Economic Evaluation of Proposed Ecosystem-based Adaptation Measures in Tha Di and Chi River Basins

Draft final report
VN: 81182922

Carried out in the scope of:

Improved Management of Extreme
Events through Ecosystem-based
Adaptation in Watersheds (ECOSWat)

PN: 20129012.1-001.00 (GIZ)

Prepared by:

ITTrms e.V., Cologne

February 2016

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1 EXECUTIVE SUMMARY

In the scope of this study, an economic evaluation of ecosystem-based adaptation (EbA) measures was carried out within the Huai Sai Bat and Tha Di river basins based on the interventions proposed by Lohr (2015b).

The raw data and reports from Lohr (2015a, 2015b) were used as the main input information. The EbA measures evaluated in this study were identified, described and presented in the GIZ-report "Pre-selection and Preparation of Ecosystem-based Measures in the Pilot Areas Huai Sai Bat and Tha Di for discussion and final decision-making in collaboration with local water committees" (Lohr 2015b).

For this study, the total costs of each measure were calculated based on estimations of unit costs and the dimensions of the specific measures. These costs include investment costs and recurring operation and maintenance costs considering a time horizon of 25 years for the Huai Sai Bat basin and of 5, 10 and 25 years for the Tha Di basin. For both a discount rate of 3 % was considered. The benefits of the measures were estimated in terms of the Total Economic Value (TEV) of the related ecosystem services. For the economic evaluation of the measures Net Present Values (NPV), Annualized Net Present Values (ANPV) and Benefit-Cost-Ratios (BCR) were calculated.

Case Study: Huai Sai Bat River Basin

Water scarcity during the dry season is considered a major threat to society in the Huai Sai Bat basin enhanced by climate change. Nine EbA measures (3 x Floodplain & Wetland Development, 3 x Sediment Pool Installation, 3 x Riparian Zone Improvement) and three *engineering* measures (dredging alternatives) were selected for economic evaluation and comparison to counteract this major threat.

The economic evaluation of the individual EbA measures shows positive NPVs and ANPVs for all except one sediment pool installation measure. Therefore, eight out of nine EbA measures can be considered to be economically reasonable. Significantly high BCRs are identified for the riparian zone improvement measures (BCR: 5,27–5,85). The floodplain & wetland development measures also show high BCRs (2,32–2,84). Relatively low BCRs are identified for sediment pool installation measures (0,96–1,10). The dredging alternatives are either economically not desirable (BCR: 0,94) or present low BCRs (1,07–1,32).

Four scenarios were developed to rank the aforementioned measures in terms of their combined efficiency to counteract the water scarcity problem in the Huai Sai Bat Basin: Scenario 1 ("Engineering") consists only of dredging of the Nong Yai reservoir, Scenario 2 ("EbA") includes all EbA measures but no engineering measures, and Scenario 3 ("Hybrid") combines a reduced set of EbA measures with a dredging alternative of the reservoir. Scenario 4 is considered as the baseline scenario with ongoing regular dredging of the Nong Yai reservoir ("Business as usual") and no EbA measure.

The final economic evaluation of these scenarios reveals positive NPVs and ANPVs for the Scenarios 2, 3 and 4, and negative values for Scenario 1. The NPV is highest for Scenario 2 ("EbA") with THB 903 Mio., followed by Scenario 3 ("Hybrid") with THB 93 Mio. and Scenario 4 ("Business as usual") with 22 Million Thai Baht. The NPV of Scenario 1 ("Engineering") is negative (THB -13 Mio.).

Considering total costs, BCR and the effectivity to secure high water storage capacity during the dry season, Scenario 3 (“Hybrid”) with its measure combination that increases and secures the storage capacity of the Nong Yai reservoir appears to be the most promising alternative to safeguard the water security in the Huai Sai Bat river basin.

Case Study: Tha Di basin

Three main challenges were identified in the basin including flooding during the rainy season, water scarcity during the dry period and water quality deterioration due to human activities. Six different measures (including EbA and engineering) were considered and their economic performance analysed. The EbA measures considered were: living weirs, flood control with wetland development, constructed wetland and riparian zone improvement. On the other hand, the engineering measures analysed were: concrete weirs and a conventional wastewater treatment plant (WWTP).

In the Tha Di basin living weirs (constructed with bamboo and banyan trees structures and filled with sand bags) have been constructed in the last years as an alternative to concrete weirs. Therefore, these two alternatives were analysed and compared. Since no literature was available on the economic value of their benefits the least-cost analysis methodology was used for the comparison. Living weirs are economically advantageous if compared to concrete weirs even under the assumption that living weirs have to be reconstructed every three years due to high flood events. This substantial difference relies on two main factors: (1) community members work voluntarily to construct and maintain living weirs; (2) construction materials are cheaper for living weirs. An economic study is necessary to estimate in field the benefits of living weirs.

The total costs of the measure flood control with wetland development are higher than the benefits in the short term (5 years) making it economically unsuitable. However, the operation and maintenance costs are relatively low and therefore the benefits are already higher than the costs in the middle term (10 years) reaching a BCR of 1,24 and more than double in the long term (25 years) with a BCR of 2,32.

The constructed wetland which will serve 10,000 population equivalents is the only measure which is already economically desirable in the short term. This is due to low investment costs and high environmental benefits. Furthermore, due to also low operation and maintenance costs the BCR continues to increase to 3,29 and 5,84 in the middle and long term, respectively.

The conventional WWTP is not economically desirable in the short term (higher costs than benefits) and a BCR lower than one but it is in the middle and long term. Although due to higher operation and maintenance costs the BCR in the long term reaches 1,40 but still lower if compared to the alternative constructed wetland.

Finally, the riparian zone improvement is also not economically desirable in the short term due to large investment costs related land acquisition and vegetation. However, operation and maintenance costs are moderate and the project becomes more economically desirable in the middle and long terms with BCR of 1,05 and 2,02.

The Tha Di basin is heterogeneous and is facing several environmental problems such as flooding, water scarcity and water quality degradation. Therefore several measures or interventions are required to minimise and mitigate the impacts of natural climate variability and human activities. EbA measures are preferred to engineering measures based on the economic analysis conducted as part of this study. Living weirs are much advantageous economically than concrete weirs and are highly socially accepted. Moreover, constructed wetlands show a better performance than conventional WWTP and may involve also communities in their design and implementation due to low-tech and decentralised approach. Flood control with wetland development and riparian zone improvement require land but they contribute with several environmental benefits which make these measures economically attractive in the middle and long terms.

Water-related agencies, such as the DWR, and other government bodies can form a river committee where the different stakeholders are represented. Such a committee should assess the feasibility of these measures and prioritise them in order to allocate budget for their implementation. It is clear that human activities have had a large impact on environmental quality in the basin and therefore ecosystem-based measures are an adequate solution to restore their services and increase the resilience of the basin.

2 INTRODUCTION

The objective of this study is to conduct an economic evaluation of EbA measures within the Huai Sai Bat and Tha Di river basin as proposed by Lohr (2015b). The evaluation is carried out following the activities described below:

a) Characterisation of the proposed measures pointing out benefits and possible risks,
b) Economic assessment of all proposed measures based on cost and benefit estimates,
c) Qualitative and quantitative evaluation of the effects on biodiversity, and
d) Comparison of proposed EbA measures with potential grey infrastructure measures.

The goal of this study is to provide a comprehensive economic evaluation and ranking of the proposed measures based on the points mentioned above, and to further enhance the knowledge of local experts.

3 DATA

The raw data and reports of Lohr (2015a, 2015b) were used as input information for this study. The EbA measures evaluated in this study were identified and described in the GIZ-report "Pre-selection and Preparation of Ecosystem-based Measures in the Pilot Areas Huai Sai Bat and Tha Di for discussion and final decision-making in collaboration with local water committees" (Lohr 2015b).

Together with experts from Khon Kaen University (Huai Sai Bat river basin) and Walailak University (Tha Di river basin) field visits to the sites of the proposed EbA measures were carried out in August 2015. The aim of these visits was to evaluate the feasibility of the proposed measures and prioritise them with regard to their efficiency in tackling the major problems within the river basins.

The estimates of costs and benefits of the measures are based on an extensive literature review of economic evaluation of river restoration and on practical experiences of the project consortium, which has experience of more than 20 years in river restoration projects.

4 METHOD

The economic evaluation is based on a Cost-Benefit-Analysis (CBA) of the proposed individual measures and of different scenarios representing varying combinations of these measures. The CBA includes estimations of cost and benefit ranges (MIN-MAX) of all types of measures in monetary terms (THB - Thai Baht). So-called EXPERT-values of costs and benefits are defined as basis for the calculation of the total costs (Investment and Operation/Maintenance), total benefits (TEV - Total Economic Value), Net Present Value (NPV), Annualized Net Present Value (ANPV) and the Benefit Cost Ratio (BCR) of single measures and scenarios. These EXPERT-values represent the assumed most reasonable values of costs and benefits within the MIN-MAX ranges. These values are derived by an ongoing estimation process involving comprehensive literature reviews, evaluation of revitalization projects in Germany and discussions including Thai and German experts. All values in the main text are based on the EXPERT estimates. MIN, MAX values are listed in the Appendix II

Based on this economic evaluation and the effects on biodiversity, the proposed measures are then ranked in terms of an economic and ecological prioritisation. A detailed description of the study's methodology can be found in Appendix I.

5 CASE STUDY *HUAI SAI BAT RIVER BASIN*

5.1 Characterisation of the Huai Sai Bat River Basin

The Huai Sai Bat, a sub-basin of the Chi River Basin, is located in North-eastern Thailand. The basin has a size of 678 km² with its major part belonging to the Khon Kaen Province, and smaller areas belonging to the Kalasin and Maha Sarakham provinces. Being a part of the Khorat Plateau, the catchment has a flat terrain with the elevation changing from 139 m.a.s.l. at the river mouth in the south to 504 m.a.s.l. in the northern mountains. 95% of the catchment area has an elevation of less than 250 m.a.s.l..

The climate of the basin is influenced by southwest monsoon from May to October, and northeast monsoon from October to February. The activities of the monsoons define the seasonality of the climate with warm and moist conditions in southwest monsoon periods, and cold and dry ones in the northeast monsoon periods. The annual average rainfall at Muong Khon Kean during 1981-2010 was 1.247 mm with over 85% rainfall occurring from May to October (http://www.tmd.go.th). The annual mean relative humidity of the air is 71,6%. Long-term low rainfall is a major factor causing droughts in the dry seasons.

There are approx. 65.000 people living in the Huai Sai Bat Basin. The population density is 96 persons/km² compared with the national average of over 130 persons/km². A majority of the region's population is living in villages distributed along the main rivers. The urban population is concentrated mostly in Kranuan, Kham Yai, and Huai Toei municipalities (Figure 5-1).

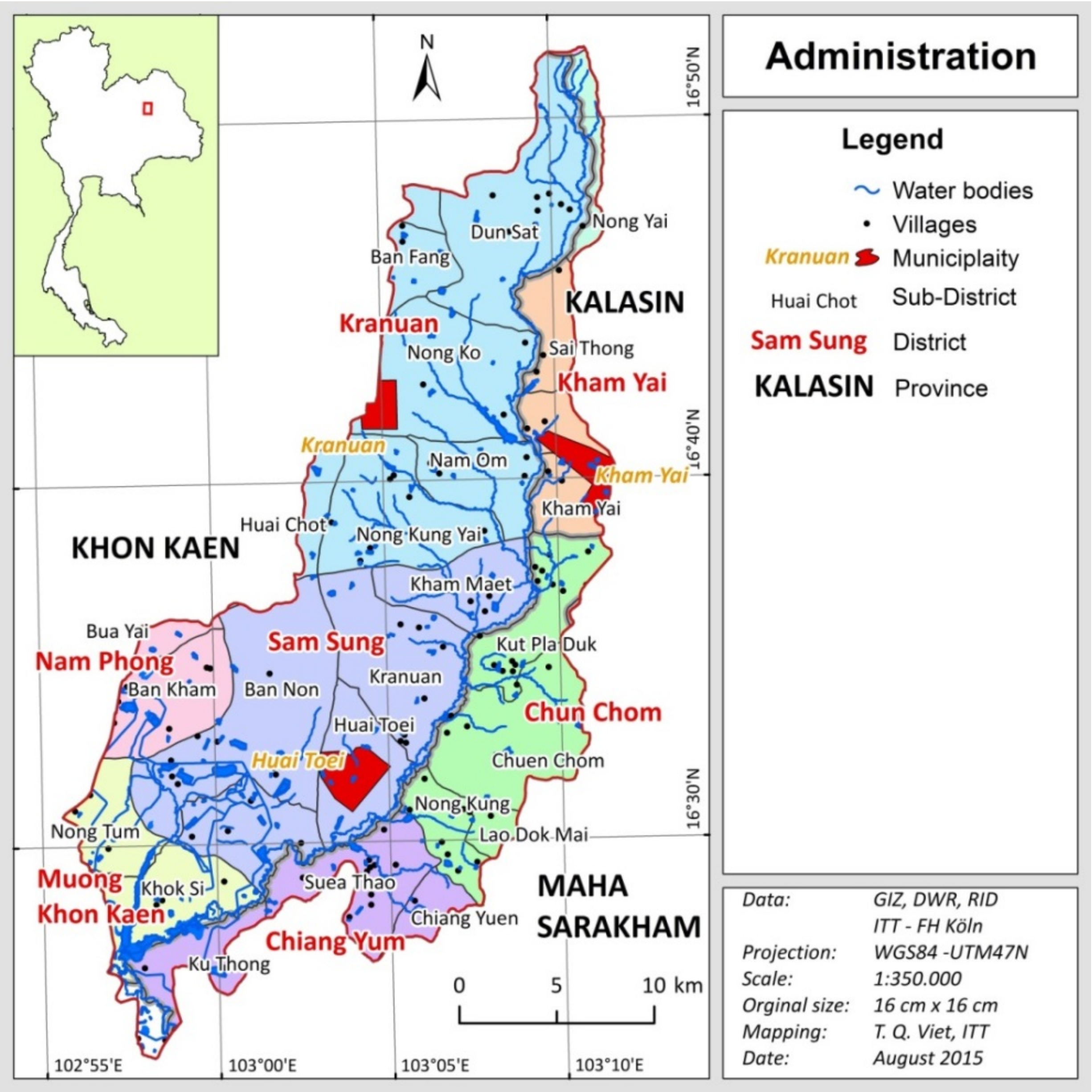


Figure 5-1: Administrative organisation in the Huai Sai Bat Basin.

Forests in the catchment have been steadily replaced by agricultural areas in the last decades. Only small fragmented pieces of deciduous and evergreen forests remain in the mountainous areas in the Northern and Central parts of the basin (Figure 5-2). Cassava and sugarcane are the major annual crops in the Northern and Central parts, while paddy rice is concentrated in the Southern part of the catchment. Rubber is the major industrial tree planted on the areas of former forests.

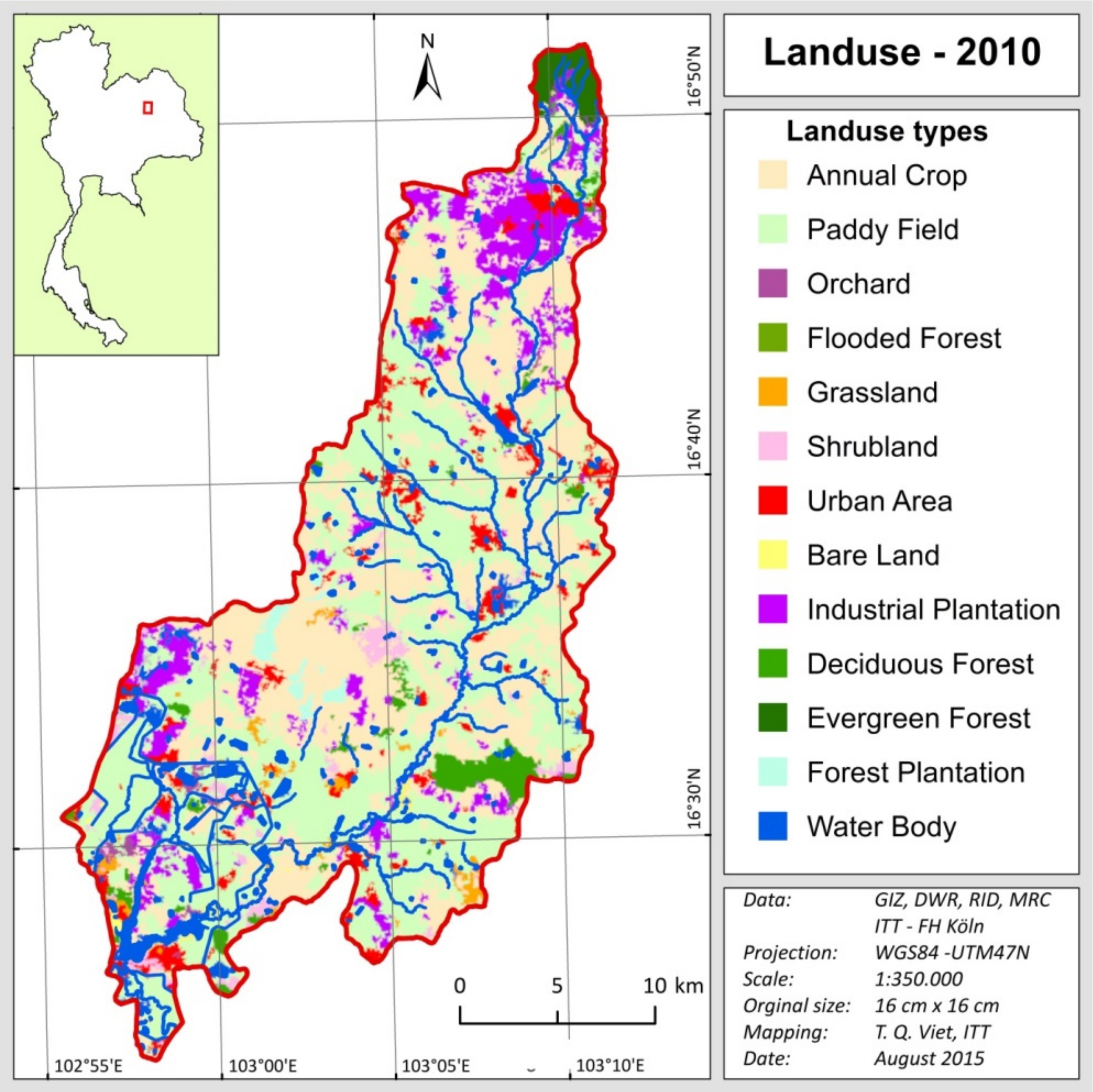


Figure 5-2: Land use in the Huai Sai Bat Basin.

Man-made features relevant to the topic treated in this study, i.e. excessive sedimentation and water shortage, are the structures for water management including two reservoirs (Nong Yai reservoir in the upper basin and Nong Lerng Yai reservoir in the lower part), several weirs along Huai Sai Bat and some tributaries, and countless small ponds distributed over the entire basin and river network, mostly used for livestock and irrigation. The following map shows the distribution of water resources availability/yield in the basin (Figure 5-3). It illustrates the uneven distribution of water resources with lower water availability in the upstream in contrast to the abundant water in the lower part of the basin.

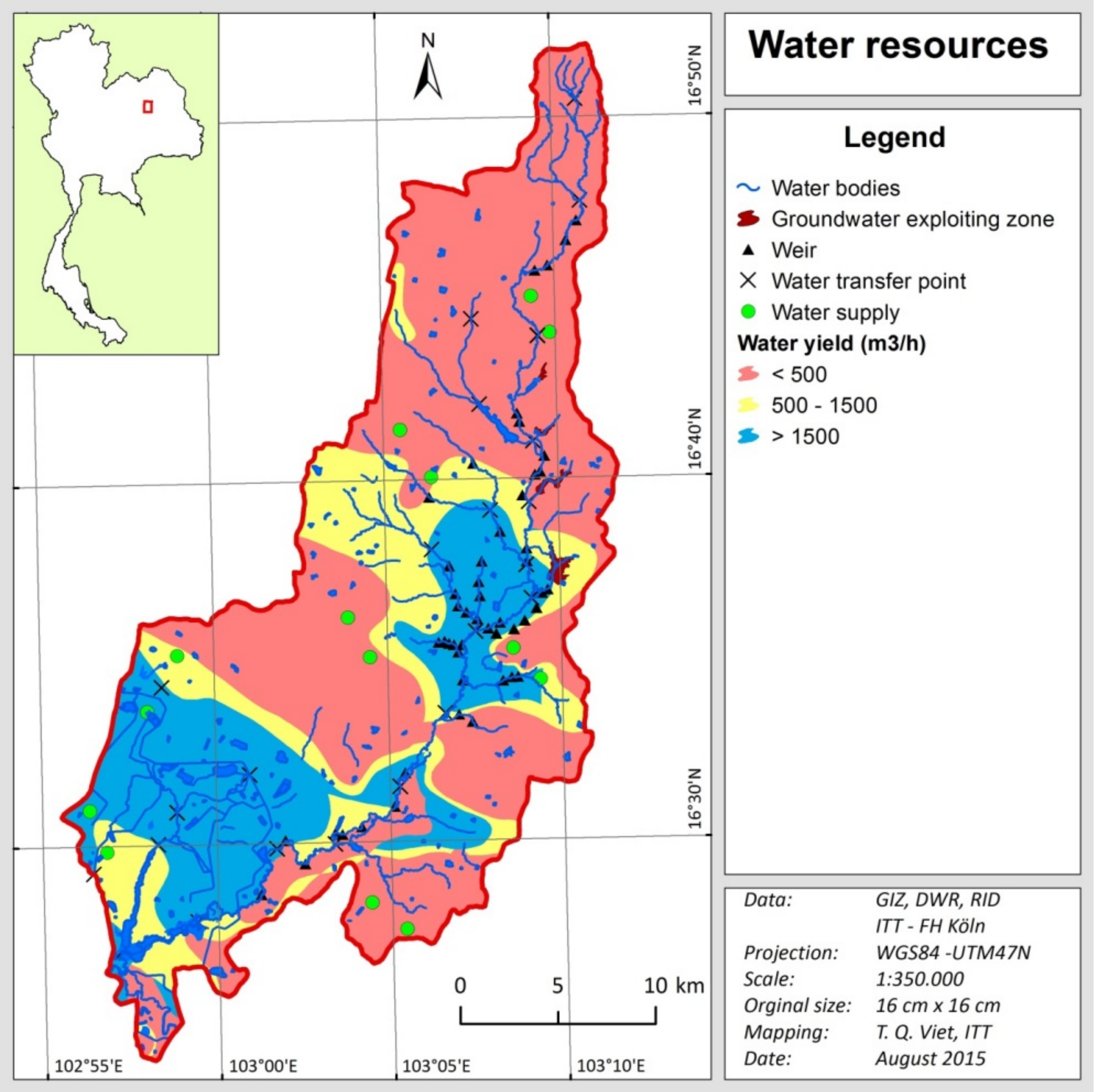


Figure 5-3: Water works and water yield in the Huai Sai Bat Basin.

5.2 Problem definition

The identification of the major threat to society in the Huai Sai Bat River Basin posed by climate change is based on the preceding vulnerability analysis for the river basin done by Lohr (2015a). As indicated in Figure 5-4, the dry period between November and March with low discharge leads to nearly dry river beds, ponds and reservoirs and little opportunities to extract water (Lohr 2015a). Consequently, the water security within the Huai Sai Bat Basin during this dry period depends strongly on water storage capacities to meet water demands for irrigation and domestic use.

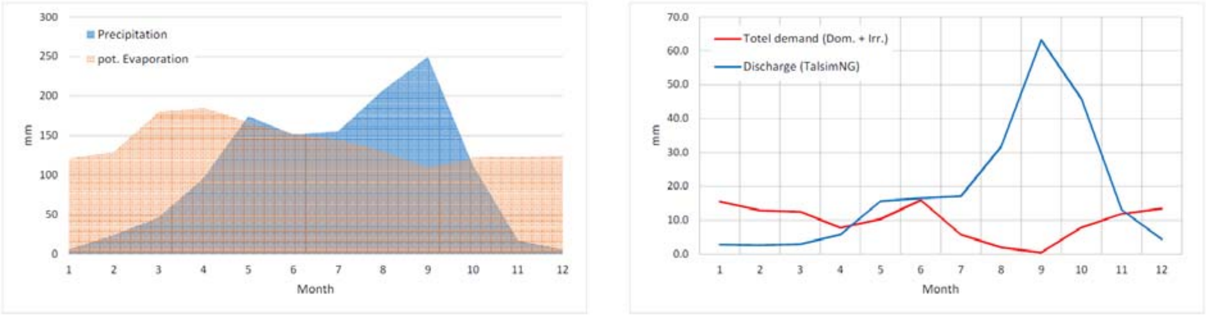


Figure 5-4: Water balance of the Huai Sai Bat Basin (Lohr 2015a).

Climate change induced changes in temperature and precipitation will tend to exacerbate the water scarcity problem in Northeastern Thailand due to projected increase in the former and and decrease in the latter during the dry season (Masaki et al. 2011, Manomaiphoon et al. 2013). The current drought severity level is highlighted in Figure 5-5, being highest in the upper part of the Huai Sai Bat Basin.

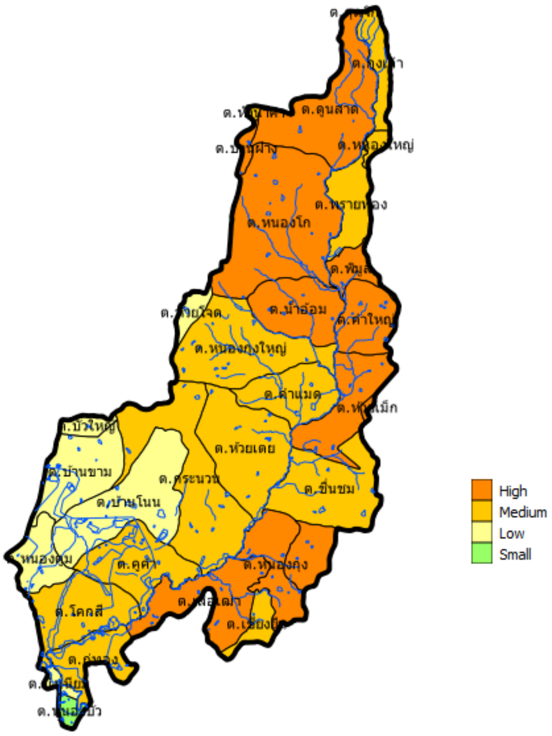


Figure 5-5: Drought Severity Level in the Huai Sai Bat River Basin (Source: Khon Kaen Integrated Water Resources Management and Development Plan Project, 2014, unpublished).

The water scarcity problem is compounded by the decreasing storage capacity due to continued intrusion of sediments into the rivers, creeks and reservoirs. The former forests turned into agricultural fields are prone to erosion and mobilisation of fine sediments, and contribute to increased sediment load.

Figure 5-6: Erosion of fine sediments along unpaved road in the upper part of the Huai Sai Bat Basin (Photo: G. Meier, 2015).

Another source of sedimentation is the severe erosion of formally dredged material from the Nong Yai reservoir which is dumped in the immediate surrounding of the reservoir's banks.

Figure 5-7: Severe erosion of sediments dredged from the reservoir and dumped in the immediate surrounding of the Nong Yai reservoir (Photo: T. Zumbroich, 2015).

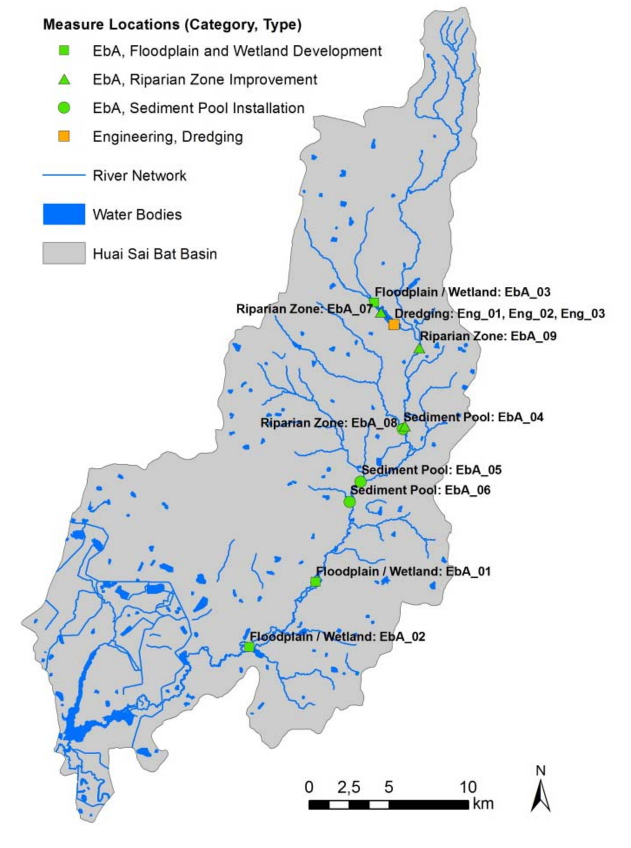
With regard to the following prioritisation of the proposed EbA measures, the **decreased water supply safety worsened by intensive sedimentation** of reservoirs and rivers is considered as the major threat induced by climate change in the Huai Sai Bat Basin.

5.3 Measure selection

The selection of the most effective EbA measures focusing on the above-stated threat of sedimentation is based on the report on pre-selecting and preparing EbA measures for the river basin (Lohr, 2015b). These proposed measures are assumed to effectively counteract the major threat – water scarcity during dry season – in the Huai Sai Bat basin. The selection is based on discussions with local experts, field visits and the expertise of the project consortium regarding near-natural river restoration projects and research. One goal of the study in hand was to compare

EbA measures with possible grey measures in terms of costs, effectiveness and benefits. For that reason, *Dredging* was selected as an *Engineering* alternative.

The specific measures of the aforementioned types (EbA and Engineering) are located throughout the entire basin to effectively increase the water storage and sediment retention capacity (Figure 5-8). The pre-selection of the measure locations according to Lohr (2015b) did not consider legal or land-property related aspects. The locations were selected due to their representative set-up for the entire basin and are considered to be initial suggestions of potential measure sites to be discussed during basin committee meetings involving all potential stakeholders.



Measure-ID	Measures (Type, Location)
EbA_01	Floodplain and Wetland Development Floodplain No.1
EbA_02	Floodplain and Wetland Development Floodplain No.2
EbA_03	Floodplain and Wetland Development Nong Yai Pre-Reservoir
EbA_04	Sediment Pool Installation Confluence Wetland No.1
EbA_05	Sediment Pool Installation Confluence Wetland No.2
EbA_06	Sediment Pool Installation Confluence Wetland No.3
EbA_07	Riparian Zone Improvement Nong Yai Reservoir
EbA_08	Riparian Zone Improvement Kham Maet
EbA_09	Riparian Zone Improvement Nam Om
Engineering_01	Alternative 1: One-time Dredging (75%) Nong Yai Reservoir
Engineering_02	Alternative 2: One-time Dredging (50%) Huai Sai Bat River
Engineering_03	Alternative 3: Regular Dredging Huai Sai Bat River

Figure 5-8: Location of EbA and Engineering measures within the Huai Sai Bat basin.

In the following section, the four types of measures are described, with focus on their effectiveness toward sediment control. Besides this primary benefit all selected EbA measures also have other beneficial impacts on the water supply safety (e. g. groundwater recharge, water storage, infiltration) and other ecosystem services, summarized in Table 5-1 at the end of this sub-chapter.

Floodplain and wetland development (EbA-measures EbA_01, EbA_02, EbA_03)

Floodplains are the areas bordering a river providing space for water and sediment retention (Figure 5-9). These areas were often dried out and separated from the river by dykes or berms in order to be brought under cultivation. The restoration of floodplains and wetlands increases the water storage capacity, sediment retention and several other ecosystem functions. Wetlands are also considered hotspots of biodiversity (EC 2015).

Figure 5-9: Examples of intact wetland/floodplain (left) (Source: http://downtoearth.danone.com/2012/07/16/the-ramsar-convention-protecting-the-wetlands-since-1971/) and restored floodplain site (right) (Source: Zumbroich Consulting).

The construction or restoration of wetlands includes marsh systems planted with emergent vegetation that are designed to retain water and sediments. Depending on the current situation (no wetland, degraded wetland, etc.) different approaches of floodplain and wetland development have to be chosen (creation, restoration, enhancement, etc.). This choice is significantly influencing the technical aspects and the costs of a wetland project.

Several key design elements have to be considered when planning wetlands:

- Maintenance of a permanent water surface by design of ponds, oxbows, etc.,
- Multiple vegetative growth zones through varying depths,
- Robust and diverse vegetation,
- Relatively impermeable soils or engineered liner,
- Sediment collection and removal (Especially if wetlands serve as a pre-reservoir a sedimentation pond at the outlet of the pre-reservoir is necessary.),
- Forebays at all major inflow points to capture coarse sediments, prevent excessive sediment accumulation in the remainder of the wetland, and minimize erosion by inflow, and
- Buffer zones around the wetland to enhance habitat value, visual aesthetics and wetland health.

Sediment pool installation (EbA-measures EbA_04, EbA_05, EbA_06)

Sediment capture ponds or pools are placed mainly at smaller tributaries or headwaters (Figure 5-10). They slow down the flow velocity and cause the deposition of suspended materials. These ponds are most effective during base flow and moderate flow events. The effectiveness of this EbA measure has to be maintained by regular removal of accumulated sediment (EC 2015).

Figure 5-10: Example of a fully developed sediment pond (left) (Source: http://saveourstream.blogspot.de/p/sediment-ponds.html) and construction works (profiling and widening cross-section profile) for the installation of a sediment pond (right) (Source: Zumbroich Consulting)

Sediment ponds require the construction of structures to capture coarse to medium silt and smaller suspended particles. Since particles of these sizes have low settling velocities, large storage volumes, long flow-path lengths, and controlled discharges are necessary to achieve efficient sedimentation rates.

Key elements of sediment ponds are

- Purpose designed inlet and outlet structures,
- High flow, overflow or bypass structures,
- An adequate access to the sediment pond,
- A designated dry out area for the removed sediment,
- A facility that will enable the sediment pond to be taken offline while maintenance (e.g. dredging) is carried out, and
- Ability to drawdown water level.

Riparian zone improvement (EbA-measures EbA_07, EbA_08, EbA_09)

Riparian buffers are treed areas alongside streams (Figure 5-11) and other water bodies such as reservoirs where restrictions do not allow for land intensive measures such as floodplain reactivation. By preserving a relatively undisturbed area adjacent to open water, riparian buffers can serve a number of functions related to water quality and flow moderation. The trees in riparian areas can efficiently take up nutrients and may also serve to increase infiltration. Riparian buffers serve to slow water as it moves off the land. This can decrease sediment inputs to surface waters (EC 2015).

Figure 5-11: Example of riparian buffer (left) (Source: http://en.wikipedia.org/wiki/Riparian_buffer) and the shading effect of riparian vegetation (right) (Source: Zumbroich Consulting).

The improvement of riparian zones is especially appropriate when the land immediately surrounding the water body lacks vegetative cover or has bare soils prone to erosion. Treed riparian buffers can stabilize river banks, lower water temperatures through shading and prevent banks to be dominate by invasive weed, shrub or tree species.

Key elements of riparian zone improvement are

- Planting of native vegetation (grasses, shrubs and trees),
- Near-natural bank stabilization or fixation through bioengineering techniques,
- Bank pull-back or re-sloping,
- Livestock exclusion and fencing,
- Off-stream or controlled livestock watering, and
- Invasive vegetation clearing and control.

Dredging of reservoirs (Engineering measures Eng_01, Eng_02, Eng_03)

One of the most popular methods in dealing with reservoir sedimentation is sediment dredging. Dredging is also probably the most controversial issue in reservoir storage rehabilitation in terms of environmental hazards. One of the major environmental concerns is that dredging re-suspends sediments which may release toxic substances. The second most important factor in dredging is the transportation and disposal of the dredged material.

Figure 5-12: Example of reservoir dredging (left) (Source: http://belldredgingpumps.com/amphibious-excavator/) and river dredging (right) (Source: Zumbroich Consulting).

Key elements for minimising environmental effects of reservoir dredging are

- Use of appropriate sediment remobilization control (e.g. *in-the-dry* working through water bypass) during dredging to avoid sediment-laden waters affecting downstream water quality, wildlife habitat and water withdrawals,
- Selection of an appropriate location for drying the dredged material without the risk of re-mobilization,
- Sample taking to check contamination of sediments and provide safe disposal of contaminated dredged material, and
- Recognition of non-contaminated sediments as a resource (e.g. construction material).

Table 5-1: Basic description of selected EbA- and Engineering measures.

Measure	Details of Measure	Possible Benefits	Possible Risks
EbA Measures			
Floodplain and wetland development	Land acquisition, channel modification, sediment removal, construction of inlet sluice and outlet sluice, creation of lakes/ponds and grassy basins/swales, plantation of native, grasses, shrubs and trees, near-natural dyke construction, riparian buffer zone establishment	• Additional economic, environmental and social benefits (e.g.: storing and slowing down river water and runoff, increase infiltration, reduction of erosion and sediment delivery, CO_2 storage, flood risk reduction, recreational opportunities, aesthetic and cultural value; • Can involve community participation/education in restoration activities; • Hotspot of biodiversity	• Space requirements; • Success rate of wetland can be low if improperly designed;
Sediment pool installation	Channel profiling, sediment forebay, construction of inlet sluice and outlet sluice permanent pool zone, temporary storage volume, shallow zone, shading (tree vegetation), regular sediment removal	• Additional economic, environmental and social benefits (e.g. reduction of pollutant sources, interception of pollution pathways, erosion and sedimentation control, fish stocks and recruiting; • Can involve community participation/education in restoration activities; • Water storage and sediment retention	• Success rate of pond can be low if improperly designed; • Maintenance (sediment removal and disposal necessary); • Potential for water-borne diseases
Riparian zone improvement	Land acquisition, tree plantation, removal of unwanted non-native vegetation types (if necessary: near-natural bank fixation, fencing)	• Additional economic, environmental and social benefits (e.g. Reduction of erosion and sediment delivery, creation of riparian habitat, ecological corridors, decrease water temperature through shading; • Can involve community participation/education in restoration activities; • Water infiltration, Nutrient uptake and sediment retention	• Space requirements;
Engineering Measure			
Dredging of reservoir	Remove excessive sediment	• Increase water storage capacity; • Immediate effect;	• Increased capacity loss due to continuous sedimentation; • Disposal of dredged material • Ecological damage

5.4 Measure costs

The cost estimates of the nine EbA measures and the three engineering measure alternatives are based on unit costs of the activities necessary to realize the respective type of measure (Table 5-2).

Table 5-2: Unit costs of activities per type of measure.

Activities	Range	Unit Costs [THB]	Floodplain & Wetland Development	Sediment Pool Installation	Riparian Zone Development	Dredging
Land acquisition [m²]	MIN	15,00	x			
	EXPERT	**30,00**				
	MAX	100,00				
Land acquisition in riparian zone [m²]	MIN	30,00		x	x	
	EXPERT	**50,00**				
	MAX	100,00				
Land profiling [m³]	MIN	240,00	x	x		
	EXPERT	**1.200,00**				
	MAX	5.400,00				
Dyke construction [m]	MIN	900,00	x			
	EXPERT	**900,00**				
	MAX	12.000,00				
Inlet sluice [unit]	MIN	20.000,00	x	x		
	EXPERT	**120.000,00**				
	MAX	120.000,00				
Outlet sluice (big) [unit]	MIN	150.000,00	x			
	EXPERT	**570.000,00**				
	MAX	570.000,00				
Outlet sluice (small) [unit]	MIN	100.000,00		x		
	EXPERT	**120.000,00**				
	MAX	350.000,00				
Vegetation (no clearing) [m²]	MIN	30,00	x	x		
	EXPERT	**42,00**				
	MAX	65,00				
Vegetation (incl. clearing) [m²]	MIN	30,00			x	
	EXPERT	**97,50**				
	MAX	500,00				
Dredging [m³]	MIN	25				x
	EXPERT	**90**				
	MAX	231				

Cost ranges are derived from an extensive literature review (EPA 2000; Nakao & Sohngen 2000; Amigues, Boulatoff *et al.* 2002; Ward, Tucker *et al.* 2003; Zentner, Glaspy *et al.* 2003; Holmes 2004; Yang & Weersink 2004; Allan & Dunbar 2005; Frimpong, Lee *et al.* 2007; Zobrist & Lippke 2007; Marais & Wannenburgh 2008; Roberts, Clark *et al.* 2009; Trepel 2010; Aarons 2011; Chang, Hsu *et al.* 2011; Gunes, Tuncsiper *et al.* 2011; Ockenden et al. 2012; Trenholm, Lantz *et al.* 2013; Gkika, Gikas *et al.* 2014; Peh, Balmford *et al.* 2014; Yang, Liu *et al.* 2014; Deeptha, Sudarsan *et al.* 2015; EC 2015; MKULNV 2015).

The cost ranges (MIN-MAX) illustrate the variability of restoration projects in regard to planning approach, technical specifications and extent of construction works, among others. The EXPERT-values represent unit costs of comparable projects planned, conducted and/or monitored by the Zumbroich Consulting (Zumbroich 1998, 2000a, 2000b, 2002 2005a, 2005b, 2005c, 2005d, 2005e, 2006a, 2006b, 2006c, 2007, 2011, 2012; Zumbroich & Meier 2009, 2012, 2015;

Zumbroich & Meier et al. 2009, 2012). The final EXPERT-values applied in this study are the result of a cost adaptation to the conditions study area involving local experts from the Huai Sai Bat river basin.

EXPERT-values are applied for the calculation of the total measure costs, the Net Present Value (NPV), the Annualized Net Present Value (ANPV) and the Benefit-Cost-Ration (BCR) of individual measures and the scenarios. Calculations based based on MIN- and MAX-values are listed in Appendix II.

The total costs of each measure are divided into one-time costs (planning, installation, opportunity) at the beginning of the implementation phase and recurring costs (maintenance and operation) on a yearly basis. The total cost analysis summarises the costs of the specific measures based on their dimensions, unit costs of the respective type of measure, a predefined time horizon and interest rate. This cost analysis provides the specific sum of costs of each selected measure and thereby a basic economic analysis to decision-makers. The advantage of using a cost analysis separate from the cost-benefit analysis is that the uncertainty associated with the analysis are minimal, as cost estimates tend to be more specific than benefit estimates. Total costs of the measures are calculated using the following formula:

$$C = \sum_{1}^{T,N} c_{t,n} (1+i)^{-t}$$

where

C is sum of costs
c is the set of individual costs per action
i is the discount rate (3%)
n is the adaption option
t is the time horizon in years (25 years)

The discount rate is set at 3% according to standards for economic valuation of projects (ADB 2013). The time horizon of the economic valuation of the measures is set to a period of 25 years.

5.5 Measure benefits

5.5.1 Ecosystem benefits

The selected EbA measures help to establish ecosystems (wetlands and riparian forests) providing a wide range of services and benefits (MA 2005, Russi et al. 2013):

- **Provisional services:** Food and fibre, fuel, genetic resources, biochemicals, natural medicines, pharmaceuticals, ornamental resources, fresh water
- **Regulatory services:** Air quality maintenance, climate regulation, water regulation, erosion control, water purification, biological control, pollination, storm protection
- **Cultural services:** recreation and ecotourism, cultural diversity, spiritual and religious values, knowledge systems, educational values, inspiration, aesthetic values, social relations, sense of place, cultural heritage values

The effects of the three selected EbA types of measures on specific ecosystem service benefits can be ranked according to EC (2015) as shown in (Table 5-3).

Table 5-3: Rating of effect of the selected EbA measures on ecosystem service benefits. (Rating: o = none, + = low, ++ = medium, +++ = high) (EC 2015).

Ecosystem Service Benefit	Type of measure		
	Floodplain & Wetland	Sediment Pool	Riparian Zone
Category: Provisioning			
Water Storage	+++	+++	+
Fish Stock and recruiting	+++	+++	++
Natural biomass production	+++	+	+
Category: Regulatory and Maintenance			
Biodiversity preservation	+++	+++	+++
Climate change adaptation	++	+	o
Groundwater recharge	+++	++	+
dFlood risk reduction	+++	++	+
Erosion/Sediment control	+++	+++	+++
Filtration of pollutants	++	+++	++
Category: Cultural			
Recreational opportunities	+++	o	+
Aesthetic/cultural value	+++	o	+

The importance of these ecosystem services for the livelihoods and wellbeing of the society in Northeast Thailand is emphasized by Blake & Promphakping (2010). For comparison, the baseline value of wetlands (excluding capture fisheries) only in the Thai part of the Mekong Basin is approximately US$ 1,2 billion, while the value of irrigation agriculture in the Lower Mekong Basin across Cambodia, Laos, Thailand and Vietnam is estimated at US$ 479 million. Another study estimates the Total Economic Value (TEV) of the ecosystem services provided by the Bung Khong Long wetland in Northeast Thailand to be US$ 1.248 per hectare per annum (Chaikumbung 2013).

For the economic valuation of the aforementioned benefits within this study, TEV estimations for the three selected EbA types of measures are made based upon TEV ranges proposed by the Mekong Region Futures Institute (MERIF) (Smaigl 2015). These value ranges are derived from the aggregation of 508 economic assessments within the Greater Mekong Sub-region between 2000 and 2013.

For verification of the transferability of these TEV ranges to the Huai Sai Bat river basin other economic valuation studies were analysed, which are not included in the project of MERIF. The TEV ranges of MERIF correspond to the ones derived in comparable studies (Brander & Eppink 2012, de Groot 2012, Russi et al. 2013, WWF 2013). In particular, the above mentioned study of the ecosystem services provided by the Bung Khong Long wetland in Northeast Thailand (Chaikumbung 2013) indicates that the TEV-values from Smaigl et al. (2015) are also representative for the Huai Sai Bat river basin:

- TEV of wetland according to Chaikumbung, 2013: 442.940 THB/ha/yr
- TEV of wetlands according to Smaigl et al., 2015: 470.670 THB/ha/yr
- The ranges for TEV per ha and year of the selected EbA measures within the study in hand are listed in Table 5-4. For a realistic estimation of the benefits of newly developed ecosystems over the defined time horizon of 25 years, an 80% effectivity of the service provision is assumed based on research on ecosystem recovery (Rey Benayas et al. 2009, Jones & Schmitz 2009).

The engineering measure (reservoir dredging) is assumed to have no additional benefits than increasing storage capacity. For the cost-benefit analysis of this study the EXPERT of the TEV are applied. MIN-MAX ranges are applied in Appendix II.

Table 5-4: Total economic value (TEV) of the ecosystem service benefits provided by the ecosystems established through EbA measures (80%-values adopted from original values according to Smaigl, 2015).

Type of EbA-measure (related ecosystem)	Annual total economic value range [THB/ha/yr]		
	MIN	EXPERT	MAX
Floodplain and Wetland Development (Wetland)	286.640	376.600	498.520
Sediment Pool Installation (Wetland)	286.640	376.600	498.520
Riparian Zone Improvement (Riparian Forest)	215.920	524.200	832.400

5.5.2 Benefits of sediment retention and water storage capacity

The benefit of major concern is the increase of water storage capacity provided by the different measures. Increasing the storage capacity is regularly achieved by dredging inside water bodies, whereas ecosystem-based measures focus on water and sediment retention inside or alongside of the water bodies. The engineering alternatives (dredging) increase the storage capacity immediately but this capacity is decreased by ongoing sedimentation if the sources and transportation paths of sediments are not considered. EbA measures in contrast provide sustainable regulatory sediment control services in the long run by preventing excessive loads of sediments entering the water bodies. The sediment retention efficiency of the different EbA measures ranges from, to 73% for riparian buffers (Smith et al. 2013) and 78% for floodplains or wetlands (Brown & Schueler 1997).

For the monetarization of the sediment retention and water storage benefits of the specific measures in the Huai Sai Bat Basin the following assumptions and specifications were made, based upon local expert interviews and field visits (for quantification see also Table 5-5):

- The benefit of the EbA and engineering measures related to sediment retention and water storage capacity is quantified as the securing or increasing of the storage capacity due to the respective measure throughout the time horizon of 25 years.
- The benefit is monetarized by valuing one unit of storage capacity in m^3 with THB 6,00 (EXPERT), THB 3,50 (MIN) and THB 8,50 (MAX), assuming these values to be equivalent to fictive water prices. These values are derived from Kumar & Young (1996) and Molle (2001) and verified by local experts of Khon Kaen University.
- It is assumed that each m^3 storage capacity, additionally gained by dredging, is "harvested" only once during dry season (no refill during dry season). During wet season the increased storage capacity is not relevant. Reservoir dredging is therefore monetarized by the increase in storage capacity.
- The benefit related to water storage is annually reduced by sediment intrusion (38.069 m^3/yr as state in Table 5-5, Code F value) coming from the reservoir's tributaries (2.600 m^3/yr, Code D value in Table 5-5) and the surrounding area of the reservoir (35.469 m^3/yr, Code G value in Table 5-5).
- The amount of sediment retained via EbA measures related to the Nong Yai reservoir (Pre-reservoir wetland and riparian buffer) is quantified based upon sediment inputs via tributaries and the surrounding area, and the above mentioned effectiveness rates of sediment retention related to the types of measures relevant for the Nong Yai reservoir (Code H and I values in Table 5-5).

Table 5-5: Dimension of Nong Yai reservoir and sedimentation indicators.

Code	Indicator	Value	Source
A	Area	609.105 m^2	GIS analysis
B	Original Depth (average)	5 m	field survey, interviews
C	Original Volume (max. storage capacity)	3.045.525 m^3	calculation (A * B)
D	Sediment input from tributaries	2.600 m^3/yr	Lohr (2014): Modelling
E	Rate of storage capacity loss (Share of original volume)	1,25%/yr	Interviews of Huai Sai Bat local experts
F	Capacity loss per year	38.069 m^3/yr	Calculation (C * E)
G	Diffuse sediment input from surrounding area of the reservoir	35.469 m^3/yr	calculation (F - D)
H	Sedimentation retention rate of riparian buffers	73%	Smith et al. (2013)
I	Sedimentation retention rate of floodplains and wetlands	78%	Brown & Schueler (1997)

5.6 Cost-benefit analysis of measures

The following Figure 5-13 and Table 5-6 illustrate and list the benefits and costs of the nine EbA measures and the three dredging alternatives. The values are based upon the aforementioned EXPERT-estimations. Detailed calculations as well as measure costs and benefits based upon MIN- and MAX-estimates are listed in Appendix II.

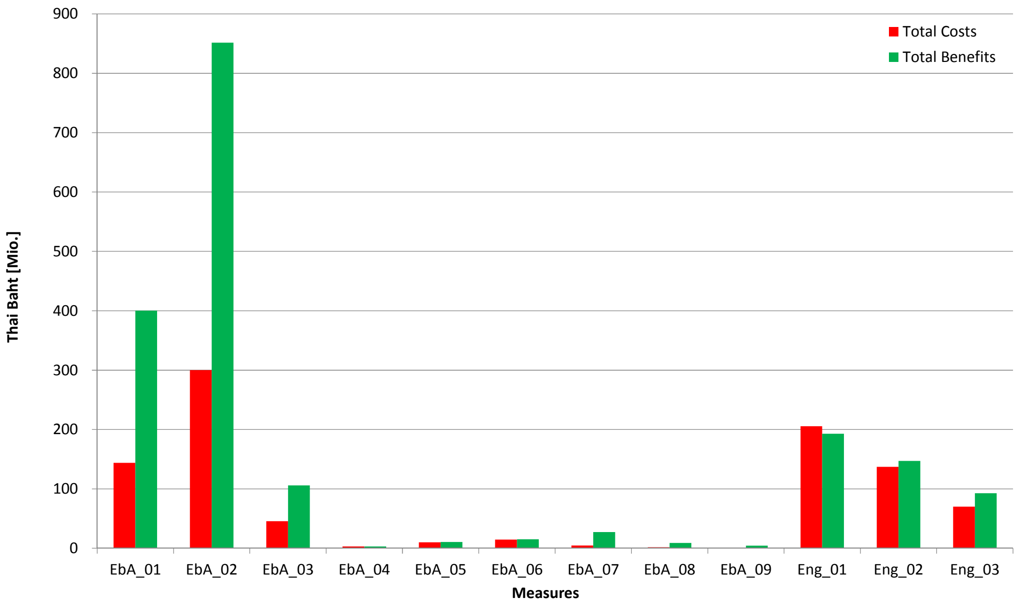


Figure 5-13: Total costs and benefits of the nine EbA measures and the three dredging alternatives.

Based on the EXPERT-values of the unit costs, the costs of the specific measures within the Huai Sai Bat Basin range from relatively low costs of Riparian Zone Improvement (approx. THB 1–5 Mio.) and moderate costs of Sediment Pool Installations (approx. THB 3–15 Mio.) to high costs of Floodplain & Wetland Development (THB 46–300 Mio.) and Dredging (THB 70–206 Mio.).

Benefits range between THB 106–400 Mio. for the Floodplain & Wetland Development measures, THB 93–193 Mio. for the dredging alternatives, THB 5–27 Mio. for the Riparian Zone Improvement measures to THB 3–15 Mio. for the Sediment Pool Installation measures.

The main reasons for the floodplain & wetland measure costs to be considerably high are the relatively large areas of the measures and the high unit costs. These high costs are mainly due to intensive land conversion, profiling of channels and ponds, and flood protection of the surrounding agricultural and urban areas by dykes.

The sediment pools represent near-natural retention basins surrounded by relatively narrow riparian zone. This design keeps the unit costs and consequently the total costs of these measures relatively low compared to cost-intensive floodplain and wetland constructions.

In contrast, the riparian zone improvements do not require profiling or other cost-intensive construction works. The major cost factor of these measures is the land acquisition for the riparian buffer zone.

For dredging of the reservoir, two one-time dredging alternatives were calculated which increase the storage capacity by 75% (Alternative 1) and 50% (Alternative 2) of the original volume. A third regular dredging alternative (Alternative 3) repetitively restores the current capacity (capacity) each seven years, by removing the amount of sediments intruded into the reservoir within this time period.

Table 5-6: Costs and Benefits of EbA and Engineering Measures.

Measure-ID	Measures (Type, Location)	Total Benefits [THB]	Total Costs [THB]
Type of measure: Floodplain and Wetland Development			
EbA_01	Floodplain and Wetland Development Floodplain No.1	400.370.217	143.851.292
EbA_02	Floodplain and Wetland Development Floodplain No.2	851.407.897	300.159.292
EbA_03	Floodplain and Wetland Development Nong Yai Pre-Reservoir	106.068.408	45.721.258
Type of measure: Sediment Pool Installation			
EbA_04	Sediment Pool Installation Confluence Wetland No.1	2.946.416	3.061.684
EbA_05	Sediment Pool Installation Confluence Wetland No.2	10.541.650	10.119.927
EbA_06	Sediment Pool Installation Confluence Wetland No.3	15.276.375	14.519.902
Type of measure: Riparian Zone Improvement			
EbA_07	Riparian Zone Improvement Nong Yai Reservoir	27.291.399	4.664.721
EbA_08	Riparian Zone Improvement Kham Maet	8.981.924	1.704.134
EbA_09	Riparian Zone Improvement Nam Om	4.509.218	855.530
Type of measure: Dredging			
Eng_01	Alternative 1: Dredging (75%) Nong Yai Reservoir	192.997.022	205.572.960
Eng_02	Alternative 2: Dredging (50%) Nong Yai Reservoir	146.906.661	137.030.670
Eng_03	Alternative 3: Regular Dredging Nong Yai Reservoir	92.597.921	70.128.564

The Cost-Benefit Analysis of the measures includes the calculation of the Net Present Value (NPV), the Annualized Net Present Value (ANPV) and the Benefit-Cost-Ratio (BCR):

$$NPV = \sum_{1}^{T,N} b_{t,n}(1+i)^{-t} - \sum_{1}^{T,N} c_{t,n}(1+i)^{-t}$$

$$ANPV = [\frac{i}{1-(1+i)^{-T}}]NPV$$

$$BCR = \sum_{1}^{T,N} b_{t,n}(1+i)^{-t} / \sum_{1}^{T,N} c_{t,n}(1+i)^{-t}$$

where

b are the benefits
c are the costs
i is the discount rate (3%)
N resp. n is measure
t is the time in years
T is the time horizon in years (25 years)

The Net Present Value (NPV) analyses the economic consequences of the individual measure types by estimating the difference in the present value of the benefits minus the present value of the costs. The Annualized Net Present Value (ANPV) indicates whether a measure type is economically desirable. If the ANPV is greater than zero, then the measure is considered to be desirable.

The benefit-cost-ratio (BCR) is the ratio of the present value of discounted benefits to the present value of the discounted costs of a measure. The BCR provides information about the desirability of the respective measure (if the ratio is greater than one then the measure is generally desirable). Additionally the BCR give the benefits per one Thai Baht (THB) spent for each measure to facilitate comparison or ranking of measures.

All except two measures (EbA_04 and Eng_01) are economically desirable regarding the selected time horizon of 25 years and an interest rate of 3 %: they show positive values of NPV, ANPV and BCR (Table 5-7). However, these values vary considerably between the measures.

Especially the floodplain & wetland development measures show high a NPV and ANPV due to high benefits in comparison to their costs. The riparian zone improvement measures provide relatively low NPV and ANPV but considerably large BCR because of very low costs compared with the ecosystem benefits that the riparian buffer strips provide in general. The riparian zone development around the Nong Yai reservoir safeguards directly the storage capacity of the reservoir by retaining a great amount of the sediments that would otherwise intrude via diffuse paths from the surrounding area without such a riparian buffer. This additional benefit results in an increased BCR compared with that of the riparian buffer strips along the Huai Sai Bat river. The Sediment Pool Installation measures have the lowest NPV, ANPV and BCR of the EbA types of measures as their benefits are only slightly higher than their costs. EbA-04 shows negative NPV and ANPV and a BCR smaller than one due to its relatively high fix costs (costs of inlet sluice and outlet sluice) and a small area (0,45 ha) providing limited ecosystem service benefits. One dredging alternative shows negative NPV and ANPV and a negative BCR. The other two alternatives show relatively small (ENG_02) or medium (ENG_03) NPV, ANPV and BCR.

Table 5-7: Results of the Cost-Benefit-Analysis for the EbA and Engineering measures in the Huai Sai Bat Basin.

Measure-ID	Measures (Type, Location)	Net Present Value [THB]	Annualized Net Present Value [THB]	Benefit-Cost-Ratio
Type of measure: Floodplain and Wetland Development				
EbA_01	Floodplain and Wetland Development Floodplain No.1	256.518.925	14.731.336	2,78
EbA_02	Floodplain and Wetland Development Floodplain No.2	551.248.605	31.657.033	2,84
EbA_03	Floodplain and Wetland Development Nong Yai Pre-Reservoir	60.347.150	3.465.608	2,32
Type of measure: Sediment Pool Installation				
EbA_04	Sediment Pool Installation Confluence Wetland No.1	-115.267	-6.620	0,96
EbA_05	Sediment Pool Installation Confluence Wetland No.2	421.723	24.219	1,04
EbA_06	Sediment Pool Installation Confluence Wetland No.3	756.473	43.443	1,05
Type of measure: Riparian Zone Improvement				
EbA_07	Riparian Zone Improvement Nong Yai Reservoir	22.626.677	1.299.402	5,85
EbA_08	Riparian Zone Improvement Kham Maet	7.277.790	417.948	5,27
EbA_09	Riparian Zone Improvement Nam Om	3.653.687	209.823	5,27
Type of measure: Dredging				
Eng_01	Alternative 1: Dredging (75%) Nong Yai Reservoir	-12.575.938	-722.209	0,94
Eng_02	Alternative 2: Dredging (50%) Nong Yai Reservoir	9.875.991	567.158	1,07
Eng_03	Alternative 3: Regular Dredging Nong Yai Reservoir	22.469.356	1.290.367	1,32

5.7 Scenarios: Engineering, EbA, Hybrid and "Business as usual"

Four scenarios were developed representing different combinations of the above described EbA and engineering measures to identify their efficiency in counteracting water scarcity during dry season in the Huai Sai Bat basin (see Table 5-8)

Scenario 1 ("Engineering") includes the dredging of the Nong Yai reservoir without any additional EbA measure. The extent of the dredging is set to 75%, meaning that the original full storage capacity of the reservoir is re-established (increasing the actual 25% storage capacity by 75% to 100% by a one-time dredging project). For the cost-benefit analysis of this scenario one-time costs of dredging and constantly decreasing storage capacity benefits during the time horizon of 25 years due to continued sedimentation were considered (see also Figure 5-14).

Scenario 2 ("EbA") includes all EbA measures but no dredging of the reservoir. The actual reservoir's storage capacity of 25% of the original capacity is constantly reduced by sedimentation but the sedimentation rate is considerably reduced due to the retention effects of the EbA measures.

Scenario 3 ("Hybrid") focuses on safeguarding the water storage capacity of the Nong Yai reservoir by the development of a floodplain and wetland serving as a pre-reservoir, an improved riparian zone around the reservoir serving as a sedimentation buffer, and a 50%-dredging of the Nong Yai reservoir to increase the current storage capacity from 25% to 75%. The background of this combined scenario is the drawbacks of the two scenarios above: Scenario 1 re-establishes the original storage capacity of the reservoir but the continuous sedimentation of the reservoir is not tackled. Scenario 2 counteracts the ongoing sedimentation of the reservoir but does not increase its storage capacity, necessary for times of water scarcity during dry season.

Scenario 4 ("Business as usual") includes only the regular dredging of the Nong Yai Reservoir restoring the current water storage capacity by removing sediments each seven years.

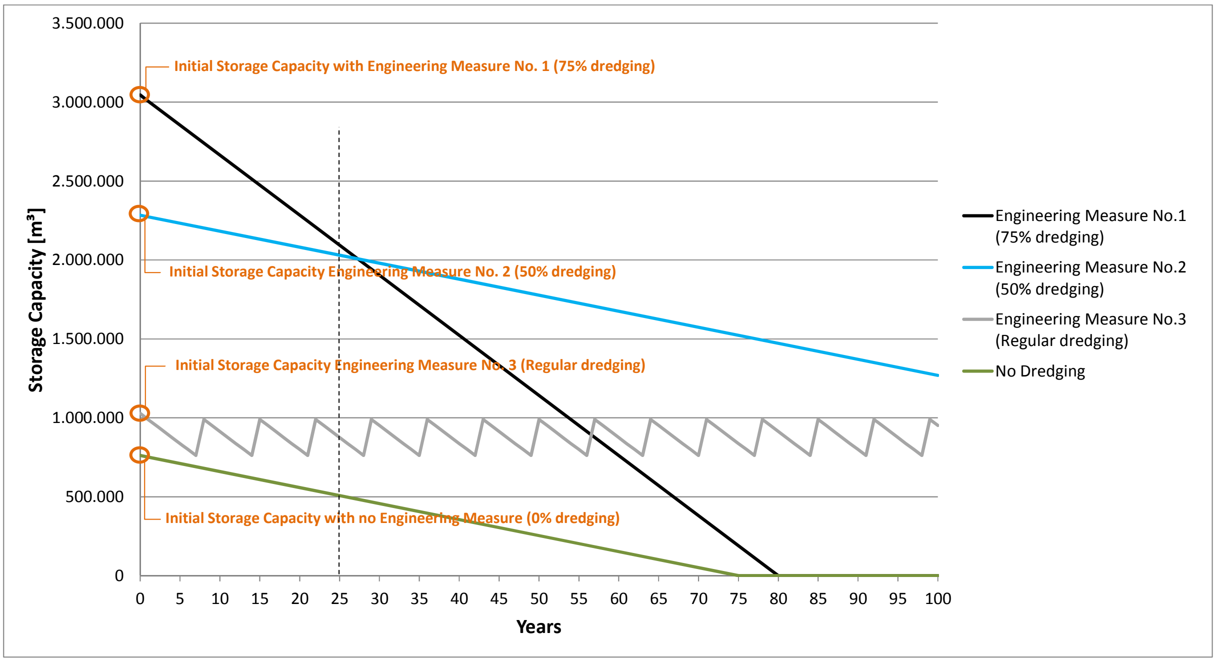


Figure 5-14: Development of storage capacity of the Nong Yai reservoir regarding four dredging alternatives.

Table 5-8: Measure combinations of the four scenarios.

	Measures	Scenario 1 “Engineering”	Scenario 2 “EbA”	Scenario 3 “Hybrid”	Scenario 4 “Business as u.”
Engineering					
Eng_01	Alternative 1: Dredging (75%) Nong Yai Reservoir	x			
Eng_02	Alternative 2: Dredging (50%) Nong Yai Reservoir			x	
Eng_03	Alternative 3: Regular Dredging Nong Yai Reservoir				x
EbA					
EbA_01	Floodplain and Wetland Development (Floodplain No.1)		x	x	
EbA_02	Floodplain and Wetland Development (Floodplain No.2)		x		
EbA_03	Floodplain and Wetland Development (Pre-Reservoir)		x		
EbA_04	Sediment Pool Installation Confluence Wetland No.1		x		
EbA_05	Sediment Pool Installation Confluence Wetland No.2		x		
EbA_06	Sediment Pool Installation Confluence Wetland No.3		x		
EbA_07	Riparian Zone Improvement Nong Yai Reservoir		x	x	
EbA_08	Riparian Zone Improvement Kham Maet		x		
EbA_09	Riparian Zone Improvement Nam Om		x		

The final results of the economic evaluation regarding the four scenarios are shown in Table 5-9:

- **Scenario 1 (“Engineering”)** provides a negative NPV and a BCR smaller than one. This alternative is therefore economically not desirable.
- **Scenario 2 (“EbA”)** shows the highest Net Present Value and Benefit-Cost-Ratio but relatively high total costs.
- Considering the total costs of the scenarios and the primary objective of the proposed measures (counteract water scarcity) as key factors for decision-making the implementation of **Scenario 3 (“Hybrid”)** is most promising: as a combination of increasing and securing the water storage capacity of the Nong Yai reservoir with engineering (Eng_02) and EbA measures (EbA_01 and EbA_07). Even if the BCR of the Hybrid-Scenario is lower as the one for the EbA-Scenario, this measure combination of the Hybrid-Scenario is considered to be the most promising alternative to adapt to the climate change induced water scarcity in the Huai Sai Bat Basin on the long run (also see Figure 5-14 for the effect of the Eng_02 on the storage capacity beyond the time horizon of 25 years).
- **Scenario 4 (“Business as usual”)** provides the lowest (non-negative) NPV and a low BCR. In comparison to Scenario 2 and 3 this alternative only contains a storage capacity of the Nong Yai reservoir of about 25 % of its original capacity. Considering the water shortage within the Huai Sai Bat river basin during the dry season this relatively low reservoir volume does not guarantee water safety according to Lohr (2015a, 2015b).

Table 5-9: Final results of the economic evaluation of the four scenarios. ***For Scenario 2 and 3 bracketed Total Costs, NPV and BCR are listed for potential scenarios without costs of land acquisition.***

Scenario	Total Costs [THB]	Total Benefits [THB]	Net Present Value (NPV) [THB]	Benefit-Cost Ratio (BCR)
Scenario 1 (Engineering)	205.572.960	192.997.022	-12.575.938	0,94
Scenario 2 (EbA)	524.657.741 *(445.485.806)*	1.427.393.503	902.735.762 *(981.907.697)*	2,72 *(3,20)*
Scenario 3 (Hybrid)	187.416.645 *(179.306.249)*	280.266.468	92.849.818 *(100.960.219)*	1,50 *(1,56)*
Scenario 4 (“Business as usual)	70.128.565	92.597.921	22.469.356	1,32

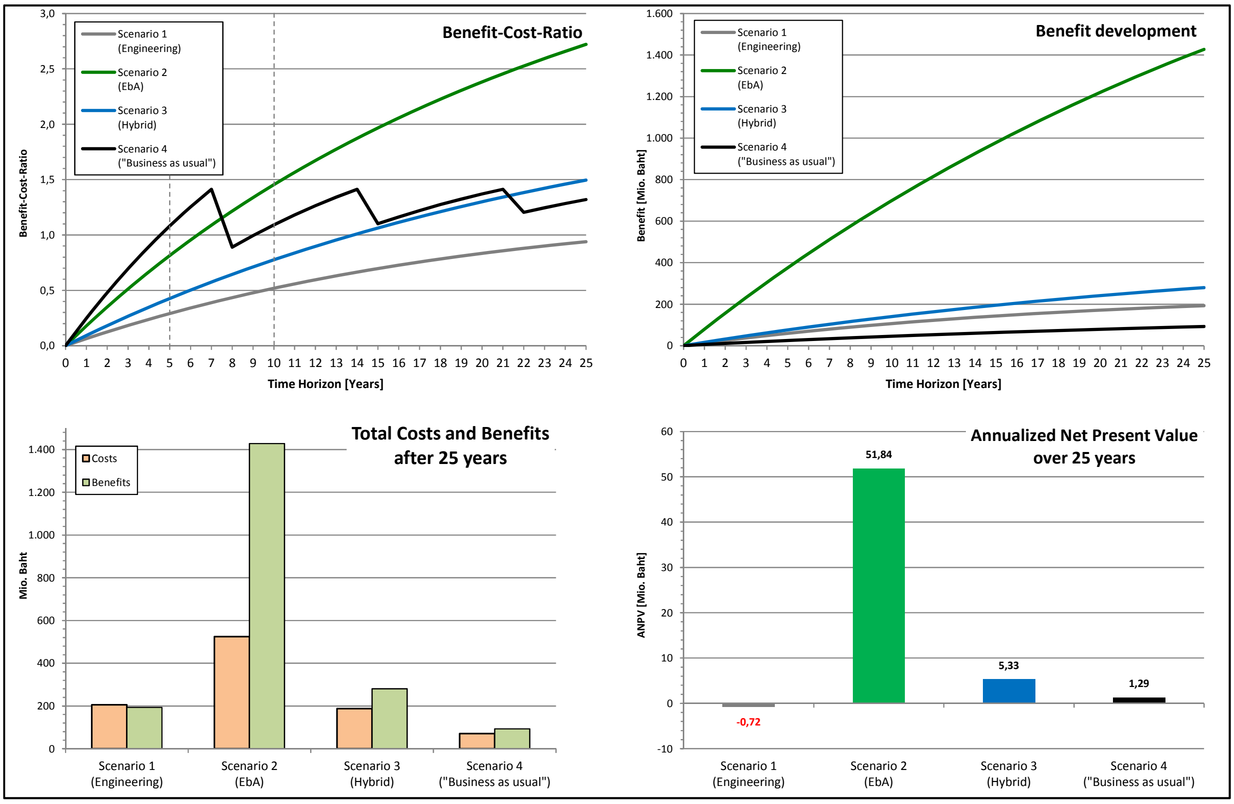


Figure 5-15: Final results of economic evaluation of the four scenarios. ***Intermediate time-steps of five and ten years are indicated in the Benefit-Cost-Ratio chart to highlight the break-even point between Scenario 1 and 2 at about 7,5 years.***

Based on the recommended prioritisation of Scenario 3 ("Hybrid") the following table shows a ranking of the individual EbA measures (Table 5-10). The prioritisation focuses mainly on the measures' effectiveness with respect to the efficiency to counteract the water scarcity problem in the upper part of the Huai Sai Bat Basin. Besides this factor, the effects on biodiversity and the TEV of the ecosystem services are also considered as ranking criteria.

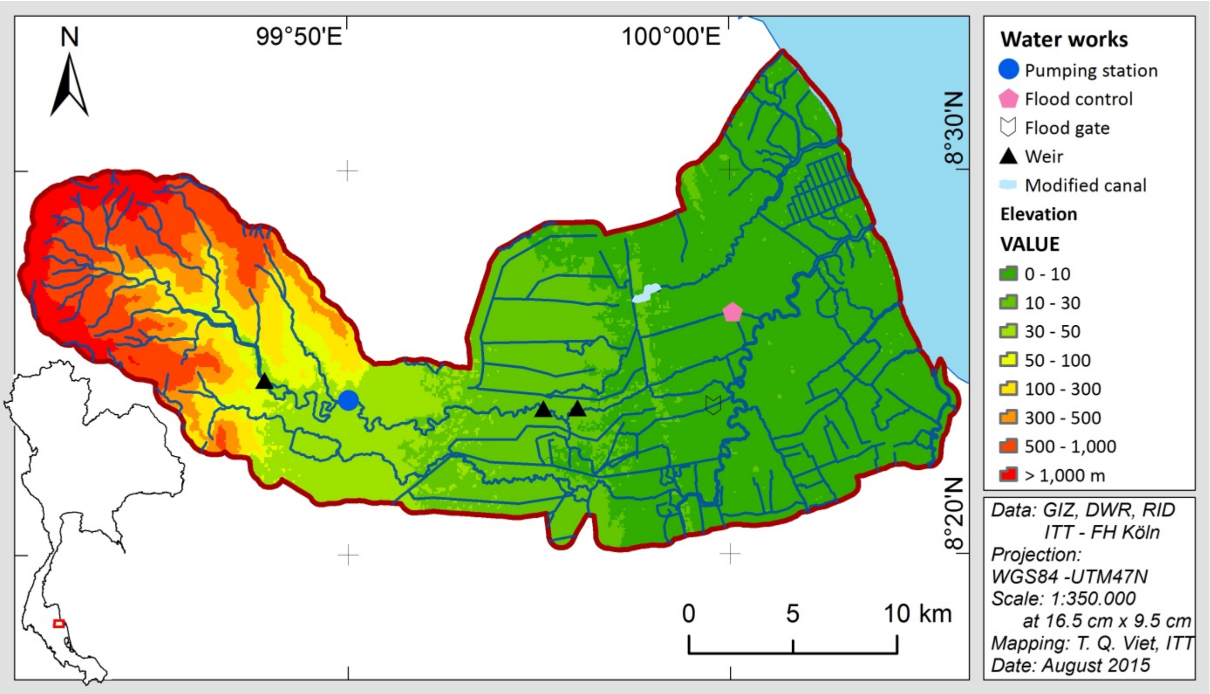
Table 5-10: Ranking of proposed EbA and Engineering measures including justification for prioritization.

Measure Code	Ranking of measures	Justification
	Priority 1	
EbA_07	Riparian Zone Improvement Nong Yai Reservoir	• Very low costs in comparison with benefits. • Indispensable for sustainable securing of reservoir's storage capacity.
EbA_03	Floodplain and Wetland Development (Pre-Reservoir)	• Relatively low costs compared with other floodplain measures. • Securing of reservoir's storage capacity only effective when all sediment intrusion paths are treated.
Eng_02	Alternative 2: Dredging (50%) Nong Yai Reservoir	• Increasing the storage capacity of the reservoir is necessary to meet water demand in dry season, besides securing of storage capacity.
	Priority 2	
EbA_08	Riparian Zone Improvement Kham Maet	• Very low costs and very high Benefit-Cost-Ratio. • Low conflict potential due to little land requirement. • Good technical feasibility.
EbA_09	Riparian Zone Improvement Nam Om	
	Priority 3	
EbA_04	Sediment Pool Installation Confluence Wetland No.1	• Low costs and high Benefit-Cost-Ratio. • Decentralised increase of water storage capacity.
EbA_05	Sediment Pool Installation Confluence Wetland No.2	
EbA_06	Sediment Pool Installation Confluence Wetland No.3	
	Priority 4	
EbA_01	Floodplain and Wetland Development (Floodplain No.1)	• High investment costs but on the other hand high Total Economic Value (TEV) of ecosystem services.
EbA_02	Floodplain and Wetland Development (Floodplain No.2)	
	Priority 5	
Eng_03	Alternative 3: Regular Dredging Nong Yai Reservoir	• Low storage capacity does not provide water security in dry season.
Eng_01	Alternative 1: Dredging (75%) Nong Yai Reservoir	• Economically not desirable (negative NPV and BCR < 1)

6 CASE STUDY THA DI RIVER BASIN

6.1 Characterisation of the Tha Di River Basin

The Tha Di river basin is located in the south-east of Thailand going from 99°41' – 100°6' E and 8°20' – 8°33' N. The basin has a drainage area of 546 km² and its elevation ranges from sea level to almost 1,800 m.a.sl. The major stream is the Tha Di River finding its headwaters in the mountain range in the western part of the basin and draining it from west to east into the Gulf of Thailand (Figure 6-1).



Data: GIZ, DWR, RID
ITT - FH Köln
Projection:
WGS84 -UTM47N
Scale: 1:350.000
at 16.5 cm x 9.5 cm
Mapping: T. Q. Viet, ITT
Date: August 2015

Figure 6-1. Elevation map of the Tha Di river basin

According to the Köppen classification, the Tha Di river basin belongs to the Af group, with a tropical climate with no clear dry season, i.e. all months have an average precipitation above 60 mm. Moreover, the average temperature remains relatively constant with no clear distinction between summer and winter. According to the Thai Meteorological Department, the average maximum temperature is around 32°C while its average minimum temperature is 23°C. The annual average rainfall at Nakhon Si Thammarat reaches 2500 mm, being one of the highest rainfall areas in Thailand (http://www.tmd.go.th). Although rainfall occurs throughout the year it concentrates in the period going from October to December. On the other hand, February and March receive the lowest rainfall rates within the year. Furthermore, the mean annual air relative humidity is 82%.

Nakhon Si Thammarat is the largest city in the region with over 100,000 inhabitants. Pak Nakhon and Khao Kaeo are two further municipalities in the region. Demographic studies from 2012 show the region is home to approx. 145,000 inhabitants with over 60% living in urban areas (Figure 6-2).

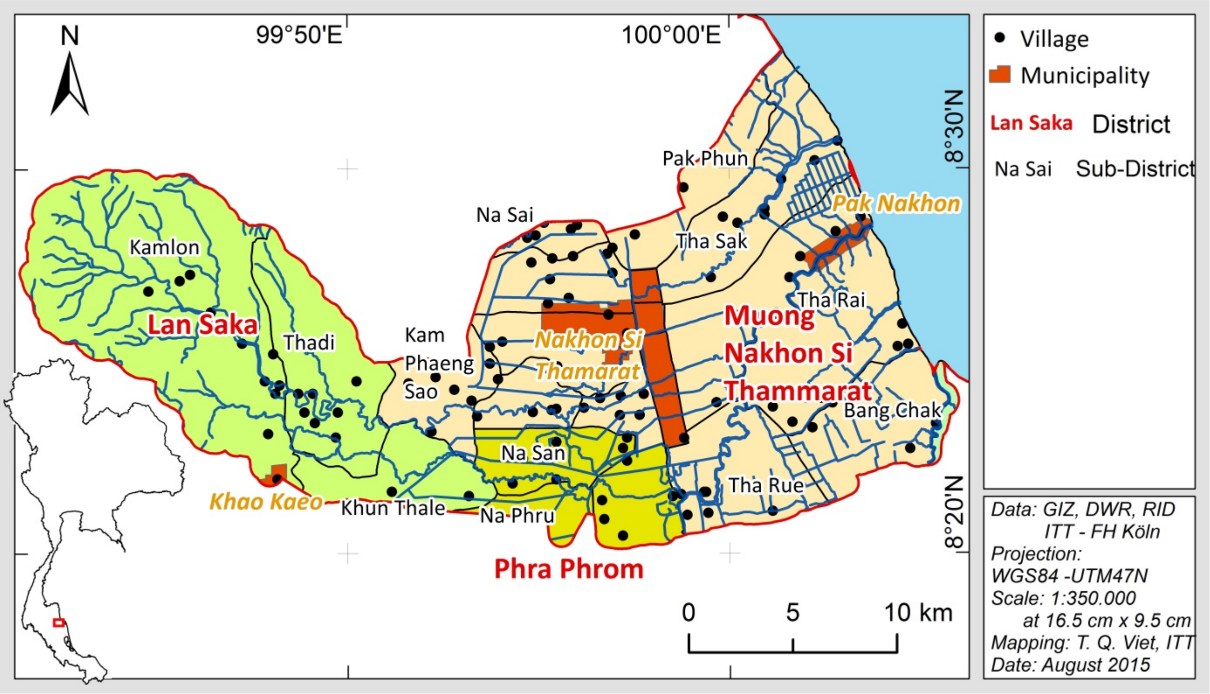


Figure 6-2. Administration in Tha Di river basin

There is a clear spatial distribution of land use in the region with a dominant forest cover in the upper parts of the basin while mixed agricultural land uses occupy large areas in midstream and lower parts of the catchment. Moreover, aquaculture is a growing activity occurring in the areas closest to the sea, downstream from the main urban settlement. Urban settlements concentrate around Nakhon Si Thammarat and major roads (Figure 6-3).

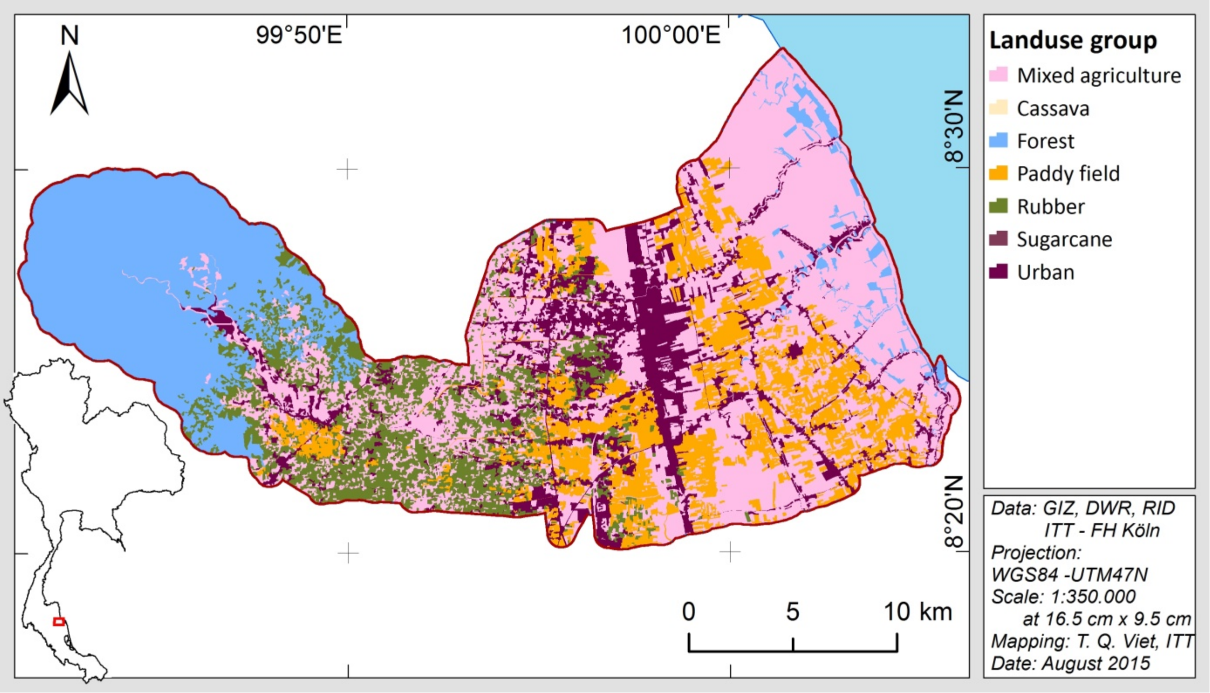


Figure 6-3. Land use classification in 2010 in Tha Di river basin

Agricultural production is an important activity in the basin supporting the livelihood of many farmers. For instance, rubber is planted in the buffer zones between forest cover in the west and annual crops in the east. Further perennial crops cultivated in the basin are mangosteen, rambutan, coconut and oil palm. The Royal Irrigation Department (RID) has constructed irrigation channels within the basin to increase yields which can be seen in Figure 6-1. The construction of these irrigational channels has drastically changed the hydrology of the basin.

Paddy rice is cultivated in the lower areas where freshwater is ample. As mentioned before, aquaculture is practiced in the lower part of the basin closest to the sea. They consist of mainly shrimp farms which account for almost 2% of the total surface. Mangrove ecosystems have been degraded but are still present in some parts near to the mouth of the river (Figure 6-3).

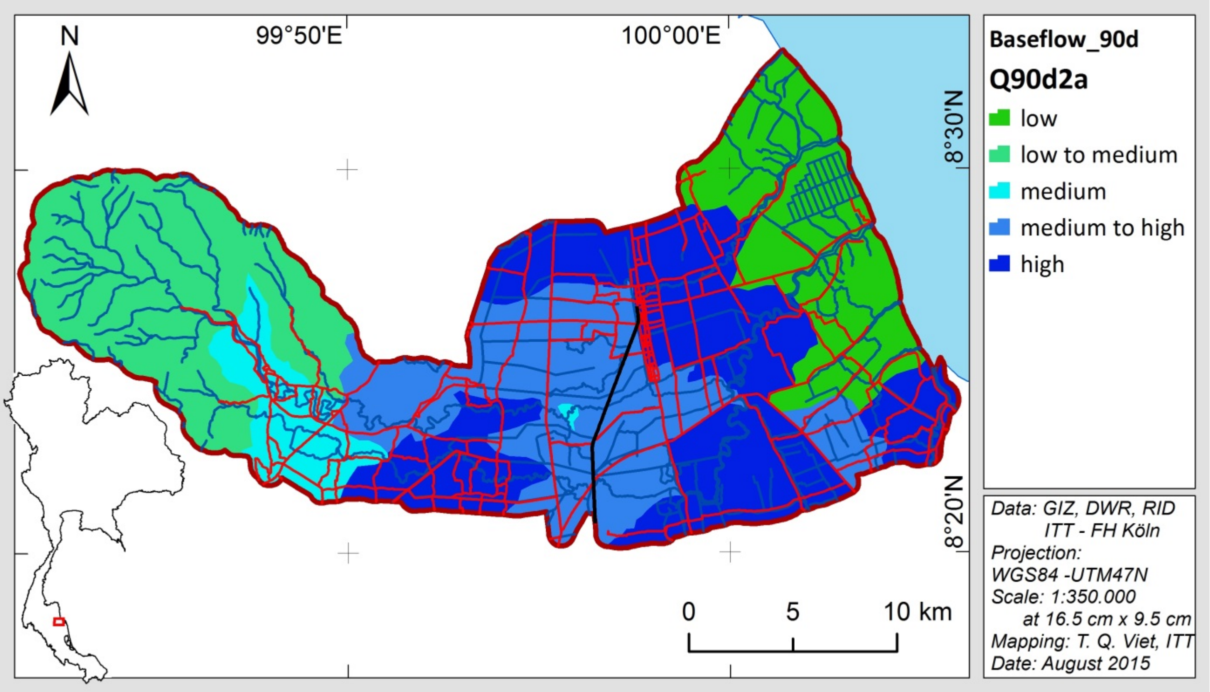


Figure 6-4: Spatial distribution of water resources availability (Thinh Quoc Viet, based on simulations of Lohr, 2015)

6.2 Problem definition

A previous vulnerability study conducted in the basin by Lohr (2015a, 2015b) lead to the identification of the most urgent challenges and problems faced by society and ecosystems in the Tha Di basin. The problems as well as their possible causes, impacts and measures are listed in the following table:

Table 6-1. Main problems and theirs causes and impacts in the Tha Di basin. Source: Lohr, 2015

Problem	Possible causes	Impacts	Measures
Flooding	Deforestation, river modification	Loss of agricultural products and inundation of urban areas	RID constructed protection walls in the urban area of Nakhon Si Thammarat (see Figure 6-5)
Water scarcity	Overexploitation of water resources	Streamflow reduction, salt water intrusion enhancement, lower agricultural yields	Communities constructed living weirs
Water quality	Untreated wastewater, mining, agriculture, aquaculture	Degradation of water quality affecting aquatic ecosystems and communities downstream	Only one WWTP treating only a small percentage of the wastewater.

Flooding is a recurrent problem occurring during the rainy season and it has received great attention since it affects farmers and urban dwellers. The RID constructed concrete walls in

Nakhon Si Thammarat as a grey engineering measure to protect the population from flooding. The following pictures show two locations within the city where flood protection walls were built:

Figure 6-5. Flood protection walls constructed downstream in Nakhon Si Thammarat

On the other hand, during the drier period the basin is facing water scarcity. Water resources are mainly used for agricultural activities as well as domestic supply. In addition, rapid population growth is becoming a further pressure into the system by increasing demand. Furthermore, the reduction of streamflow observed in the main streams and rivers is also enhancing salt water intrusion processes in the transition zone downstream. However, this problem in particular requires deeper studies to fully understand the causes and impacts of salt water intrusion and will not be considered in this report.

Finally, water quality is already an issue in the basin due to the increase of pollution sources. For instance, the amount of fertilizers and pesticides used in agriculture is uncertain but it affects water quality. Moreover, most of the wastewater generated in urban and rural settlements remains untreated and it is directly discharged into the main rivers and canals affecting fluvial and coastal ecosystems. Water quality degradation is especially important during the dry period where less surface water is available for dilution of wastewater and agricultural effluents.

6.3 Measure selection

Lohr (2015b) identified potential measures which can be implemented in the region to tackle the main problems and challenges presented in the previous section. The complete set of suggested measures include: (1) Bank erosion control, (2) Riparian zone development, (3) River bed enhancement, (4) Constructed wetland, (5) Flood control with wetland (including living weir for water diversion).

The potential locations for these measures were visited during the field visit in August 2015. Subsequently, the plausibility and effectiveness of these measures were discussed among the group of experts of the project consortium and with Khun Suthira, as local expert professor from the Walailak University. Moreover, a meeting was held in September with Dr. Lohr to discuss thoroughly and in-depth the measures he proposed for the region. The result of these discussions is shown in Table 6-2 with a final discussion of the EbA potential measures for the basin as well as alternative grey or engineering measures such as a conventional wastewater treatment plant (WWTP) and concrete weirs.

Table 6-2: Basic description of selected EbA- and Engineering measures.

Measure	Details of Measure	Positive aspects	Negative aspects
EbA Measures			
Living weirs	River bed stabilisation, foundation construction using bamboo and cassava sacks filled with sand, planting of trees (e.g. Banyan , Sago) for root structural support	• Groundwater recharge • Crop yield increase • Sedimentation upstream • Water storage • Low cost • High social acceptance	• Longer construction period • Uncertainty regarding the robustness during strong flood events
Flood control with wetland	Living weir construction to divert water to the terrain depression, terrain profiling, tree and native plant species plantation, permeability tests, eventually lining	• Flood retention area to protect areas downstream • Low profiling required since a terrain depression already exists • Biodiversity preservation • Community involvement and participation	• Drainage to be assessed • Difficult to reliably quantify multiple functions • Maintenance required (sediment removal and disposal) • Potential for water-borne diseases
Constructed Wetland	Terrain profiling, installation of baffles,	• Water quality improvement • Replicable due to its decentralised approach • Low cost and know-how • Local material can be used for construction	• Requires space (which can be reduced with a vertical flow CW) • Foul odours can be generated • Requires prior treatment (e.g. septic tank) • It needs an agency or community in charge for maintenance and operation
Engineering Measures			
Concrete weir	River bed stabilisation, construction using concrete	• Groundwater recharge • Crop yield increase • Sedimentation upstream • Water storage	• High cost • Engineers required for construction • Low social acceptance
Conventional WWTP	Land acquisition, terrain profiling, equipment installation, wastewater collection	• Water quality improvement • Efficient treatment • Eventually less total area as CW	• High operation costs • Know-how for operation and maintenance • Centralised treatment • Wastewater collection needed

All the measures presented above, excepting the flood control with wetland, can be implemented in different places in the basin. For instance, living weirs have been constructed in many streams and rivers of the basin during the last year. The next map suggests possible locations for the EbA measures based on the work conducted by Lohr (2015b). Moreover, also exemplary sizes for the respective measures will be suggested in order to make the comparison between green and grey measures possible.

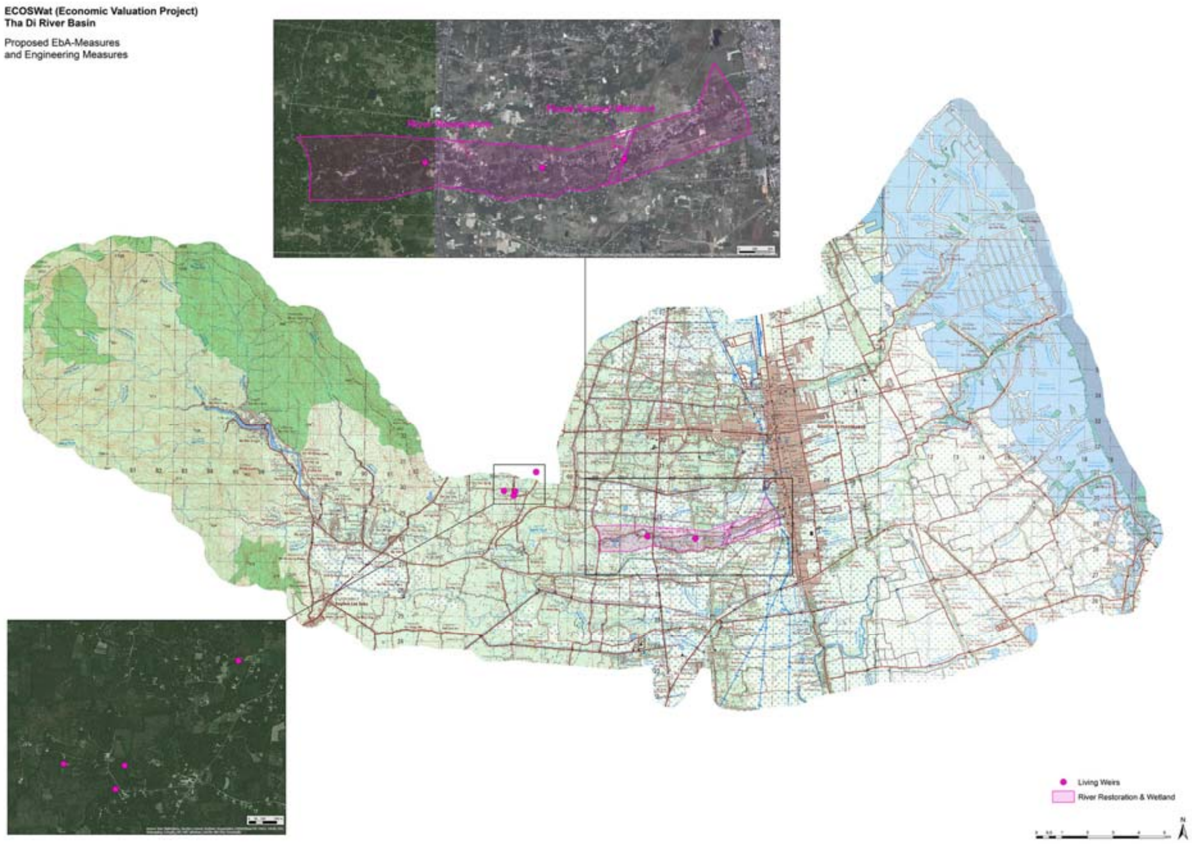


Figure 6-6. Examplary locations of suggested EbA measures in the Tha Di basin.

In the following section each measure as well as the main considerations to be taken into consideration for their implementation is briefly explained. Afterwards, the costs and benefits of each measure will be presented individually as the basic data to apply the Cost-Benefit Analysis (CBA) methodology. Based on the results the most economically efficient measures for the region will be identified and suggested.

Living Weir

Due to the inefficient grey infrastructure as well as lack of financial support in the basin, communities have been constructing living weirs in different rivers and streams within the catchment. The main objective of these structures is to slow down the flow of the river, store water upstream of the weir, increase the groundwater table and crop yields. Living weirs are constructed using bamboos as support and filling it with sand-filled cassava starch sacks. In the structure Banyan and Sago trees are planted so that with time the growing roots offer a structural support. The sand and sacks are expected to be washed out with time. The construction is based on local knowledge and has high social acceptance. There are no reports or studies available on the stability and robustness of such structures.

The key elements to consider and further investigate include:

- Main advantages are groundwater table increase as well as crop yields. Surface water level can also be increased during the dry period. However, studies are needed to quantify them;
- Uncertainty of robustness during strong flood events, hydraulic studies are also required;

- High social acceptance facilitates their construction and maintenance.

Figure 6-7. Example of a living weir with river bank stabilisation in the Tha Di river

Flood Control with Wetland

This measure aims at mitigating the impacts of flooding in the main Tha Di river before Nakhon Si Thammarat. Lohr (2015b) proposed the construction of a controllable living weir in the main channel to divert water during high streamflow events. Water should be diverted to a terrain depression located between the rail tracks and a road (Figure 6-8). Furthermore, this depression could be permanently inundated to create a wetland.

Figure 6-8. Space between the railway and the road which could be inundated during high streamflow periods and create a wetland

Key aspects of this measure:

- Drainage survey necessary;
- Total storage volume has to be calculated;
- Requires a controllable living weir (eventually hybrid weir);
- Wetland increases biodiversity and uptake of nutrients.

Constructed Wetland (CW)

Wetlands are natural ecosystems which can be imitated to treat wastewater cost-effectively with high affordability, low maintenance costs, and minimum technical dependency (Wisartsakul, 2011). Constructed wetlands are a decentralized solution for wastewater treatment, especially effective with domestic water. Many studies worldwide have shown high removal rates of nutrients and pathogens (Deeptha et al. 2015). For instance, Vymazal and Kröpfelová (2008) did a comprehensive review of the use of this technique in many countries around the world for different types of wastewater. In this study, examples in Thailand are shown where CWs were used to treat effluents from pig farms (Kantawanichkul et al. 2001; Kantawanichkul & Somprasert 2005). According to Garcia et al. (2010) a good treatment unit should be able to treat wastewater without any dilution process. However, often a primary treatment is needed because clogging is a common problem in wetlands. For instance, primary treatment can be performed with techniques such as septic tanks or Imhoff tanks.

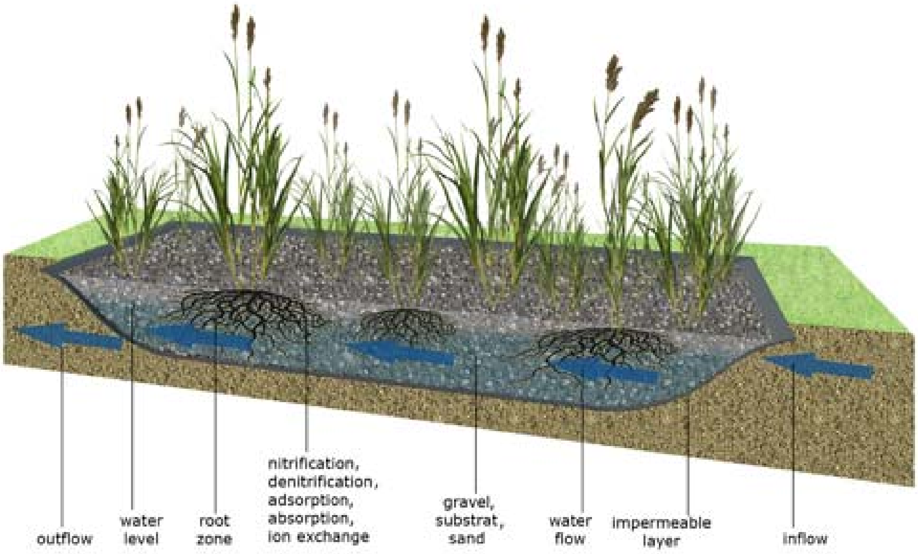


Figure 6-9. Schematic figure of a constructed wetland. Source: LIMNOS, 2010

Brix et al. (2007) reported the construction of three CWs in coastal areas of the Thailand after the tsunami of 2004. Two of the three CWs were designed using vertical flow (VF) to clean the water. One of the main advantages of VF wetlands, compared to horizontal flow, is that the total surface is drastically reduced. The design and size of the wetland will depend on the raw quality of the influent.

Key considerations while selecting a CW include:

- Selection of CW type: horizontal flow, vertical flow, hybrid
- Plant selection (native species are recommended)
- Inflow from CW should go through a prior treatment (e.g. septic tank)
- Terrain preparation including baffles and pipelines
- Lining to avoid seepage and contamination of groundwater

Concrete Weir

Weirs are engineering structures which alter the flow of a river. Usually, weirs fulfill one (or several) of four fundamental reasons: (i) water level management, (ii) discharge measurement, (iii) environmental enhancement, (iv) channel stabilisation (Rickard et al. 2003). In spite of their positive effects weirs can also negatively impact the environment. For instance, weirs acts also as barriers for fish migration or navigation; they can also trap debris flowing in the river. These impacts are similar to those of the living weirs, since they also alter the river flow.

Key issues which have to be taken into account while constructing a concrete weir are:

- Selection of the appropriate river section for its construction
- External financial resources required
- Inefficient grey infrastructure in the basin
- Low social acceptance

Figure 6-10. Construction of a concrete weir in the Lam Pa Chi river. Author: Santiago Penedo

Conventional Wastewater Treatment Plant

Wastewater treatment plants consist of a centralized process to transform domestic or industrial sewage into an effluent which can either disposed in natural water bodies or reused for other purposes such as irrigation or washing. The main purpose of treatment plants is to minimise the environmental impact of domestic and industrial effluents. For this, wastewater has to be collected and conveyed to the treatment plant. In the plant, water goes through several processes designed to reduce the concentration of hazardous substances. Conventional Wastewater treatment plants (WWTP) can be classified according to the level of treatment achieved into (i) primary, (ii) secondary, (iii) tertiary and/or advanced. Primary treatment involves the removal of suspended solids and organic matter. Furthermore, secondary treatment removes biodegradable organic matter and usually a disinfection process is included. Finally, tertiary plants remove smaller particles suspended through microfiltration, membrane filtration or adsorption. The following figure shows a typical centralised wastewater treatment process.

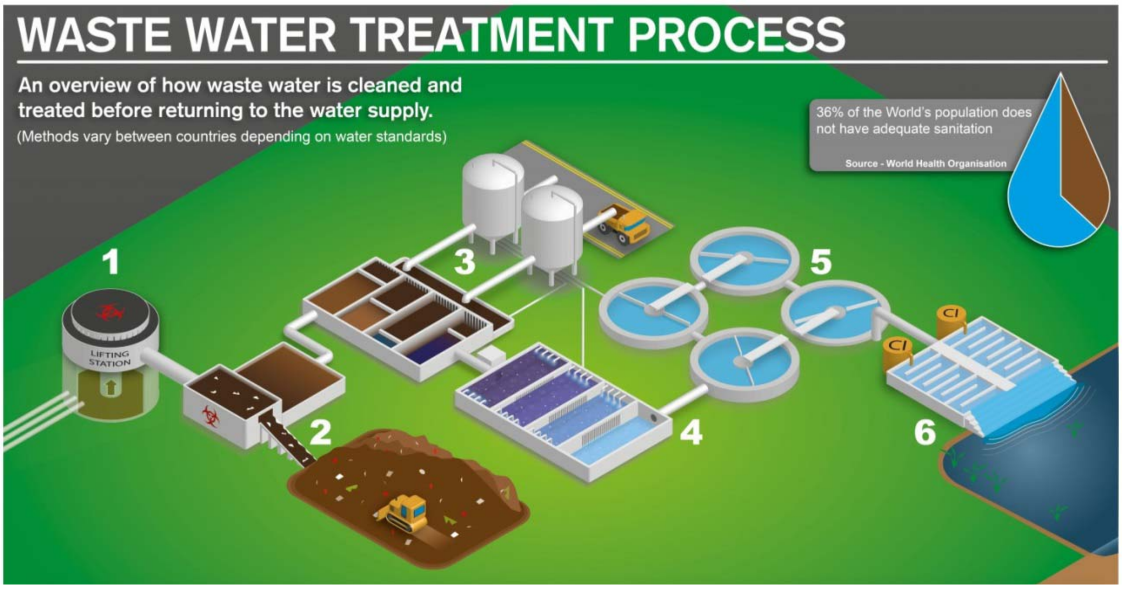


Figure 6-11. Schematic diagram of a conventioanl wastewater treatment plant (WWTP). Source: Scutt, 2012

WWTP should generate an effluent in accordance with environmental law and standards which can be disposed in water bodies or even recycled in irrigation or other purposes. Sludge is also a by-product of the treatment process which needs to be discarded.

Main factors to consider while designing a WWTP:

- Level of treatment needs to be determined in advance
- Engineers and planners (know-how) are needed to construct and operate the plant
- Investment and operation costs are considerable
- Land is required for the construction of the plant

6.4 Measure costs

Measure type costs for the Tha Di basin are estimated as unit costs, e. g. costs per unit (referring to living and concrete weirs), costs per population equivalent [p.e.] for treated wastewater or costs per square meter [m²] of wetland or riparian zone. The total costs of each measure type are divided into investment (one-time) and recurring (operation and maintenance) costs on a yearly basis.

The specific costs were estimated, if possible, using local data provided by our partner Khun Suthira. For instance, the minimum and maximum costs for the living weirs represent the actual investments incurred by communities in the basin. Moreover, the cost range for the concrete weirs was estimated based on literature values (RMC 2006; Jones et al. 2015) and information provided by civil engineer Khun Pakorn from the Walailak University. For this study, only weirs for small rivers were considered due to hydraulic constraints for big weirs.

The costs for both the constructed wetlands and the conventional WWTP were obtained from a literature review (Tousignant et al. 1999; Newton 2006; Brix et al. 2007; Ghermandi et al. 2009; Balkema et al. 2010; Deeptha et al. 2015; Tsagarakis et al. 2003; Hernandez-Sancho et al. 2011; Hernández-Sancho et al. 2015; Mara 2004; Gkika et al. 2014; Iglesias et al. 2010; Nogueira et al. 2012; Zhou et al. 2009). The values presented in Table 6-3 do not include the price of land acquisition. Furthermore, the table shows the maximum and minimum costs (one-time and recurring) for each measure type.

Table 6-3: Unit costs of selected EbA- and engineering measure types in the Tha Di basin

Measure type	Unit	One-time costs [THB] (planning, installation)			Recurring costs [% of investment costs or unit costs in THB] (maintenance, operation)		
		MIN	MEAN / EXPERT	MAX	MIN	MEAN / EXPERT	MAX
Living weirs	unit	29.000	39.500	50.000	2,0%	3,5%	5,0%
Flood control with wetland	unit	300.000	525.000	750.000	1,0%	2,0%	3,0%
Constructed wetland	p.e.	450	900	2.500	0,04	0,07	0,21
Conventional treatment plant	p.e.	1.300	1,700	3,600	0,62	0,90	1,33
Concrete weir	Unit	500.000	1.250.000	2.000.000	2,0%	4,0%	6,0%

The suggested costs may vary due to several factors such as materials used or size of the treatment plants. The maximum and minimum values aim at showing the variation range. The expert values were estimated based on literature and information from our local partners. Moreover, in case where no specific information for the basin was available the mean value was used. The following table shows the specific costs for activities which are needed to implement the EbA and engineering measures such as land acquisition.

Table 6-4. Cost of specific activities for each measure

Activities	Range	Unit Costs [THB]	Flood control with wetland	Constructed Wetland	Riparian Zone Development	Conventional Treatment Plant
Land acquisition [m²]	MIN EXPERT MAX	50,00 **100,00** 300,00	x	x	x	x
Inlet sluice [unit]	MIN EXPERT MAX	60.000 **360.000** 360.000	x			
Vegetation (no clearing) [m²]	MIN EXPERT MAX	90,00 **120,00** 180,00	x			
Vegetation (incl. clearing) [m²]	MIN EXPERT MAX	90,00 **300,00** 1.500,00			x	

The total costs of the measures were calculated using the following formula as used for the Huai Sai Bat river basin:

$$C = \sum_{1}^{T,N} c_{t,n} (1+i)^{-t}$$

where

C is sum of costs
c is the set of individual costs per action
i is the discount rate
n is the adaption option

t is the time horizon in years

The discount rate was also set at 3% according to standards for economic valuation of projects (ADB 2013). Three different time horizons were considered to analyse the economic impacts of the measures in short (5 years), middle (10 years) and long (25 years) terms. All costs were converted to the national currency (Thai Baht, THB) considering the following conversion rates: 40 THB for EUR-€ and 36 THB for USD-$.

The dimension of the measures was based on geo-spatial analysis as well as hypothetical scenarios like the case of wastewater treatment. A treatment plant for 10.000 inhabitants was considered assuming a daily water use per capita of 150 litres, which represents 1.500 m^3 of wastewater treated every day.

Tsagarakis et al. (2003) suggest a land requirement of 0,33 m^2 for each p.e. for a conventional WWTP, while Hoffman et al. (2011) suggest 1,2 m^2 for each p.e. for a vertical flow constructed wetland in warm climates. Considering a treatment plant to serve 10.000 p.e. the land requirements would be 3.300 m^2 for the conventional WWTP and 12.000 m^2 for the constructed wetland, respectively.

6.5 Benefit identification

Monetarisation of benefits and services provided by EbA and engineering measures is a great challenge due to the uncertainties related to their estimation. Nevertheless, it is very important to make such services visible through their valuation in order to incorporate them in policy and decision making. In this section, a monetary calculation, if possible, of each measure is presented.

Since no studies were available for living weirs an alternative method was used to compare the economic effectiveness of both living and concrete weirs. The least-cost analysis methodology suggested by Rao et al. (2013) was selected to compare these two measures. For the other measures, the Cost-Benefit Analysis (CBA, as used for Huai Sai Bat basin) was applied to assess their economic performance.

In order to compare both the living and concrete weirs the equation presented in the previous section was used to estimate the annualized costs for three different periods (5, 10 and 25 years) with a 3% discount rate. The results are shown in the Table 6-5. It is evident that living weirs are economically advantageous if compared to concrete weirs even under the assumption that living weirs have to be reconstructed every three years due to high flood events.

Even if the maximum cost for a living weir is assumed, it represents only a fraction of the minimum cost of a concrete weir. This substantial difference relies on two main factors: (1) community members work voluntarily to construct and maintain living weirs; (2) construction materials are cheaper for living weirs.

Table 6-5. Total costs for both living and concrete weirs per unit

Measure	Annualized Costs [THB] 5 years, 3%	Annualized Costs [THB] 10 years, 3%	Annualized Costs [THB] 25 years, 3%
Living Weir	MIN: 11.484 **MEAN: 16.366** MAX: 21.633	MIN: 10.487 **MEAN: 14.958** MAX: 19.787	MIN: 7.083 **MEAN: 10.197** MAX: 13.604
Concrete Weir	MIN: 104.580 **MEAN: 272.899** MAX: 454.956	MIN: 54.265 **MEAN: 146.326** MAX: 251.181	MIN: 23.483 **MEAN: 67.413** MAX: 121.792

The ecological benefits from living weirs include groundwater table, ecosystem and vegetation restoration. Moreover, it is argued that living weirs can increase crop yields and store water during the dry period. These benefits, however, have to be thoroughly assessed in the field and quantified in order to estimate their economic value.

For the economic valuation of the other measures two different approaches were used. As for the Huai Sai Bat basin the benefits were transferred using the values for TEV proposed by the MERIF (Smaigl 2015). Wetland and evergreen forest were selected as comparable ecosystems for the flood control with wetland and the riparian zone improvement, respectively. Table 6-6 shows the minimum, mean and maximum value for each ecosystem per hectare per year.

Table 6-6: Total economic value (TEV) of the ecosystem service benefits provided by the ecosystems established through EbA measures (80%-values adopted from original values according to Smaigl, 2015).

Type of EbA-measure (related ecosystem)	Annual total economic value range [THB/ha/yr]		
	MIN	MEAN	MAX
Flood control with wetland (wetland)	286.640	376.600	498.520
Riparian zone improvement (riparian forest)	215.920	524.200	832.400

These values were, as mentioned before, compared to literature studies to assess their suitability. Two wetland studies (Chaikumbung 2013, Smaigl et al. 2015) and two for mangroves (Brander et al. 2012; Wiwatthanapornchai et al. 2014) which although not directly used in this study valid the benefit range presented by Smaigl (2015).

For both wastewater treatment systems the main identified benefit was the water quality improvement. To estimate the economic benefit a shadow price approach was applied. The shadow prices were assumed as avoided costs resulting from removing pollutants during the treatment as done by Hernández-Sancho et al. (2015). Four typical wastewater parameters were considered: (i) chemical oxygen demand (COD); (ii) total suspended solids (TSS); (iii) nitrogen (N); (iv) phosphorous (P). Table 6-7 shows shadow prices for the four parameters and for different types of receiving water bodies. For the Tha Di basin typical values for sea were used.

Table 6-7. Shadow prices for undesirable outputs in wastewater. Source: Hernández-Sancho et al. (2015)

Water body	COD [THB/kg]	TSS [THB/kg]	N [THB/kg]	P [THB/kg]
River	4	0,2	652	1236
Sea	0,4	0,04	168	300
Wetland	4,8	0,4	2608	4136
Reuse	5,6	0,4	1048	3172

Moreover, a wastewater quality had to be considered to calculate the amount of pollutants to be removed. Metcalf and Eddy (2002) proposed three different loads for the four wastewater quality parameters. For this study, the moderate scenario was considered.

Table 6-8. Estimated load for wastewater for three scenarios

Parameter	High	Moderate	Low
COD [mg/L]	1250	750	220
TSS [mg/]	350	285	100
Phosphorus [mg/L]	17.0	11.5	5.0
Nitrogen [mg/L]	91.0	65.5	21.0

Typical removal percentages for each type of treatment were considered according to the following table.

Table 6-9. Type of treatment and the respective contaminant removal for different parameters. Source: (Molinos-Senante et al. 2012)

Treatment	Contaminant removal [%]
Constructed Wetland	COD: 55-85 TSS: 85-95 P: 20-60 N: 30-70
Conventional Treatment Plant	COD: 70-90 TSS: 70-90 P: 20-70 N: 20-85

The economic benefit for treating wastewater was obtained in THB per m³, based on the mass of pollutants removed (kg/year), the shadow prices for COD, TSS, P and N (THB/kg) and the removal performance for each treatment technology (%). The following table shows the environmental benefits for each treatment and parameter.

Table 6-10. Economic benefits in THB per m³ of wastewater treated per quality parameter

Parameter	Constructed wetland			Conventional WWTP		
	MIN	MEAN	MAX	MIN	MEAN	MAX
COD	0,17	0,21	0,26	0,21	0,24	0,27
TSS	0,01	0,01	0,01	0,01	0,01	0,01
P	0,39	0,77	1,16	0,39	0,87	1,35
N	5,90	9,83	13,76	3,93	9,83	15,72
Total	6,46	10,82	15,18	4,54	10,94	17,35

6.6 Cost-benefit analysis of measures

The CBA of the suggested measures included the same calculations as for the Huai Sai Bat basin: Net Present Value (NPV), Annualized Net Present Value (ANPV) and Benefit-Cost-Ratio (BCR):

$$NPV = \sum_{1}^{T,N} b_{t,n}(1+i)^{-t} - \sum_{1}^{T,N} c_{t,n}(1+i)^{-t}$$

$$ANPV = [\frac{i}{1-(1+i)^{-T}}]NPV$$

$$BCR = \sum_{1}^{T,N} b_{t,n}(1+i)^{-t} / \sum_{1}^{T,N} c_{t,n}(1+i)^{-t}$$

where

b are the benefits
c are the costs
i is the discount rate (3%)
N resp. n is measure
t is the time in years
T is the time horizon in years

Table 6-11 lists the total benefits and costs of the four considered measures as well as the NPV, the ANPV and the BCR for three different time horizons. These three time horizons represent the short, middle and long term to assess the economic performance of each measure.

Table 6-11: Total costs and benefits of EbA and engineering measures for three different time horizons

Measure	Total Benefits [THB]	Total Costs [THB]	NPV [THB]	ANPV [THB]	BCR
Flood control with wetland					
5 years	15.522.460	22.344.738	-6.822.279	-1.489.676	0,69
10 years	28.912.269	23.310.635	5.601.635	656.682	1,24
25 years	59.020.123	25.842.515	33.537.608	1.925.993	2,32
Constructed wetland					
5 years	27.125.092	14.370.115	12.754.977	2.785.108	1,89
10 years	50.523.435	15.379.467	35.143.968	4.119.945	3,29
25 years	103.136.121	17.649.059	85.487.062	4.909.340	5,84
Conventional WWTP					
5 years	27.442.528	32.374.338	-4.931.811	-1.076.883	0,85
10 years	51.114.693	45.351.716	5.762.977	675.597	1,13
25 years	104.343.087	74.532.190	29.810.897	1.711.976	1,40
Riparian zone improvement					
5 years	18.005.119	31.030.434	-13.025.315	-2.844.137	0,58
10 years	33.536.492	31.919.296	1.617.917	189.585	1,05
25 years	68.459.790	33.917.958	34.541.832	1.983.664	2,02

The total costs of the measure flood control with wetland are higher than the benefits in the short term (5 years) making it economically unsuitable. However, the operation and maintenance costs are relatively low and therefore the benefits are already higher than the costs in the middle term

(10 years) reaching a BCR of 1,24 and more than double in the long term (25 years) with a BCR of 2,32.

The measure constructed wetland is the only economically desirable in the short term due to low investment costs and high environmental benefits. Furthermore, due to also low operation and maintenance costs the BCR continues to increase to 3,29 and 5,84 in the middle and long term, respectively.

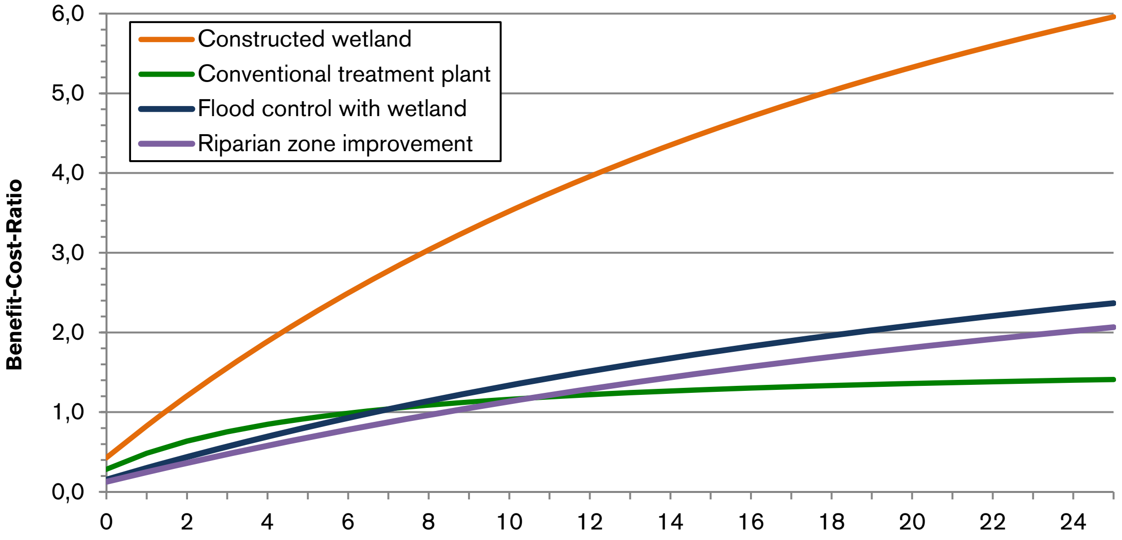


Figure 6-12. Benefit-Cost Ratio for the analysed measures over a 25 years time period

The conventional WWTP is not economically desirable in the short term (higher costs than benefits) and a BCR lower than one but it is in the middle and long term. Although due to higher operation and maintenance costs the BCR in the long term reaches 1,40 but still lower if compared to the alternative constructed wetland.

Finally, the riparian zone improvement is also not economically desirable in the short term due to large investment costs including land acquisition and vegetation. However, operation and maintenance are almost negligible and the project becomes more economically desirable in the middle and long terms with BCR of 1,05 and 2,02.

The Tha Di basin is heterogeneous and is facing several environmental problems such as flooding, water scarcity and water quality degradation. Therefore several measures or interventions are required to minimise and mitigate the impacts of natural climate variability and human activities.

EbA measures are preferred to engineering measures due to their economic performance. Living weirs are much advantageous economically than concrete weirs and are highly socially accepted. Moreover, constructed wetlands show a better performance than conventional WWTP and may involve also communities in their design and implementation due to low-tech and decentralised approach.

Finally, flood control with wetland and riparian zone improvement require land in order to be implemented. Although such measures are not economically feasible in the short term due to high investment costs their positive impacts increase steadily with time making them attractive in the middle and long terms (Figure 6-12).

Water-related agencies and other government bodies should form a river committee where the different stakeholders are represented including farmers, urban dwellers, the research community and other relevant actors. It was already appointed by Lohr (2015b) that water management is needed in this basin. A committee can develop a river basin plan where the suitability and prioritisation of these measures could be undertaken in a participatory way. It is clear that human activities have had a large impact on the environmental quality in the basin and therefore it should be aimed at recovering natural ecosystems and their services to ensure a sustainable development in the region.

7 LITERATURE

Aarons, S. R. (2011). "Dairy farm impacts of fencing riparian land: An analysis of farmers' perceptions of the costs and benefits." Journal of Soil and Water Conservation 66(5): 140A-147A.

ADB (Asian Development Bank) (2013). "Cost-Benefit Analysis for Development - A Practical Guide." Mandaluyong City, Philippines: Asia Development Bank.

Allan, M. P. & J. A. Dunbar (2005). "Dredging vs. New Reservoirs." Texas Water Development Board -TWDB Contract #2004-483-534. Project Report.

Amigues, J. P., C. Boulatoff, B. Desaigues, C. Gauthier & J. E. Keith (2002). "The benefits and costs of riparian analysis habitat preservation: A willingness to accept/willingness to pay contingent valuation approach." Ecological Economics 43(1): 17-31.

Balkema, A. et al., 2010. Socio-economic analysis of constructed wetlands systems for hygienic sanitation in Tanzania. *Water Practice and Technology*, 5(1), pp.wpt2010022–wpt2010022. Available at: http://wpt.iwaponline.com/content/5/1/wpt2010022.abstract [Accessed December 17, 2015].

Blake J. H. & B. Promphakping (2013): "Water Resources Development, Wetlands-Based Livelihoods and Notations of Wellbeing: Perspectives from Northeast Thailand." Journal of Lao Studies, 5(1): 1-28.

Brander, L. & F. Eppink (2012): “The Economics of Ecosystems and Biodiversity for Southeast Asia (ASEAN TEEB)”. Scoping Study. Prepared for GIZ and ACB. Laguna, Philippines: ASEAN Center for Biological Diversity.

Brix, H., Koottatep, T. & Laugesen, C.H., 2007. Wastewater treatment in tsunami affected areas of Thailand by constructed wetlands. *Water science and technology: a journal of the International Association on Water Pollution Research*, 56(3), pp.69–74. Available at: http://www.ncbi.nlm.nih.gov/pubmed/17802840 [Accessed December 17, 2015].

Brown, W. & T. R. Schueler (1997). "National Pollutant Removal Performance Database for Stormwater Best Management Practices." Ellicott City, MD: Center for Watershed Protection.

Chaikumbung, M. (2013). "Estimating wetland values: A comparison of benefit transfer and choice experiment values." Kasetsart University, Thailand (PhD.Thesis).

Chang, C. L., Y. S. Hsu, B. J. Lee, C. Y. Wang & L. J. Weng (2011). "A cost-benefit analysis for the implementation of riparian buffer strips in the Shihmen reservoir watershed." International Journal of Sediment Research 26(3): 395-401.

Clarkson B. R., Ausseil A. E. & P. Gerbeaux (2013). "Wetland ecosystem services." In Dymond J. R (ed.) *Ecosystem services in New Zealand - Conditions and trends*. Manaaki Whenua Press, Lincoln, New Zealand.

Center for Water Protection (CWP) (2013). "Cost-Effectiveness Study of Urban Stormwater BMPs in the James River Basin." Project report prepared by the Center for Watershed Protection for the James River Association.

Deeptha, V.T., Sudarsan, J.S. & Baskar, G., 2015. Performance and cost evaluation of constructed wetland for domestic waste water treatment. Journal of environmental biology / Academy of Environmental Biology, India, 36(5), pp.1071–4. Available at: http://www.ncbi.nlm.nih.gov/pubmed/26521546 [Accessed December 17, 2015]

De Groot R., Brander L., van der Ploeg S., Costanza R., Bernard F., Braat L., Christie M., Crossman N., Ghermandi A., Hein L., et al. (2012). "Global estimates of the value of ecosystems and their services in monetary units." Ecosystem Services 1: 50–61.

EC (2015). "Natural Water Retention Measures.European Commission." Retrieved October 15, 2015 from http://www.nwrm.eu/

Eddy & Metcalf, I. et al., 2002. *Wastewater Engineering: Treatment and Reuse*, McGraw-Hill Education. Available at:

https://books.google.ca/books/about/Wastewater_Engineering_Treatment_and_Reu.html?id=-eoeAQAAIAAJ&pgis=1 [Accessed January 11, 2016].

Frimpong, E. A., J. G. Lee & A. L. Ross-Davis (2007). "Floodplain influence on the cost of riparian buffers and implications for conservation programs." Journal of Soil and Water Conservation 62(1): 33-39.

García, J. et al., 2010. Contaminant Removal Processes in Subsurface-Flow Constructed Wetlands: A Review. Critical Reviews in Environmental Science and Technology, 40(7), pp.561–661. Available at: http://www.tandfonline.com/doi/abs/10.1080/10643380802471076 [Accessed December 17, 2015].

Ghermandi, A. et al., 2009. *The Values of Natural and Constructed Wetlands: A Meta-Analysis*, Available at: http://papers.tinbergen.nl/09080.pdf [Accessed January 6, 2016].

Gkika, D., Gikas, G.D. & Tsihrintzis, V.A., 2014. Construction and operation costs of constructed wetlands treating wastewater. *Water science and technology : a journal of the International Association on Water Pollution Research*, 70(5), pp.803–810. Available at: http://www.ncbi.nlm.nih.gov/pubmed/25225926 [Accessed January 6, 2016].

Gunes, K., B. Tuncsiper, F. Masi, S. Ayaz, D. Leszczynska, N. Findik Hecan & H. Ahmad (2011). "Construction and maintenance cost analyzing of constructed wetland systems." Water Practice and Technology 6(3).

Hernández-Sancho, F. et al., 2015. *Economic Valuation of Wastewater - The cost of action and the cost of no action*, Available at: http://unep.org/gpa/Documents/GWI/Wastewater Evaluation Report Mail.pdf [Accessed December 19, 2015].

Hernandez-Sancho, F., Molinos-Senante, M. & Sala-Garrido, R., 2011. Cost modelling for wastewater treatment processes. *Desalination*, 268(1-3), pp.1–5. Available at: http://www.sciencedirect.com/science/article/pii/S0011916410006910 [Accessed November 7, 2015].

Hernández-Sancho, F., Molinos-Senante, M. & Sala-Garrido, R., 2010. Economic valuation of environmental benefits from wastewater treatment processes: an empirical approach for Spain. *The Science of the total environment*, 408(4), pp.953–7. Available at: http://www.sciencedirect.com/science/article/pii/S0048969709009711 [Accessed January 6, 2016].

Hoffmann, H. et al., 2011. Technology Review of Constructed Wetlands. In *Subsurface Flow Constructed Wetland for Greywater and Domestic Wastewater Treatment*. Eschborn: Deutsche Gesselschaft für Internationale Zusammenarbeit GmbH.

Holmes, T. P., J. C. Bergstrom, E. Huszar, S. B. Kask & F. Orr III (2004). "Contingent valuation, net marginal benefits, and the scale of riparian ecosystem restoration." Ecological Economics 49(1): 19-30.

Iglesias, R. et al., 2010. Water reuse in Spain: Data overview and costs estimation of suitable treatment trains. *Desalination*, 263(1-3), pp.1–10. Available at: http://www.sciencedirect.com/science/article/pii/S0011916410004303 [Accessed January 6, 2016].

Jones HP, Schmitz OJ (2009). "Rapid recovery of damaged ecosystems." Plos One 4: e5653. doi:10.1371/journal.pone.0005653.

Jones, P., Keating, K. & Pettit, A., 2015. *Cost Estimation for Control Assets - Summary of Evidence Report - SC080039/R5*, Bristol, BS1 5AH

Kantawanichkul, S., Neamkam, P. & Shutes, R.B., 2001. Nitrogen removal in a combined system: vertical vegetated bed over horizontal flow sand bed. *Water science and technology : a journal of the International Association on Water Pollution Research*, 44(11-12), pp.137–42. Available at: http://www.ncbi.nlm.nih.gov/pubmed/11804085 [Accessed December 17, 2015].

Kantawanichkul, S. & Somprasert, S., 2005. Using a compact combined constructed wetland system to treat agricultural wastewater with high nitrogen. *Water science and technology : a journal of the International*

Association on Water Pollution Research, 51(9), pp.47–53. Available at: http://www.ncbi.nlm.nih.gov/pubmed/16042242 [Accessed December 17, 2015].

Karodpati, S.M. & Kote, A.S. (2013). Energy-Efficient and Cost-Effective Sewage Treatment Using Phytorid Technology. Energy - Efficient and Cost - Effective Sewage Treatment Using Phytorid Technology International Journal of Advanced Technology in Civil Engineering, 2(1), p.4.

Kumar, R. & C. Young (1996). Economic Policies for Sustainable Water Use in Thailand. CREED Working Paper Series No. 4. International Institute for Environment and Development, London. Institute for Environmental Studies, Amsterdam.

Lohr, H. (2015a). "Vulnerability analysis for the river basins of Huai Sai Bat, Tha Di and Trang." Project report within the GIZ-program *Improved Management of Extreme Events through Ecosystem-based Adaptation in Watersheds (ECOSWat)*, PN: 12.9012.1-001.00, GIZ Thailand, Bangkok.

Lohr, H. (2015b). "Pre-Selection of Ecosystem-based Measures." Project report within the GIZ-program *Improved Management of Extreme Events through Ecosystem-based Adaptation in Watersheds (ECOSWat)*, PN: 12.9012.1-001.00, GIZ Thailand, Bangkok.

MA (Millennium Ecosystem Assessment) (2005). "Ecosystems and Human Well-being: Synthesis." Island Press, Washington, DC.

Manomaiphoon, K., M. Octaviani, K. Torsi & S. Towprayoon (2013). "Projected changes in means and extremes of temperature and precipitation over Thailand under three future emissions scenarios." Climate Research 58(2): 97-115.

Mara, D., 2004. *Domestic Wastewater Treatment in Developing Countries*, London: Routledge - Paperback. Available at: http://www.amazon.com/Domestic-Wastewater-Treatment-Developing-Countries/dp/1844070190.

Marais, C. & A. M. Wannenburgh (2008). "Restoration of water resources (natural capital) through the clearing of invasive alien plants from riparian areas in South Africa - Costs and water benefits." South African Journal of Botany 74(3): 526-537.

Masaki, Y., Y. Ishigooka, T. Kuwagata, S. Goto, S. Sawano & T. Hasegawa (2011). "Expected changes in future agro-climatological conditions in Northeast Thailand and their differences between general circulation models." Theoretical and Applied Climatology 106(3-4): 383-401.

Meier, G. & Zumbroich T. (2009): "Priorisierung von geplanten Maßnahmen an der Unteren Dhünn und Oberen Wupper." Vortrag vor dem projektbegleitenden Fachausschuss bestehend aus Bezirksregierung Köln, Bezirksregierung Düsseldorf, Wupperverband, Landesverband Rheinland, 15.06.2009, Wuppertal.

MKUNLV (2015): "Maßnahmensteckbriefe HYMO: Maßnahmen – Hydromorphologie (HY) – Oberflächengewässer (OW)." Ministerium für Klimaschutz, Umwelt, Landwirtschaft, Natur- und Verbraucherschutz des Landes Nordrhein-Westfalen. Retrieved October 16, 2015, from http://www.flussgebiete.nrw.de/index.php/Ma%C3%9Fnahmensteckbriefe_HYMO

Molinos-Senante, M. et al., 2012. Assessment of wastewater treatment plant design for small communities: environmental and economic aspects. *The Science of the total environment*, 427-428, pp.11–8. Available at: http://www.sciencedirect.com/science/article/pii/S0048969712005207 [Accessed January 6, 2016].

Molle, F. (2001). Water Pricing in Thailand: Theory and Practice. Kasetsart University, DORAS Center, Research Report n°7, 78 p.

Nakao, M. & B. Sohngen (2000). "The effect of site quality on the costs of reducing soil erosion with Riparian buffers." Journal of Soil and Water Conservation 55(2): 231-237.

Newton, R., 2006. Constructed Wetlands For Wastewater Treatment. *Website*. Available at: http://rydberg.biology.colostate.edu/phytoremediation/2006/Rebecca Newton Website Files/public_html/Intro.html [Accessed December 12, 2015].

Nogueira, R. et al., 2012. Economic and environmental assessment of small and decentralized wastewater treatment systems. *Desalination and Water Treatment*, 4(1-3), pp.16–21. Available at: http://www.tandfonline.com/doi/abs/10.5004/dwt.2009.349#.Vo1Z2VKUTCs [Accessed January 6, 2016].

Ockenden, M. C., C. Deasy, J. N. Quinton, A. P. Bailey, B. Surridge & C. Stoate (2012). "Evaluation of field wetlands for mitigation of diffuse pollution from agriculture: Sediment retention, cost and effectiveness." Environmental Science and Policy 24: 110-119.

Peh, K. S. H., A. Balmford, R. H. Field, A. Lamb, J. C. Birch, R. B. Bradbury, C. Brown, S. H. M. Butchart, M. Lester, R. Morrison, I. Sedgwick, C. Soans, A. J. Stattersfield, P. A. Stroh, R. D. Swetnam, D. H. L. Thomas, M. Walpole, S. Warrington & F. M. R. Hughes (2014). "Benefits and costs of ecological restoration: Rapid assessment of changing ecosystem service values at a U.K. wetland." Ecology and Evolution 4(20): 3875-3886.

Rao, N.S. et al., 2013. *An Economic Analysis of Ecosystem-based Adaptation and Engineering Options for Climate Change Adaptation in Lami Town, Republic of the Fiji Islands. A technical report by the Secretariat of the Pacific Regional Environment Programme.*, Apia, Samoa.

Rickard, C., Day, R. & Purseglove, J., 2003. *River Weirs – Good Practice Guide - Section A*, Bristol.

RMC, 2006. *Zone 7 Stream Management Master Plant*,

Roberts, D. C., C. D. Clark, B. C. English, W. M. Park & R. K. Roberts (2009). "Estimating annualized riparian buffer costs for the harpeth river watershed." Review of Agricultural Economics 31(4): 894-913.

Russi, D., ten Brick, P., Farmer, A., Bdura, T., Coates, D., Förster, J., Kumar, R. & N. Davidson (2013). "The economics of ecosystems and biodiversity (TEEB) for water and wetlands." London and Brussels, Institute for European Environmental Policy (IEEP) & Ramsar Secretariat. 78 p.

Smajgl, A. (2015). "Ecosystem Value Estimation – Technical Document." Prepared by Mekong Region Futures Institute (MERFI) for USAID Mekong Adaption and Resilience to Climate Change (USAID Mekong ARCC).

Smith, C. M., Williams, J. R., Nejadhashemi, A., Woznicki, S. A. and J. C. Leatherman (2013). "An Economic Analysis of Reservoir Sediment Management: Cropland Management vs. Dredging." Proceedings of the Southern Agricultural Economics Association (SAEA) Annual Meeting, Orlando, Florida, 3-5 February 2013.

Tousignant, E., Fankhauser, O. & Hurd, S., 1999. *Guidance Manual for the Design, Construction and Operations of Constructed Wetlands for Rural Applications in Ontario*, Funded by the Candapt Program of the Agricultural Adaptation Council, Ontario. Available at: http://agrienvarchive.ca/bioenergy/download/wetlands_manual.pdf [Accessed January 6, 2016].

Trenholm, R., V. Lantz, R. Martínez-Espiñeira & S. Little (2013). "Cost-benefit analysis of riparian protection in an eastern Canadian watershed." Journal of Environmental Management 116: 81-94.

Trepel, M. (2010). "Assessing the cost-effectiveness of the water purification function of wetlands for environmental planning." Ecological Complexity 7(3): 320-326.

Tsagarakis, K.P., Mara, D.D. & Angelakis, A.N., 2003. Application of Cost Criteria for Selection of Municipal Wastewater Treatment Systems. *Water, Air, and Soil Pollution*, 142(1-4), pp.187–210. Available at: http://link.springer.com/article/10.1023/A%3A1022032232487 [Accessed January 6, 2016].

U.S. Environmental Protection Agency (EPA) (2000). "A Guide to Developing and Documenting Cost Estimates during the Feasibility Study." EPA 540-R-00-002, OSWER 9355.0-75. July 2000.

Vymazal, J. & Kröpfelová, L., 2008. *Wastewater Treatment in Constructed Wetlands with Horizontal Sub-Surface Flow*, Dordrecht: Springer Netherlands. Available at: http://link.springer.com/10.1007/978-1-4020-8580-2 [Accessed December 17, 2015].

Ward, D., N. Tucker & J. Wilson (2003). "Cost-effectiveness of revegetating degraded riparian habitats adjacent to macadamia orchards in reducing rodent damage." Crop Protection 22(7): 935-940.

Wiwatthanapornchai, S., Piputsitee, C. & Boonyawat, S., 2014. The Economic Value of Laem Phak Bia Mangrove Ecosystem Services in Phetchaburi Province, Thailand. *Modern Applied Science*, 8(5), pp.36–44.

WWF (World Wide Fund) (2013): The economic value of ecosystem services in the Mekong basin – What we know, and what we need to know. WWF-Report, October 2013.

Yang, W., W. Liu, Y. Liu, R. C. Corry & R. D. Kreutzwiser (2014). "Cost-effective targeting of riparian buffers to achieve water quality and wildlife habitat benefits." International Journal of River Basin Management 12(1): 43-55.

Yang, W. & A. Weersink (2004). "Cost-effective targeting of riparian buffers." Canadian Journal of Agricultural Economics 52(1): 17-34.

Zentner, J., J. Glaspy & D. Schenk (2003). "Wetland and riparian woodland restoration costs." Ecological Restoration 21(3): 166-173.

Zhang, D., Gersberg, R.M. & Keat, T.S., 2009. Constructed wetlands in China. Ecological Engineering, 35(10), pp.1367–1378. Available at: http://www.sciencedirect.com/science/article/pii/S0925857409002171 [Accessed September 1, 2015].

Zhang, D.Q. et al., 2014. Application of constructed wetlands for wastewater treatment in developing countries--a review of recent developments (2000-2013). *Journal of environmental management*, 141, pp.116–31. Available at: http://www.sciencedirect.com/science/article/pii/S0301479714001509 [Accessed January 12, 2016].

Zhou, J.B. et al., 2009. Emergy evaluations for constructed wetland and conventional wastewater treatments. *Communications in Nonlinear Science and Numerical Simulation*, 14(4), pp.1781–1789. Available at: http://www.sciencedirect.com/science/article/pii/S1007570407002353 [Accessed January 11, 2016].

Zobrist, K. W. & B. R. Lippke (2007). "Economic costs of different riparian management regulations in the Pacific Northwest." Western Journal of Applied Forestry 22(1): 36-41.

Zumbroich, T. (1998). Ausführungsplanung HOAI – Innerörtlich – Einzelbauwerk – Zufluss Sieg. *Wasserverband Rhein-Sieg-Kreis,* (Project Report, unpublished).

Zumbroich, T. (2000a). Detailplanung zur ökologischen Optimierung einer Strecke des Eipbachs in Eitorf (Brückenstraße). *Wasserverband Rhein-Sieg-Kreis,* (Project Report, unpublished).

Zumbroich, T. (2000b). Ausführungsplanung HOAI – Innerörtlich – 100m – Zufluss Sieg. *Wasserverband Rhein-Sieg-Kreis,* (Project Report, unpublished).

Zumbroich, T. (2002). Ausführungsplanung und Bauüberwachung HOAI – Innerörtlich – 400m – Zufluss Rhein. *Stadtverwaltung,* (Project Report, unpublished).

Zumbroich, T. (2005a). Leistungsphasen 1-9 HOAI – Mischlage – Umgestaltung der Dhünn in Leverkusen im Bereich des Geländes der Landesgartenschau 3.000m, *Wupperverband,* (Project Report, unpublished).

Zumbroich, T. (2005b). Ausführungsplanung HOAI am Saalbach – Freie Landschaft – 200m – Zulauf Wupper. *Wupperverband,* (Project Report, unpublished).

Zumbroich, T. (2005c). Entwurfsplanung HOAI – Innerstädtisch – 16.000m – Zulauf Emscher. *Emschergenossenschaft,* (Project Report, unpublished).

Zumbroich, T. (2005d). Entwurfsplanung HOAI – Innerstädtisch – 3.000m – Zulauf Emscher. *Emschergenossenschaft,* (Project Report, unpublished).

Zumbroich, T. (2005e). Ausführungsplanung HOAI am Borbecker Mühlenbach – Mischlage – 200m – Zulauf Emscher. *Emschergenossenschaft,* (Project Report, unpublished).

Zumbroich, T. (2006a). Renaturierungsplanung am Endenicher Bach – Leistungsphase 1-9 HOAI - Innerstädtisch – 300m – Zulauf Rhein. *Stadtverwaltung,* (Project Report, unpublished).

Zumbroich, T. (2006b). Entwurfsplanung HOAI – Innerstädtisch – 2.000m – Zulauf Wupper. *Wupperverband,* (Project Report, unpublished).

Zumbroich, T. (2006c). Entwurfsplanung HOAI – Innerstädtisch – 1.500m – Zulauf Wupper. *Wupperverband,* (Project Report, unpublished).

Zumbroich, T. (2007). Renaturierungsplanung – Leistungsphase 1-4 HOAI - Innerstädtisch – 2.000m – Zulauf Emscher. *Emschergenossenschaft,* (Project Report, unpublished).

Zumbroich T., Meier G. & Klüver M. (2009): "Konzept zur naturnahen Entwicklung für die Bever und ihre Zuläufe." Auftraggeber: Wupperverband (unpublished).

Zumbroich T. & Meier G. (2009): "Priorisierung von geplanten Maßnahmen an der Unteren Dhünn und Oberen Wupper." Auftraggeber: Wupperverband (unpublished).

Zumbroich, T. (2011). Renaturierungsplanung von Gewässerstrecken im Bereich der Klosteranlage Heisterbach – Leistungsphasen 1-9 HOAI – Ertüchtigung von drei Teichen intramuros. *Rhein-Sieg-Kreis – Projekt der Regionale 2010,* (Project Report, unpublished).

Zumbroich, T., Meier, G, J. Roehrig (2012). Adaptive Methode zur Bewertung der Gewässerstruktur und zur Priorisierung von wasserwirtschaftlichen Entwicklungsmaßnahmen, *gefördert im Rahmen des Ziel 2 – Programms NRW 2007-2013 „Regionale Entwicklung und Beschäftigung (EFRE)“ unter dem Förderkennzeichen 005-1010-0023,* (Project Report, unpublished).

Zumbroich T. & Meier G. (2012): "EU-WRRL-Umsetzungsfahrplan der Kooperation KOE_59." Auftraggeber: Wasserverband Rhein-Sieg-Kreis. http://www.wasserverband-rsk.de/umsetzungsfahrplan.php

Zumbroich, T. (2012). Vorplanung zur ökologischen Umgestaltung der Berne und einige ihrer Zuläufe in Essen - gewässerökologischer Teil. *Hydro-Ingenieure (im Auftrag der Emschergenossenschaft),* (Project Report, unpublished).

Zumbroich, T. (2015). Renaturierungsplanung des Borbecker Mühlenbaches in Essen, Hydro-Ingenieure *(im Auftrag der Emschergenossenschaft),* (Project Report, unpublished).

Zumbroich, T. & G. Meier (2015). Bewertung des hydromorphologischen Zustandes der Oberflächenwasserkörper Luxemburgs auf Grundlage der Strukturgütekartierung, *Administration de la Gestion de lÉau, Luxembourg 2015* (Project Report, unpublished).