural land uses in research area (Google Earth, 2014)

Mapping the hydrology in and around the research area

It was chosen to map the hydrology of an area that stretches out to a length of 30 km along the Day from the Red River conjunction onwards, and which is bounded by the Tich River in the West and the Nhue River in the East (see figure 25).
The missing stroke of satellite images led to missing parts in this map.

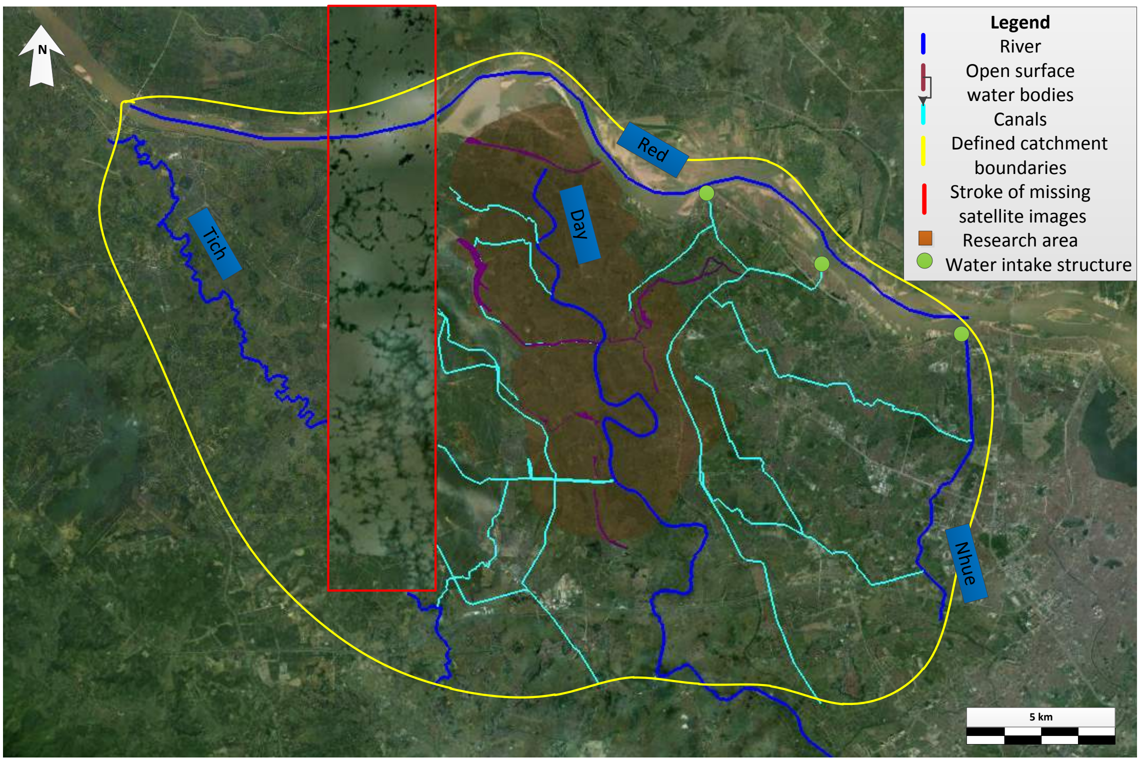

Figure 25: hydrological map around research area (Google Earth, 2014)

Appendix C: Results from working with different datasets in QGIS (mapping step B)

B1) Hydrosheds

Mapping the hydroshed layers in QGIS

Four Hydrosheds Raster layers have been downloaded and this are the observations made:

<u>The DEM-layer:</u>
Has been used to construct watersheds in B2

The Basins-layer:
This layer depicts the larger basins/watersheds.
It outlines the shape of the Day/Nhue-sub basin very well. However, for detailed watershed mapping around the research area, it is not useful.

Drainage directions-layer:
This layer shows the drainage directions in the basin. Stream segments that are created from this layer are the output in the rivers-layer, which also yields a stronger graphical representation of the area.

The Rivers-layer:
It can be observed that this layer follows the path of the Day River very well, only including small deviations from its path.

B2) Watershed mapping using GRASS

Trying out different values for the user input on cells per basin (from now on called cell number), the following steps were found to yield watershed maps with some distinct differences:

1.000-5.000-10.000-15.000-25.000

The quality of the output was determined by looking at the output for the watersheds, flow accumulation and stream segments, and comparing this output to the actual path of the rivers in the area. For instance, the basin of the Red River itself would actually be split up for some cell number, which is a non-desired output, since it is certainly not the case.
When going higher than 25.000, it was found that the watersheds became too large, resulting in less useful output.

These steps have been used for creating watersheds for with both DEM-models (for specifications, see appendix A). The results are presented in the table below:

Table 5: results of mapping watersheds with different cells per basin values and different DEM datasets:

Cells per basin	Hydrosheds DEM	Aster DEM version 2
1.000	Watersheds are too large	Almost whole GRASS region one large watershed
5.000	Not detailed enough and Red River split up	Watersheds quite small, Red River not visible at all
10.000	Not detailed enough and Red River split up	Only very minor changes from above
15.000	Watersheds are well depicted, but Day watershed is merged with another watershed	Similar watersheds like above, some are simply split up
25.000	Best map, depicting the Day basin well, and well outlined basins around the Day	Similar watersheds but are split differently again

General remarks for other three outputs when using different inputs for the cell number value:
Stream Segments: the higher the cell number, the less stream segments are created
Drainage direction and Accumulation: remain unchanged when varying the amount of cells per basin

As stated in appendix A, the chosen watershed map should fulfil three criteria:
-A map that depicts the Day River the best on its path within the research area
-A watershed map that depicts the basin of the Red River well in the area around Hanoi
-Watersheds should not be too big, or too small

The Aster version 2 dataset not yield any useful watershed maps according to the criteria above. This might be due to the very flat topography.
The three criteria's were fulfilled in the best way by processing the Hydrosheds DEM using 25.000 cells per basin: the path of the Day was outlined correctly for this segment, and basins had a reasonable size. Furthermore, the watershed created for the Red River and flow accumulation and streams segment that belong to it followed the path of the original river very well. Accordingly, this map was chosen for the analysis in step C of the mapping paragraph.

Appendix D: The classification of ecosystem services for this research

(Liquete et al., 2013) identified four "best established ecosystem service classifications" (Liquete et al., 2013, p. 4): The Millennium Ecosystem Assessment (MEA, 2005), the Economics of Ecosystems and Biodiversity (TEEB, 2010), the Common International Classification of Ecosystem Services (CICES, 2010), and (Beaumont et al., 2007). These have been used in 32% of the 145 papers that have been subject to this study.
Even though definitions on ecosystem services (ESS) are similar in scientific papers, they have been categorized very differently, depending on the type of research that is carried out, and in which ecosystem this is done (Liquete et al, 2013). Some classifications handle very specific categories for each ESS, while others just handle one general category. For instance when looking at the four papers mentioned earlier, the MEA, TEEB and Beaumont et al. use the ESS "food" or "food provision", while CICES splits this ESS up into "Terrestrial plant and animal", "Freshwater plant and animal" and "Marine plant and animal". This splitting or clustering of ESS happens likewise in all different ESS categories. However, main categories remain the same, at least with regards to the four papers looked at.
ESS are usually divided into four main categories:
-Provisioning services
-Regulating services
-Habitat services
-Cultural services

Comments on the classification of ESS for this paper (see chapter 6.1)
Several ESS have been clustered into larger ESS, for instance for the cluster of "Biotic materials and biofuels". For this research, the individual components "Ornamental resources", "Genetic resources", "Medicinal resources" and "Raw materials" are too specific in order to be evaluated individually for every alternative. Similarly, "air quality and climate regulation" and "biological control and pollination" have been created out of 2 individual ESS in the WLE. Cultural ESS were clustered into "Cultural values", since little information has been obtained on the cultural dimension of the ecological engineering interventions presented in this paper. Likewise, the two habitat ESS have been combined.
(Liquete et al., 2013) also provided a good guideline, since this research clustered ESS together. However, this was done for a research concerning the coastal and marine environment, so the presented classification was chosen for this paper.
Next to clustering, some ESS have been renamed. On one hand, this has been done to handle a shorter description, e.g. "soil fertility" instead of "maintenance of soil fertility". On the other hand, it was done to specify ESS according to this research: for instance, "waste treatment" is renamed "water purification", since this is the function that the ecological system can provide to treat the waste of the system.(Rao et al., 2013) Since floods are the only extreme weather event that occurs in the research area, "Moderation of extreme events" was renamed "Flood protection".

The final results are 12 different ESS (3 provisioning, 7 regulating, 1 habitat, 1 cultural), which are briefly defined below: (sources: WLE, 2014; MEA, 2005; TEEB, 2010)

Provisioning ESS
Food provision: food that humans obtain from managed systems like agriculture, livestock and aquaculture, as well as from wild sources.

Water: provision of ground- and surface water for human purposes like drinking water and irrigation, as well as water retained for ecosystem functioning

Biotic materials and biofuels: provision of species variety (e.g. timber, ornamental resources, and animals), biochemicals and fibers that serve the human environment for purposes like building, medicine, and energy.

Regulating ESS
Water purification: the ability of ecosystem components to treat and purify water polluted with human and animal waste as well as other pollutants like nutrient overloads from agriculture.

Regulation of water flows: for instance natural drainage, irrigation and water retention functions.

Erosion prevention: the protection of land from erosion, a key factor in land degradation.

Soil fertility: maintaining the fertility of soils, which includes soil formation and nutrient cycling.

Flood protection: the ecosystem's ability to build resilience to extreme flood events

Air quality and climate regulation: the influence of biomass on the air quality as pollutant and gas sinks, as well as on climatic factors like heat and water fluxes.

Life cycle maintenance: this incorporates pollination, which is inevitable for crop productivity and plant health, as well as regulation of pests and vector borne diseases.

Habitat ESS

Habitat: the provision of suitable habitats for species as well as the maintenance of genetic diversity

Cultural ESS

Cultural services: for this research, have been clustered as one ESS, representing the non-material benefits to the human environment like aesthetic, spiritual and psychological values.

Appendix E: Additional illustrations for the selected alternatives

Vegetative buffers

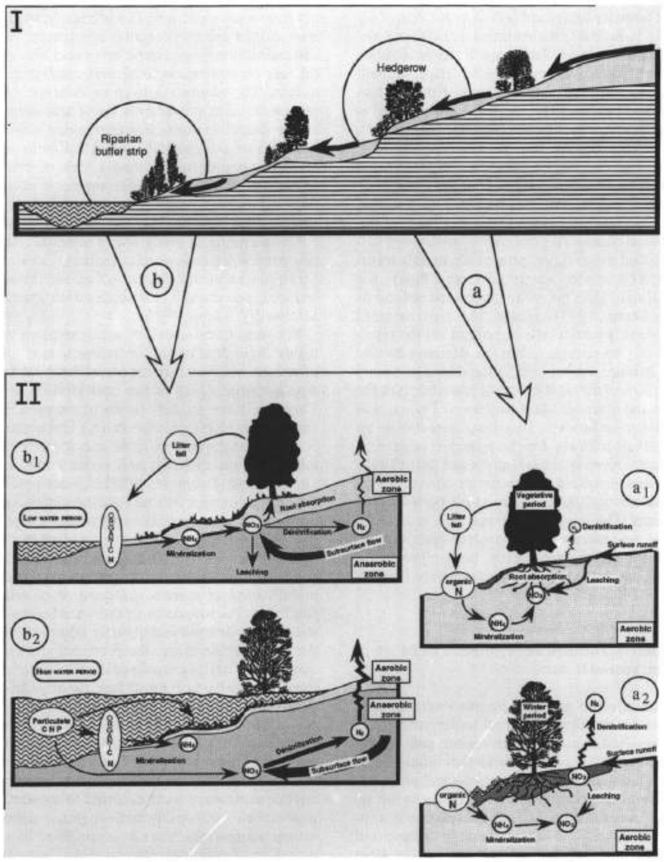

Figure 26: Model of nitrogen cycling in (a) upland buffers, i.e. hedgerow and (b) riparian strips: (Vought et al., 1995)

Water retention additives

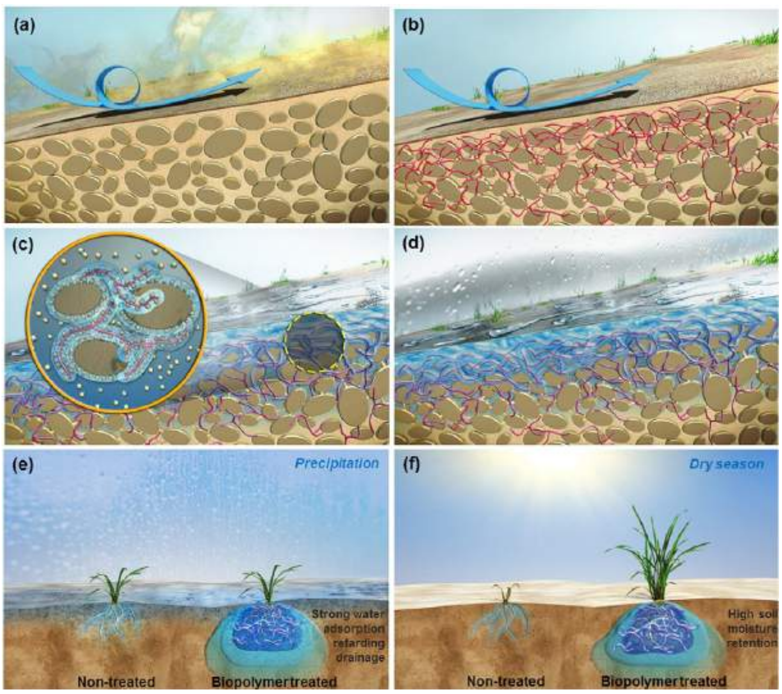

Figure 27: Erosion resistance model of biopolymer treated soil. (a) Erodible natural soil. (b) Improved biopolymer treated soil. (c) Bound water zone via hydrophilic adsorption. (d) Surface coating effect. (e) High water absorbability under precipitation. (f) Soil moisture retention under an intense heat environment (Chang et al., 2015)

Wastewater stabilization ponds

Figure 28: Image of a waste stabilization pond (van Lier & de Kreuk, 2014)

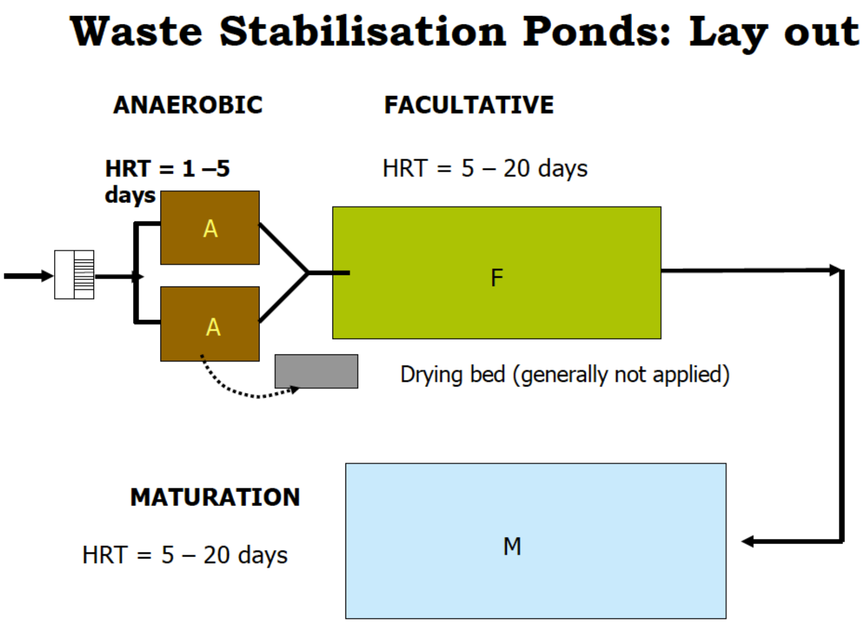

Figure 29: Layout of a waste stabilization pond (van Lier & de Kreuk, 2014)

Appendix F: Quantitative information on the selected alternatives

Constructed wastewater treatment wetlands

In order to determine if constructed wastewater treatment wetlands are a feasible option for treating wastewater in the research area, the following calculations were done:

Area needed to treat wastewater of 1 person
1 PE = population equivalent = 60g BOD_5 d^{-1}

(Vyzamal, 2011) and (Zapater-Pereyra et al., 2015) designate 5 m^2 PE^{-1} as a usual/ high estimate, respectively.

Due to population density of 1,136 persons per km^2 (ICEM, 2007), area available for one inhabitant is:
1 km^2 / 1136= 1,000,000 m^2 / 1,136 = 880 m^2

Of the 880 m^2 available area per inhabitant, 5 m^2 (0.6%) of this area would be needed to treat the wastewater of a PE.

For the whole of the Research area (A=88,080,000 m^2), the following is true:
Number of inhabitants= 88.08 km^2 * 1,136 inhabitants/km^2 =100,058 inhabitants

Resulting in a theoretical value for the area required to treat all the inhabitant's wastewater in the research area:
A_{tot}= 100,058 inhabitants * 5 m^2/inhabitant = 500,290 m^2 (which logically is 0.6% of the research area)

It is estimated that this would be a realistic option, since less than 1% of the area per inhabitant would need to be transformed to a treatment wetland!

Tropical wetlands removal efficiencies and other characteristics (Kivaisi, 2001):

Carbon sink function: net primary productivity around 1000 kg C m^{-2} y^{-1}

Table 6: Removal efficiencies of pollutants in a tropical constructed treatment wetland (Kivaisi, 2001):

BOD	Nitrogen	Phosphorous	Indicator bacteria
75-90	30-50	20-60	60-99

Compared to other characteristic treatment systems in developing countries (see table 7), wetlands rank well. They also provide several other ecosystem services like carbon sequestration or habitat provision next to their main function.

Table 7: Typical characteristics of the main wastewater treatment systems in developing countries (Vyzamal, 2010)

Treatment systems	Removal Efficiencies (%)				Requirements		Construction cost (US $ /Inhabitant.)	Total HRT (Days)	Quantity of sludge to be removed ($m^3 Inhab^{-1} yr^{-2}$)
	BOD	N	P	Coliforms	Land (m^2/Inhab.)	Power (W/Inhab.)			
Preliminary treatment	0–5	~0	~0	~0	<0.001	~0	2–8	–	–
Primary treatment	35–40	10–25	10–20	30–40	0.03–0.05	~0	20–30	0.1–0.5	0.6–1.3
Facultative pond	75–85	30–50	20–60	60–99	2.0–5.0	~0	10–30	15–30	–
Anaerobic pond/Facultative pond	75–90	30–50	20–60	60–99.9	13–3.5	~0	10–25	12–24	–
Facultative aerated lagoon	75–90	30–50	20–60	60–96	0.25–0.5	1.0–1.7	10–25	3–9	–
Completely mixed Aerated sediment pond	75–90	30–50	20–60	60–99	0.2–0.5	1.0–1.7	10–25	4–9	–
Conventional activated Sludge	85–93	30–40	30–45	60–90	0.2–0.3	13–2.8	60–120	0.4–0.6	1.1–1.5
Extended aeration (continuous flow)	93–98	15–30	10–20	65–90	0.25–0.35	23–4.0	40–80	0.8–1.2	0.7–1.2
Sequence batch reactor	85–95	30–40	30–45	60–90	0.2–0.3	1.5–1.0	50–80	0.4–1.2	0.7–1.5
Low rate trickling filter	85–93	30–40	30–45	60–90	0.5–0.7	0.2–0.6	50–90	NA[a]	0.4–0.6
High rate trickling filter	80–90	30–40	30–45	60–90	0.3–0.45	0.5–1.0	40–70	NA	1.1–1.5
Upflow anaerobic sludge Blanket reactor	60–80	10–25	10–20	60–90	0.05–0.10	~0	20–40	0.3–0.5	0.07–0.1
Septic tank-anaerobic filter	70–90	10–25	10–20	60–90	0.2–0.4	~0	30–80	1.0–2.0	0.07–0.1
Slow rate infiltration	94–99	65–95	75–99	>99	10–50	~0	10–20	NA	
Rapid infiltration	86–98	10–80	30-99	>99	1–6	~0	5–15	NA	
Subsurface infiltration	90–98	10–40	85–95	>99	1–5	~0	5–15	NA	
Overland flow	85–95	10–80	20–50	90– >99	1–6	~0	5–15	NA	

Vegetative strips

Table 8: Meadows and pastures and their effect on water balance compared to arable land

Source [location]	Parameter	Arable land	Meadows and pastures	Impact with regards to meadows/pastures
(BIO intelligence service, 2014) [Spain]	Runoff (m^3/ha)	1884	643-962	49-66% less runoff
(Kedziora, 2010) [Poland]	Runoff (mm) dry year	108	0	100% less runoff
(Kedziora, 2010) [Poland]	Runoff (mm) normal year	233	155	33% less runoff

(Kedziora, 2010) [Poland]	Runoff (mm) wet year	351	271	23% less runoff
(Kedziora, 2010) [Poland]	Evapotranspiration dry year (mm)	364	490	35% higher ET
(Kedziora, 2010) [Poland]	Evapotranspiration normal year (mm)	422	510	21% higher ET
(Kedziora, 2010) [Poland]	Evapotranspiration wet year (mm)	507	549	8% higher ET

Table 9: Buffer strips and their effect on runoff, compared to the absence of buffer strips:

Source	Runoff reduction (%)
(Borin, Passoni, Thiene, & Tempesta, 2009)	78
(CORPEN, 2007) (with a 10m buffer strip)	50

Table 10: Buffer strips and their effect on pollution reduction:

Source	Width of buffer strip (m) [landscape type/location]	P reduction (%)	N reduction (%)	Organic matter reduction (%)
(JRC, 2013)	5 [flat area]	15-20	n.a.	n.a.
(JRC, 2013)	5 [hilly area]	42-96	27-81	83-90
(Borin et al., 2009)	6 [Padova, Italy]	74	80	n.a.
(Leung et al., 2015)	10 [hilly area]	95	n.a.	n.a.

Table 11: ***Buffer strips and their effect on erosion control***

Source	Width of buffer strip (m) [landscape type/location]	TSS reduction (%)	Sediment reduction (%)
(JRC, 2013)	5 [hilly area]	55-97	n.a.
(Borin et al., 2009)	6 [Padova, Italy]	n.a.	94

Crop practices and tillage variation

Table 12: ***Nitrate losses in agricultural fields using low tillage techniques and crop rotation (Besnard and Rio 2006)***

	Nitrate losses from land (kg/ha/year)
No tillage in pastures	240
Reduced tillage in pastures	165
Crop rotation with rapeseed and weed	250-270
Bare soil	505-550

Table 13: ***Improved water retention and pollution reduction due to no-till agriculture***

Source	Findings
(Soane et al., 2012)	Runoff: 55mm with no till, 94 with ploughing (Italy)
Biedermann (2013)	88% reduction in N concentration in runoff.
Biedermann (2013)	50 % (mulchseed) – 90 % (direct drilling) reduction of herbicide loss in runoff.

Table 14: ***Improved water retention in upper soil layer (0-0.15m): characteristics for no and low-till agriculture (mulchboard tillage as reference)*** **(Bescansa et al. 2006)**

Matric potential of water (kPa)	Soil water retention no tillage (m^3/m^3)	Soil water retention low tillage (m^3/m^3)	Soil water retention mulchboard tillage (m^3/m^3)
0	0.383	0.435	0.431
-33	0.366	0.322	0.326
-50	0.319	0.291	0.287
1500	0.230	0.219	0.217

Basins and ponds

Table 15: ***Pollution removal through detention basins (NWRM, 2014):***

Measurement series number	Reduction suspended solids (%)	Total phosphorus reduction	Total nitrogen reduction	Metals
1	61	14-70	15-45	n.a.
2	30-90	19	31	26-54%